TASKS FOR VEGETATION SCIENCE – 47

Sabkha Ecosystems

Volume IV: Cash Crop Halophyte and Biodiversity Conservation

edited by M. Ajmal Khan, Benno Böer, Münir Öztürk,
Thabit Zahran Al Abdessalaam, Miguel Clüsener-Godt
and Bilquees Gul

Springer

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With support of
Pakistan Academy of Sciences

Springer

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ISSN 0167-9406 ISSN 1875-130X (electronic)
ISBN 978-94-007-7410-0 ISBN 978-94-007-7411-7 (eBook)
DOI 10.1007/978-94-007-7411-7
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2002024322

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Foreword

Many years ago we started seriously looking into the possibility of developing coastal salt deserts into man-made ecosystems for agricultural productivity, with the food supply requirements of the growing global human population in mind. It was in Italy, on the island of Sicily that scientists enthusiastically invented the slogan “Cash Crop Halophytes”. Well, here is the first volume dealing with this subject. Lieth and Lieth supported this development as much as they could, and we are very happy to provide the foreword to this volume. Academicians in the past had limited access to the world of business people, land-owners, land-developers, bankers, politicians, and decision makers. This has fortunately changed. The world has begun to listen. This is important and needs to be continued.

Studies undertaken in the arid regions have revealed that various medicinal/aromatic plants can be cultivated easily on slightly saline-alkaline soils using sea water irrigation. Many salt-tolerant plant taxa found in nature can be domesticated to provide better economic returns. In the same time they can assist ameliorating degraded saline lands, which is in the best economical interest of the rural communities. In order to advance food production on saline soils, more salt-tolerant species need to be catalogued with special reference to their ecology and salt tolerance. There is no dearth of biodiversity in saline habitats, particularly in coastal areas. What is needed is vision, planning and involvement of scientific and agricultural authorities and politicians.

As one of the results of our joint perseverance the International Society of Halophyte Utilization (ISHU) was formed. ISHU was at first located in Germany, and, later, based on a number of reasons, it was relocated to Egypt. From there it has been moved to Pakistan, where it is currently being located, at the University of Karachi, with the same acronym, but a new name: the Institute for Sustainable Halophyte Research. It has been supported by UNESCO. Numerous other projects generated good results, for example in the United Arab Emirates, Mexico, The Netherlands, Eritrea, and other countries. The editors tried to identify and invite them all to make contributions to this volume.

Springer as the selected publishing house has produced already three volumes of the book series on Sabkha Ecosystems: the first volume dealt with the definition and acceptance of the term “sabkha” for the international scientific community, as well as with the sabkha ecosystems of the Arabian Peninsula and adjacent countries. The second volume dealt with sabkha ecosystems of West and Central Asia, and volume three brought information of sabkhat in Africa and southern Europe. We thank the colleagues from Springer for their continuous support.

Three more volumes are anticipated to complete this globally most comprehensive series on sabkha ecosystems:

(a) Cash crop halophytes and biodiversity conservation
(b) Sabkha ecosystems of the Americas
(c) Sabkha ecosystems of Asia/Pacific

With this, the series will undoubtedly be the most comprehensive scientific documentation providing information about sabkha ecosystems, their ecology, their development potential, and heritage and education value.

The theme of Volume IV *Cash Crop Halophyte and Biodiversity Conservation* is very timely: no longer do we merely try to understand the importance of sabkha ecosystems for sustainable development, but we also start to understand the tremendous importance of sabkha for the conservation of halophyte biodiversity, the huge capacity of halophytes for the production of economically important products, but we also start understanding the capacity of halophytes to counter-act adverse environmental impacts, such as climate change, marine discharge waters, ecosystem restoration, and the enhancement of primary productivity.

This volume includes elaborations on the advantage of genetic manipulation of halophytes versus the genetic modification of conventional cash crops towards high salinity tolerance. It offers an initial insight into the possibility of reducing the adverse impacts of marine cooling waters for power plants via halophyte farms, sheds some light on the huge capacity of seagrass and macro-algae domestication, and, for a first, it discusses the possibility to reduce land-based marine pollution (nitrogene, phosphates, potassium) to minimize harmful-algal-blooms, as well as atmospheric carbon levels, via the establishment of floating mangroves in sub-tropical and tropical coastal environments.

The biodiversity conservation of halophytes has been addressed several times over the last few years, but the people of the world have still not developed a “World Halophyte Garden”, with the aim to conserve the entire halophyte germplasm of the world in one single garden, in order to have the genetic material available that will be needed for future coastal and marine restoration and development projects.

We would not like to conclude this foreword without paying tribute to the late President of the United Arab Emirates, and Ruler of Abu Dhabi, His Highness Sheikh Zayed bin Sultan al Nahayan: it was under his wise leadership that the UAE developed into the foremost country globally for the development of mangrove coverage. Unlike most other countries, the UAE has succeeded to increase their mangrove coverage significantly.

We wish the editors and authors of this volume the best of success and we encourage the scientific community to take the results, recommendations and suggestions very serious. Here are a number of highly important ideas and findings presented, which are of great value for mankind, to deal with issues of relevance to keep the global human life support systems intact, and with a special view to the global water crisis, the global food crisis, and above all, the possibility to sequestrate carbon from the atmosphere, which is a key element regarding the very serious threat to human life support system: global climate change.

We have to realize: Halophytes are really a blessing for mankind. Let us use it.

Osnabrück, Germany
Prof. emeritus Dr. Helmut Lieth
and Mrs. Marina Lieth

Preface

The State of Qatar has undergone substantial economic and social developments during the last few decades, with the population nearing 1.9 million in 2013. To sustain this growth, demand for water has increased significantly in a region that is already known for its limited water resources. Though carbon-intensive desalinization of seawater has been used to redress water scarcity, this scenario makes agricultural food production very challenging. Food security is a real threat to development in the Arab world, where levels of reliance on food imports are among the highest in the world.

In November 2012, Qatar University supported the Qatar National Food Security Program, established by HH Sheikh Tamim Bin Hamad, in hosting an International Conference on *Food Security in Dry Lands*. The event brought together governmental officials, researchers, development experts, and representatives of civil society to dialogue about strategies for reducing food insecurity and boosting food production in dry lands.

As the national institution of higher education with a mission to support the social and economic development of the country, Qatar University is committed to the vision of HH Sheikh Hamad Bin Khalifa Al Thani for sustainable development. Through its various research centers and academic programs, the University contributes to the investigation of potential solutions to sustainability challenges. We believe that innovative education, collaborative research, and dialogue among stakeholders are absolutely essential in addressing the development challenges of our time.

It is with this background in mind that I accepted to write this Preface of *Sabkha Ecosystems Volume IV: Cash Crop Halophyte and Biodiversity Conservation*.

Most countries of the Arab Region suffer from a lack of freshwater, and this is certainly one of our most limiting resources. The situation is similar in other dry lands in the world. Climate change makes the unstable water-security situation even less predictable. Seawater, however, is available in abundance in our region and in many dry land countries. The international scientific community has made limited but steady progress developing salt-tolerant plant species as cash-crops, and attempts are ongoing to enhance research and implementation in farming and landscaping. The Gulf's marine ecosystems provide a particularly appealing opportunity for this area of research.

The editors and authors of this new volume have relentlessly continued to work on this important contribution towards food-security, and research and development of salt-tolerant cash-crops under hyper-saline conditions.

They have already produced three volumes, dealing with the Arabian Peninsula and adjacent countries, West and Central Asia, Africa and Southern Europe, and this new volume deals with global experiences and suggestions regarding cash crop halophytes and halophyte biodiversity conservation *ex situ* and *in situ*.

The fourth volume includes contributions from various parts of the world, and provides new information about several halophyte research and development aspects. The development aspects are more pronounced in comparison to the three earlier volumes, which indicates an increased interest in the application of salt-water and sea-water irrigation in agriculture.

I thank the contributors for their efforts and professionalism, and I encourage all concerned stakeholders, students, researchers, academicians, decision makers, donors, and the agricultural sector to actively support and participate in this important cause.

President, Qatar University,
Doha, Qatar

Sheikha Abdulla Al Misnad, Ph.D.

Acknowledgements

We gratefully acknowledge the financial assistance given by Pakistan Academy of Sciences for the publication of volume IV and Institute of Sustainable Halophyte Utilization, University of Karachi, for other technical support. Thanks are also due to Dr. Muhammad Zaheer Ahmed, Assistant Professor, Institute of Sustainable Halophyte Utilization, University of Karachi, for his work in organizing the manuscripts.

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Introduction

The world's population has increased by another billion humans over the last decade, and has reached a total exceeding seven billion people. However, planet Earth and its natural resources did not grow, including air to breath, food to eat, and water to drink. Some of resources, for example fossil fuel, fresh-water and biodiversity, even declined. Climate change and increased resources consumption are expected to accelerate this undesired situation. This is particularly difficult in the dry lands. Various different forecast models predict a continuous increase of the human population at least until 2040, and at least by another billion, reaching a total of eight billion people. With this in mind, we have to find new avenues for the production of food and clean energy, as well as reduce the pressure on limited fresh-water resources for agriculture in dry land countries.

The overall research and development work of numerous scientists, developers, and specialists is of great importance to achieve progress in this field. Significant achievements have been made however, their full potential is not yet used: Freshwater intensive *Cynodon dactylon* (Bermuda-grass), for example, could theoretically be replaced by *Sesuvium portulacastrum*, which can be irrigated with full strength sweater, provided it has a coarse substrate. Even though *Sesuvium* is now widely used in coastal dry desert places between Sharm El-Sheikh, Kuwait, Doha, Al Ain, and Muscat, it is still being irrigated mainly with fresh-water. The irrigation and drainage technology for halophyte amenity plants needs to be studied, improved, and applied. It was already shown in the 1990s in Abu Dhabi's experimental farm, that *Sesuvium* is seawater tolerant.

This volume contains a number of chapters dealing with halophyte ecology, bio-geography, ecophysiology, hyper-saline soils, biofuels, biosaline agriculture, biosaline landscaping, climate change mitigation, and biodiversity. It also contains the communication of innovative ideas, such as the research into floating mangroves, seagrass terraces, as well as a World Halophyte Garden containing all known salt-tolerant plant species. It is hoped that the information provided will not only advance vegetation science, but that it will truly generate more inter-disciplinarity, networking, awareness, and inspire farmers, and agricultural and landscaping stakeholders to seriously engage in halophyte cash crop production in coastal hyper-saline areas.

Benno Böer
M. Ajmal Khan

The original version of this book was revised. An erratum to this book can be found at http://dx.doi.org/10.1007/978-94-007-7411-7_26

Spatial Distribution of Soil Salinity and Management Aspects in the Northern United Arab Emirates

Mahmoud A. Abdelfattah and Shabbir A. Shahid

Abstract

The United Arab Emirates is situated in the hyper-arid dry land system where the aridity index (P/PET) is less than 0.05, and hence it is a water stress country. To offset the crop water requirements, irrigation is accomplished mainly with saline/brackish ground water, few progressive farmers use desalinated water using small scale reverse osmosis plants. Mismanagement of these resources leads to soil salinization in the agriculture regions, and in the coastal lands through sea water intrusion. Owing to better management of salt-affected soils to optimize agriculture production, it is essential to characterize root zone salinity as spatial distribution. Regular monitoring identifies future spread of the salinity problem and leads to informed decisions. We attempted to assess soil salinity in the Northern Emirates through a soil survey by investigating 10,200 observation sites on a grid basis, and measuring water and root zone salinity of some agricultural farms. We used a combination of techniques, i.e., remote sensing, GIS, grid survey observation at a depth of 50 cm, and laboratory analyses of soil samples. The electrical conductivity "EC" of 1:1 soil:water suspension was measured for all the observation sites and correlated to EC of soil saturation extract (ECe). Based on the USDA salinity classes (0–2, 2–4, 4–8, 8–6, 16–40 & >40 dS m^{-1}), the NE is divided into

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_1,

six salinity zones, revealing large area (83 %) as non-saline, 10 % (very slightly saline), 4 % (slightly saline), and 3 % moderately, strongly, and very strongly saline, the latter two types are confined to the coastal sabkha (due to sea water intrusion), and at the edge of the mountain and inter-dunal sabkhas. Salinity is also observed in agricultural farms irrigated with saline waters, where it has been diagnosed that root zone salinity is not managed properly. We have outlined the management aspects for these saline soils which can be used as a guide for future management and land use planning in the study area.

Keywords
Salinity mapping • Sabkha • Hyper-arid conditions • RS • GIS • Northern Emirates • UAE

1 Introduction

The United Arab Emirates (UAE), federation of seven emirates, is situated in the hyper-arid dryland system where the ratio of precipitation (P) and Potential Evapotranspiration (PET), defined as aridity index (P/PET), is less than 0.05, and hence it is a water stress country. Among seven emirates constituting UAE, Abu Dhabi and Dubai emirates have completed soil inventory and salinity mapping [1, 2], but the Northern Emirates (NE) (Ajman, Fujairah, Ras Al Khaimah, Sharjah, and Umm Al Quwain), and hence this has formed the focus of the paper. Soil salinity is the most discussed issue worldwide from agriculture production and ecosystem management perspectives. It is spreading globally over one billion hectares in all continents. However, the level of salinity problem varies trans-country and even within the country at different locations, landforms, and irrigated agriculture regions to farmers' fields [3]. Worldwide, one in five hectares of irrigated land is suffering from soil salinity and vast areas in China, India, Pakistan, Central Asia, and the United States is losing productivity [4]. About 77 million hectares have been salinized as a consequence of human activities, with 58 % of these concentrated in irrigated areas [5]. On average, 20 % of the world's irrigated lands are affected by salts, but this figure increases to more than 30 % in countries such as Egypt, Iran and Argentina. Generally, soil salinity is limiting food production in many countries of the world. Earlier estimate presents 10 % of the total arable land to be affected by salinity and sodicity and extends over more than 100 countries and almost all continents [6]. However, recent estimates of soil salinity worldwide do not occur, and this is the area where future emphasis should be given. The mechanisms of salinization varies based on many factors, it can be developed through poor management of saline water irrigation, water balance between rainfall, stream flow, groundwater level and evapotranspiration, deforestation and subsequent rise of water table and evaporation, water percolation through saline materials; and seawater intrusion [7]. The salinity can be primary (naturally occurring dryland salinity) and human-induced salinity (secondary). Regardless of salinity types, the development of plants and soil organisms on these lands are affected leading to low crop yields [8].

For an efficient management of salt-affected soils, we need to measure and map soil salinity which is spatially variable and dynamic. This variability is the outcome of different pedological factors like water table depth, topography, parent material, etc. [9]. To keep track of spatial and temporal dynamism of soil salinity and to anticipate future spread, mapping, and regular monitoring is of prime importance [10]. Several studies have assessed and monitored salt-affected soils at national and regional scales [11]. Examples are irrigated agriculture in Arab countries [12], India

[13], Thailand [14], Iran [15], Egypt [16], China [17], and Sudan [18]. Recently, presented a comprehensive review on the developments in soil salinity, assessment, modeling, monitoring from regional to submicroscopic levels, as well as procedural matters (RS, GIS, geostatistics, modeling, submicroscopic, modern and routine methods) [3]. A full section on high-tech in soil salinity mapping and monitoring including papers from Spain, South Africa, Thailand, Uzbekistan, Russia, Egypt, Iran, Morocco, USA and India, has been dedicated in the recently published book "Developments in soil salinity assessment and reclamation" [19].

Keeping in mind the influence of soil salinity on agriculture production and ecosystem services, we characterize and map soil salinity status in the Northern Emirates to develop salinity zones for informed decisions to manage soil resources. Managing saline soils is highly site specific and depends on factors such as nature of soils, soluble salts, and local hydrological conditions.

1.1 UAE and the Dry Land Systems

Dry land Systems (DLS) refer to land areas where the mean annual precipitation (P) is less than two-third of potential evapotranspiration (PET). Figure 1 shows global dryland systems (DLS), where either there is lack of water or facing water stress to various levels [20]. Four dry land subtypes are widely recognized based on P/PET: dry sub-humid (0.5–0.65), semiarid (0.2–0.5), arid (0.05–0.2) and hyper-arid (<0.05), showing an increasing level of aridity or moisture deficit. Hyper-arid areas are considered as true deserts. The global DLS (hyper-arid, arid, semi-arid, dry sub-humid) presents different agro-climatic conditions. Therefore, it can be genuinely stated that, drylands management options may be very different for one DLS than the others, for example sub-humid dryland system with rainfall between 200 and 800 mm per annum will require different management than the arid and hyper-arid climates, where rainfall is less than 200 mm per annum. Dry lands have less than 8 % of the world's renewable water resources, the water scarcity in addition to other factors (such as soil and water salinity), are the main limitation in sustainable food production in DLS marginal lands. In such countries agriculture is practiced on environmental cost (high water abstraction and low renewable water) due to depletion of water resources and increase in soil and water salinization. The UAE is situated in the hyper-arid DLS (Fig. 1).

1.2 The Study Area

The NE lies between latitude 24° 44′ and 26° 04′ N and longitude 55° 20′ and 56° 22′ E (Fig. 2) and consist of five (Ajman, Fujairah, Ras Al Khaimah, Sharjah, and Umm Al Quwain) of the seven emirates that make up the UAE. Together they make up 8.2 % of the UAE surface area (82,880 km^2). The climate of the NE is generally hot and dry with a sub-tropical arid climate, and is warm in winter with hot and humid conditions in summer. Temperature may reach 48 °C [21] (Table 1). The soil temperature regime is hyperthermic (mean annual soil temperature is 22 °C or higher, and the difference between mean summer and mean winter soil temperature is 6 °C or more either at a depth of 50 cm below the soil surface or at a densic, lithic, or paralithic contact, whichever is sallower) [22]. The average annual rainfall in the coastal area is 120 mm, but in some mountainous areas it often reaches 350 mm. The landscape ranges from small areas of level coastal plains and sabkha (salt scald) to undulating desert sand plains, extensive areas of linear and transverse dunes, an alluvial plain up to 15 km wide, and mountainous rocky outcrops along the Hajar Mountains which rise to 2,980 m. In the western part, there are linear dunes up to 100 m high, interspersed with small areas of almost level deflation plains and flats.

1.3 Agriculture and Farms in the NE

Most of the farms in the NE are in the three emirates of Sharjah, Ras Al Khaimah, and Fujairah, with smaller numbers in the other two emirates. Sharjah and Ras Al Khaimah have much larger areas in farms than the other three

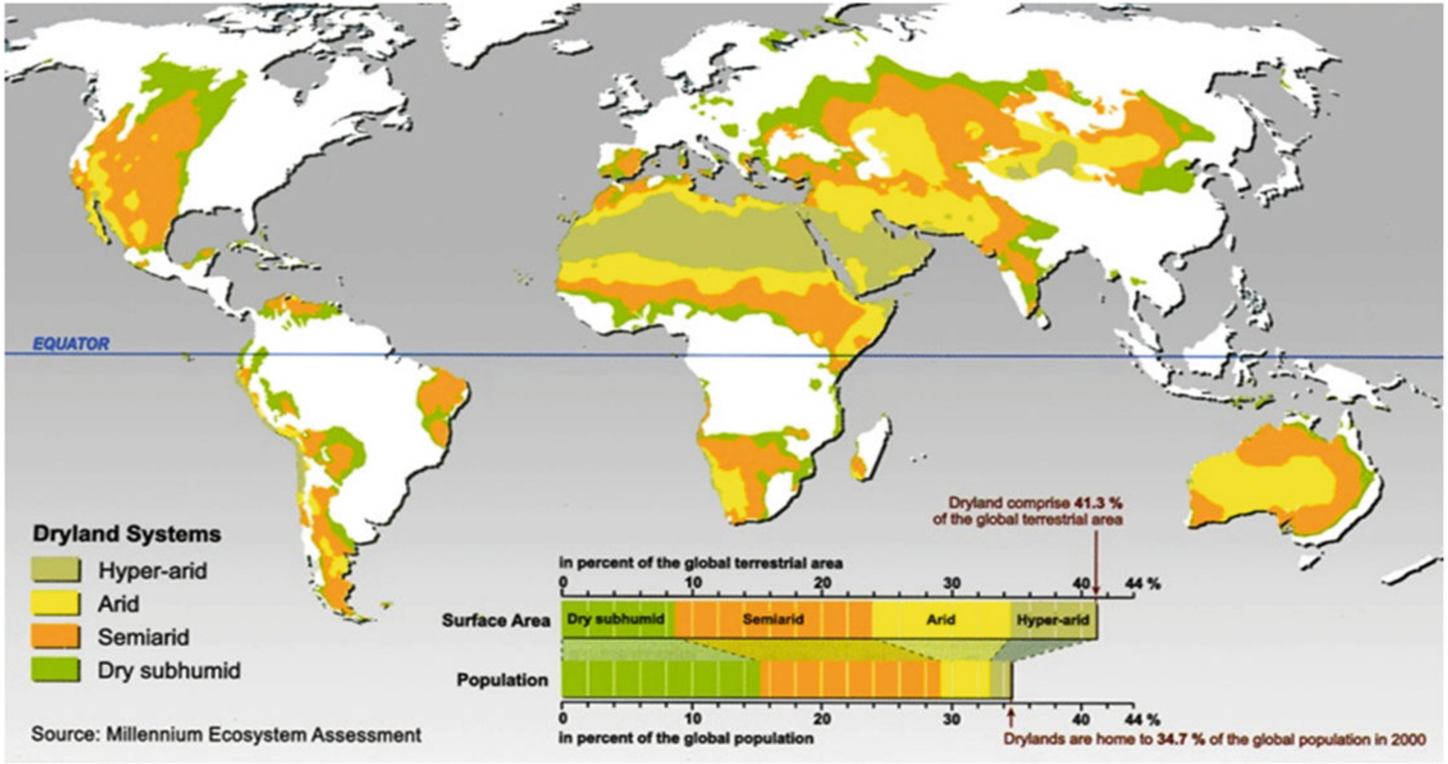

Fig. 1 Dryland systems (Source: MEA [20])

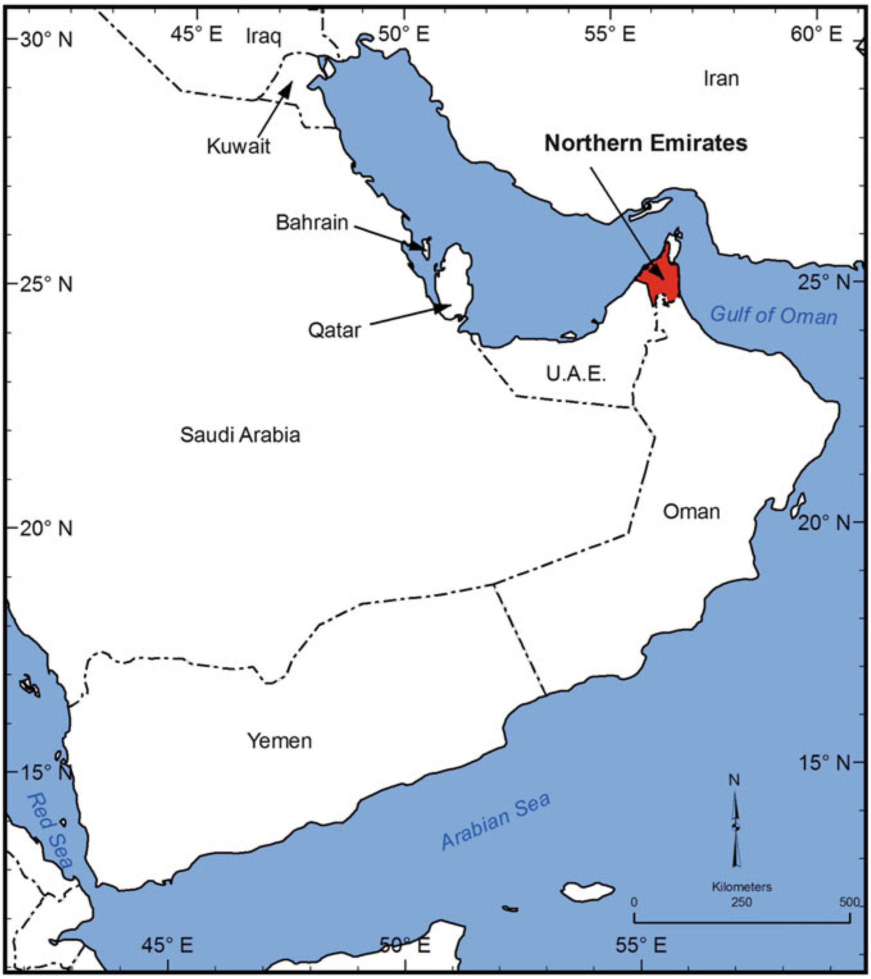

Fig. 2 Location map for the Northern Emirates

Table 1 Climatic data for the Northern Emirates

	Air temperature (°C)			Soil temperature (°C)			Relative humidity (%)			Rainfall (mm)	Evaporation (mm/day)	Wind speed (km/h)	
Month	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Mean	Mean	Mean	Max.
Jan	31.7	18.3	09.0	33.8	21.7	12.8	100	60	2	18.3	9.2	10	66
Feb	34.1	20.7	07.7	39.8	25.0	13.0	100	53	1	15.1	11.5	9	47
Mar	38.1	24.2	12.4	46.1	30.1	16.9	100	43	1	3.7	9.7	10	52
Apr	43.2	29.0	15.4	52.5	35.7	21.6	100	33	2	8	11.1	10	54
May	46.5	33.5	19.8	55.2	41.2	28.4	100	27	2	0	15.0	10	50
Jun	48.6	35.7	23.7	57.3	43.7	32.0	100	33	2	0	15.8	10	41
Jul	47.8	36.3	26.6	56.8	44.4	34.2	91	40	2	0	14.9	12	49
Aug	47.7	36.3	28.2	57.4	44.2	32.3	96	41	4	1.6	14.6	11	49
Sep	45.5	33.7	22.9	55.4	40.9	29.2	98	42	2	3.8	14.0	10	51
Oct	43.0	30.1	18.9	50.2	36.3	25.3	100	45	4	0	13.9	8	47
Nov	38.0	25.2	13.5	44.1	30.3	19.5	100	54	7	0.8	11.5	8	35
Dec	31.4	20.2	08.8	35.9	24.2	12.4	100	63	7	14.1	10.0	8	40
Mean/ (total)	41.3	28.6	17.2	48.7	34.8	23.1	98	44.4	3.0	(65.4)	12.6	09.8	48.4

Source: NCMS [51] and Raafat [21]

Table 2 Cultivated areas and number of farms by Emirate in 2009

	Emirates					
	Sharjah	Ajman	Umm Al Quwain	Ras Al Khaimah	Fujairah	Total
Palm tree	4,824	502	385	3,762	2,258	11,731
Other permanent crops	1,551	357	182	1,066	978	4,134
Crop and fodder	1,599	248	289	2,419	359	4,914
Vegetables	1,667	184	176	2,446	721	5,194
Greenhouses	23	2	2	55	19	101
Shifting area	3,244	682	334	3,498	860	8,618
Cultivated area (ha)	12,908	1,975	1,368	13,246	5,195	34,692
Number of farms	4,392	691	343	4,465	5,324	
Average farm size (ha)	3.02	3.04	4.94	3.04	1.23	

Source: Ministry of Environment and Water [52]

emirates. Farms range from 1 to 5 ha in size (Table 2). Crops grown include dates, vegetables, and fodder. The area south of Ras Al Khaimah in the north is an important farming center because of the high suitability and low salinity of the soils in the area.

2 Materials and Methods

In recent years new techniques have been developed for salinity mapping including remote sensing (RS), geophysical methods, determining the electrical conductivity of a soil ‘saturation extract’ (ECe) or at different soil:water ratios [19, 23]. The choice of the technique ultimately depends upon the purpose of the study, size of the area, frequency of measurement, and accuracy required. To have a clear view of the current status of soil salinity in the NE, we have used a set of techniques for soil salinity assessment and mapping. This has involved an interpretation of RS imagery (Indian Remote Sensing “IRS”, Landsat ETM, ASTER, and SRTM DEM) supported by ground truthing of over 10,200 sites at 0–50 cm depth where EC of 1:1 soil:water suspensions was measured. This was later correlated to ECe using a relationship ($ECe = EC\ 1{:}1 \times 3.35$) developed on UAE soils [3]. GIS was used for data entry, management, processing, interpretations, and production of maps as detailed below.

2.1 Processing of Remote Sensing Imagery

Remote sensing (RS) coupled with conventional ground truthing data [24], and the integration between RS, GIS, and spatial statistics provide useful tools for modeling variability to diagnose pattern of characteristics [25]. Delineation of saline soils using these techniques has been proven efficient in different studies [26–31]. In this study IRS imagery, Landsat ETM satellite data, ASTER-derived digital elevation, Shuttle Radar Terrain Mission (SRTM) and Digital Elevation Model (DEM) were used. Orthorectified Landsat imagery from ‘NASA’s Global Orthorectified Landsat Data Set’ [32] was used as the survey control for the IRS imagery. Although the spatial resolution of the Landsat imagery is too coarse to be used as a backdrop to the field maps, it is nevertheless very useful for spectral analysis of the soils. In addition to the six-band calibrated mosaic, enhanced Landsat 742 RGB GeoTIFF combinations were prepared so that the use of an image processing system was not required to view the data. Figure 3 depicts unsupervised classification of the alluvial plain, adjacent to Hajar Mountain, draped over the SRTM digital elevation model (DEM). Comparing locations on this image against the corresponding soil map indicates that some of the differences in this image correlate with differences in soil and landscape features. The resulted map was used as guide prior to fieldwork activities.

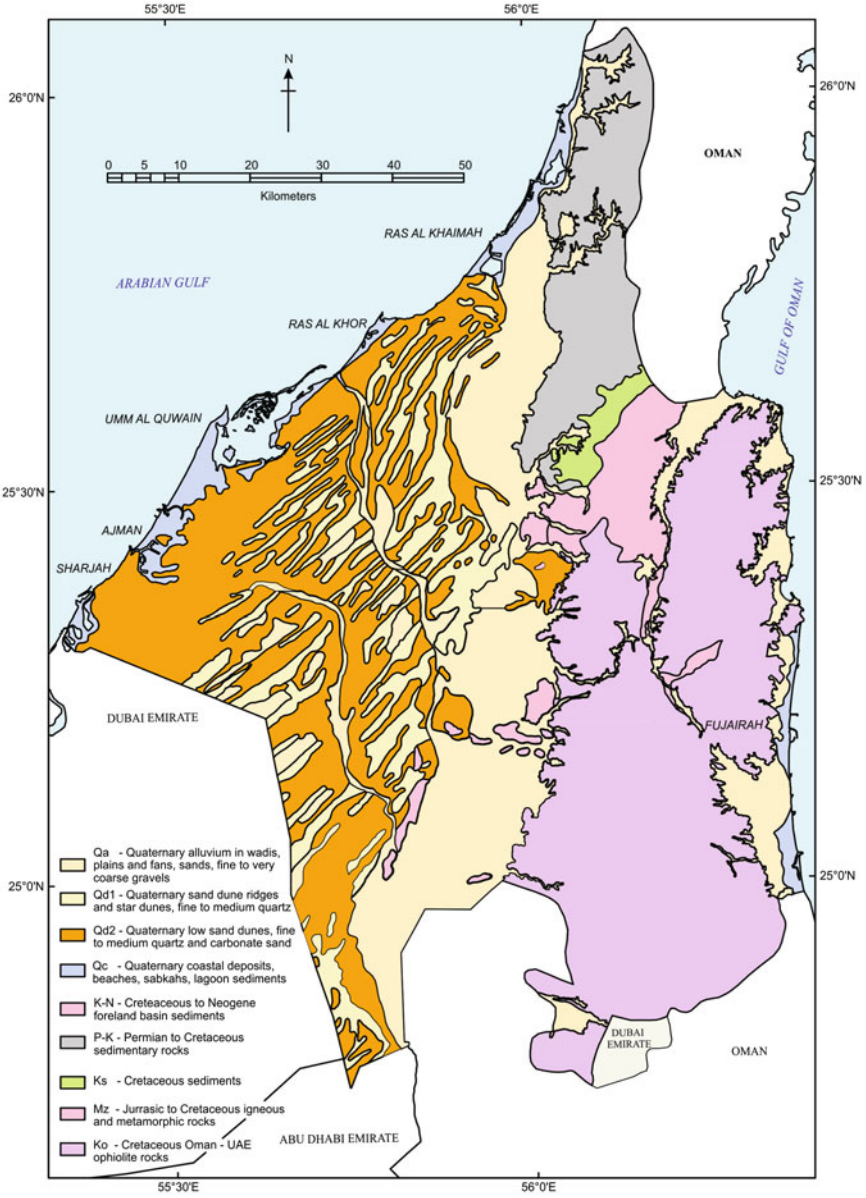

Fig. 3 Unsupervised classification for the western alluvial plain draped over the SRTM digital elevation model

2.2 Fieldwork and Data Collection

Soil salinity mapping is a part of a larger soil inventory study in the NE [33]. Fieldwork at a scale of 1:50,000 was undertaken during 2010–2012. A total of 10,200 observation sites (Fig. 4) at a grid of 550 × 550m to a depth of 200 cm across the study area were investigated. Each site was described for morphological description (i.e., slope, landscape, landform, erosion, land use and cover, drainage class, surface condition) and in-depth soil horizons

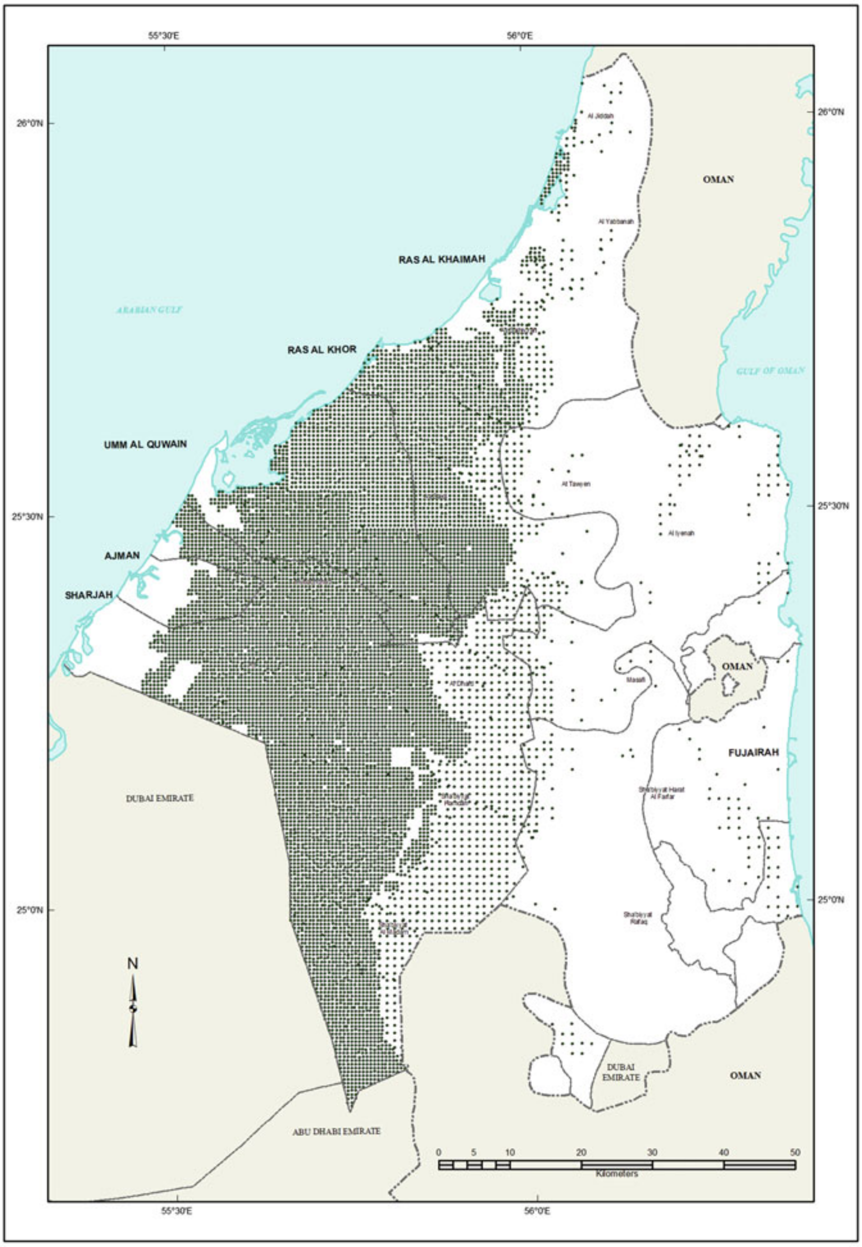

Fig. 4 Location of observation points in the study area

description (colour, texture, structure, consistence, concretions, gravels, excavation difficulty, and effervescence). Soil samples from different horizons (2–5 at least) of each investigated sites were analysed in the field for salinity measurement using 1:1 soil water suspension. Representative samples were analysed using soil paste extract for ECe for correlation. Relationships between the EC and ions were established from 1:1 and saturated paste extracts using regression equations [34]. They found that these soil properties are highly correlated but the correlation depends on ionic charge and soil texture (fine texture with less than 60 % of sand as opposed to coarse texture). Based on these relationships and the analysed samples from the same area in the laboratory, the EC of the 1:1 soil water suspension were converted into ECe by multiplying them by a factor of 3.35. This was based on a comparison of field (EC 1:1 soil water suspension) and laboratory (ECe soil paste extract) measured results from UAE soils. The EC values were used to calculate an average EC value (weighted for horizon thickness) for the first 50 cm layers of soil at each site. This ECe value was used to calculate the average salinity of each soil type and subsequently soil map unit, which was later used to develop the overall salinity map. The data in Table 3 demonstrate soil classes, their extent, and the overall soil salinity value for each.

2.3 Converting Point Data into a Generalized Map

The salinity map was generated as an attribute of the soil map. The soil map is composed of number of map units; each of them consists of number of component soils in different proportions. For each soil component, a representative ECe value was assigned, and then an overall ECe value was calculated for the map unit based on a weighted average of the components making up the map unit (Table 3). Each map unit was then placed into one of six salinity zones. The ECe 0–1.99 dS m^{-1} is rated as 1 (non-saline), ECe 2–3.99 dS m^{-1} is rated as 2 (very slightly saline), ECe 4–7.99 dS m^{-1} is rated as 3 (slightly saline), ECe 8–15.99 dS m^{-1} is rated as 4 (moderately saline), ECe 16–39.99 dS m^{-1} is rated as 5 (strongly saline), and ECe >40 dS m^{-1} is rated as 6 (very strongly saline) (Table 4) [35] and the appropriate rating allocated to the map unit. This procedure has been repeated for each map unit to generate the salinity map for the whole area at a scale of 1:50,000. Table 4 shows the ECe rating categories for salinity in the 0–50 cm layer and summary of areas identified for each emirate. A map illustrating the distribution of salinity in the 0–50 cm soil layer is presented in Fig. 5.

3 Results and Discussion

3.1 Delineation of Surface Salinity

The landscape salinity zones can guide for informed decisions on land use planning, such as designing experiments [36–39], sampling strategy [40, 41], and soil reclamation [42]. In the present study a depth of 0–50 cm was chosen to represent plant root zone depth. The high electrolyte concentrations reduce water absorption by plants due to increase in osmotic pressure in the soil solution. Salts may also interfere with the exchange capacity of nutrient ions, thereby resulting in nutritional imbalances in plants. Field investigation revealed high saline zones in the sea coast developed through sea water intrusion. The coastal area was either devoid of vegetation or only highly salt tolerant (halophytes) vegetation was recorded such as in Um Al Quwain (Fig. 6). Figure 7 presents typical salt crust in the coastal sabkha of the NE. Soil salinity has also been recorded in agricultural farms, but to a much lower level compared with sabkha area (Fig. 8).

3.2 Classification of Saline Soils in the Coastal Sabkha of the NE

In the USDA Soil Taxonomy [22] hierarchy (order, suborder, great group and sub group), true saline soils are identified in the order “Aridisols” and suborder “Salids” divided into Aquisalids and Haplosalids (great groups). At the subgroup levels various Aquisalids (gypsic, calcic, anhydritic, typic) and Haplosalids (duric, petrogypsic, gypsic, calcic, typic) are reported. The Salids are equivalent to Solonchaks (saline soils in Russian classification system). In the Northern Emirates, only Salids have been mapped. The Salids have a salic horizon within 100 cm of the surface. Salic horizon has accumulation of salts more soluble than gypsum in cold water. It is characterized by the followings: (1) 15 cm or more thick and has, 90 consecutive days or more in normal years; an electrical

Table 3 Soil classes, their extent, and the overall soil salinity value

Soil class	Extent (ha)	Salinity 0–50 cm (ECe dS m^{-1})	Soil class	Extent (ha)	Salinity 0–50 cm (ECe dS m^{-1})
Oxyaquic Torriorthents, sandy, carbonatic, hyperthermic	1,336	4	Typic Haplocalcids, sandy-skeletal, mixed, hyperthermic	6,066	0.9
Typic Torriorthents, fragmental, mixed, hyperthermic	9,259	1	Typic Haplocalcids, sandy, mixed, hyperthermic	7,875	0.5
Typic Torriorthents, sandy-skeletal, mixed, hyperthermic	36,996	1.5	Typic Haplocalcids, sandy, carbonatic, hyperthermic	5,403	0.5
Typic Torriorthents, sandy-skeletal, mixed, hyperthermic	10,581	1	Sodic Haplocambids, coarse-loamy, mixed, active, hyperthermic	3,372	3.7
Typic Torriorthents, sandy-skeletal, mixed, hyperthermic	5,327	8.5	Typic Haplocambids, coarse-silty, carbonatic, hyperthermic	4,390	2.3
Typic Torriorthents, sandy, mixed, hyperthermic	8,152	2	Typic Haplocambids, sandy over loamy, carbonatic, hyperthermic	250	1.5
Typic Torriorthents, sandy, mixed, hyperthermic	3,558	0.3	Leptic Haplogypsids, coarse-loamy over sandy or sandy-skeletal, carbonatic, hyperthermic	1,077	15
Typic Torriorthents, coarse-loamy, carbonatic, hyperthermic	5,064	3	Typic Haplogypsids, loamy-skeletal, mixed, superactive, hyperthermic	9,204	7
Typic Torriorthents, coarse-loamy, carbonatic, hyperthermic	23,204	2.5	Typic Calcigypsids, coarse-loamy, carbonatic, hyperthermic	5,224	4
Typic Torriorthents, coarse-loamy, carbonatic, hyperthermic	988	3	Gypsic Aquisalids, sandy, carbonatic, hyperthermic	1,023	75
Typic Torripsamments, carbonatic, hyperthermic	200,157	0.15	Gypsic Aquisalids, coarse-loamy, carbonatic, hyperthermic	1,476	40
Typic Torripsamments, carbonatic, hyperthermic	21,914	0.25	Typic Aquisalids, sandy, carbonatic, hyperthermic, shallow	378	28
Sodic Haplocalcids, coarse-loamy, carbonatic, hyperthermic	1,509	3.6	Gypsic Haplosalids, sandy, carbonatic, hyperthermic	1,508	55
Typic Haplocalcids, sandy-skeletal, mixed, hyperthermic	22,175	0.9	Gypsic Haplosalids, coarse-silty, gypsic, hyperthermic	346	5.5

conductivity (EC) ≥30 dS m^{-1} in the water extracted from a saturated paste; and (2) A product of ECe (dS m^{-1}) and thickness (cm), equal to 900 or more [22]. Salids have been mapped in the coastal salt flat above the high-tide level (coastal sabkha). These soils are strongly to very strongly saline (ECe exceeds 50 dS m^{-1}), due to the capillary rise of saline water and subsequent evaporation from a subsurface water table that lies within 200 cm of the surface. Salids are further classified at Great Group level into Aquisalids and Haplosalids.

Table 4 Salinity ratings in the 0–50 cm layer and summary of areas identified for each emirate

Rating category	Electrical conductivity (ECe dS/m)	Yield restriction	Area (ha)						
			Ajman	Fujairah	RAK[a]	Sharjah	UAQ[a]	Total	%
Non saline	0 to <2	Salinity effects mostly negligible	6,398	25,603	65,594	190,786	46,265	334,646	83.39
Very slightly saline	2 to <4	Yields of very sensitive crops may be restricted	2,537	131	15,330	11,585	10,830	40,412	10.07
Slightly saline	4 to <8	Yield of many crops restricted	0	3,826	5,248	10,422	0	19,495	4.86
Moderately saline	8 to <16	Only tolerant crops yield satisfactory	0	0	0	32	459	491	0.12
Strongly saline	16 to <40	Only a few very tolerant crops yield satisfactory	0	0	380	1,617	1,923	3,920	0.98
Very strongly saline	≥40	Halophytes are the only option	0	218	1,414	0	687	2,319	0.58
Total area (ha)			8,935	29,777	87,966	214,441	60,164	401,283	
Total area (%)			2.23	7.42	22.92	53.44	14.99		

[a] *RAK* Ras Al Khaimah, *UAQ* Umm Al Quwain

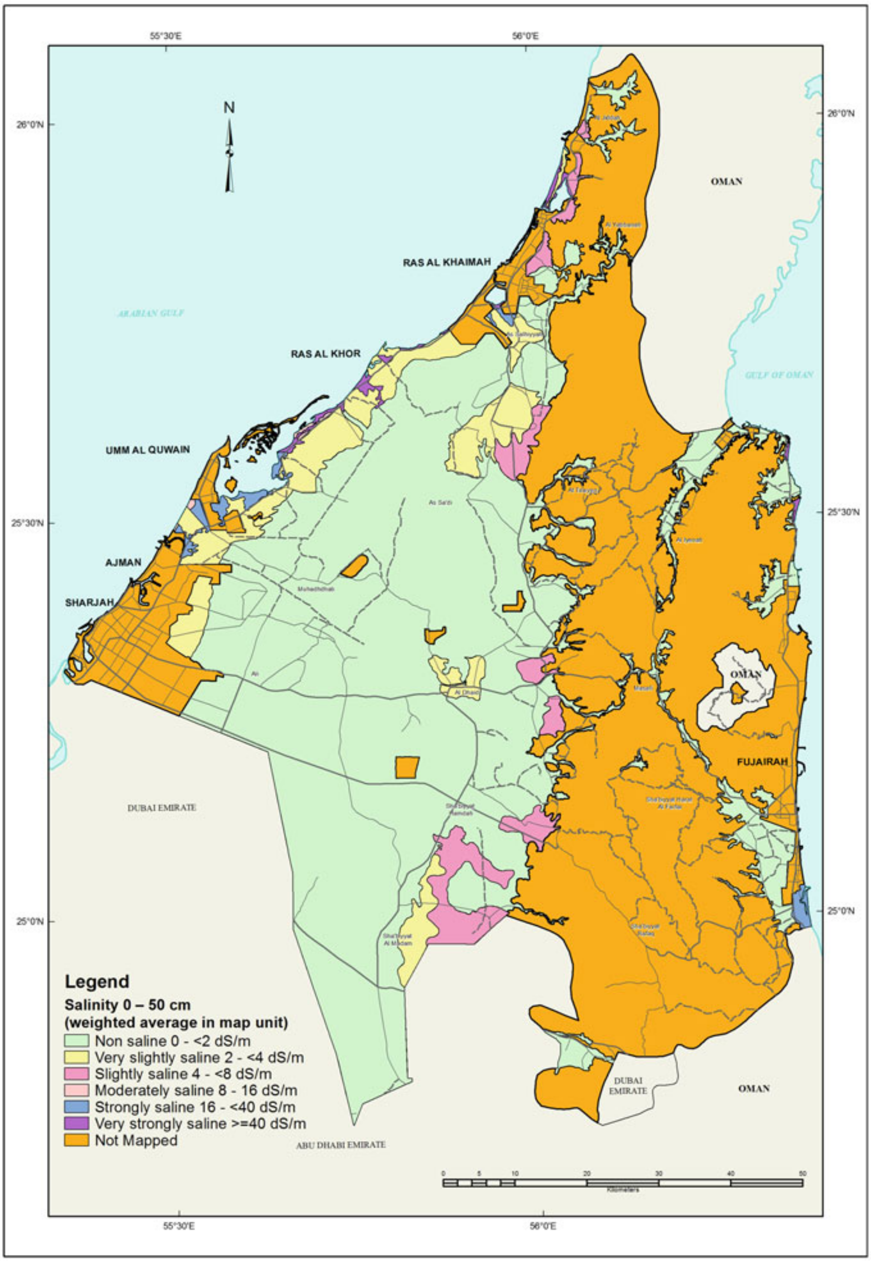

Fig. 5 Soil salinity map of the Northern Emirates

3.2.1 Aquisalids

Aquisalids are saturated with water in one or more layers within 100 cm of the surface. These are highly saline soils in wet areas where capillary rise and evaporation concentrate salts near the surface. These soils have redoximorphic features in the layers normally saturated with water (Fig. 9). Vegetation on Aquisalids is limited to salt-tolerant species and halophytes. Two subgroups of Aquisalids have been identified; (a) Gypsic Aquisalids (Aquisalids that, in addition to having a salt-rich salic horizon), also have an

Fig. 6 Coastal sabkha with halophytes near Um Al Quwain

Fig. 7 An example of coastal sabkha with surface salt crust in the Northern Emirates

accumulation of gypsum (gypsic horizon) within 100 cm of the surface, and (b) Typic Aquisalids: These Aquisalids only have a salic horizon and do not have a calcic or gypsic horizon within 100 cm of the surface.

3.2.2 Haplosalids

Haplosalids are the Salids that are not saturated with water within 100 cm of the surface. One subgroup is recognized in the NE – Gypsic Haplosalids: These are the Haplosalids that have

Fig. 8 Accumulation of salinity in the root zone of agricultural farms in the Northern Emirates

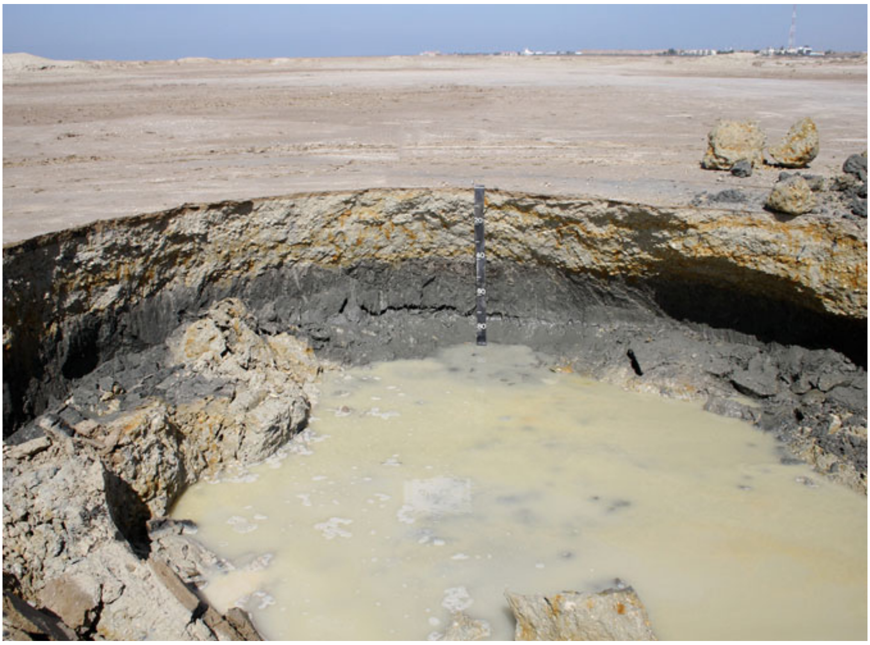

Fig. 9 Redoximorphic features in the Aquisalids of the Northern Emirates

both a salic horizon and a gypsic horizon within 100 cm of the soil surface. Due to their immediate vicinity to the sea, these coastal soils are not suitable for agriculture production. These soils have continuous sea water intrusion, which has been increased in recent years due to high water abstraction, and this has led salids extended slightly inland. These soils present only halophytes. Salt harvesting for commercial purposes (industrial use) could be an ideal choice from such areas.

3.3 Micromorphological Views of Saline Soils in the NE

Study of soil thin sections (25–30 μm thick) under the polarizing microscope allows in-situ views of soil fabric and its components. This is different to soil assessment whereby water is added into the soil (disturbed assessment) and soil extract studied by various equipment, this gives average composition and soil sample loses its recognition. Thin section preserves soil recognition. Recently [3] has published a review on soil micromorphological aspects of salt crusts from arid regions. We attempted to include this important assessment in the NE soil investigation, whereby we studied Gypsic Aquisalids under the polarizing microscope.

The investigation revealed dominance of gypsum crystals and brownish microcrystalline calcite. The b-fabric is granostriad (clay), infillings were not observed, intergrowth of blocky gypsum found, microstructure is mainly vughy. Figure 10a shows an image (plane polarized light) of blocky gypsum crystals (Gyp) with remnants and coatings of clay material, Fig. 10b shows same feature as (10a) but under crossed polarized light, clearly illustrating low order grey interference colors of gypsum. Magnified view of clay coatings (C) and gypsum crystals (gyp) is shown in Fig. 10c (plane polarized light) and 10d (crossed polars). The total view of thin sections under the polarizing microscope through point counting did not show halite (NaCl) and other crystals, perhaps due to high solubility of halite has been dissolved during sample impregnation with crystic resin and thin section preparation.

3.4 Soil Salinity Map

Information about spatial variability and temporal distribution of soil salinity is vital for site-specific management since they are the most important factors influencing soil quality and agricultural production [43]. The effective control of soil salinity and waterlogging requires, among others, the knowledge of the magnitude, the extent, and the distribution of root zone salinity (inventory), the knowledge of the changes and trends of soil salinity over time (monitoring), and the ability to determine the impact of management changes upon saline conditions [44]. In the NE, soil salinity map (to 50 cm depth) was developed as an attribute of soil map that was produced at a scale of 1:50,000 (Fig. 5). The results indicate that most of the soil survey area is shown as non-saline and consists of predominantly native sandy soils (unused) with little or no accumulation of salts within the upper 50 cm of the soil. However, it should be noted that local areas of more saline soils do occur within this area but are too small to map within the scale of the present study. These are often a result of past irrigation of small farms where repeated applications of water containing even small amounts of salt results in an accumulation of salt in the soil profile. The highest levels of salinity are found along the coasts in the sabkha where the soils are moderate, strong or very strongly saline. This is a natural occurrence resulting from the upward movement of salts from a water table toward the soil surface due to evaporation. Intermediate salinity levels (very slightly saline or slightly saline) occur in some soils on the alluvial plain, often associated with soils that are loamy in at least part of the profile.

3.5 Extent and Spatial Distribution of Soil Salinity

As shown in Fig. 5, saline areas are dominant along the coastal areas and minor inland. The non-saline areas (0 to <2 dS m^{-1}) is the most common soils in the NE and covers an area of 334,646 ha (83.39 %), distributed in Sharjah (190,786 ha), Ras Al Khaima (65,594 ha) and

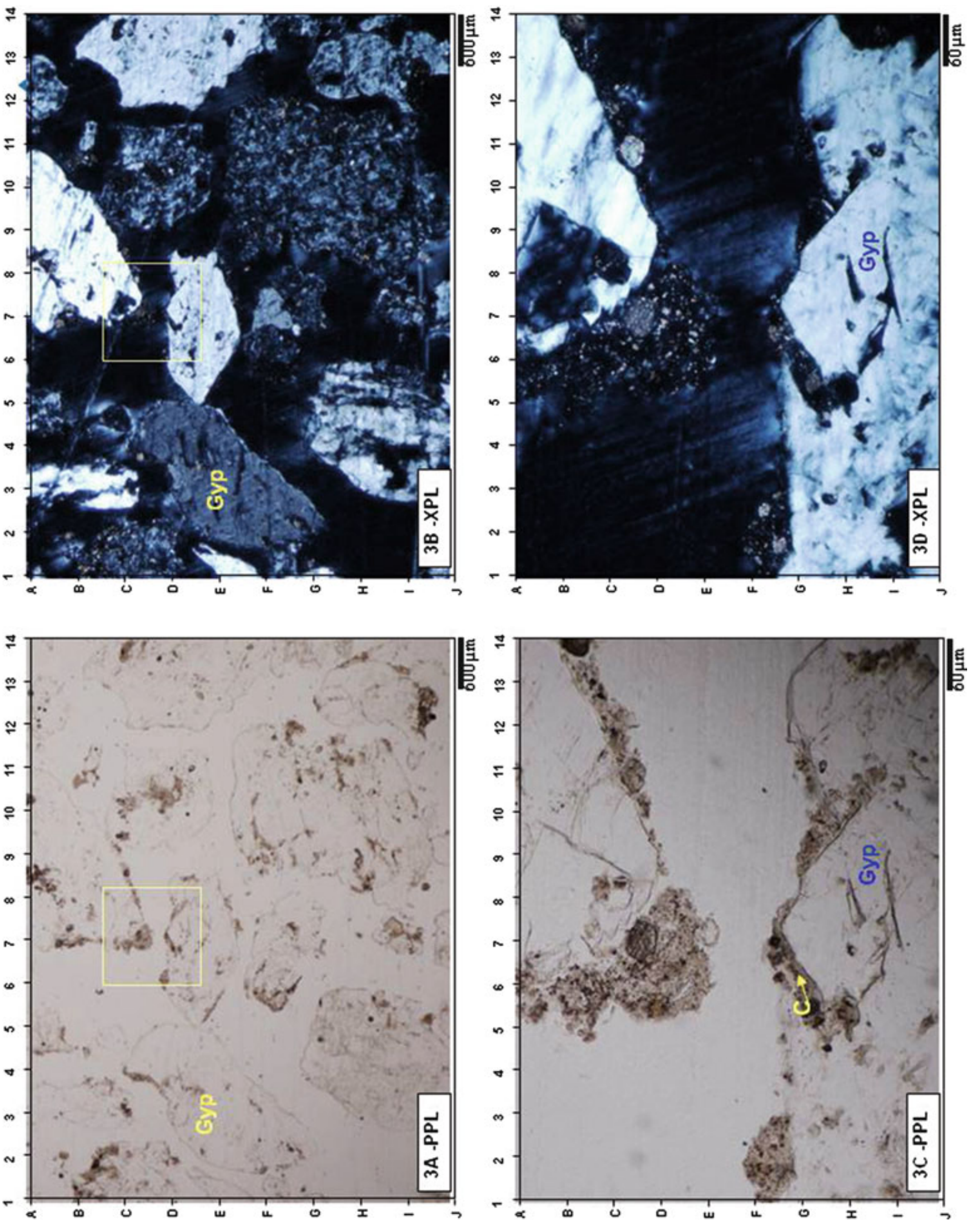

Fig. 10 Micrographs from a Gypsic Aquisalids in the coastal sabkha of the NE

Um Al Quwain (46,265 ha), with lesser extent in Fujairah (25,603 ha) and Ajman (6,398 ha). The very slightly saline soils (2 to <4 dS m^{-1}) represent the second common soils with an area of 40,412 ha (10.07 %) and distributed in Ras Al Khaima (15,330 ha), Sharjah (11,585), and Um Al Quwain (10,830 ha), with lesser areas in Ajman (2,537) and Fujairah (131 ha). The slightly saline soils (4 to <8 dS m^{-1}) covers an area of 19,495 ha (4.86 %) and concentrated mainly in Sharjah (10,422 ha), Ras Al Khaima (5,248), and Fujairah (3,826 ha). The moderately saline soils (8 to <16 dS m^{-1}) are very small elongated stripes along the coastline of the Arabian Gulf and covers an area of 491 ha (0.12 %) concentrated mainly in the coastal areas of Um Al Quwain (459 ha) and Sharjah (32 ha). The strongly saline soils (16 to <40 dS m^{-1}) are represented by a small batches of sabkha distributed along the coastal area of the Arabian Gulf and the Gulf of Oman and cover an area of 3,920 ha (0.98 %), concentrated in Um Al Quwain (1,923 ha), Sharjah (1,617 ha), and Ras Al Khaima (380 ha). The very strongly saline soils (≥40 dS m^{-1}) are represented by a small batches of sabkha distributed along the coastal area of the Arabian Gulf and the Gulf of Oman and cover an area of 2,319 ha (0.58 ha), concentrated in Ras Al Khaima (1,414 ha), Um Al Quwain (687) and Fujairah (218 ha).

It is evident from above that an area of about 6.54 % presents soil salinity (ECe) over 4 dS m^{-1} and mainly confined to the coastal land. This is a good sign that most of the soils are non-saline and have the potential to be converted to agricultural regions, with the condition that these areas have sufficient soil depth (to 200 cm) and devoid of water table (within 200 cm) and have sufficient irrigation water. The land use planners and decision makers can use the salinity map for future land use planning.

3.6 Management of Farm Salinity Through Assessment of Water Salinities

In order to assess water salinity in agricultural farms, many water samples were collected from the water wells. These samples were analyzed for water salinity (EC), and compared with water salinity classes; C1 (Low salinity 0.1–0.25 dS m^{-1}); C2 (medium salinity 0.25–0.75 dS m^{-1}); C3 (high salinity 0.75–2.25 dS m^{-1}); C4 (very high salinity 2.25–10.0 dS m^{-1}); C5 (strong salinity 10.0–25.0 dS m^{-1}); and C6 (very strong salinity 25–45 dS m^{-1}). In order to have better presentation of various salinity classes we have modified the Richards water salinity classification, from four to six classes [45]. The water salinity revealed per cent water samples distributed into various salinity classes C1 (1.0 %), C3 (26.4 %), C4 (44.0 %), C5 (24.2 %) and C6 (4.4 %), no water sample was found in the C2 category. Major concern of water salinity is in the range of above 2.25 dS m^{-1}, where most of the vegetable crops yield is reduced (low salinity threshold values). During field survey, we found few farms have the facilities of small scale reverse osmosis to desalinate water for irrigation purpose, these waters are classified as C1 class((<0.25 dS m^{-1}), where only less than 1.1 % of the farms surveyed represent this type of modern irrigation facilities.

3.7 Prediction of Soil Salinity Management in Agricultural Farms

Root zone salinity monitoring in various agricultural fields (where soil is sandy and sand is over 90 %) revealed root zone soil salinity (ECe) essentially equals to the irrigation water applied (ECw = ECe), however, in other textured soils (fine texture) 50 % greater than the irrigation water salinity (ECe = 1.5 × IW salinity) is reported in the literature (ECe = ECw × 1.5) [3]. Based on this information we evaluated root zone salinity to assess if the farm salinity is well managed or otherwise. We used ratio of (ECe/ECw), if the ratio is less than 1.1 we considered farm salinity is well managed, and if ratio is more than 1.1 we considered farm salinity not managed properly. The results of many farms surveyed showed variable root zone salinities based on the irrigation water salinity and management practices. The percent distribution of samples in different ECe/ECw have been found as, <1.1 (25 %), ≥1.1–≤5.0 (48 %), ≥5.1–<10.0 (12 %), ≥10.0 (15 %). The result shows that in over 75 % farms root zone salinity is not well managed.

It is evident that the farm salinity is not managed properly, and hence, we recommend following management aspects to optimize farm resources uses for better crop production:

- Prior to sowing seeds it is essential to collect soil samples at potential rootzone (0–20 cm) depth and sent to soil and water testing laboratory for salinity analysis.
- The extension worker should translate the root zone salinity to the farmer and help him in the following aspects:
  - What crop to be selected (based on salt-tolerance level).
  - How much, and how frequent irrigation water to be applied keeping in mind the leaching requirement (ET + LR).
  - Guide the farmer to regularly monitor root zone salinity at the farms, or send to government laboratory for testing to assure root zone salinity should not increase above the threshold salinity level.
  - Provide advisory services on other aspects (nutrient management, pest management, post-harvest losses, and marketing).

We believe it is necessary to explain in a user friendly manner as how the root zone salinity affects crop production. A saline land with salinity (ECe) 5 dS m^{-1} will not be ideal for vegetable crops such as beans (threshold salinity 1 dS m^{-1}), but suitable resource for forage production such as barley (salinity threshold 8 dS m^{-1}), and sorghum (threshold salinity 6.8 dS m^{-1}). Under such condition, either, the root zone salinity is reduced through leaching or a salt-tolerant crop with high salinity threshold to be used for better crop production.

This suggests that the diagnoses of salinity problem become prime importance for proper crop selection.

It has been experienced that such an important component is mostly missing in crop production as the farmer in general is ignorant due to its inaccessibility to soil and water testing laboratories and poor extension-framers link. The explanation below and the table can be used as a general guide for yield prediction in saline conditions compared to the yield from a non-saline soil.

Crops can tolerate salinity up to certain levels without a measurable loss in yield (this is called threshold level). As a general rule, the more the crops are salt tolerant, the higher the threshold level. At salinity levels greater than the threshold, crop yield reduces linearly as salinity increases. Using the salinity values a salinity/yield model was developed [46], predictions of expected yield loss can be made. Maas and Hoffman expressed salt tolerance of crops by the following relationship:

$$\mathrm{Yr} = 100 - \mathrm{s}\left(\mathrm{ECe} - \mathrm{t}\right)$$

where Yr = percentage of the yield of crop grown in saline conditions relative to that obtained on non-saline conditions; t = threshold salinity level where yield decrease begin; s = percent yield loss per increase of 1 ECe (dS m^{-1}) in excess of t. Table 5 may be used as a guide to predict yield losses.

3.8 Water Quality, Crop Water Requirement and Drainage Water in Saline Production Systems – Serious Concerns

The survey of the agricultural farms in the Northern Emirates and discussions with farm supervisors has reflected that in most of the saline production systems, emphasis has been mainly given to either water salinity or soil salinity, the soil and water sodicity aspects have merely been ignored. This is justified that the soils in the region are sandy in texture, and therefore soil sodicity is not a problem, but soil salinity, over-ruling the effect of water sodicity (high SAR-nutrient imbalance) in crop production in sandy soils. The general consensus, that, the soils are sandy "is not correct" as other soil textural classes have been mapped in the national soil surveys [2, 33, 47] showing potential for irrigated agriculture.

Let us put an examples of two waters, W1 (EC 0.5 dS m^{-1} and SAR 60 $(\mathrm{mmol\ L^{-1}})^{0.5}$, W2 (EC

Table 5 General threshold (t) and slope (s) values to calculate crop yield as a function of soil salinity for various crops (Hoffman [50]; cf Shahid and Rahman [23])

	Threshold (t)	Slope (s)
Crops	ECe dS/m	% yield loss per 1 ECe (dS/m) above (t)
Alfalfa (*Medicago sativa*)	2.0	7.3
Barley for grain (*Hordeum vulgare*)	8.0	5.0
Bean (*Phaseolus vulgaris*)	1.0	18.9
Bean, dry edible (*Phaseolus vulgaris*)	1.0	19.0
Cabbage (*Brassica oleracea*)	1.8	9.7
Carrot (*Daucus carota*)	1.0	14.1
Clover (*Trifolium spp.*)	1.5	12.0
Corn for grain (*Zea mays*)	1.7	12.0
Corn for silage (*Zea mays*)	1.8	7.4
Cucumber (*Cucumis sativus*)	2.5	13.0
Date (*Phoenix dactylifera*)	4.0	3.6
Lettuce (*Latuca sativa*)	1.3	13.0
Onion (*Allium cepa*)	1.2	16.1
Pepper (*Capsicum annum*)	1.5	14.1
Potato (*Salanum tuberosum*)	1.7	12.0
Radish (*Raphanus sativus*)	1.2	13.0
Sorghum for grain (*Sorghum bicolor*)	6.8	16.0
Soybean (*Glycine max*)	5.0	20.0
Spinach (*Spinacia oleracea*)	2.0	7.6
Sugar beet (*Beta vulgaris*)	7.0	5.9
Tomato (*Lycopersicum esculentum*)	2.5	9.9
Wheat for grain (*Triticum aestivum*)	6.0	7.1

s = % yield loss per 1 ECe (dS/m) increase above t (ECe) value; t = salinity threshold ECe (dS/m), where yield is optimum

5 dS m^{-1} and SAR 5 (mmol L^{-1})$^{0.5}$. Ignoring the role of sodicity, W1 will be rated as good quality water compared to W2, whereas, soil scientists will consider W1 as bad quality water, because high SAR will affect physical properties of soils, through soil dispersion and plugging of soil pores and ion balance. The adverse effect of sodium on soil structure, clay dispersion, and water infiltration is well documented in the literature. The rectification of water sodicity requires the addition of gypsum ($CaSO_4.2H_2O$), which on dissolution release Ca and lower SAR in the water. Ignoring the gypsum addition, may lead to a soil to highly sodic, which will require higher costs of reclamation.

Irrigation water requirement is usually based on evapotranspiration-ET (water consumed by the crop and lost through soil) and application of water in excess of crop requirements needed to leach salts out of the root zone (leaching requirement) and thus control root zone salinity. The ET is a measure of evaporation data (class A pan) and transpiration from crops in weighing lysimeter experiments conducted on different crops. In such experiments, usually, fresh water is used to offset water requirements of crops and to determine ET. In such water requirements determinations, the concept does not consider the decrease in water uptake (saline water) by plants compared to when fresh water is used for irrigation, and thus increase in leaching that occurs when plant yield decreases. The possibilities to use saline waters at low leaching fractions have been significantly overlooked due to use of current guidelines, such as [48]. The combination of the assumption of fixed crop ET (regardless of salinity of irrigation water) with the salt tolerance calculation from average root zone salinity estimates or measurements results in overestimation of the quantity of water needed for leaching [49]. From these facts, it can be concluded, that in most of the salt-tolerant production systems, irrigation in excess of ET + LR has been practiced, and that has exerted pressure on the drainage system. It is, therefore, essential to consider the use of irrigation water salinity, water uptake by salt-tolerant crops (ET) and variable leaching requirement in determining crop water requirements, this can save precious water resources, decrease pressure on drainage system, and this way water requirements can be optimized and saved water can be used for other crops.

The other major concern in salt-tolerant production systems is the lack of baseline soil information (EC, ESP, nutrients, soil depth etc.). The seed germination requires good soil conditions, moisture at field capacity, highly saline soil will hinder seed germination, shallow depth may not be enough for long rooted crops and also develop water logging, high sodicity will affect plant nutrition and soils physical health, therefore, it is essential to establish baseline soil information and use holistic approach to deal such issues for better agriculture.

4 Conclusion and Recommendations

The paper presents six soil salinity zones in the NE. The saline soils are concentrated along the coastal sabkha and reduced inland. The coastal sabkha is special habitat where halophytes are adapted to these environments. The soils where water table is recognized, unique biogeochemical processes of oxidation, reduction, and accumulation of salts, gypsum, and other minerals under very high climatic temperatures are observed. The extent of these soils is limited and is progressively decreasing as coastal areas are developed. The study revealed that the root zone salinity in many farms has been poorly managed. It also concludes that soil and water salinity are one of the key features that impact the use and management of land resources in the NE. Hence it is recommended to enhance the links between research-extension-farmers for better technology adoption leading to sustainable management of soils for crop production.

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Gypsum Crystals Formation and Habits, Umm Said Sabkha, Qatar

Mariam Al-Youssef

Abstract

This is the first study of gypsum crystal habits and crystallography in the famous, large, costal Umm Said Sabkha in the Qatar Peninsula. Eighty one sediment samples rich in crystals, four shallow core samples and eleven brine samples were collected for detailed studies. Gypsum crystals of various habits and sizes are formed in the surface crust and at shallow depths in the Sabkha sediments. The proportion of gypsum crystals increases in the location of fine sediments than in the sand sediments. The crystals are of acicular, prismatic, lenticular and sub-lenticular, inter-grown sub-lenticular, pyramidal, elliptical and semi-elliptical, and pseudo-tetragonal shapes. The crystals are euhedral, simple and tabular on (010), and the cleavage (010) is very good. Twinning on the (101) and the (100) is common. The crystals faces are parallel to two axes and include (110) prism, (111) pyramid, (011) a-dome, (101) b-dome and the a, b and c pinacoids.

Prismatic and acicular crystals of large and thick size are the dominant habits in the deposits within the Sabkha. Pyramidal, lenticular and sub-lenticular crystals are less dominant and occur mainly in the locations of fine sediments saturated by halite, whereas the crystals of desert raised shape are dominant in the sand dune area in the southwestern part of the Sabkha. The crystals formed above groundwater level and a few centimeters depth from the surface.

Shallow groundwater level, saturation of sediments by brines, high temperature, high evaporation and saturation of brines by SO_4^{-2} and CaO_3^{2-} provide suitable conditions for the formation of gypsum crystals in the sediments. In addition, the type of host sediments plays an important role in the amount and habit of gypsum crystals in the Sabkha. The general elevation of Umm Said Sabkha above sea level (+1) leads to greater rates of evaporation over groundwater recharge in the Sabkha.

The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_2, © Springer Science+Business Media Dordrecht 2014

The main conclusion of this study are: (1) the conditions for formation of gypsum in the Umm Said Sabkha are available and accordingly, this Sabkha is a suitable place for establishing a project for cultivation of this important mineral and exploiting it economically; (2) making a center for scientific students and researchers to study the growth and development stages of gypsum crystals, and the conditions affecting their form, shape~~s~~, size and other aspects; and (3) This work can be used as a model for the study and utilization of the coastal and inland Sabkhas in Qatar and neighboring countries.

1 Introduction

Although evaporate minerals in the Arabian Gulf Sabkhas have been investigated by several workers, gypsum crystal habits are not studied. Only limited information about the crystals in the Sabkhas is available in some previous reports. The surface deposits of Abu Samra Sabkha in the southeastern part of Qatar include small colorless and brownish gypsum crystals mixed with quartz at a depth of 60 cm from the surface [1].

Gypsum crystals up to 12.7 cm long and flattened in the direction of c axis (their best cleavage normal to the b-pinacoid) in the Fishakh Sabkha, on the western coast of Qatar [2]. In Umm Said Sabkha, gypsum crystals occur in a thin bed (about 30–50 cm thick) associated with carbonate mud and increasing in thickness in the northwestern part of the Sabkha. The crystals also occur in a 25 cm thick bed within the beach ridge. Desert rose gypsum crystals usually occur within the calcareous sand on the surface or at depths of more than 70 cm [3, 4].

Various habits of gypsum crystals present in Abu Dhabi Sabkha sediments~~;~~ include gypsum crystal mushes in algal flat locations, gypsum sand crystals in the areas of sandy sediments and large bladed crystals in muddy sediments of intertidal and lagoonal facies, in addition; large and fine lenticular crystals are present with anhydrite in the Sabkha [5–18].

In Al-Khiran Sabkha, in the south of Kuwait, white thin layers of primary gypsum nodules are present below the crust. The nodule layers are confined to the upper 0.1–0.25 m of the pan sediments of the Sabkha, usually 0.7–0.8 m above the ground water table [19].

In the Al-Kharrar Sabkha (coastal Sabkha on the coast of the Red Sea) gypsum crystals are presents in the sediments in the southern part of the Sabkha. Within the Sabkha, gypsum and other evaporite minerals formed by floodwater from the lagoon and subsequent rapid evaporation [20]. In the eastern coast of Saudi Arabia, south of Dhahran desert raised gypsum crystals formed on the surface; but are dominant at 1 m depth above the groundwater level [21].

In other parts of the word, gypsum crystals of various sizes and shapes are formed in the seas and lakes at different depths and in various conditions and deposits. For example, pure polygonal gypsum crystals are present at 2 m depth in Lago Verde and in Lago Flaco lakes in California at 2 m depth [22]. Authigenic tabular gypsum crystals formed in the seafloor during a short period in oxygen-rich bottom water under-saturated with respect to Ca^{2+} and CO_3^{2-} [23]. Single and twinned euhedral gypsum crystals with well-developed crystal faces, about 15 μm long and 5 μm broad formed in deep-sea (at depth 4,500–5,500 m) in the Central East Pacific within manganese nodules and deposits composed of red clay and siliceous radiolarian ooze [24]. Interlocked euhedral prismatic, tabular to lenticular and rosette-like gypsum crystals (few millimeters to 10 cm in size) are formed in Bannock basin, eastern Mediterranean at depth between 3,200 and 3,420 m. The sediments of the basin floor are dark, H_2S and foraminifera rich, and commonly laminated. Most gypsum crystals are Holocene in age. The water column above the basin has normal salinity down to depth 3,150 m; but below this depth the basin is filled with hypersaline brines [25].

This is the first study of the gypsum crystals and their crystallography in the large, costal Sabkha in Qatar; Umm Said Sabkhas. The study seeks to identify the various habits and vertical and horizontal distribution of the crystals in the sediments of the Sabkha. The factors that affected the crystals formation and shape are discussed in the study. Crystal formation speed and the reasons for increase or decrease in the growth rate identified. Furthermore, important series of science questions are answered in the study, such as:

1. What is the mineralogical characteristic of gypsum of Umm Said Sabkha?
2. What is the relation between the brines geochemistry and the formation and density of gypsum crystals in the Sabkha?
3. What is the role of sediment types in the formation and in the shape of gypsum crystals, and how has the porosity and permeability of the Sabkhas sediments affected gypsum crystals formation and habit?
4. Is there any relationship between the formation and habits of gypsum crystals and microbial mats in the Sabkha?
5. Are gypsum crystals primary or secondary, and what is the relation between anhydrite and gypsum formation in the Sabkha?
6. What is controlling the creation, formation and development of the crystals? Why are some shapes dominant in some locations and disappeared in others and what is the rate of growth of the crystals within the Sabkha?

2 General Setting of the Studied Area

Umm Said Sabkha is the largest coastal Sabkha in the Qatar Peninsula. It is located on the southeastern coast and extended inland between 4 and 14 km (Fig. 1). The Sabkha area is about 350 km^2 (nearly 60 % of the total area of all coastal Sabkhas in Qatar). The surface of the Sabkha is almost flat, with very low gradients. It is mainly between 1 and 2 m from sea level, rising to 3–4 m along the western edge. The Sabkha typically floods with seawater during the spring, as strong easterly winds combine with high spring tides and cause flooding to about 7–10 km from the sea [26]. A lithified beach ridge is present along the northeastern side, except in a few parts where a coastal sand bar is present. This bar is of marine origin and now extends up to 3.5 km inside the Sabkha. It is located along the eastern part of the Sabkha, formed by the action of long shore drift caused by the prevailing “Al Shamal” wind. The northwestern part of the Sabkha is bounded by a high supra-tidal flat, which is about 1–1.5 m higher than the present supra-tidal region. A shallow embayment with tidal channels is located on the southeastern edge of the Sabkha [3].

The principal sediments of Umm Said Sabkha are variable, including deposits of the intertidal, supra-tidal and high supra-tidal zones. The intertidal zone is inundated by lagoonal waters through tidal channels and the high tide sometimes reaches the supra-tidal zone [4]. The surface deposits within the Sabkha are mainly of saline and gypsiferous sand, with silt flats of Quaternary age. Former beach deposits, consisting of calcareous sand of marine origin and coastal dunes, locally cemented, are present in the northeast and southwest. They are also found in small elongate areas along the western edge. Eolian sand, dominantly siliceous sand dunes and sand sheets are present in various parts. Barchan dunes are dominant in the middle and western parts, whereas longitudinal dunes dominate in the southern parts of the Sabkha. Accumulation of eolian sand is greatest near the margins of the Sabkha, especially along the southeastern coast [27].

There are small, NW-SE trending terraces of marine calcareous sand in the middle of the northern part of the Sabkha. Terraces are also present in the southeast and locally along the western edge. These terraces result from regression during the Pleistocene. Calcareous sandstone, locally conglomeratic, of Pleistocene age is present in very limited locations, especially in the west, northwest and southwest. Dolomite and limestone of the Upper Dammam Formation

Fig. 1 Landsat image mosaic, showing Umm Said Sabkhaon the southeastern coast

appear at the surface in some locations, in the southwest and western part of the Sabkha.

Near to the north and northwestern edge of Umm Said Sabkha is Dammam Formation limestone (Middle Eocene). Sand with gypsum discs is present in the supra-tidal part of the Sabkha and laminated gypsum in the west. There is a gypsum crystal mush, rich in halite, in the north and northeast. In the southeastern intertidal area, carbonate mud of Quaternary age extends from the northeast to southwest.

The levels below sea-level are explained as the results of evaporation and capillarity. The groundwater level in Umm Said Sabkha is between 20 and 70 cm below the surface [4], being deeper towards the northern and western margins. This is because the amount of rain in the area is small [28, 29]. Because Umm Said Sabkha is a coastal Sabkha connected directly with the sea, the principal source of its groundwater is seawater. This influx occurs as surface flooding during high tides and storm conditions, and by groundwater reflux seepage from the sea to the Sabkha area. In addition, Umm Said Sabkha receives very limited freshwater from the land at its western side during rainy periods.

The movement of water in the Sabkha occurs in both vertical and horizontal directions. In the first instance, seawater floods across the Sabkha surface, especially during high tides and storm conditions [30]. A much smaller proportion of freshwater also drains to the Sabkha from land, sinks vertically and mixes with the seawater brines. Some of this water drains directly back towards the sea [31]. Seawater also moves across the Sabkha surface in tidal drainage channels, and penetrates vertically into the Sabkha over most of its area.

Several factors control the horizontal and vertical flux of water: the shallow groundwater level; high rates of evaporation; porous and permeable sediment (dominant quartz sand) at least in the surface meter or more of the Sabkha; high tides and episodic storms. When exposed to sunlight during most of the tidal period, the water moves easily by capillarity action to the surface under conditions of strong evaporation [30].

3 Tidal Regime

The Qatar Peninsula is affected by normal semi–diurnal tides. The tidal range is 2.23 m in the northwest and 1.01 m in the southwest. It is about 0.79 m at the middle part of the western coast and 1.87–2.88 m in the northeast [32]. Occasionally the high tide on the eastern coast reaches a height 3.91 m above mean sea-level, whereas it only reaches 1.49 m above mean sea-level on the western coast [31]. The average of the daily tidal range is 1.0 m on the eastern coast and up to 1.5 m on the western coast [33].

From March to the end of July the wind is north-northwest and its speed average is between 25 and 30 km/h. This causes relatively long term strong unidirectional currents on both the eastern and western coast of Qatar [34]. When the current approaches the northern coast of Qatar it branches into two, one parallel to the east coast and the other along the west. When these currents flow alongside coastal embayments, some water moves into them, depositing a proportion of the load of suspended sediment [28].

4 Methodology

4.1 Sample Collection

Field studies were carried out in Umm Said Sabkha during April 2010 and July 2010. Throughout fieldwork, observations were made for gypsum crystals dominant on the surface and at shallow depths in the sediments of the Sabkha. The distribution and shapes of the crystals within the Sabkha were identified and the size of the crystals was measured. Information about the sediments and other characteristics present in the locations rich in gypsum crystals, such as groundwater level, type and size of the sediments, microbial mats dominant in the Sabkha were recorded. Gypsum crystals and sediment samples (81 samples) rich in crystals in addition to shallow core samples (4 cores) were collected from 41 locations (Fig. 2 and Table 1). Photographs for the crystals and the locations rich in crystals were taken in the field. Eleven brine samples were also collected from pit stations in various locations within the Sabkha.

4.2 Hand Specimen and Binocular Microscopic Study

Initially, the core samples were cut lengthwise into two halves, then the surface of the samples

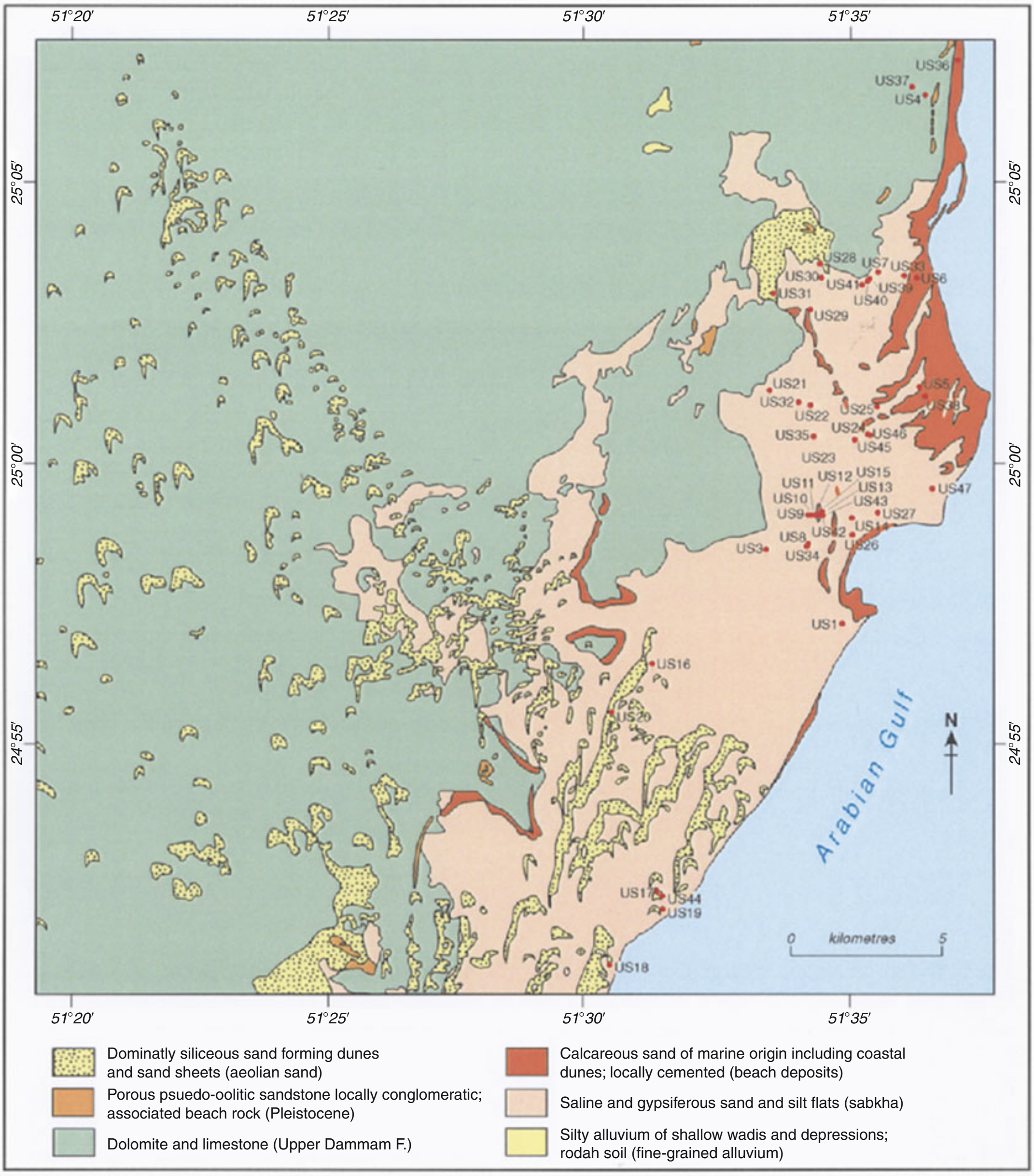


Fig. 2 Locations of the study stations in the Umm Said Sabkha (Base map after Hunting Geology and Geophysics Limited, 1980)

was cleaned using a knife. After that, the core samples were described and their length and color defined. Photographs were taken of these cores and their important sediment features (Fig. 3). After that, the core samples and other studied samples were dried in the laboratory by leaving them uncovered and exposed to the atmosphere for 2 days. A sieving process was undertaken for the core and pit samples, using small meshes before commencing the binocular microscopic study. Gypsum crystals, fragments and grains were picked out. The color of the

Table 1 Names and locations of the studied stations in Umm Said Sabkha

	Location		Sample types
Stations	Latitude	Longitude	P=pit, C=core, B=brine
US1	N=25° 02′ 75″	E=51° 34′ 45″	C,
US2	N=25° 03′ 40″	E=51° 33′ 61″	P,
US3	N=24° 58′ 46″	E =51° 33′ 36″	P, B
US4	N=25° 06′ 57″	E=51° 36′ 43″	P,
US5	N=25° 01′ 41″	E=51° 36′ 49″	P,
US6	N=25° 03′ 38″	E=51° 36′ 31″	P,
US7	N=25° 03′ 42″	E=51° 35′ 54″	P,
US8	N=24° 58′ 59″	E=51° 34′ 22″	C, B,
US9	N=24° 59′ 08″	E=51° 34′ 30″	P,
US10	N=24° 59′ 08″	E=51° 34′ 33″	C, B,
US11	N=24° 59′ 08″	E=51° 34′ 38″	C, B,
US12	N=24° 59′ 08″	E =51° 34′ 40″	C, B,
US13	N=24° 59′ 09″	E=51° 34′ 53″	P,
US14	N=24° 59′ 04″	E=51° 35′ 04″	P,
US15	N=24° 59′ 08″	E=51° 34′ 52″	P,
US16	N=24° 56′ 47″	E=51° 31′ 26″	P, B,
US17	N=24° 52′ 54″	E=51° 31′ 39″	P,
US18	N=24° 51′ 17″	E=51° 30′ 48″	P,
US19	N=24° 52′ 08″	E=51° 31′ 44″	C,
US20	N=24° 55′ 57″	E=51° 30′ 55″	P, B,
US21	N=25° 01′ 36″	E=51° 33′ 50″	P,
US22	N=25° 01′ 03″	E=51° 34′ 21″	P,
US23	N=25° 00′ 36″	E =51° 34′ 38″	C,
US24	N=25° 00′ 55″	E=51° 35′ 35″	P,
US25	N=25° 01′ 01″	E=51° 35′ 59″	P, B,
US26	N=24° 58′ 55″	E=51° 35′ 02″	P,
US27	N=24° 59′ oo″	E=51° 35′ 59″	P,
US28	N=25° 03′ 59″	E=51° 34′ 47″	P,
US29	N=25° 02′ 72″	E=51° 34′ 24″	P,
US30	N=25° 03′ 30″	E=51° 34′ 94″	P,
US31	N=25° 03′ 04″	E=51° 33′ 62″	P,
US32	N=25° 01′ 19″	E=51° 34′ 9″	P,
US33	N=25° 03′ 42″	E=51° 36′ 11″	P, B,
US34	N=24° 58′ 58″	E=51° 34′ 22″	P,
US35	N=25° 00′ 50″	E=51° 34′ 35″	P,
US36	N=25° 07′ 19″	E=51° 37′ 06″	P,
US37	N=25° 1 5′ 52″	E=51° 31′ 10″	P,
US38	N=25° 01′ 25″	E=51° 36′ 45″	P,
US39	N=25° 03′ 34″	E=51° 35′ 39″	P,
US40	N=25° 03′ 30″	E=51° 35′ 37″	P,
US41	N=25° 03′ 18″	E=51° 35′ 21″	P,
US42	N=24° 59′ 11″	E=51° 34′ 47″	P,
US43	N=24° 59′ 09″	E=51° 34′ 50″	P,
US44	N=24° 52′ 35″	E=51° 31′ 41″	P,
US45	N=25° 00′ 46″	E=51° 35′ 11″	P,
US46	N=25° 00′ 56″	E=51° 35′ 33″	P, B,
US47	N=24° 59′ 59″	E=51° 36′ 59″	P, B,

Fig. 3 Core samples from Umm Said Sabkha (Note that sand is dominant in the core sediments and microbial mats abundance in the third core)

sediments was defined by using a rock-color chart and the size and the shape of the crystals and fragments were defined under the binocular microscope by using a grain size scale. Photographs of the various crystals and fragments were taken under a polarizing microscope. Tables were drawn up to include a summary of the major characteristics of the studied samples in relation to depth and to graphic logs.

4.3 Scanning Electron Microscopy (SEM)

Gypsum crystals and gypsum fragments were studied by using scanning electron microscope (Jeol/JSM-6400). For the study, the samples were fixed on the surface of stage with double sided sticky tape and thinly coated with gold. The samples were positioned in the SEM, viewed, studied and photographed.

4.4 Smear Slides and Thin Sections Study

Thin= sections and smear slides were made for about 43 sediment samples rich in gypsum from the Sabkha. The samples for this study were chosen according to variations of color and appearance at various depths (following the hand specimen and binocular microscopic studies). Various habits of gypsum crystals and fragments were determined. Photographs were taken of the components under the polarizing microscope to show the various shapes of gypsum crystals and important characteristics.

4.5 Analyses of Brine

Chemical analyses of 11 brine samples from Umm Said Sabkha were studied. The temperature range for the brine was 21–23 °C. The analysis of these was completed to define the pH, conductivity, cations Na^+, Mg^{2+}, Ca^{2+}, Sr^{+2} and anions Cl^-, SO_4^{2-}, HCO_3^- of the samples. A simple statistical approach was used to establish relationships between the different elements measured.

Expandable ion analyzer, EA. 920, was used to define pH and conductivity. The buffer – standard solution, pH9.18 at 25 °C was used for calibration. The conductivity and pH were defined by immersing the probe of the tool which connected directly with its cell into the water samples. The value for conductivity and pH was read directly after the indicator of the tool reached the stability point. A Philips pv 8060 IEP – AES was used to determine the cations and Sr^{2-} of the water samples.

To determine anions, the water samples were diluted in distilled water at a ratio of 1:5 ml. To determine Cl^-, potassium chromate (K_2CrO_4) was used as an indicator and silver nitrate solution (prepared by adding 10.2 gm of silver nitrate – $AgNO_3$/0.06 – to 1 l of distilled water) were used in calibration. The value of Cl^- in the samples was defined from the relation between the normality of the water sample and $AgNO_3$ and the volume of silver nitrate and water samples. To determine SO_4^{2-}, about 200 ml of diluted water samples were added to 5 ml of HCl (6 N. 1:1) (the hydrochloric acid was prepared by adding 83 ml of concentrated HCl to 300 ml of distilled water). This solution was topped up to 1 l using distilled brine. 15 ml of a warm solution of $BaCl_2$ was added to the last solution. The value for SO_4^{2-} was defined from the weight of the dried filtered precipitate.

To determine the HCO_3^- of the water samples, methyl orange was used as an indicator (3 drops were added to 10 ml of each diluted water sample). The samples were assuaged by sulphuric acid solution (the titration solution of sulphuric acid was prepared by adding 5.6 ml of concentrated sulphuric acid to 1 l of distilled water). The value of the carbonate in each sample was defined from the gradations of the burette at the point of the change of color to pink.

Published methods were used for determining seawater salinity and pH [35], for trace metals in seawater [36], for major constituents in seawater [37] and for anions and cations in seawater [38].

5 Result of the Study

5.1 Field Study

In the Umm Said Sabkha deposits, the crystals are mainly present at shallow depths and in the surface crust. Mostly two or three types of the crystals are present in each location at depth between 0.0 and 120 cm.

Most of the surface of the Sabkha is covered by sand and halite, especially in the southwestern part of the Sabkha (a, b, c, d and e in Fig. 4). Fine sediments with dark grey or black color occur in various locations at depths between 30 and 90 cm, especially beside the swamp-like areas within the Sabkha (f in Fig. 4). These are organic-carbon rich mud derived from microbial mat growth. Large numbers of small gypsum crystals are dominant underneath these deposits, whereas very small proportion of gypsum crystals occurs in sandy sediments around the fine deposits. A compact brown crust of siliciclastic sand, gypsum and halite covers the northern and northwestern parts of the Sabkha (c in Fig. 4).

Large numbers of acicular gypsum crystals were found in the southwestern part of the Sabkha, beside and within a large artificial pit (a in Fig. 5). The crystals vary in their length and thickness. Big numbers of very thin of these crystals (less than 0.5 cm in thick) are connected together and form remarkable aggregates of crystals, covering the surface of the area for several meters, especially in the southern part of the Sabkha (b, c, d and e in Fig. 5) whereas, huge number of these crystals are present with very fine sediments of sand and carbonate, and formed the surface crust (f in Fig. 5). Large numbers of prismatic crystals accumulate as a surface crust, about 2 cm thick, with an irregular surface. The crystals vary in their length from 0.5 to 2 cm and twinning is dominant in a large number of them (a, b, c and d in Fig. 6). Within and at the edge of the pit, spherical crystal aggregates of about 14 cm in diameter are formed from accumulation of prismatic gypsum crystals based on a crust of fine carbonate sediments. The crystals are flat, hard, about 0.8 mm thick and of light beige. Twining appears in some of the crystals color (e, f, in Fig. 6, and a and b in Fig. 7).

Gypsum crystals of desert rose shape (3.5–21 cm long and 3–12.5 cm wide) are present on the surface or at shallow depths in some locations, in the north and northwest, and especially in the sand dunes area in the southwestern part of the Sabkha. They are also found on the surface of small hills in the middle of the north and in the southeastern parts of the Sabkha (c and d in Fig. 7). The crystals are enriched with fine-grained inclusions, may be grains of heavy minerals; but this needs a specially, separate study.

5.2 Laboratory Study

5.2.1 Sediments Samples

The laboratory procedures showed that gypsum is typically found through Umm Said Sabkha deposits as crystal fragments and as crystals of various habits and sizes (a, b, c, d, e and f in

Fig. 4 General view of southwestern and northwestern part of Umm Said Sabkha (Note the surface covered by sand and halite)

Figs. 8, 9 and 10). The crystals are acicular, prismatic, lenticular and sub-lenticular, inter-grown sub-lenticular (desert-rose crystals), pyramidal, and elliptical and semielliptical. Some pseudo-tetragonal shaped crystals are also found.

The acicular crystals range in length from 1 to 6 mm and in thickness from 0.5 to 3.5 mm. The length of the lenticular and sub-lenticular crystals is from 0.3 to 6 mm and the width is from 0.4 to 4.7 mm. The prismatic crystals vary in length

Fig. 5 Large numbers of a circular gypsum crystals vary in their length and thickness on the surface of southwestern part of Umm Said Sabkha, beside artificial lake (Note in **f** big numbers of very thin acicular crystals are connected together and forms remarkable aggregates of crystals, covering Sabkha surface for several metres)

from 1 to 2 mm and in width from 0.4 to 4 mm. Swallow-tail twinning is found in some of prismatic habits. The length of pyramidal crystals is from 0.3 to 6 mm and the width is from 0.2 to 1.8 mm. For inter-grown sub-lenticular crystals, the length is 0.5 to 6 mm and width about 2 mm.

The length of the fragments of broken crystals range in length from <1 mm to 1.2 cm with

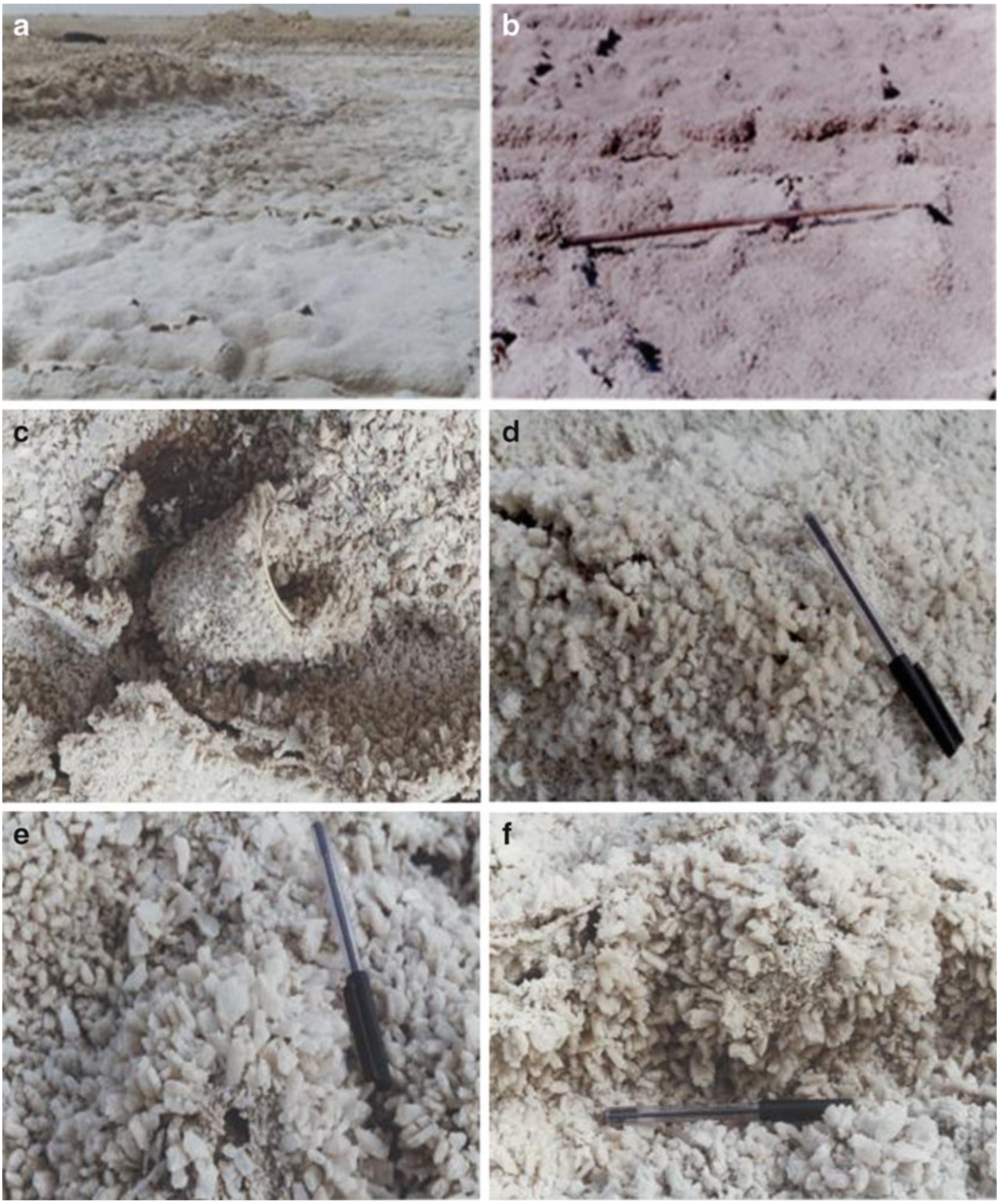


Fig. 6 Huge number of prismatic gypsum crystals vary in their length and some with twinning tail beside artificial lake, southwestern part of the Umm Said Sabkha

thickness about 1 mm, although they mostly appear to be fragments of larger mono-crystalline grains that have broken, either during sampling or by natural processes.

In the northern part of the Sabkha, gypsum crystals and fragments of broken crystals are present at depths of 3 to 19 cm. The crystals are acicular, pyramidal, inter-grown sub-lenticular

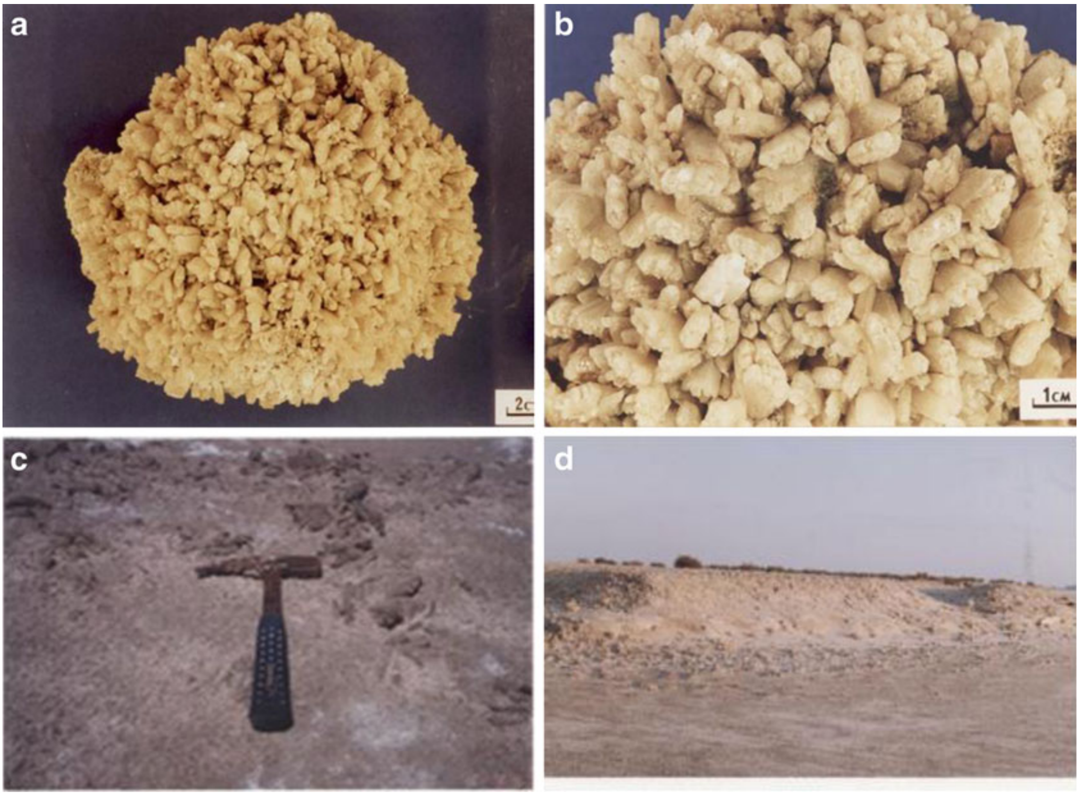


Fig. 7 Spherical crystals formed from accumulation of prismatic crystals bed on a crust of fine carbonate sediments (**a** and **b**) in the southwestern part of Umm Said Sabkha and gypsum crystals of desert rose shape are present on the surface (**c** and **d**) in the northwestern part of the Sabkha

(desert rose shapes), prismatic and lenticular. They range in length from 1 to 6 mm for acicular, 1 to 2.3 mm for pyramidal, 1 to 1.5 mm for the inter-grown sub-lenticular and from 1 to 3.2 mm for prismatic crystals. The thickness of the acicular crystals varies between 0.6 and 3.5 mm.

In the middle of the northern part of the Sabkha, gypsum is also found in the sediments as complete crystals and as fragments of crystals. The crystals are prismatic, lenticular and sub-lenticular, pyramidal and inter-grown sub-lenticular. The length of the prismatic crystals is from <1 to 6 mm and the thickness is from 0.4 to 4 mm. The lenticular and sub-lenticular crystals vary in their length from 0.4 to 6 mm and in their width from 0.3 to 3 mm. The inter-grown sub-lenticular crystals range in length from 0.5 to 4 mm and in their width from 0.3 to 2 mm. For the pyramidal crystals, the length is from 0.3 to 6 mm and the width from 0.2 to 4 mm. The acicular crystals range in length from 1 to 4 mm and their thickness is <1 mm. The fragments of broken gypsum crystals vary in their length from <1 to 1.6 mm and in their width from <1 to 1 mm, while their thickness is from 0.6 to 0.8 mm.

In the northwestern part of the Sabkha, the sediments are rich in complete crystals of lenticular and sub-lenticular, prismatic and inter-grown sub-lenticular habits. Gypsum fragments of broken crystals are also found in the sediments. The lenticular and sub-lenticular crystals range in length from 0.3 to 3 mm and in width from 0.4 to 2.8 mm. The length of the prismatic crystals is from 1 to 3 mm and the width from 0.4 to 0.7 mm. For acicular crystals, the length ranges from 1 to 4 mm and the thickness from 0.5 to 2 mm. The length for pyramidal crystals ranges from 0.8 to 3 mm and the width is from 0.5 to 1.2 mm.

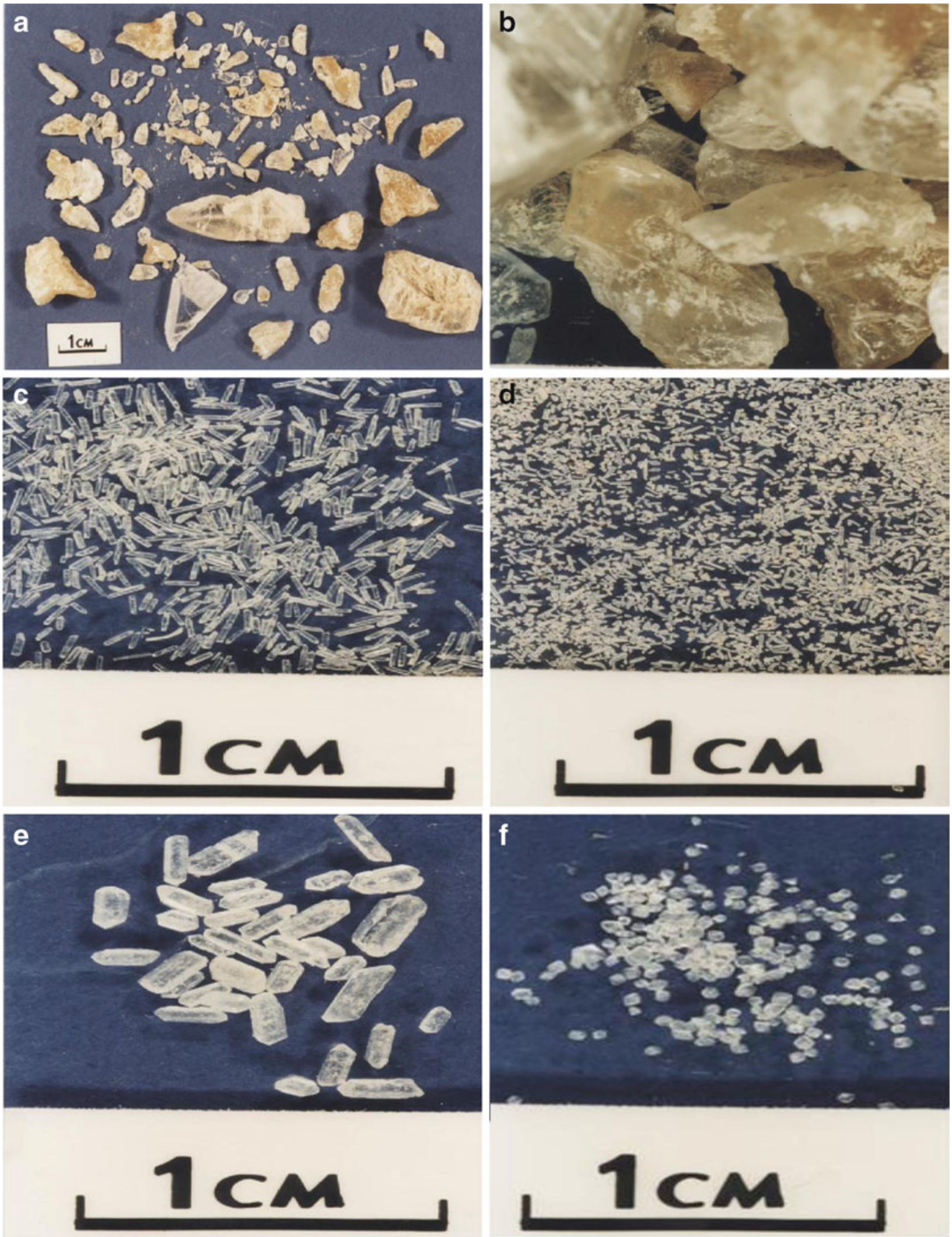


Fig. 8 Gypsum fragments of broken crystals and gypsum crystals of acicular and pyramidal shape, Umm Said Sabkha (Note the crystals vary in their length and thickness)

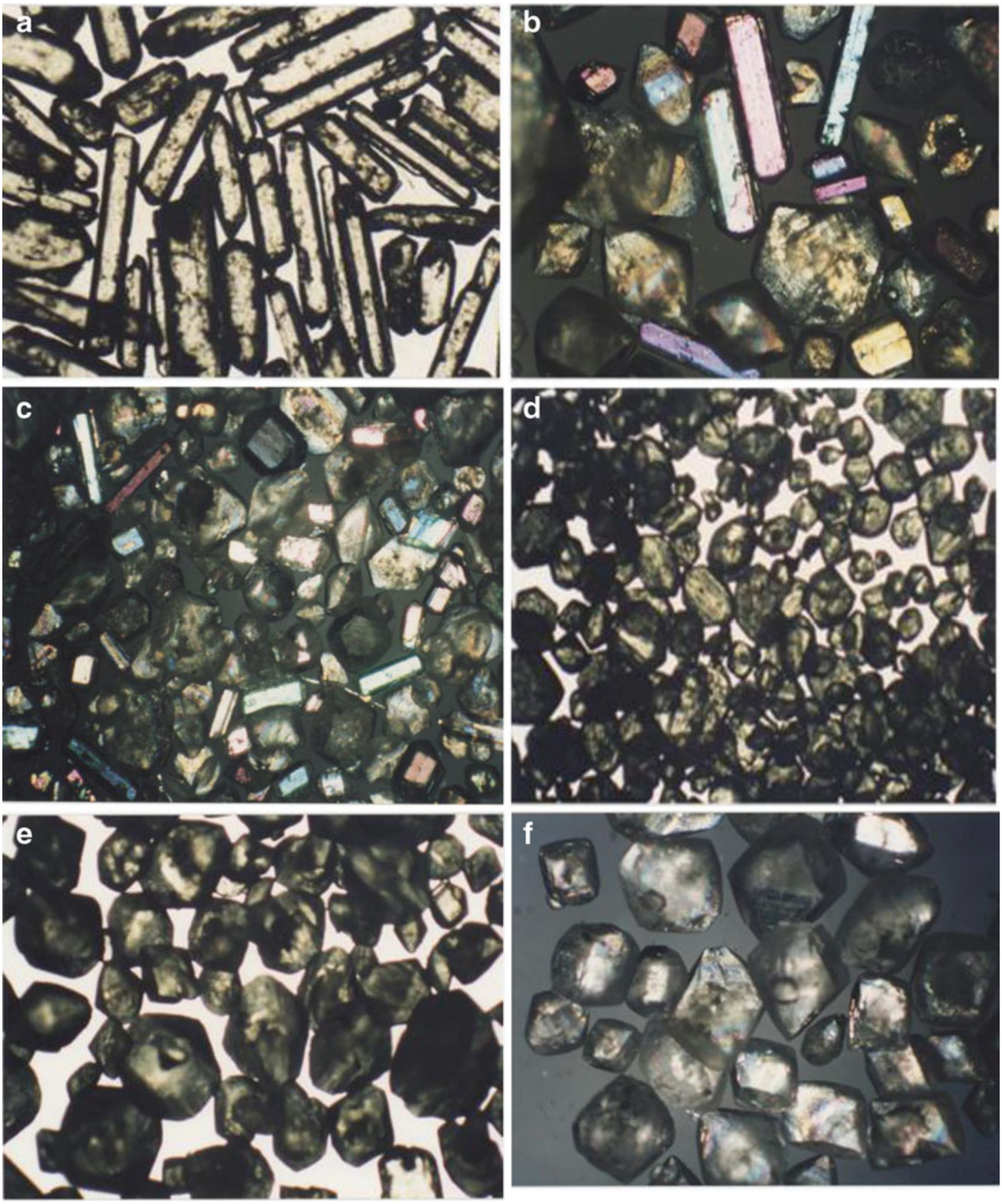


Fig. 9 Huge number of acicular, prismatic and pyramidal shapes of crystals found in the Umm Said Sabkha deposits

The inter-grown sub-lenticular crystals are of about 2 mm length.

In the southwestern part of the Sabkha (sand dunes area), large gypsum crystals of desert rose habit are formed at depths of 4–66 cm. The crystals are about 17 cm long, with width ranging from 6.5 to 7 cm and in thickness from 2 to 3 cm.

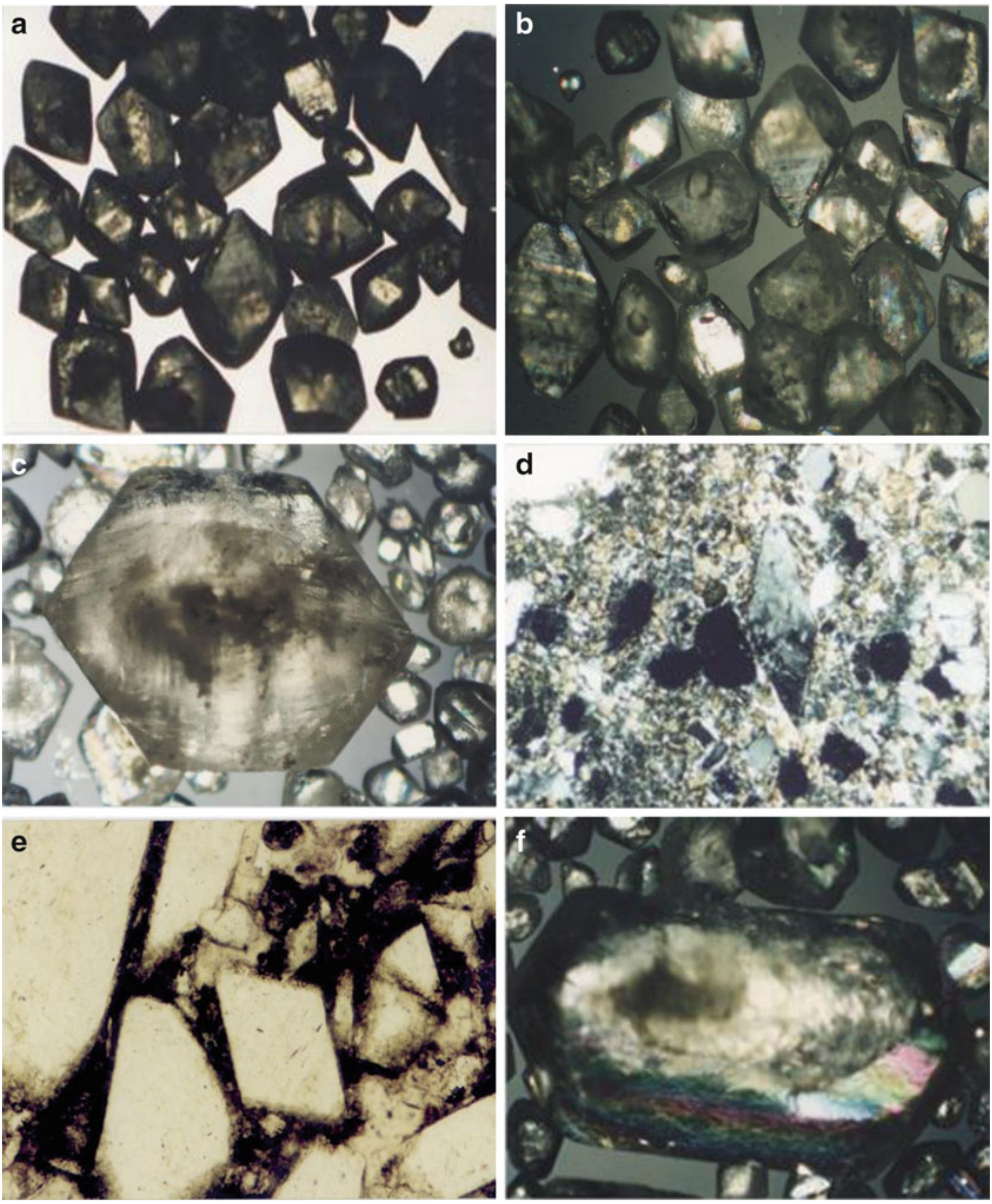


Fig. 10 Gypsum crystals of various habits and sizes found in the Umm Said Sabkha deposits (Note: **a, b, c** and **e** pyramidal and typical pyramidal, **d** lenticular and **f** thick, short prismatic)

5.2.2 Gypsum Crystallography

The crystallographic study of the dominant gypsum crystals in the sediments of Umm Said Sabkhas showed that: all the complete gypsum crystals present in the Sabkha are euhedral and tabular, with well-developed (010) faces. The (010) cleavage is conspicuous. Twinning on the (101) and the (100) is common. The crystals

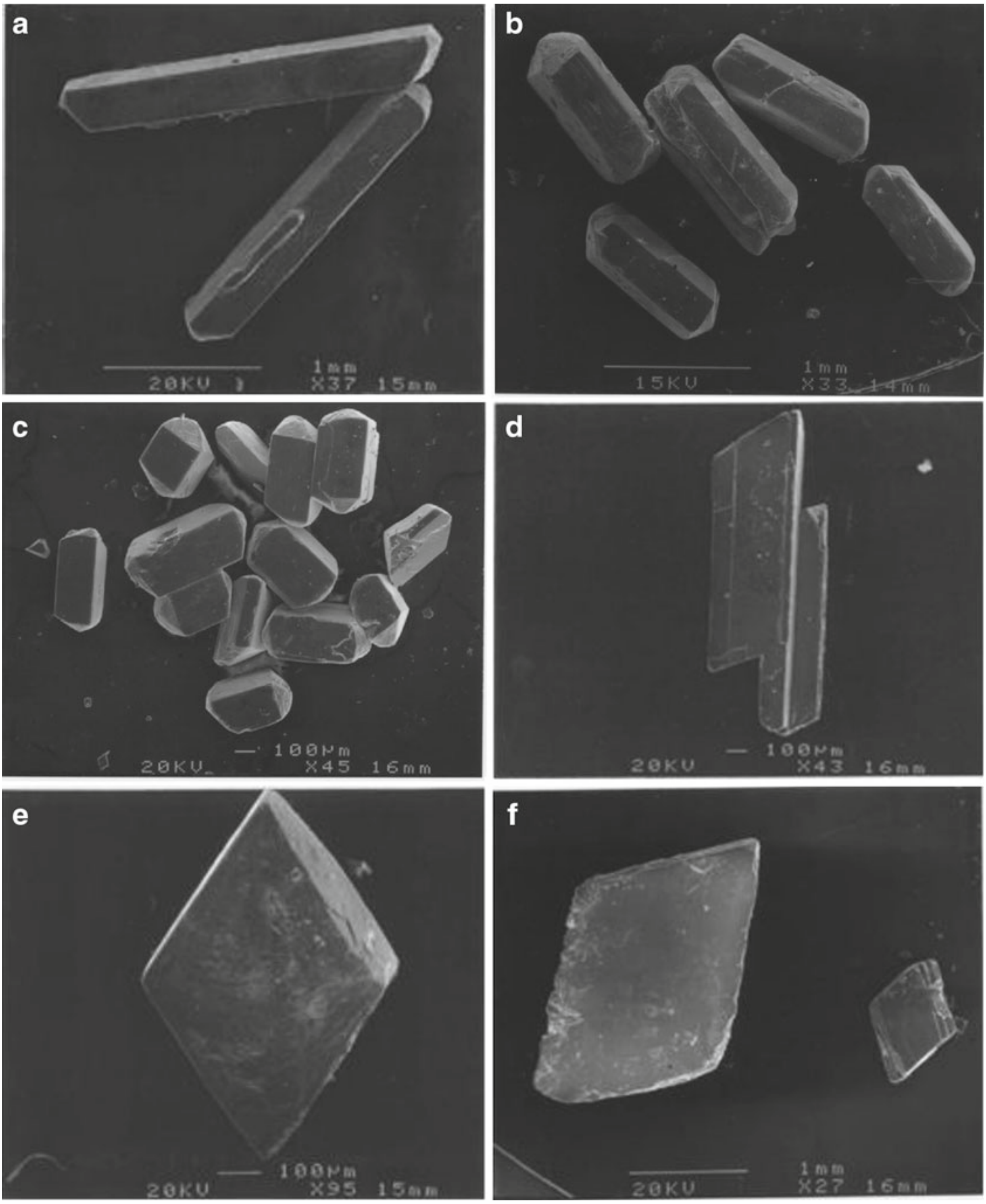


Fig. 11 Typical elongated, short thick prismatic and pyramidal crystals, Umm Said Sabkha (Note the twining crystal grow in same time and move smoothly by side in the crystals **d** and perfect cleavage parallel to the side **b**-pinacoid)

include (110) prism, (111) pyramid, (011) a-dome, (101) b-dome and the a, b and c pinacoids. The various habits of the crystals, including these faces are shown in Figs. 11, 12 and 13. The prismatic crystals are found in two shapes: (1) Elongated, thin prismatic crystals, attaining lengths of about 2 cm and thicknesses of about 0.4 mm. (2) Stubby, thick prismatic

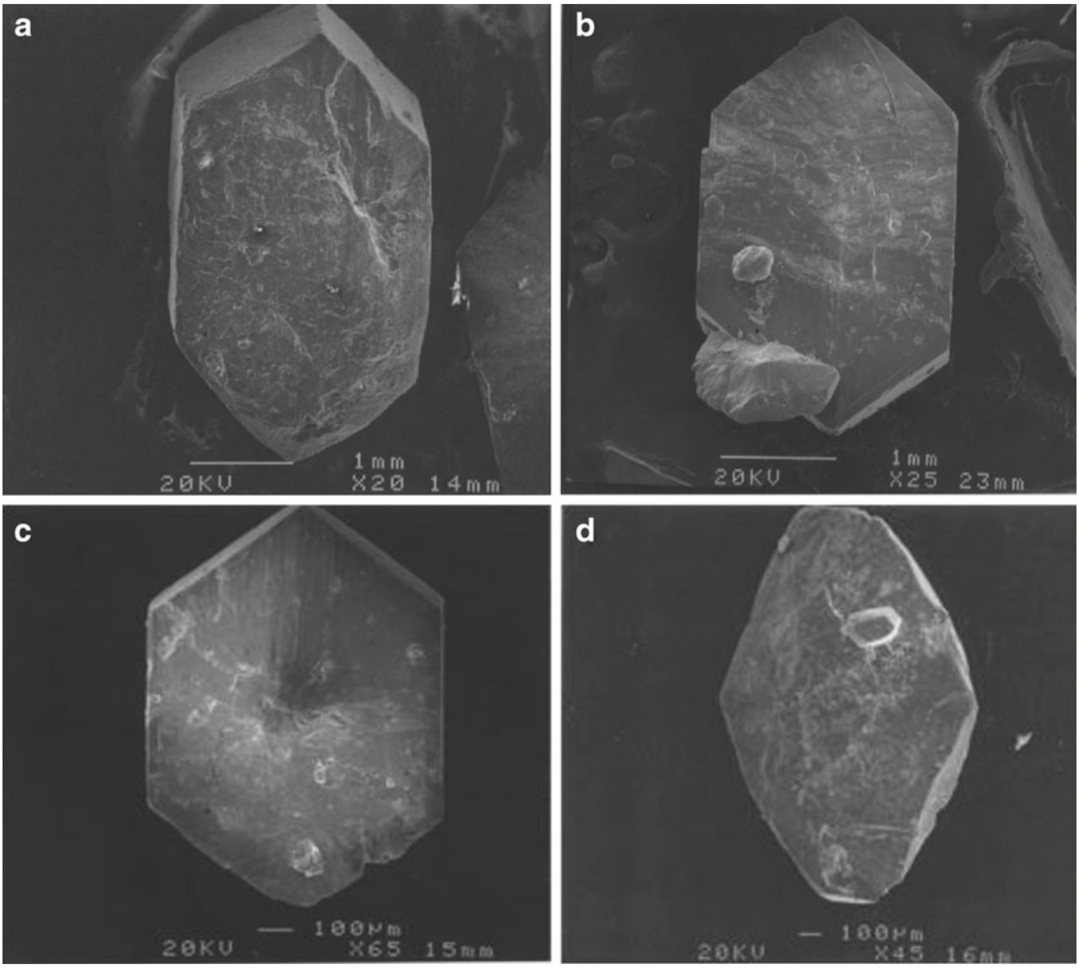


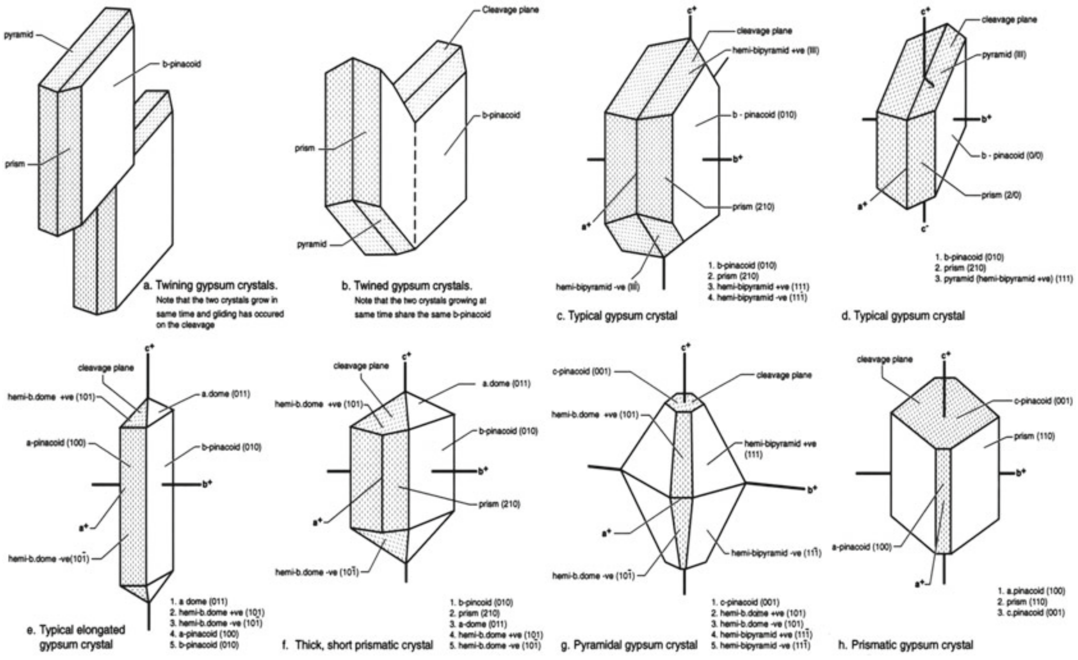
Fig. 12 Typical pseudo-hexagonal and pyramidal gypsum crystals, Umm Said Sabkha

crystals, usually short, having lengths less than 0.7 mm and thicknesses of about 0.5 mm (c, d and e in Fig. 8, a in Fig. 9 and a, b and c in Fig. 11). Both the elongated and stubby thick prismatic crystals include b-pinacoid and a-pinacoid types (e, f and h in Fig. 13). Twinned prismatic crystals are also present, including swallow-tail twins, and length-parallel twins in the prismatic forms (d in Fig. 11 and a and b in Fig. 13).

5.2.3 Brine Chemistry

The Chemical characteristics and mean of brine elements in the Umm Said Sabkha are summarized in Table 2 and Fig. 14. In the brine samples the mean of pH is 6.9, with a range between 6.4 and 7.2. The highest value was recorded in station US47 from the eastern part of the Sabkha (at a depth of about 100 cm) and in station US12 from the middle of the southern part of the Sabkha (at a depth of about 70 cm). The lowest value was recorded in station US16 from the southwestern part of the Sabkha (at a depth of about 66 cm).

The mean for Na^+ is 73.9 ppt (range 39.8–113.3 ppt) and it is 114.9 ppt for Cl^- (range 61.5–177.3 ppt). The highest values of Na^+ and Cl^- were


a. Twining gypsum crystals. Note that the two crystals grow in same time and gliding has occured on the cleavage

b. Twined gypsum crystals. Note that the two crystals growing at same time share the same b-pinacoid

c. Typical gypsum crystal

d. Typical gypsum crystal

e. Typical elongated gypsum crystal

f. Thick, short prismatic crystal

g. Pyramidal gypsum crystal

h. Prismatic gypsum crystal

Fig. 13 Dominant habits of gypsum crystals in Umm Said Sabkha sediments

recorded in a sample from station US16 in the southwestern part of the Sabkha (at a depth of 66 cm). The lowest amounts for the two elements were recorded in a sample from station US11 (surface water) in the middle of the southern part of the Sabkha. These two elements are mainly concentrated in a shallow marine lagoon in the middle of the southern part of the Sabkha and in the southwestern part where sand dunes are present. In general, the proportion of Na^+ and Cl^- increase in the middle and to the western part of the Sabkha.

The relationship between Na^+ and Cl^- according to the statistical study gives $R^2=0.95$ (a in Fig. 15). It gives $R^2=0.43$ for Cl^- with Mg^{+2} (b in Fig. 15), but there is no relationship between Cl^- and Ca^{2+} in Sabkha brines.

The mean for Ca^{2+} is 1.4 ppt (range 0.1–2.1 ppt) and for SO_4^{2-} 8.3 ppt (range 3.3–14.8 ppt). The highest proportion of Ca^{2+} was recorded in a sample from station US3 in the southwestern part of the Sabkha. The brine sample from station US16 in the southwestern part of the Sabkha also included high proportion of Ca^{2+} (2 ppt). The highest sulphate concentration was found in the middle of the southern part of the Sabkha and the lowest in the southwestern part. It looks like the Ca^{2+} increases to the south and eastern part of the Sabkha. There is a decrease in the proportion of SO_4^{2-} to the south and a concentration in the middle of the southern part of the Sabkha.

Statistical study of the relationship of Ca^{2+} with SO_4^{2-}, and Cl^- showed that there is no apparent relationship between these cations and ions. The relationship of SO_4^{2-} with Mg^{2+} is very low, with $R^2=0.28$ (c in Fig. 15).

The mean for Mg^{2+} is 6.3 ppt (range 1–11.9 ppt). The highest proportion was recorded in a sample from a station in the middle of the southern part of the Sabkha and the lowest proportion in a sample from a station in the southwestern part of the Sabkha. The highest proportion of Mg^{2+} was found in the central and southwestern part of the Sabkha. The statistic study showed that there is a good relationship between Mg^{2+} and Ca^{2+} in the brines, $R^2=0.55$ (d in Fig. 15).

Table 2 Results of chemical analyses of 11 water samples from Umm Said Sabkha

	Location												
Station	Longitude	Latitude	Dep. (cm)	pH	Cond.	Na + (ppt.)	Cl^- (ppt.)	Ca^{2+} (ppt.)	SO_4^{2-} (ppt)	Mg^{2+} (ppt)	Sr^{2+}(ppt)	HCO_3^{2-} (ppt)	TDS (ppt)
US3	N = 24° 58′ 46″	E = 51° 33′ 36″	6.0	6.9	191.4	70.6	94.3	2.1	6.1	1.0	0.04	0.07	174.1
US8	N = 24° 58′ 59″	E = 51° 34′ 22″	20.0	6.9	225.0	106.1	157.6	0.7	6.9	11.4	0.02	0.08	302.6
US10	N = 24° 59′ 08″	E = 51° 34′ 33″	12.0	7.0	222.0	101.0	162.9	0.1	14.8	11.9	0.02	0.08	290.8
US11	N = 24° 59′ 08″	E = 51° 34′ 38″	Surf. Wat.	6.9	137.9	39.8	61.5	1.8	7.8	3.8	0.03	0.08	114.8
US12	N = 24° 59′ 08″	E = 51° 34′ 40″	70.0	7.2	228.0	99.9	156.6	1.7	6.7	2.8	0.04	0.10	267.9
US16	N = 24° 56′ 47″	E = 51° 31′ 26″	66.0	6.4	238.0	113.3	177.3	2.0	6.6	9.4	0.05	0.04	289.0
US20	N = 24° 55′ 57″	E = 51° 30′ 55″	40.0	6.9	179.7	40.3	70.2	1.3	7.1	4.1	0.03	0.08	123.1
US25	N = 25° 01′01″	E = 51° 35′ 59″	47.0	7.0	183.7	61.1	96.9	1.4	8.8	6.5	0.03	0.08	174.8
US33	N = 25° 03′ 42″	E = 51° 36′ 11″	50.0	6.7	179.6	59.6	97.8	1.4	11.5	5.9	0.04	0.07	176.2
US46	N = 25° 00′ 56″	E = 51° 35′ 33″	50	6.6	207.0	77.7	118.6	1.1	11.3	8.1	0.03	0.06	216.9
US47	N = 24° 59′ 59″	E = 51° 36′ 59″	100.0	7.2	65.1	43.4	69.8	1.7	3.3	4.4	0.03	0.08	122.6
Mean				6.9	187.0	73.9	114.9	1.4	8.3	6.3	0.03	0.08	204.8
Standard seawater in gram/litre						10.56	18.98	0.40	2.65	1.27	0.008		34.3

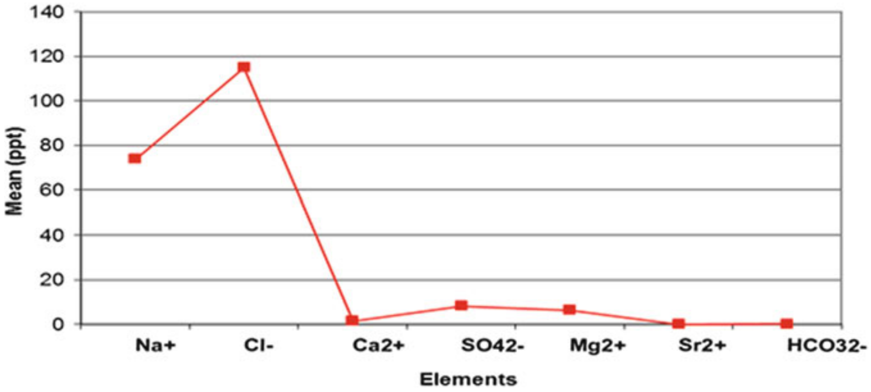


Fig. 14 Mean of brine elements in 11 samples from the Umm Said Sabkha

The mean for HCO_3 in the brines is 0.1 ppt (range 0.04–0.1 ppt). The concentration of HCO_3 in the brines within the Sabkha increases to the middle of the northern part of the Sabkha.

The mean for Sr^{2+} recorded in the brines is 0.04 (range from 0.02 to 0.05 ppt). The highest concentration of Sr^{2+} in the selected samples within the Sabkha is found in the middle of the Sabkha.

The mean for TDS is 204.8 ppt (range between 114.8 and 302.6 ppt). The highest proportion is found in station US8 in the northern part of the Sabkha at a depth of about 20 cm and the lowest proportion was in station US11, present to the north from station US8. The highest TDS (230 ppt) in the selection area was recorded in five brines from the southern part of the Sabkha and the lowest TDS (122.6 ppt) was recorded in the southeastern part of the Sabkha.

The statistical study of the relationship between TDS and brines cations and anions showed that there is no apparent relationship between TDS and Ca^{2+}. The relationship of TDS with Na^+ and Cl^- is very good as expected, giving $R^2=0.97$ and 0.98, respectively (a and b in Fig. 16). Relatively good relationship found between TDS and Mg^{2+}, $R^2=0.5$ (c in Fig. 16). No relationship was found between SO_4^{2-} and TDS in the brine samples.

6 Discussion

6.1 Sediment Samples

Most of the surface of Umm Said Sabkha is covered by sand. This is because the accumulations of sand dunes in Qatar are mainly present in the south. A large amount of these sands was probably carried into the Sabkha by wind. A compact brown crust of siliciclastic sand, gypsum and halite covers the northern and northwestern part of the Sabkha. The crust is not present in the eastern part of the Sabkha, because it is affected by seawater influx during the daily high tides. For the same reason, halite and gypsum are not formed in the sediments near the eastern coast of the Sabkha; the renewed of seawater does not give the opportunity for underground water within the Sabkha to reach to the saturation point.

Various habits of gypsum crystals; of different sizes are present in Umm Said Sabkha sediments on the surface and at shallow depths (few cm from the surface). The crystals formed in the supra-tidal area and dominant in the northern and western part of the Sabkha, and beneath the algal mats in the intertidal zone within the Sabkha. The crystals are of acicular, prismatic, lenticular and sub-lenticular, inter-grown sub-lenticular,

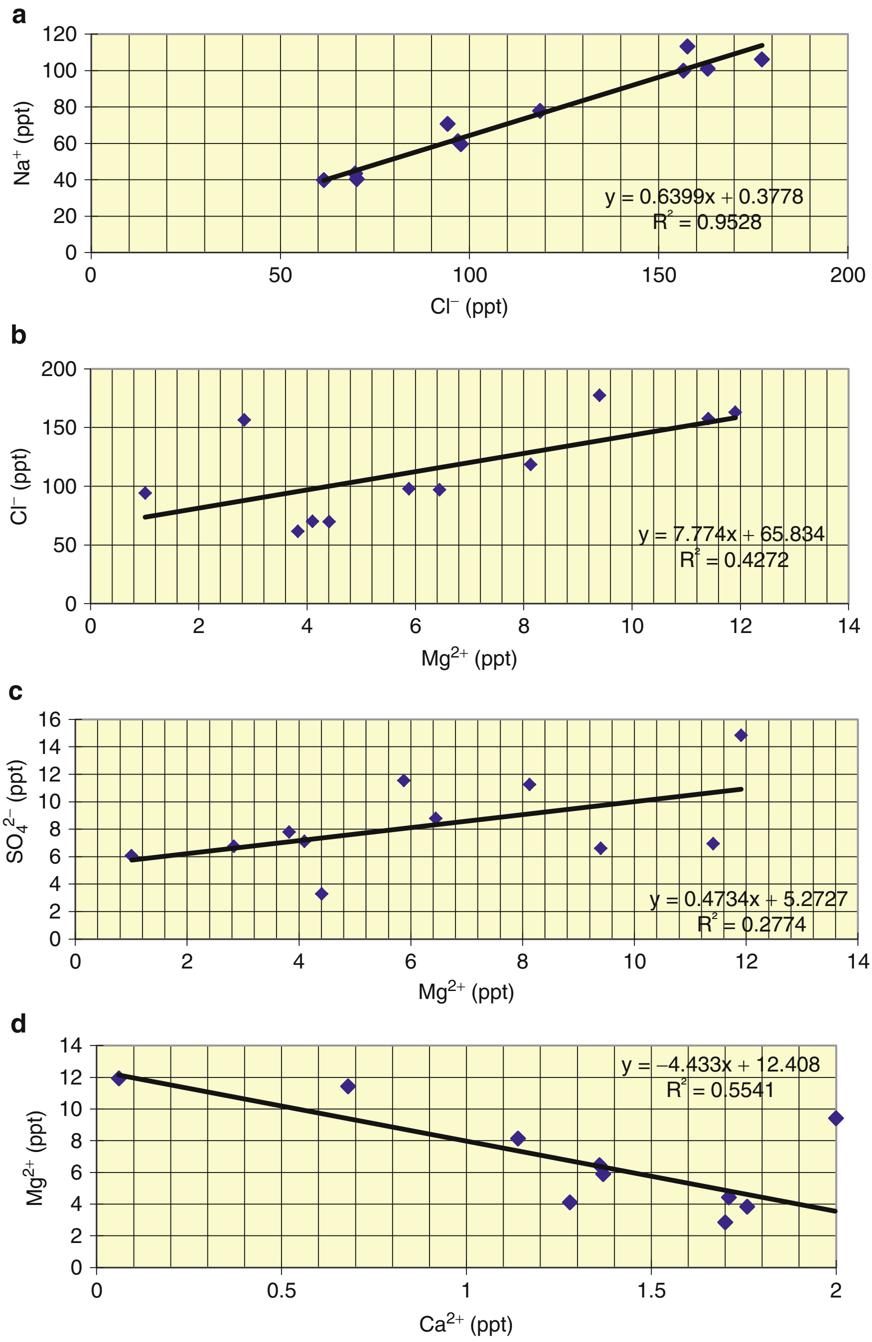


Fig. 15 Relation between Na^+ and Cl^-, Mg^{2+} and Cl^-, SO_4^{2-} and Mg^{2+}, and Mg^{2+} and Ca^{2+} in 11 brines, Umm Said Sabkha

pyramidal, elliptical and semi-elliptical, and pseudo-tetragonal shapes. They are euhedral, simple and tabular on (010), and the cleavage (010) is very good on the crystal surface. Twinning on the (101) and the (100) is common. The crystals show (110) prism, (111) pyramid, (011) a-dome, (101) b-dome and the a, b and c pinacoids (the crystal faces are parallel to two axes).

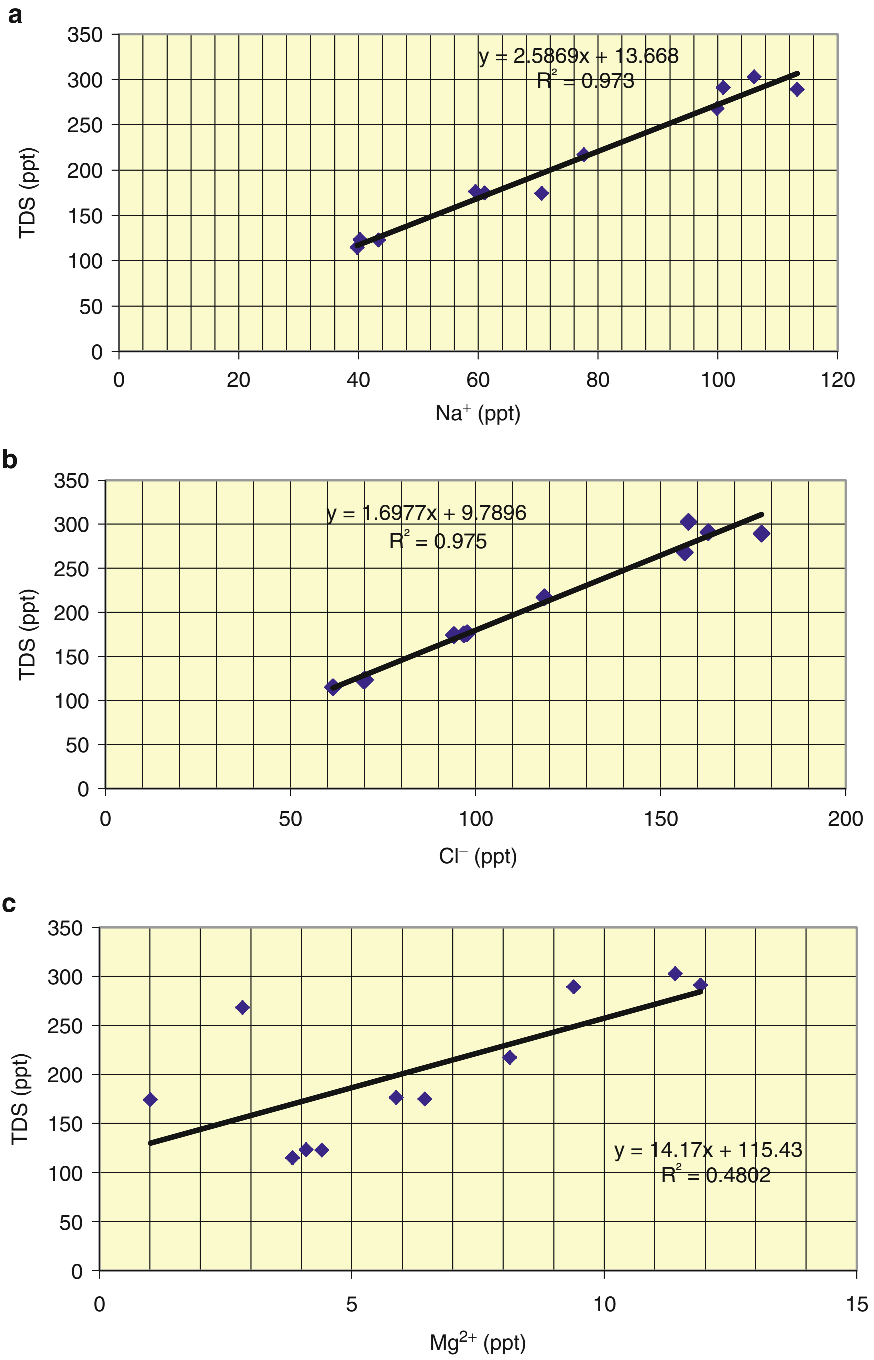


Fig. 16 Relation between TDS (ppt) with Na^+(ppt), Cl^- (ppt) and Mg^{2+} (ppt) in 11 brines, Umm Said Sabkha

The size of the crystals is less than 1 cm, except for those present on or in the surface crust and or at shallow depths of the Sabkha. For example, prismatic lenticular and sub-lenticular habits are the dominant surface gypsum crystals in the Sabkha; their size is about 2 cm. Desert rose crystals are mainly dominant in the sand dune areas in the south and southwestern part of the Sabkha. The length of these crystals is about 17 cm, with width 6.5–7 cm and thickness 2–3 cm.

Suitable conditions such as high ground water level, high temperature, saturation of Sabkha sediments by brines, low rainfall and a high rate of evaporation are probably reasons for formation of these crystals in Umm Said Sabkha. It is reported in coastal Sabkhas gypsum precipitated from surface brines at temperatures 38–42 °C [8]. At more than 42 °C, gypsum may slowly dehydrate to anhydrite over some months; but lower temperatures and rainstorms or a marine flood can rehydrate the anhydrite in a matter of hours [39].

The main reasons for variation in the amount and habit of gypsum crystals in Umm Said Sabkha are: (1) It is a large coastal Sabkha, accordingly the evaporation process is more active inside and at the land edges direction within the Sabkha than at the coast edges direction leading to a greater proportion of gypsum in the former; (2) the difference between the principal sediment types is the second important reason. In Umm Said Sabkha sand sediments are dominant over fine deposits (present at depth from the surface to more than 1 m), especially in the south and south western part of the Sabkha; the repeated marine flooding at high tides tends to dissolve the uppermost halite and re-precipitates it at slightly greater depths, leaving the surface and upper layers with relatively more gypsum; (3) Umm Said Sabkha is dominated by seawater influx; (4) rainfall proportion is small in Qatar, especially in the south; (5) the surface drainage of rainwater is fed Umm Said Sabkha only from the west and north; and (6) Umm Said Sabkha has a mean elevation of +1 m above sea. This leads to greater rates of evaporation over groundwater recharge.

In general, the proportion of gypsum crystals in Umm Said Sabkha increases in the locations of fine sediments than in the sand sediments. It seems that fine grained sediment allows more than one habit of the crystals to form in comparison with coarse grained sediment. The evaporation process in fine sediments is slower than that in coarser sediments, allowing the brines to be retained in the sediments for enough to form more than one shape of crystals. The more rapid evaporation process through coarse sand does not give enough time for such a wide range of crystal shapes to form.

The proportion of prismatic crystals in the Sabkha sediments is high because of the dominance quartz sand and its presence for more than a meter below the surface. Quartz sand is distinguished by high porosity, which allows water to move easily between the sediments and the distance between the grains allows formation of elongated, thin prismatic gypsum crystal. Prismatic crystals grow mostly in sediment-free solution [40]. He believes that elongate prismatic gypsum forms in acid conditions, whether or not organic material is present. The dominance of prismatic crystals in the studied Sabkha is conformable with this. The total dissolved solid (TDS) of Umm Said Sabkha brines averages about 205 ppt. This is probably another reason for the dominance of prismatic crystals in Umm Said Sabkha.

The large number of acicular gypsum crystals present on the surface in the southeastern part of the Sabkha, near the artificial pit, is probably because the brine in this area is saturated with SO_4^{2+}. Acicular crystals are usually dominant in pure aqueous solution supersaturated with gypsum [41]. For this reason, gypsum crystals are also dominant on the surface, within and at the margin of the pit in this part of the Sabkha.

The presence of pyramidal crystals in Umm Said Sabkha sediments and their dominance in some locations within the Sabkha is probably because fine sediments are abundant in these locations. It was suggested that organic matter associated with clay stops the growth of the (111) face of the crystals; accordingly the pyramidal gypsum habits are usually dominant in clay-rich organic deposits [40]. In the present study, pyramidal crystals are found in fine carbonate sediments lacking organic material. The grain-size of the sediments probably controls the formation of this type of gypsum habit in Umm Said Sabkha.

Lenticular and sub-lenticular crystals habits are dominant in the locations of fine sediments saturated by halite. This is because the permeability of fine sediments is low, reducing the evaporation rate from the sediments at shallow depths, and giving enough time for various shapes of gypsum crystals to form. It believed that organic matter is a major factor for growth of lenticular habit under alkaline rather than acidic conditions [40, 42]. This leads to rapid perpendicular growth of gypsum crystals from (111) and (103), and consequently minimizes growth parallel to the crystallographic c axis. Normally there is slow growth perpendicular to the forms (110) and (010) leading to a tabular morphology combined with the (111) and (103) growth leading to lenticular crystals. In the Umm Said Sabkha, where lenticular and sub-lenticular crystals are dominant, microbial mats are also present in the sediments. These crystals, however, are also found in other locations of the Sabkha, and are of large size, although there is no organic material in the sediments.

Because of the quartz sand and the high TDS of the brines, large gypsum crystals of desert rose habit are dominant in Umm Said Sabkha, especially in the southwestern part of the Sabkha (sand dune area) at depths from 20 cm to about 1 m from the surface. The high porosity and permeability of sand lets water move to the surface by capillarity, accordingly the salinity became saturated at shallow depths, allowing gypsum crystals to form and grow large in size. During rainy period, the saturation brines (rich in SiO_4^{-2} and Ca^{+2}) moved down and the crystals formed at depth. The color of the crystals is light brown in depth as the crystals are wet; but light grey on the surface after the crystals dried. Such as this desert rose crystals also formed in same condition in the eastern coast of the Arabian Peninsula [21]. It believed that the type of sediments affected the size of gypsum crystals of southern Texas [43]. High porosity and permeability of the sediments caused rapid migration of brine ions and accordingly large crystals of gypsum formed in the area.

6.2 Brine Chemistry

The values of pH are almost the same in all the samples and similar to those reported by previous studies of the brines of some Sabkhas and the seawater of Qatar. There is no relation between the depth and pH of the studied samples. Previously reported that the pH value of the Sabkha brines is less than that of the normal seawater [44]; for sea water pH is around 8.2 and it can decrease to 6.3 with increased CO_2 as during photosynthesis, but it does not normally exceed 8.4. Algae mats usually reduce pH to 6.5 [45]. The decrease of pH in the brines of the studied Sabkha was probably not caused by phytoplankton and algal mat, because the proportion of them in the sediments was low, except for those locations rich in algae mats. Here the algae mats increase the probation of pH in the brines (they consume CO_2 during photosynthesis and produce oxygen). There appears to be some relationship between pH and the overall salinity of the Sabkha brines. The brines of high salinity have low pH. Krumgalz study related to salt effect on the pH of hyper-saline solution found similar results [46]. However, in Umm Said Sabkha, there is similarity in the relationship between pH and salinity, but no clear relationship between pH and TDS. It is reported that high salinity reduces the activity of pH in the brines, and with a decrease in the salinity the activity of pH in the brines increases [11]. This situation is similar to the cases in our studied Sabkha. In Umm Said Sabkha the TDS in the brines is 204.8 %, Na^+ 73.9 ppt and Cl^- 114.9 ppt. The concentration of brines affects the hydrogen ion activity in natural marine and geochemical systems. Changing the hydrogen ion activity will affect the solubility of number of elements and minerals and also the equilibrium kinetics of many processes [46–48]. Probably this situation will reflect on the gypsum formation within the Sabkha.

The mean concentration for Na^+ and Cl^- in the brine samples is high (73.9 and 114.9 ppt respectively). The factors causing the high concentration of Na^+ and Cl^- in the brines of Umm Said Sabkha are: (1) the evaporation processes from the surface and from shallow subsurface water within the Sabkha; (2) Umm Said Sabkha is coastal Sabkha and mainly fed by seawater. Small proportion of fresh water reaches to the Sabkha by surface drainage during rainy period only at its northern and western side; (3) the accumulations of sand dunes inside the water of the eastern coast of Qatar make the water shallower, leading to increased salinity on the eastern coast; (4) the sand accumulations beside the western side of Umm Said Sabkha restrict surface drainage into the Sabkha; (5) the eastern coast of Qatar is complex as it displays a greater number of inlets. The sand and eroded materials carried by sea currents could be accumulated in between these coastal shapes, and thus the water in these locations became shallow. Evaporation process from these positions would became high, and accordingly increase the salinity of the water of the eastern coast; and (6), a high percentage of sodium chloride in the Sabkha sediments (about 63 % according to [30]). Halite in the sediments could be easily dissolved by water, hence the brines of the Sabkha became saturated in Na^+ and Cl^-. Accordingly, the good relationship between Na^+ and Cl^- ($R^2>0.9$) of Umm Said Sabkha brines is a normal situation, as Sabkha brine is usually distinguished by high salinity.

The highest proportion of Na^+ (113.3 ppt) and Cl^- (177.3 ppt) in the brines was found in the southwestern part of the Sabkha, where sand dunes dominate. The surface of the land in this location is covered with recent, thin white deposits of halite (0.1–0.4 cm thick). The sand present in the area is at least 1 m thick and this allows for very active evaporation to occur, leading to formation of a halite crust. The lowest proportion for Na^+ (39.8 ppt) and Cl^- (61.5 ppt) in the Sabkha brines was found in a sample from a surface channel (station 11) in the middle of the southern part of the Sabkha, taking a direction from land to the coast. The reason for the low salinity in the water channel is probably because it is affected by rainwater or fresh water from the land.

The average of Ca^{2+} and SO_4^{2-} is approximately three times higher than that of the seawater (1.4 ppt and 8.3 ppt respectively). The concentration of Ca^{2+} and SO_4^{2-} increases to the south. Gypsum in the Sabkha sediments is probably an important source for Ca^{2+} and SO_4^{2-} in the brine; it is a dominant evaporate mineral in the sediments of the Sabkha, but because the formation of gypsum in the area is currently active, much Ca^{2+} and SO_4^{-2} is utilized in the formation of this mineral. As evidence, the two brine samples from stations US 3 and US 16 included about 2 ppt Ca^{2+}, probably because of dissolution of gypsum and calcite in nearby rocks. Gypsum proportion at stations US3 and US16 was high. For same reason, the brine sample US10 from the middle of Umm Said Sabkha included the highest proportion of SO_4^{2-} (14.8 ppt); the deposits here include high gypsum. Previously reported the carbonates in Umm Said Sabkha deposits at depth between surface and 130 cm are dolomite, calcite, aragonite and Mg-calcite [30]. She added that dolomite and calcite are dominant whereas the proportion of aragonite and Mg-calcite are very small. These carbonate deposits and calcite minerals within the Sabkha sediments probably formed secondary source of Ca^{2+} and SO_4^{2-} cations of gypsum formation in the Umm Said Sabkha. After the melt of carbonate deposits in the water, water becomes saturated by $Ca^{2+}$and SO_4^{-2}, accordingly the activity of formation of gypsum increases.

Mg^{2+} in Umm Said Sabkha brines is high, about 6.3 ppt. The highest proportion for Mg^{2+} was recorded in sample US16 (9.4 ppt). The sample also included a high proportion of Cl^- (177.3 ppt) and this means that magnesium chloride is the reason for the high proportion of Mg^{2+} in this sample. For this reason, most of the brine samples from Umm Said Sabkha included a high proportion of Mg^{2+} whilst including a high proportion of Cl^-; Mg^{2+} simply increases with salinity and Cl^-.

No doubt that the deposits from outside the Sabkha, rich in magnesium and calcite form another source for Mg^{2+} and Ca^{2+} in the Sabkha brine after they carried to the Sabkha by surface drainages during rainy periods. It was reported that clay minerals in Qatar included about 8–10 % magnesium [49]. The carbonate rocks of the Fhaihil member of the Lower Eocene contain very high $MgCO_3$. The percentage of MgO in the Midra (and Sila) Shales of the Lower Dammam Formation is between 3.3 and 10.9 %. It is between 7.155 and 10.10 in the red and green clays of the Lower Dam Formation of the Miocene. Some sand dunes in the southwestern part of Qatar included high percentage (1.10–14 %) of MgO [49]. The clay of Al-Nakhsh area in the southwestern part of Qatar is rich in MgO [50]. The proportion of dolomite and Mg-calcite in Umm Said Sabkha deposits is 9 and 0.7 % [30]. These could also form another source for Mg^{2+} and Ca^{2+} in the Sabkha brine and for formation of gypsum in the Umm Said Sabkha.

No good relationship was found between Mg^{2+} and Ca^{2+} in the brines, probably because the balance was affected by utilized Ca^{2+} in gypsum formation. It was suggested that the low ratio of Mg/Ca in Umm Said Sabkha brines is because of the formation of gypsum and dolomite [51]. A considerable amount of Ca^{2+} is lost as gypsum, calcium carbonate or dolomite. Because the salinity of Umm Said Sabkha is high the relationship between Mg^{2+} and Cl^- in the brines is relatively good; but since Mg^{2+} is affected by the salinity, this reflected on the relationship between Mg^{2+} and TDS.

The amount of Sr^{2+} in the brines from Umm Said Sabkhas is about twice that found in the seawater. The overall mean of Sr^{2+} in Umm Said Sabkha sediments is reported around 850 ppm [30]. Sr^{2+} in the Sabkhas sediments is probably the reason for the increase of this element in the brines. The highest concentration of Sr^{2+} was found in the southwestern part of the Sabkha and the desert rose gypsum crystals are dominant in this part of the Sabkha. These crystals are rich in fine grains of different colors; may be heavy minerals and if they are, they will probably form another source for Sr^{2+}; but this need more study.

The concentration of HCO_3^- in the brines of study area is small, but it is higher than that of seawater. The minor concentration of HCO_3^- in the Sabkha brines is probably because the proportion of microbial mat in the Sabkha is small. Microbial mats are mainly dominant in the central part of the Sabkha within the swamp areas, and these probably lead to a high concentration of HCO_3^-. In addition to that, the remains of dead plants in the northern and western parts of the Sabkha probably increase the proportion of HCO_3^- in the sediments of this part of the Sabkha. Later HCO_3^- could be concentrated in rainwater and penetrate inside the Sabkha and mix with Sabkha brines at shallow depths.

The proportion of TDS (total dissolved solids) in Umm Said Sabkha brine is high (mean is 204.8 ppt with range between 114.8 and 302.6 ppt), a normal situation for coastal sandy Sabkha, fed by seawater and affected by very active evaporation process. In Umm Said Sabkha the TDS concentrated is in the middle and in the western and southwestern part of the Sabkha. This is because Umm Said Sabkha is coastal Sabkha; seawater forms the main source for groundwater in the Sabkha by seepage into the sediments during high tide. There is no major barrier between sea and Sabkha so that regular flooding occurs during each high tide, extending still further inland across the Sabkha during exceptionally high tides and storm conditions. According to the high daily evaporation process the salinity of the interstitial brines in the Sabkha is high and increases in the middle and to the western direction of the Sabkha edges.

The brine sample from station US8 included the highest proportion of TDS (302.6) because the level of the surface in this part of the Sabkha (as seen from field study) is low with compact halite fragments present on the surface. The lowest proportion of TDS (114.8 ppt) was recorded in a brine sample from an elongated narrow channel extending inside the Sabkha. The water in the channel is probably mixed with fresh water from the land, which thus decreases its salinity. The relationship between TDS, Na^+ and Cl^- of the brine samples of the Sabkha is very clear as a normal case of any brine, the brine being of Cl^- type rather than dominant in SO_4^{-2} or HCO_3.

7 Conclusion

Umm Said Sabkha is large coastal Sabkha, located on the southeastern coast of Qatar. Most of the surface of Umm Said Sabkha is covered by sand, reaching in depth to more than 1 m. Fine sediments, with a dark grey or black color of organic-carbon rich in mud, are found in some locations within the Sabkhaat depths between 30 and 90 cm.

Various habits of gypsum crystals, of different sizes are present in the sediments on the surface and at shallow depths (few centimeters from the surface). The crystals formed in the supra-tidal area and dominant in the northern and western part of the Sabkha, and beneath the algal mats in the intertidal zone within the Sabkha. The opportunity of forming gypsum is high away from the eastern border of the Sabkha. This is because of the saturation of Sabkha brine by evaporation processes, whereas water at the eastern part of the Sabkha, adjacent to the coast often does not reach the saturation point, because water renewal by tide processes.

In general, the proportion and habits of gypsum crystals in sand sediments are small, but both increases in the locations of fine sediments than in the sand sediments. This is because the fine grained sediments allow more than one habit of the crystals to form in comparison with coarse grained sediment. The evaporation process from fine sediments is slower than that from coarser sediments, allowing the finer sediments to retain the brines long enough to form more than one shape of crystals. The crystals in sediments are acicular, prismatic, lenticular and sub-lenticular, inter-grown sub-lenticular, pyramidal, elliptical and semi-elliptical, and pseudo-tetragonal. They are euhedral, simple and tabular on (010), and the cleavage (010) is very good on the crystal surface. Twinning on the (101) and the (100) is common. The crystals include (110) prism, (111) pyramid, (011) a-dome, (101) b- dome and a, b and c pinacoids (the crystal faces are parallel to two axes).

In general, the size of gypsum crystals in the Sabkha sediments is less than 1 cm, but those present on the surface or in the surface crust and or at shallow depths are about 2 cm. For desert rose crystals the length is about 17 cm, width 6.5–7 cm, and thickness 2–3 cm.

Suitable conditions such as high ground water level, high temperature, saturation of Sabkha sediments by brines, low rainfall and a high rate of evaporation are probably reasons for formation of these crystals in Umm Said Sabkha. Those gypsum crystals in the Sabkha mainly formed as primary precipitates from saturated brine solutions within the pore spaces of near-surface sediments. Some also formed as a result of the reaction between the saline groundwater and calcium carbonate of the original sediments or by replacement of aragonite and by hydration of anhydrite.

The shallow level of brines and the saturation of brines by SO_4 and Ca^{2+} are the most important factors for formation of gypsum crystals. The sediment grains size and the constant or difference of the grains size with the depth in addition to the type of sediment (sand, clay, silt and or mixed of these minerals and the present of organic materials and fragments in deposits) definitely affected the shape and size of gypsum crystals in the Sabkha deposits.

The main reasons for variation in the amount and habit of gypsum crystals in Umm Said Sabkha are:(1) Umm Said Sabkha is large coastal Sabkha present on the eastern coast of Qatar, accordingly in this part of the Sabkha the renewed of sea water does not give the opportunity for groundwater to reach to the saturation point there for, the formation of gypsum is active inside and at the land edges direction within the Sabkha than at the coast edges direction; (2) the difference between the principal sediment types within the Sabkha; (3) Umm Said Sabkha is dominated by seawater influx and the amount of seasonal rainwater that reach the Sabkha is small and the surface drainage fed the Sabkha only from the west and north.

The proportion of prismatic crystals in the Sabkha sediments is high. The crystals are present on the surface or at shallow depths because of the availability of suitable condition for their formation, e.g., abundance of sand deposits, organic sediment, acidic conditions and high evaporation process that allow brine within the Sabkha to saturated or supersaturated with SO_4^{2+}. The prismatic crystals are found in two shapes: (1) Elongated, thin prismatic crystals, attaining lengths about 2 cm and thicknesses about 0.4 mm, and (2) Stubby, thick prismatic crystals, usually short, having lengths less than 0.7 mm and thicknesses about of 0.5 mm. Both the elongated and stubby thick prismatic crystals include b-pinacoid and a-pinacoid types. Twinned prismatic crystals are also present, including swallow-tail twins~~;~~ and length-parallel twins in the prismatic forms.

The prismatic and acicular crystals are dominant over other crystals habits in the southwestern part of the Sabkha. Mostly two or three types of the crystals are present in each location at depth between 0.0 and 120 cm. Fragments of broken gypsum crystals up to several centimeters length are present in some samples from various locations within the Sabkha, especially in the northern part.

The pyramidal crystals are dominant in some locations within the Sabkha. They are found in fine carbonate sediments lacking organic material. The fine size of the sediments probably controls the formation of this type of gypsum habit.

The lenticular and sub lenticular crystal~~s~~ habits are dominant in the locations of fine sediments saturated by halite and or included microbial mats. This is because the permeability of fine sediments is low, reducing the evaporation rate from the sediments at shallow depths, and giving enough time for various shapes of gypsum crystals to form.

The organic matter plays an important role in the growth of lenticular shape in the Sabkha sediments under alkaline conditions. This leads to rapid perpendicular growth of gypsum crystals form (111) and minimizes growth parallel to the crystallographic c axis. The slow perpendicular growth of the forms (110) and (010) has probably leading led to the growth of the lenticular crystals.

Large gypsum crystals of desert rose habit are dominant in Umm Said Sabkha, especially in the southwestern part of the Sabkha (sand dune area) at depths from 20 to about 1 m from the surface. This is because of the high TDS of the brines. The high porosity and permeability of quartz sand caused rapid migration of brine ions to the surface by capillarity, accordingly the salinity became saturated at shallow depths, allowing gypsum crystals to form and grow large in size. During rainy period, the saturated brines (rich in SiO_4^{-2} and Ca^{+2}) moved down and the crystals formed at depth. Wet crystals, at depth, are light brown; but turn light grey on the surface after drying.

The brine of Umm Said Sabkha is concentrated with Na^+ and Cl^-, and the TDS content is high. Most likely the high proportion of Na^+ and Cl^- results from the high evaporation process of seawater within the Sabkha. Halite deposits in the Sabkha rocks is another source of sodium and chlorine in groundwater within the Sabkha. There is good statistical relationship between Na^+, Cl^- and TDS in the brines. This is a normal situation, as Sabkha brine is usually distinguished by high salinity. Such a high percentage of salts mean that water reached the saturation point, so it could be evidence of the effectiveness of gypsum formation in the Sabkha sediments, because gypsum is mainly formed in an advanced stage than halite.

Ca^{2+} and SO_4^{2-} average in brine samples is approximately three times higher than that of the seawater sample. Gypsum in the Sabkha sediments, in addition to carbonate deposits and calcite formed decidedly acted as a secondary source for Ca^{2+} and SO_4^{2-} in the Sabkhabrines, and ultimately of gypsum formation in the Sabkha.

Mg^{2+} in Umm Said Sabkha brines is high, about 6.3 ppt. Most of the brine samples also contain a high proportion of Cl^-, pointing to magnesium chloride in the brine. The dolomite deposits and Mg-calcite in and outside the Sabkha could form another source for Mg^{2+} and Ca^{2+} in the Sabkha brine. No good relationship was found between Mg^{2+} and Ca^{2+} in the brines, probably because the balance was affected by utilized Ca^{2+} in gypsum formation where a considerable amount of Ca^{2+} is lost as gypsum. Because the salinity of Umm Said Sabkha is high the relationship between Mg^{2+} and Cl^- in the brines is relatively good; but since Mg^{2+} is affected by the salinity, this reflected on the relationship between Mg^{2+} and TDS.

The pH values of the brine samples are almost similar and there is no relation between the depth and pH of the studied samples. The decrease of pH in the brines of the Sabkha was probably not caused by phytoplankton and algal mat, because the proportion of them in the sediments was low, except for those locations rich in algae mats. Here the algae mats increase the probation of pH in the brines. There appears to be some relationship between pH and the overall salinity of the Sabkha brines. The brines of high salinity have low pH, but there is no clear relationship between pH and TDS. On the other hand, the pH values of brines average about 6.9. This is only very mildly acidic, being less than that of the normal seawater (8.2) but more than that of normal rainwater. The brines of higher salinity have lower pH. The high salinity decreases the activity of pH in the brine; accordingly, the chemical activity becomes high within the Sabkha, and provides good conditions for gypsum formation in the western and central part of the Sabkha.

The proportion of TDS in the Sabkha brine is high and this is a normal situation for coastal sandy Sabkha, fed by seawater, and affected by very active evaporation process.

According to the high daily evaporation process the salinity of the interstitial brines in the Sabkha is high and increases in the middle and to the western direction of the Sabkha edges and decreases to the sea direction. The relationship between TDS, Na^+ and Cl^- of the brine samples of the Sabkha is very clear as a normal case of any brine, the brine being of Cl^- type rather than dominant in SO_4^{2-} or HCO_3^-.

According to the statistical study the relationship of TDS with Na^+ and Cl^- ($R^2=0.97$ and 0.98, respectively) is very good. Relatively good relationship is found between TDS and Mg^{2+}, $R^2=0.5$, between TDS and Ca^{2+}, cumulative and TDS with Mg^{2+} cumulative; $R^2=0.96$ and 0.92 respectively (d and e in Fig. 6.26 of thesis). No relationship was found between SO_4^{2-} and TDS in the brine samples. There is no apparent relationship between TDS and m Mg/m Ca, and TDS with Mg/Ca.

This is a normal situation; Umm Said Sabkha is a wide coastal Sabkha fed by seawater and affected by high evaporation process; in addition, the formation of the evaporates deposits, especially gypsum, is active.

8 Recommendations

Due to the availability of appropriate conditions for the growth of gypsum in the Umm Said Sabkha, this study recommends the following:

1. Establish a gypsum farm in the Umm Said Sabkha and exploited the Sabkha economically in several ways, such as construction, decorative, cement, industry, for medical purposes, soil treatment, and so on.
2. Allocate area from the Sabkha to set up a scientific laboratory and also museum for gypsum crystals. School students, researchers and those interested in this mineral can visit this lab for science benefit.
3. A small museum includes various shapes of gypsum crystals from Qatar, posters, pictures and scientific summaries for gypsum mineral be created in the project area. Part of the museum area will be used for presentation of the minute sizes of gypsum crystals and slides under the microscope.
4. Scientific publications about gypsum growth and shapes will be prepared as a result of the gypsum farm project.
5. This study is a first study for identify the different types of gypsum crystals that grow in the Umm Said Sabkha. It takes into consideration all conditions and factors affecting growth, shapes, proportion and distribution of gypsum crystals in the Umm Said Sabkha. Accordingly, the study is suitable as a model for study the other coastal and inland Sabkhas in Qatar in addition to the Sabkhas of neighboring areas and those that have the same climatic conditions and sedimentary.

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Distribution, Ecology and Ecophysiology of Mangroves in Pakistan

Irfan Aziz and Farzeen Khan

Abstract

Mangroves refer to an ecological group of evergreen woody plants distributed in a zone of tidal influence – both on sheltered coasts and at the banks of estuaries. They provide a variety of ecosystem goods and services to human society and also prevent coastal areas from hazards of hurricanes and Tsunamis. Mangroves usually grow in variable flooding regimes but salinity appears to be the most important factor affecting their growth and distribution. Best growth of mangroves is found in half strength seawater while a 50 % growth reduction is found in full strength seawater. However, survival of different mangrove species in hyper-saline conditions could vary with different morphological and physiological adaptations. This review is an attempt to gather information on distribution, growth dynamics and eco-physiology of mangroves in Pakistan. Information gathered with the help of past and present researches would help in the restoration and methodical care of the mangroves along the coast of Pakistan besides developing them as source of commercial products and spot for a burgeoning ecotourism industry.

1 Introduction

Mangroves are evergreen trees in the intertidal zones of sheltered coasts and banks of estuaries [1]. Although 'exclusive' mangrove species are much debated for their distinct physiological and morphological characteristics [2] but plant communities in such forests comprise of trees, shrubs and salt tolerant grasses from different flowering plants and some of the fern species [1, 3]. Together, all such plant components constitute 'mangal' ecosystem [4]. From ecological perspectives, it is rather difficult to define physical boundaries of mangrove environments [5] because they usually occupy different zones such as fringe (high tides), creeks (medium tides) and

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_3,

scrublands with restricted hydrology [4]. This zonation occurs because different mangroves prefer to grow in different flooding conditions with some species requiring more water (e.g. members of the genus *Rhizophora* and *Avicennia*) then others (e.g. *Excoecaria agallocha*, and *Aegiceras corniculatum* etc.) in addition to variable topography and soil type [6].

Growth and distribution of mangroves depends upon variable flooding regimes, high light intensity, high temperatures, muddy and anaerobic soils, but, salinity is the most crucial factor [7]. Although, mangroves can tolerate highly saline conditions, regular flushing through fresh water streams and rivers are known to optimize their growth as indicated in several eco-physiological studies [8–12]. Osmotic properties (Succulence, ionic regulation and accumulation of compatible osmotica) seem to play a major role in their salt tolerance [13, 14]. Synthesis of organic solutes is energy dependent and may cause growth reduction under highly saline conditions [15–17]. In most of the equatorial and wet tropical regions, where rainfall is higher than 1,500 mm, soil salinity is low to moderate (often lower than seawater) resulting in tall, dense and diverse mangroves [18]. In subtropical arid regions, mangrove diversity is usually low with stunted growth owing to the high soil salinities. This could be one of the reasons besides pollution and human exploitation, why do we have low diversity in coastal areas including the Indus delta where reduction in soil salinity largely depends upon river water inputs.

Mangroves are among the endangered species on our earth. Besides their characteristic beauty for landscaping, they also provide a wide variety of ecosystem goods and services to human society. They provide valuable timber, food, medicine, fuel and building material to local communities. They serve as nurseries for marine life including fish and help stabilize shoreline to prevent from devastating impact of Tsunamis and hurricanes [17]. This paper is an attempt to discuss distribution, ecology and ecophysiology of mangroves in deltaic regions that would not only help resource managers about their methodical care but also in their rehabilitation. Raising mangrove nurseries in appropriate ecological conditions would also help in developing them as source of viable commercial products.

2 Distribution and Extent of Mangrove Forests

The distribution and zonation of mangroves are influenced by various factors including salinity, type of the substrate and tidal energy [18]. On a global scale, mangroves are broadly distributed in two major zones; the “Atlantic East Pacific” and the “Indo West Pacific” [19]. These regions have similar areas of mangrove forests, but the Indo West Pacific region is about five times more diverse with 58 species compared to 12 in East Pacific. The Indo-Malayan region has the highest number (48) of mangrove species [18]. Southeast Asia is considered as the centre of origin of mangrove speciation where diverse terrestrial flora and consistently wet and humid climate has favored the growth of mangroves since the end of cretaceous period [20]. However, during the last 30 years 25 % reduction in the total mangrove area has been observed globally [21].

Pakistan has 3.3 million ha of forests (including both natural and irrigated) which is just 4.1 % of the total land area [22] of which mangroves occupy 98,128 ha [23]. During 1970s it was considered as the fifth largest block worldwide with eight species [24] covering an area of about 400,000 ha but, since then a rapid decline has resulted in total mangrove cover of less than one million ha with a record low in 2004 (86,000 ha; [25]). Diversion of river water to irrigation system has been a major contributing factor for mangrove destruction besides human exploitation and pollution. Coastline of Pakistan is about 1,050 km, shared by the Sindh (350 km) and Balochistan (700 km) provinces. Mangroves mainly exist in five distinct zones including the Indus Delta (92,412 ha), Sandspit (1,056 ha), Miani Hor (4,018 ha) at Sonmiani bay, Kalmat Khor (407 ha) and Jiwani at Gwadar bay (235 ha) [23]. The dominant mangrove (about 90 %) is *Avicennia marina* with few small populations of *Ceriops tagal* in the Indus Delta and *Rhizophora mucronata* at Miani Hor [23]. Restoration of mangroves by the forest

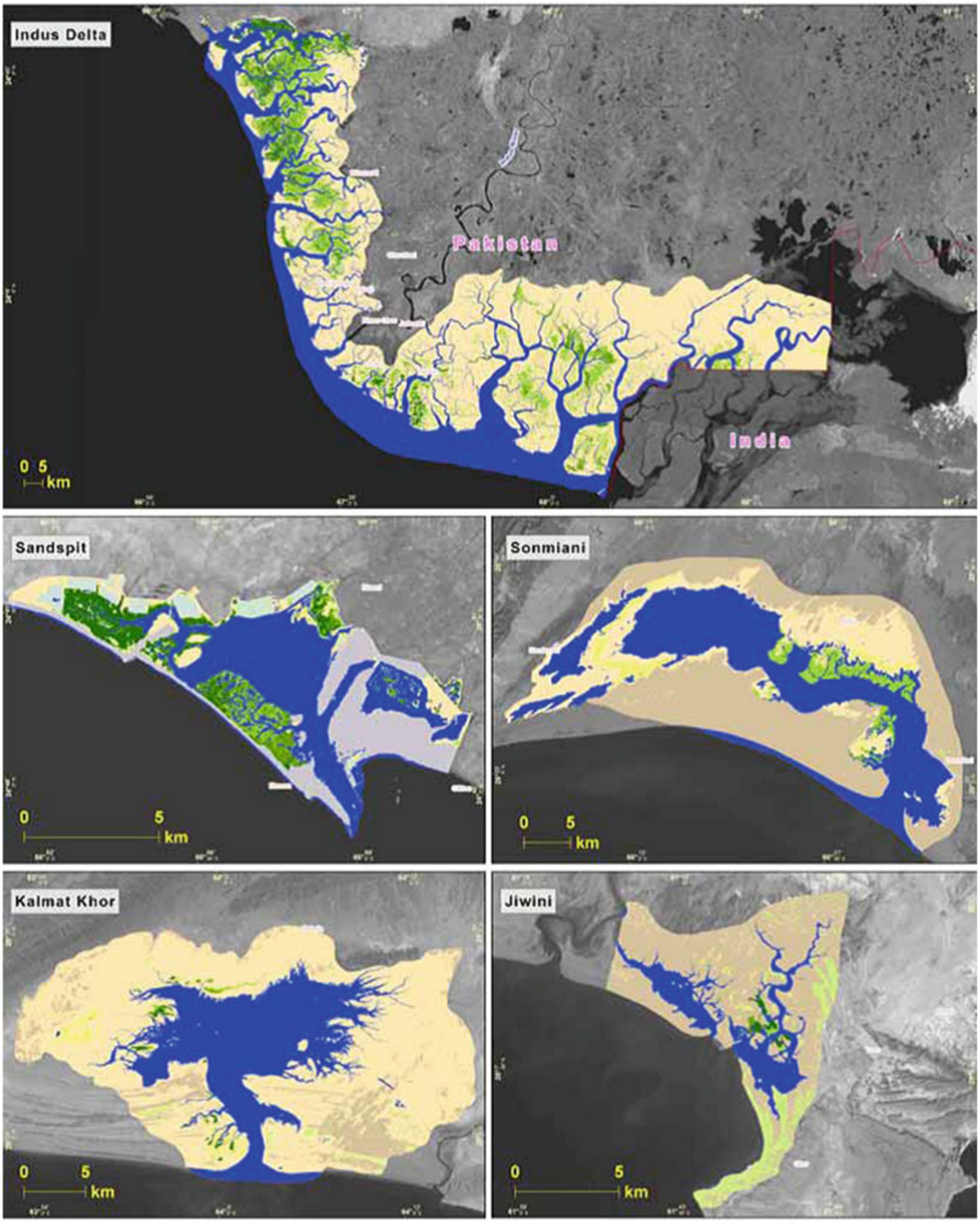

Fig. 1 Distribution of mangroves in Pakistan (Source: [23])

department has recently saved *Aegiceras corniculatum* from complete extinction besides planting *R. mucronata* and *C. tagal* in some of the creeks of the Indus Delta including Keti Bunder and Shah Bunder [26]. Due to this colossal effort about 13 % increase in total mangrove cover has been observed in the last 5 years [23]. Results of image analysis have revealed an estimate of 98,128 ha mangrove in different areas of Sindh and Balochistan (Fig. 1, Table 1) compared to 86,000 ha in 2005 [23].

Table 1 Distribution of different mangrove species in coastal areas of Pakistan (Modified from [23, 26])

Province	Area	Species
Sindh	Sandspit and Hawksbay	*Avicennia marina*
	Korangi/Clifton creeks	*Avicennia marina*
	Rehri creek	*Avicennia marina*, *Ceriops tagal*
	Keti Bunder	*Avicennia marina*, *Aegiceras corniculatum*, *Rhizophora mucronata*
	Shah Bunder (Daboo and Pakar creeks)	*Avicennia marina*, *Ceriops tagal*, *Aegiceras corniculatum*
	Khudi creek	*Avicennia marina*, *Rhizophora mucronata*
	Phiti, Patiani, Sisa and Sir creeks	*Avicennia marina*
	China creek	*Avicennia marina*
	Khai creek	*Ceriops tagal*
Balochistan	Jiwani	*Avicennia marina*
	Kalmat Khor	*Avicennia marina*
	Miani Hor (Sonmiani bay)	*Avicennia marina*, *Ceriops tagal* and *Rhizophora mucronata*

Mangrove restoration is of considerable importance to regional planners, resource managers and researchers. Despite the fact that extensive mangrove plantation has been practiced in the last decade, empirical data on the effectiveness of their restoration are lacking. Further, there is a need to understand optimal conditions for their growth which includes studies on salt tolerance, tidal frequency, geomorphology and mineral availability. Such studies would help in improving productivity and effective management of the mangrove ecosystems.

3 Mangrove Ecology

Mangroves grow best where fresh water mixes with seawater, but restricted growth is a common feature in hyper saline conditions of salt marshes in arid zones. Other environmental factors including temperature, tidal regimes and rainfall also have a strong influence over the growth, survival and distribution of mangroves [27]. Low temperatures largely restrict the growth as well as latitudinal limits as a number of mangrove species are found in tropical and sub-tropical zones [4] with mean sea surface temperatures of more than 24 °C [28]. Although occurrence of few mangrove species is not uncommon in temperate zones such as New Zealand [29] they are generally intolerant to extremely cold climates particularly frost [30]. Areas of higher coastal rainfall tend to support diverse mangrove communities [18]. However, in arid climates better growth of mangroves depend exclusively on the availability of fresh water flowing through rivers. In creek systems of the Pakistani coasts such as Korangi creek, Sandspit and Hawksbay, substrate salinity is more or less equal to seawater (52–54 ds m^{-1}) during the high tides but, during low tide it may reach as high as 72 ds m^{-1}, especially during winters [8]. In this situation, seawater does not cover the substrate completely. Higher rates of evaporation results in accumulation of salts in the form of crust on soil surface which could be lethal for mangroves. To cope with such extreme ecological conditions, *Avicennia marina* form cable roots with pneumatophores [4]. While cable roots continuously exclude and secrete salts that help to prevent excessive salt build up in plants during low tides [31], pneumatophores help in gas exchange during high tide when hypoxic or anoxic conditions prevail for a longer period of time. Mangrove forests near the sea and most of the deltaic regions are regularly inundated at least twice on a daily basis hence species like *Rhizophora mucronata* and *Ceriops tagal* usually inhabit such zones together with *Avicennia marina* (Table 2). Both members of family Rhizophoraceae have stilt (aerial) roots

Table 2 Leaf water potential (−MPa) in mangroves (Modified from [8, 32])

Salinity (−MPa) equivalent to the approximate values in % seawater				
Species	(−0.02) 0 %	(−0.7) 25 %	(−1.4) 50 %	(−2.8) 100 %
Avicennia marina	3.1 ± 0.2	4.6 ± 0.1	4.8 ± 0.25	5.1 ± 0.3
Ceriops tagal	2.7 ± 0.2	3.8 ± 0.2	4.3 ± 0.2	5.5 ± 0.2
Rhizophora mucronata	2.2 ± 0.1	3.1 ± 0.2	3.1 ± 0.2	5.6 ± 0.1

that can exclude but not secrete salts like *Avicennia marina* [4] but have tremendous ability to thrive in persistent flooding. These root characteristics indicate inter-specific differences among different mangrove species to cope with salts, however, presence of lenticels in both type of root systems help them survive under an-aerobic conditions. Further, due to the large variation in substrate salinity mangroves growing in the creek systems usually form scrub like physiognomy while trees in the deltaic zones are comparatively tall where plants experience lesser fluctuations in salinity [25].

4 Mangrove Ecophysiology

Studies on eco-physiological responses reveal that the two principal factors bringing about changes in growth, water and osmotic relations of mangroves are salt and persistent flooding. As discussed in the above section that survival and sustained growth of mangroves under hypoxic or anoxic conditions depends upon the type of root development, their salt tolerance could vary despite of the presence of such morpho-physiological characteristics [17]. For example, members of the genus *Rhizophora* and *Laguncularia* show comparatively less salt tolerance under flooding conditions than most of the members of *Avicennia* [9]. Stilt roots of *Rhizophora* cannot secrete salts like those of pneumatophores in *Avicennia* and lack of free oxygen could also interfere with salt exclusion as well as selectivity of potassium over sodium [16]. All of these features suggest better salt tolerance of *Avicennia* over other mangrove groups, however, such assumptions require further testing.

Mangroves employ several strategies to accommodate the presence of salts and they have developed both mechanisms of salt avoidance and tolerance [33]. They possess various kinds of adaptations to survive in salt stress such as (i) salt exclusion at root level by ultra-filtration [34] (ii) salt secretion via glands [35] (iii) ion accumulation in leaf cells [36], (iv) leaf succulence [35] and (v) accumulating organic acids as osmotica to defy toxic effects of salts [37].We will review some of the eco-physiological responses regarding growth, water and osmotic relations in mangroves under non-saline, moderate and highly saline conditions that would give us some useful information about their salt tolerance limits and metabolic cost.

4.1 Growth

Mangroves of the Indus delta show much better growth than in pure coastal zones where usually stunted growth is observed [25] validating the notion that mangroves grow best where fresh water mixes with seawater [10, 11]. This assumption is supported by several field and lab studies on mangroves. Seedlings of most of the mangrove species, including those of *Avicennia*, *Rhizophora* and *Xylocarpus* usually grow best in salinities of 10–20 ppt, that is about one third to two third the concentration of seawater (35 ppt) [38]. Other reports indicate that about half strength of seawater is ideal for their growth. Optimum growth of Pakistani mangroves is observed in 50 % seawater with tallest plants of *Avicennia marina* followed by *Rhizophora mucronata* and *Ceriops tagal* while in full strength seawater all species showed poor growth but none of them dies [32]. Growth responses of *Aegiceras corniculatum* from Pakistan are yet to be explored. However, some reports on this species from the coasts of India showed that its

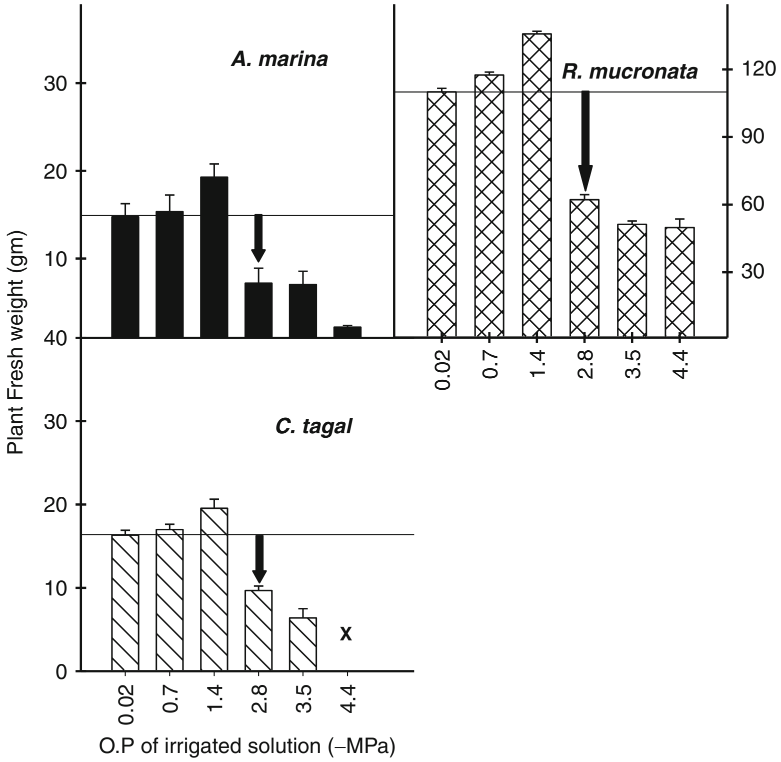

Fig. 2 Relative salt tolerance expressed as 50 % growth depression compared to the non-saline control in mangroves

growth is optimized at about 250 mM NaCl which is almost equivalent to the half strength of seawater [39, 40]. Similar results for growth optima are reported on mangroves of Bangladesh [41] and those inhabiting Gujarat coast of India [40]. All of the above findings suggest that mangrove populations in the arid zones of the subcontinent are probably better equipped for salt tolerance than those growing in more mesic conditions of Australia and South Africa [8].

4.2 Relative Salt Tolerance

Relative salt tolerance is often expressed as the salt level causing a 50 % reduction in shoot growth [42, 43]. The substrate concentration leading to an overall growth depression of 50 % (in terms of total fresh weight of the plants) in comparison to non-saline control is widely used by eco-physiologists as “threshold of salinity tolerance” [44–46]. In most of the monocots especially grasses this ‘threshold’ is highly variable e.g. in *Bouteluoa curtipendula* and *Buchlon dactyloides* [47] it is 140 mM NaCl (about 12 ds m^{-1}); in *Cynodon* genus about 22 ds m^{-1} [48] and *Distichlis spicata* reaching near to the seawater salinity [47, 49]. In most of the dicots however, 50 % growth depression is found in higher salinities from near about half strength of seawater (*Aster tripolium*) to about full strength (100 %) seawater and even in higher salinities in some members of Amaranthaceae (formerly called Chenopodiaceae) and Ficoidaceae [50]. Experiments conducted on *Rhizophora mucronata*, *Ceriops tagal* and *Avicennia marina* show a 50 % growth depression in full strength seawater (Ec = 52 ds m^{-1}; OP = 2.8 MPa) (Fig. 2). In terms of survival, plants of *Rhizophora mucronata* and *Avicennia marina* stay alive in up to 150 % seawater (Ec = 85 ds m^{-1}; OP = 4.4 MPa) 6 weeks after the highest salinity is reached (unpublished data), while those of *Ceriops tagal* up to 125 % seawater (Ec = 70 ds m^{-1}; OP = 3.5 MPa). Few seedlings of *Avicennia marina* could survive in double strength seawater (Ec = 98 ds m^{-1}) for

Table 3 Leaf ionic composition (mmol L^{-1} tissue water) in mangroves. (modified from [8, 32])

Species	Salinity (–MPa)	Na^+	K^+	Ca^{++}	Cl^-	Na/K ratio
Avicennia marina	0.02	28.4 ± 1.2	27.1 ± 3.3	44.7 ± 1.2	38.6 ± 1.2	1.04 ± 1.1
	0.7	193 ± 4.2	25.5 ± 4.1	40.0 ± 3.3	201 ± 1.2	7.51 ± 2.3
	1.4	240 ± 3.7	28.3 ± 1.6	53.1 ± 3.2	384 ± 1.2	8.51 ± 2.2
	2.8	533 ± 4.8	10.7 ± 1.8	29.0 ± 6.8	584 ± 1.2	49.61 ± 3.2
Ceriops tagal	0.02	24.7 ± 1.2	63.7 ± 2.1	54.7 ± 1.2	24.8 ± 8.2	0.38 ± 3.3
	0.7	25.2 ± 3.8	71.7 ± 7.8	52.7 ± 1.2	28.7 ± 3.1	0.35 ± 1.8
	1.4	81.0 ± 6.1	60.7 ± 3.1	65.7 ± 1.2	95.7 ± 6.1	1.33 ± 4.1
	2.8	376 ± 7.0	29.7 ± 3.2	38.7 ± 1.2	478 ± 5.9	12.6 ± 2.9
Rhizophora mucronata	0.02	28.5 ± 6.8	102 ± 7.2	105 ± 1.2	30.7 ± 7.0	0.28 ± 4.5
	0.7	141 ± 6.1	93.7 ± 3.0	112 ± 1.2	179 ± 5.2	1.54 ± 3.4
	1.4	280 ± 8.1	95.7 ± 6.2	121 ± 1.2	290 ± 8.0	2.94 ± 2.8
	2.8	351 ± 7.8	40.7 ± 4.2	73 ± 1.2	510 ± 1.2	8.6 ± 3.1

about 2 weeks, but those of *Rhizophora mucronata* start to wilt within 48 h and dies on 4th day after the highest salinity is reached. However, effect of long and short term exposures to salinity needs further testing at different stages of life cycle as seedling stage of plants is said to be rather sensitive than the adult.

4.3 Water Relations and Gas Exchange

Hyper-saline conditions in the growing medium cause significant decreases in water potential [8], ion toxicity, deprivation of nutrients or a combination of all [51]. Growth and survival of most salt tolerant plants are dependent on the high levels of ion accumulation in their tissues for the maintenance of turgor and osmotic adjustment [45]. *Avicennia marina* rapidly decreases leaf water potential with the introduction of salinity and any further increases in salinity has little effect (Table 2). Salt tolerant plants employing this strategy are commonly called 'osmoregulators' and this strategy is found in most of the highly salt tolerant plants in salt marshes like *Salicornia europaea* [52] and *Allenrolfea occidentalis* [53]. *Ceriops tagal* and *R. mucronata* progressively decrease their water potential with the increases in media salinity representing their subsequent adjustment to the saline conditions (Table 2). Plants following this strategy are called 'osmoconformers' [8, 52, 54]. Low soil water potential strongly influences water loss by stomatal closure which may decrease the rate of carbon dioxide accumulation and uptake [55, 56]. Under such conditions, if a plant is capable of maintaining high photosynthetic rates despite of low transpiration and conductance then its water use efficiency (WUE) is said to be higher which helps plant accumulating higher biomass [46, 50]. Reports on some mangroves indicate a higher water use efficiency and less salt sensitivity in *A. marina* than *A. corniculatum* and other mangrove species [57]. Among mangrove species of our coasts, *Ceriops tagal* also appears to be salt sensitive having low water use efficiency and poor growth. On the contrary, *R. mucronata* and *A. marina* show a better growth response in 100 % seawater with higher water use efficiency [32].

4.4 Ionic and Osmotic Relations

Osmotic adjustment in salt tolerant plants is achieved by the net accumulation of both inorganic and organic solutes in mangroves [58] which help them in maintaining turgor potential [33]. Given the high energy cost to synthesize organic solutes, it is beneficial for the plants to accumulate inorganic ions such as sodium (Na^+) for the purpose of osmotic adjustment assuming their minimum interference with cell metabolism [59]. *Avicennia marina* accumulates higher sodium (Na^+) and chloride (Cl^-) in leaves than *R. mucronata* and *C. tagal* in all salinities (Table 3) with higher Na/K ratio. The magnitude of Cl^- is 1.2 times the amount of Na^+ in all

Table 4 Types of Osmotica (reported in literature) in mangroves of Pakistan

Family	Species	Osmolyte	References
Acanthaceae	*Avicennia marina*	Pinitol	[79]
		Proline	[7]
		Glycinebetaine	[36, 79]
Myrsinaceae	*Aegiceras corniculatum*	Aspartic acid	[83]
		Mannitol	[81]
		Proline	[40, 84]
		Starch/Polysaccharide	[39]
Rhizophoraceae	*Ceriops tagal*	Proline	[7, 39]
		Pinitol	[36]
	Rhizophora mucronata	Pinitol/soluble carbohydrates	[36]

mangroves supposedly required for osmotic adjustment [60]. However, in hyper-saline conditions, plants usually avoid excessive build up of salts in their tissues to prevent themselves from ion toxicity [61] either by secreting salts through leaf glands or excluding them via root ultra-filtration or both [9]. Recent findings suggest that *A. marina* commonly known for secreting salts through leaf glands [11] also has the ability of salt exclusion at root level [9, 62, 63] while *R. mucronata* and *C. tagal* are strictly salt excluders. The ability of ultra-filtration is also manifested by lower amounts of leaf Na^+ in both species when compared to *A. marina*, particularly in 100 % seawater [8]. Restriction of Na^+ influx in xylem stream [64] and/or effective sequestration of ions in the leaf and root apoplast prevent excessive salt build up in plants [64–66]. This ionic balance is primarily controlled by plasma membrane and vacuolar Na^+/H^+ antiporters as well as V-type H-ATPase and H-PPase [67] and has been current focus of research in halophytes at different developmental stages. In mangroves however, few reports are available on this aspect [65, 68] and needs special attention to understand salt tolerance mechanism at different developmental stages. Increased accumulation of Na^+ is generally coupled with reduced Ca^{++} [42] and a decline in carbon assimilation in very high salinities [39]. However, in moderate salinities an increase in Ca^{++} could help in H_2O_2 mediated Na^+ homeostasis besides serving as a signaling molecule which could help in growth promotion [69, 70]. Optimum growth of mangroves in 50 % seawater could also be linked to an increased leaf Ca^{++} in comparison to the full strength seawater (Table 3). However, this assumption of H_2O_2 mediated Na^+ homeostasis in mangroves by Ca^{++} signaling needs further testing.

It is generally assumed that if Na^+ and Cl^- are sequestered in the vacuole, organic solutes must be accumulated in the cytosol and organelles to achieve an osmotic balance [61]. Eventually, such solutes should be non-toxic and compatible with cytoplasmic enzymes over a wide range of concentrations [71]. Most of these solutes either raise the surface tension of water [72] or may be excluded from the protein surface to form hydration shells that helps in stabilizing protein structures against toxic ions [45]. Some of these solutes e.g. proline and glycinebetaine could help in Na^+ and Cl^- exclusion from the cytoplasm and replace them with K^+ and glutamate restoring cell water content and promoting growth [73–75]. In this way, they become 'osmoprotectants' for various enzymes and structural proteins [76]. Osmolytes are diverse in nature chemically, including amino acids [77] sugars [33, 61, 78], sugar alcohols or polyols [79], quaternary ammonium compounds such as glycinebetaine, trigonelline [51] and polysaccharides [80]. Although, pinitol and mannitol (polyols) are the most common compatible solutes in mangroves all over the world [12, 81] nitrogenous compounds like proline [8, 40] and glycinebetaine [32, 36] and some organic acids such as aspartate [82] are also common in mangroves of Pakistan (Table 4). The extent of osmolytes has long been debated for contribution in osmolality as their synthesis comes with energy cost involving potential growth arrest in some plants [61]. If 3.5 mol for Na^+ alone and 7 mol are needed to accumulate 1 mol of NaCl as an osmoticum [59] approximately 41 mol would be required for the synthesis of proline, 50 for GB and 52 for sucrose [61]. Recent findings however suggest that if little amount of these organic compounds are accumulated in plants, they may serve as 'osmoprotectants' [70, 76, 79] and to some extent involved in ROS (reactive oxygen species) scavenging [75], hence they could be potent antioxidants in some of the salt tolerant plants [70, 85]. Exogenous application of some of these compounds are not only helpful in improving plant growth under saline conditions [83, 85, 86] but also help in ROS scavenging [85] besides facilitating in Na^+ exclusion at root level in some crops [74]. In view of the above findings, studies on role of antioxidants and compatible osmolytes in salt tolerance of mangroves from the coasts of Pakistan are under progress. Protection of mangroves through foliar application of chemicals has also shown some promising results, which would help in sustainable use of precious ecosystems.

5 Conclusions

Optimum growth of mangrove seedlings is observed in half strength of seawater whereas, a 50 % growth depression in full strength of seawater. However, range of salinity for their survival appears different with *A. marina* seedlings tolerating almost double strength of seawater for a short time period, *R. mucronata* in 150 % and *C. tagal* in 125 % seawater. It appears that *A. marina* could be grown in creeks where higher fluctuation in salinity occurs. *Rhizophora mucronata* could be grown near seafront with little changes in soil salinity and *C. tagal* being more salt sensitive could be planted in areas where continuous supply of fresh water is available. Although optimum growth of *A. corniculatum* from Indian coasts appears similar to other species, detailed screening on this plant from Pakistani coast needs to be done.

6 Future Prospects

1. Considering variable responses for salt tolerance at different stages of life cycle, experiments on ionic and osmotic stress for long and short term exposure to salinity are needed.
2. Evaporative water loss during low tides may result in complete dryness of the substrate where most of the mangrove species could not survive. Hence, it would be interesting to plan studies on drought tolerance and ways to improve drought and salinity tolerance of mangroves.
3. Although, understanding of Na^+ exclusion from roots and leaves are well understood in mangroves but, molecular basis for transport processes remain obscured in mangroves. Further, studies on Ca^{++} signaling in Na^+ homeostasis are also needed.
4. Studies on genes involved in up-regulation of different osmolytes in mangroves under salt stress could be vital for genetic engineering of crop plants.

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Halophytes for the Production of Liquid Biofuels

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Abstract

We discuss the potential of using halophytes as a source for producing liquid biofuels. We review the potential pathways for converting oilseeds into biodiesel and bio-derived synthetic paraffinic kerosene and presents some preliminary data on biomass composition and pretreatment of the halophyte *Salicornia bigelovii*. Six samples of *S. bigelovii* cultivated at three fertilizer levels (F1: 1 gN/m^2, F2: 1.5 gN/m^2 and F3: 2 gN/m^2) and two salinity levels (S1: 10 ppt and S5: 50 ppt salt) were analyzed with regard to chemical composition and bioethanol potential. Chemical characterization showed that *S. bigelovii* contained, 16.31–55.67 g/100gTS (total solids) of carbohydrates, 5.42–16.60 g/100gTS of lignin, 27.85–66.37 g/100gTS of total extractives (including extractable ash), and 2.18–9.68 g/100gTS of structural ash, depending on the plant fraction and cultivation conditions. Enzymatic hydrolysis of the pretreated samples revealed high glucose recoveries of up to 90 % (of glucose in raw *S. bigelovii*) corresponding to ethanol yield of 111 kg ethanol/dry ton *S. bigelovii*.

1 Introduction

As the use of fossil fuels increases, the greenhouse gas emissions from their burning also increases, pushing us to look for alternative fuels that can be developed from plant biomass sources. One of the drawbacks of using plants for biofuels is that they can compete for land and freshwater resources with conventional food crops [1, 2]. If second generation biofuel crops can be developed that use marginal land and water sources, then the competition with food production is minimized [1]. Halophytes, which are able to grow in salinized soils using saline water, have been proposed

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_4, © Springer Science+Business Media Dordrecht 2014

for use as bioenergy crops [3, 4]. Halophytes have been explored for the production of both lignocellulosic biomass for ethanol production [3], as well as for the production of biodiesel and hydro-processed fuels from oilseeds [4, 5]. Typical limitation on the use of halophyte biomass for biofuels is the high ash content of the straw.

As part of an integrated seawater aquaculture/agriculture project being developed in Abu Dhabi, we are investigating the potential of using oilseeds for the production of liquid biofuel, as well as investigating the potential of using the residual biomass to produce ethanol. The halophyte oilseed literature is reviewed, while recent data is presented on the characterization of biomass of the annual halophyte *Salicornia bigelovii,* which is a potential candidate crop species for this project.

2 Oils

2.1 Biodiesel

Oils from halophyte oilseeds can be converted to biodiesel via trans-esterification. Halophytes are reported to be the potential candidates for biodiesel production and the fatty acid methyl esters of the oil of many such are comparable to oils currently used for the production of biodiesel [4]. In another report, the oil content of six halophytes varied between 22 and 25 % and there was generally high composition of unsaturated fatty acids [6]. The annual succulent saltmarsh plant *Salicornia bigelovii*, has been cultivated in Mexico using seawater, and mean seed yields were 2 t/ha, with seeds yielding 28 % oil [7]. These yields are comparable to soybean yields grown on freshwater. Biodiesel derived from halophyte oil should be able to be used to supplant petroleum-based diesel for ground transportation.

2.2 Bio-derived Synthetic Paraffinic Kerosene (Bio-SPK)

Though biodiesel and ethanol derived from biomass feedstock are technologically proven fuel alternatives for some modes of ground transport, both are limited from becoming aviation fuel substitutes. The aviation sector cannot use ethanol and biodiesel due their reduced specific energy relative to jet fuel [8]. However, the aviation industry is looking for a renewable drop in fuel that can substitute for jet fuel [5]. Recently a process has been developing to convert vegetable oils into paraffins that can substitute for petroleum based jet fuels [9]. Oils are converted to the shorter chain diesel-range paraffins using a proprietary process, which removes oxygen molecules from the oil and converts olefins to paraffin's by reaction with hydrogen. A second reaction then cracks and isomerizes the diesel range paraffins, to paraffins and iso-paraffins with carbon numbers in the jet range [9]. This process is agnostic with respect to the composition of the oil, so ostensibly a wide range of halophyte oils could be used to produce Bio-SPK.

2.3 Residue Biomass

Significant amount of lignocellulosic biomass is produced in halophyte cultivation where up to 90 % of the *S. bigelovii* plant is the straw/bush fraction [7]. The lignocellulosic part of the halophyte can be converted into biofuels by biological conversion using enzymatic hydrolysis and microbial fermentation. Lignocellulosic biomasses often contain significant amounts of alkali metals e.g. potassium and sodium [10], which represent a challenge in utilizing biomass for high temperature energy processes such as combustion, resulting in problems with fouling, slagging, and corrosion [11]. For halophyte crops such as *S. bigelovii,* the sodium content of stems and spikes has been reported to be 6–12 % of the dry biomass and the total ash content to be up to 30 % of dry biomass [12]. The aim of this study was to examine if *S. bigelovii* straw could be a suitable biomass for second generation bio-ethanol production.

The processing of lignocellulosic biomass to sugars for fermentation to ethanol and other products requires specifically designed pretreatment processes. In general, it involves the breaking up of the naturally resistant carbohydrate-lignin shield that limits the accessibility of enzymes to cellulose and hemicelluloses [13–15]. The pretreated slurry then undergoes enzymatic

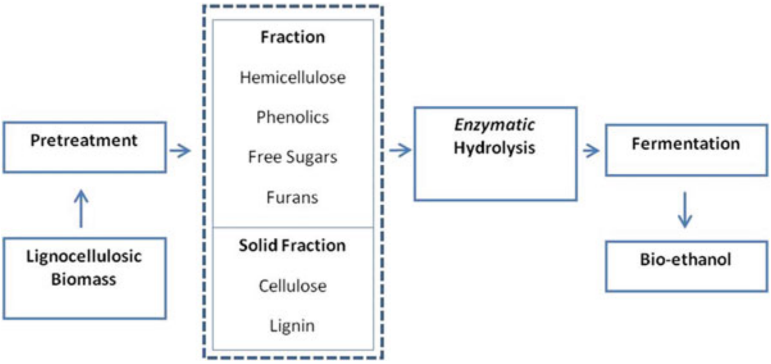

Fig. 1 Processes needed to convert lignocellulosic straw of *S. bigelovii* into bioethanol

hydrolysis where carbohydrates are hydrolyzed to monomeric sugars which can be fermented in the microbial process to e.g. bio-ethanol (Fig. 1).

In this study six samples of *S. bigelovii* cultivated at three fertilizer levels (F1: 1 gN/m^2, F2: 1.5 gN/m^2 and F3: 2 gN/m^2) and two salinity levels (S1: 10 ppt and S5: 50 ppt salt) were analyzed to determine chemical composition and bioethanol production potential.

3 Materials and Methods

Biomass composition characterization was performed according to National Renewable Energy Laboratory protocol (NREL/TP-510-42618), using pre-hydrolysis with concentrated sulfuric acid (72 %) at 30 °C followed by a dilute acid hydrolysis (4 % sulfuric acid) at 121 °C. The sugar content in the hydrolyzate was analyzed using High Performance Liquid Chromatography (HPLC), while acid-insoluble lignin was quantified gravimetrically. The biomass was extracted with water and ethanol prior to the acid hydrolysis (using a Soxhlet apparatus) to remove the extractives.

Preliminary trials of the hydrothermal pretreatment have been carried out at the Technical University of Denmark. The process was performed at 10 % dry matter loading, at three temperature levels (190, 200 and 210 °C) without a catalyst and at one temperature level (200 °C) with a catalyst (0.5 % sulfuric acid). Processing time was maintained at 10 min. The raw material used for pretreatment was washed with fresh water to bring down the salt content of the plant to avoid corrosion of the equipment. The fibers have been subjected to enzymatic hydrolysis according to National Renewable Energy Laboratory protocol (NREL/TP-510-42629), using 50 g/L dry biomass loading, 15 FPU cellulase enzyme loading (with cellulase-to-hemicellulase ratio of 1:9), in total volume of 25 ml. Glucose released during the enzymatic hydrolysis was quantified using HPLC. Liquid fractions (hydrolyzates) obtained from the pretreatment process were hydrolyzed with sulfuric acid (to degrade residual oligosaccharides) and analyzed for glucose content using HPLC.

4 Results

4.1 Halophyte Compositional Analysis

The six samples were fractionated into stem and seed spikes for chemical characterization (Table 1).

The analyses showed that *S. bigelovii* contained 27.85–66.37 g/100gTS (total solids) of total extractives (including extractable ash), 16.31–55.67 g/100gTS of carbohydrates, 5.42–16.60 g/100gTS of lignin and 2.18–9.68 g/100gTS of ash incorporated in the plant matrix (structural ash), depending on the plant fraction and cultivation conditions. The results show clearly that *S. bigelovii* seed spikes have a significantly different composition than the stems ($P<0.01$).

Table 1 Chemical composition of the different samples of *S. bigelovii* cultivated at three fertilizer levels (F1: 1 gN/m^2, F2: 1.5 gN/m^2 and F3: 2 gN/m^2) and two salinity levels (S1: 10 ppt and S5: 50 ppt)

S. bigelovii sample	Glucan (g/100 g DM)	Xylan (g/100 g DM)	Arabinan (g/100 g DM)	Total sugars (g/100 g DM)	Lignin (g/100 g DM)	Structural ash (g/100 g DM)	Extractives (g/100 g DM)
Stem, S1, F1	16.55	11.18	3.34	31.07	16.60	6.27	37.22
Stem, S1, F2	27.12	22.63	5.93	55.67	14.08	2.34	27.85
Stem, S1, F3	22.31	17.80	4.48	44.59	15.58	2.18	29.10
Stem, S5, F1	20.11	18.04	2.31	40.47	12.19	2.35	37.32
Stem, S5, F2	20.54	18.91	4.62	44.07	13.56	3.42	36.65
Stem, S5, F3	18.08	15.38	3.82	37.27	10.49	5.04	42.95
Spike, S1, F1	9.02	7.39	6.61	23.02	5.42	7.99	57.54
Spike, S1, F2	7.79	7.34	5.26	20.39	7.29	5.64	59.25
Spike, S1, F3	8.92	7.72	6.39	23.03	9.37	7.04	54.13
Spike, S5, F1	7.01	5.39	5.69	18.09	7.97	6.86	66.37
Spike, S5, F2	7.72	7.34	4.85	19.91	7.76	8.31	63.10
Spike, S5, F3	6.58	5.53	4.20	16.31	7.44	9.68	65.03

Fig. 2 Liquid fraction and digestible fiber fraction produced by pretreatment of S. *bigelovii*

Fertilizer level was found to have a significant influence ($P<0.05$) on the carbohydrates, extractives and ash, while salinity was a significant factor for ash and extractives content in both fractions of the plants ($P<0.05$). The results suggest that *S. bigelovii* stems cultivated at low salinity (10 ppt) and medium fertilizer grade (1.5 g N/m^2) contain the highest carbohydrate content and are of high value for biofuels production, while seed spikes can be more suitable for extracting value-added active components (having a high extractives content).

4.2 Pretreatment and Enzymatic Hydrolysis

Fractionation of the dry biomass produced a liquid fraction containing extracted sugars (primarily pentose sugars) and a digestible fiber fraction (Fig. 2). The highest concentrations of monomeric sugars of 7 g/l were extracted in to the liquid phase when using the acid catalyst. Significantly less monomeric sugars were extracted without the catalyst (Table 2).

Table 2 Sugar monomers extracted into the liquid fraction during pretreatment

Pretreatment conditions	210 °C/no catalyst	200 °C/catalyst
Glucose Extracted to the hydrolyzate [g/L]	0.05 ± 0.00	0.79 ± 0.25
Xylose Extracted to the hydrolyzate [g/L]	0.92 ± 0.04	4.69 ± 0.25
Arabinose Extracted to the hydrolyzate [g/L]	0.00 ± 0.00	1.56 ± 0.05
Total sugar concentration In the hydrolyzate [g/L]	0.97 ± 0.05	7.05 ± 0.56

Table 3 Summarized results of the hydrothermal pretreatment and enzymatic hydrolysis

Pretreatment conditions	210 °C/no catalyst	200 °C/catalyst
Glucose recovery in fibers [% of glucose in raw *S. bigelovii*]	89.49 ± 6.96	80.63 ± 4.70
Glucose yield from the fibers [kg/ton *S. bigelovii* (dry biomass)]	217.9 ± 1.69	196.3 ± 1.14
Theoretical ethanol yield from the fibers [kg/ton *S. bigelovii* (dry biomass)]	111.10	100.10

Enzymatic hydrolysis of the pretreated fiber samples revealed that all of the treatment conditions produced highly digestible cellulose-rich pulp. The highest glucose recoveries were observed for samples pretreated at 210 °C (with no catalyst) and 200 °C (with the catalyst) (Table 3). These results suggest ethanol yield of 100–111 kg ethanol/dry ton *S. bigelovii*, which is about half of the typical lignocellulosic residue (e.g. corn stover, which has ethanol potential of 230 kg/dry ton) [16].

5 Discussion and Conclusions

The most promising approach to developing biofuels from halophytes would be a system whereby multiple products would be obtained from a single species or farming operation. For example, in the case of *S. bigelovii*, oil could be used for biodiesel or Bio-SPK production. Seed meal could be used for animal feed [7]. The straw could be used to produce ethanol. Other value added products might be derived from the biomass conversion to ethanol. Preliminary trials on the pretreatment and enzymatic hydrolysis of *S. bigelovii* revealed that the biomass has potential as a lignocellulosic bioethanol feedstock. High glucose recoveries show that this biomass can be efficiently pretreated without the use of chemicals, making the process more sustainable. Since *S. bigelovii* contains less cellulose (up to 27 % in the stems, 20–24 % in the mixed plant) than typical lignocellulosic materials (e.g. corn stover cellulose content is up to 45 % [17], the overall ethanol potential is lower for the *S. bigelovii*. This result could be increased by separating the spikes from the stems prior to the pretreatment (mixed plant was used in this study), since cellulose is mainly contained in the stem fraction of the plant. Furthermore, pentose sugars could be utilized in a pentose-hexose co-fermentation using genetically modified microorganisms. The pretreatment and fermentation research should be continued to fully explore bioethanol potential of this plant. In this way multiple products and revenue streams are obtained from a single crop, and greater economic and energy efficiency is achieved.

Acknowledgements This research was supported from a grant from the Sustainable Bioenergy Research Consortium of the Masdar Institute of Science and Technology.

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Feasibility of Halophyte Domestication for High-Salinity Agriculture

J. Jed Brown, Edward P. Glenn, and S.E. Smith

Abstract

We discuss the process of domesticating wild halophytes to serve as crop plants using seawater irrigation. First steps in this domestication involve determining whether halophyte species exist that may produce significant amounts of a usable product under seawater irrigation and that this is a sustainable agronomic practice. This is followed by development of strategies to improve crop productivity via selecting appropriate species for domestication and then affecting agronomic traits through plant breeding. We demonstrate that halophytes may be productive under seawater irrigation, that this management system may be sustainable, and there are demonstrated pathways toward domestication.

Keywords

New crops • Crop domestication • Salinity • Salt-affected soils • Seawater • Drainage water reuse • Halophytes

1 Introduction

Concomitant with increased human population and demands for food, fiber and energy crops has been a worldwide increase in irrigated agriculture. Unfortunately, this has also resulted in increases in salinized cropland where most non salt-tolerant crop plants are unproductive. This, along with a desire to utilize naturally saline soils or water for crop production, has led to interest in alterative, salt-tolerant crop plants and cropping systems often using saline water. Only limited progress has been made in developing salt-tolerant varieties of

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_5, © Springer Science+Business Media Dordrecht 2014

conventional crops, due to the complex anatomical and physiological attributes needed to confer tolerance and the multigenic nature of tolerance mechanisms [1–3]. A more prudent approach may be to attempt to domesticate wild halophytes that have evolved inherently high salt tolerance [4]. Halophytes are defined as plants which complete their life cycle where salt concentration is equivalent to at least 200 mM NaCl in the external medium equal to 11.6 g L^{-1} Total Dissolved Solids (TDS) under conditions similar to those that might be encountered in the natural environment [5], whereas others use 5 g L^{-1} TDS to define a halophyte [6]. In general, 5 g L^{-1} TDS is considered to be the extreme upper limit for salt content of irrigation water for conventional (i.e., glycophytic crop plants) [7].

In this overview paper, we address three points that have been raised as obstacles to the use of halophytes as crops. First, that halophytes have inherently low productivity; second that irrigation with saline water is not a sustainable practice; and third that as wild plants, halophytes have numerous traits that may make them undesirable as crop plants.

2 Halophyte Productivity

Interest in halophyte crop production began during 1950s [8–10]. An international effort to develop halophyte crops was undertaken in the 1970s, enunciated as the "Biosaline concept" for production of food, fuels and chemicals using non-traditional soils and water supplies [11], such as reclaimed drainage water from irrigated crop land or seawater. However, the concept was met with skepticism by many agricultural scientists. U.S. Department of Agriculture Salinity Laboratory stated, "We do not anticipate practical use of seawater for agriculture nor high levels of production per unit area of halophytes" [12]. More recently, a halophyte ecologist, concluded, "A sustainable agriculture based on irrigation with seawater on a large scale seems to be still an utopic illusion" [13]. These statements were largely based on the assumption that halophytes are not as productive as conventional crops. Here productivity was sometimes defined as in traditional cropping systems, generally as mass of usable product (e.g., seeds or fruits) per unit of area over a cropping season. However, in some cases emphasis was only on total plant biomass and did not include harvest index (the proportion of total plant biomass that represents a usable product) in making these comparisons. Nevertheless, field and greenhouse trials conducted over the past 40 years clearly show that halophytes can maintain high productivity of biomass and seeds/fruit on root zone salinities up to seawater and beyond.

The evidence for a tradeoff between high salinity tolerance and reduced growth rates has been previously given [3]. They compared relative growth rates (RGR) by measuring total plant biomass of euhalophytes (the most tolerant species, able to grow on seawater) and less tolerant miohalophytes (less tolerant but able to grow on brackish water) with non-halophytes under both saline and non-saline conditions. The growth rates of the three classes of plants did not differ significantly ($P \leq 0.05$) under non-saline conditions, showing that halophytes are not inherently slow growing plants. As expected, halophytes outperformed non-halophytes under saline conditions. Furthermore, the salinity for optimal RGR of the euhalophyte *Salicornia dolichostachya* was 300 mM NaCl (17.1 g L^{-1}) in the greenhouse, and that high productivity (total plant biomass) was maintained up to full seawater salinity in field experiments [14].

A series of productivity trials have been undertaken with halophytes under agronomic conditions, with salinities varying from brackish (1–20 g L^{-1} TDS) to full-strength or even hypersaline salinity (30–40 g L^{-1} TDS) [15]. Some of these have involved plot trials of several hundred ha (Fig. 1). Table 1 lists biomass and seed yields of a selection of halophytes under cultivation and gives references to publications. Biomass yields of the most productive species have been in the range of 10–20 t ha^{-1}, within the range of conventional forage crops. Seed yields of the euhalophytic species *Salicornia bigelovii*, a potential oilseed crop, have ranged from 1 t kg ha^{-1} under large-scale cultivation to 2 t kg ha^{-1} in small plot trials, under full seawater irrigation. These are similar to yields of conventional oilseed crops [22].

Fig. 1 *Upper panel*: 200-ha *Salicornia bigelovii* farm irrigated with seawater in Eritrea, Africa. *Lower panels*: mechanized Salicornia harvest and center pivot irrigation with seawater in Raz Al Zawr, Saudi Arabia

Table 1 Examples of halophyte biomass and seed yields under in different agronomic settings

Location and species	Yield (dry tonnes ha^{-1})	Soil type	Irrigation salinity (g L^{-1})	Reference
Safford AZ				[16]
Atriplex barclayana	14.7	Loam	0.6	
A. nummularia	12.3	Loam	0.6	
San Joaquin CA				[17]
A. barclayana var sonorae	11.1	Clay	1.0	
var barclayana	9.2	Clay	1.0	
Marana AZ				[18, 19]
A. lentiformis	20.1	Loam	2.0	
Puerto Penasco Mexico				[20, 21]
A. lentiformis	17.9	Sand	4.0	
Batis maritima	17.4	Sand	4.0	
Salicornia bigelovii				
Biomass	15.4	Sand	4.0	
Seed	2.0	Sand	4.0	

3 Sustainability of High-Salinity Agriculture

The initial reaction of agricultural engineers to the prospects of high-salinity agriculture was negative. Starting in the 1950s, institutions such as the USDA Salinity Laboratory in Riverside, California, began emphasizing the hazards that even mildly saline irrigation water poses to crops and soils [23]. Irrigation water with a salinity of only 1.44 g L^{-1} TDS was classified as presenting a very high salinity hazard and was declared to be not suitable for irrigation under ordinary conditions [23]. In the 1970s, recommendations for managing salinity called for large leaching fractions to maintain crop productivity, and surface or subsurface drainage systems to convey saline water away from the fields for off-site disposal [7, 24]. Of course, these recommendations were based on the reality that agriculture at that time was dependent on glycophytic (non salt-tolerant) crop species with very low levels of inherent salt tolerance.

However, attitudes towards the use of saline water are changing. It was realized early on that while sodic (high sodium) water can cause dispersal of clay particles that impairs permeability, this effect disappears when the total electrolyte concentration exceeds about 15 meq (e.g., 0.85 g L^{-1}NaCl) [25]. Hence, high salinity water is not inherently damaging to most soils. Faced with the need to recycle saline drainage water within irrigation districts, Qadir and Oster evaluated over 30 years of research from around the world and concluded that high-salinity water may be used as part of sustainable agricultural systems where disposal of drain water outside the district is not possible [26]. Furthermore, a reevaluation of crop leaching requirements has concluded that previous guidelines recommended much more water than was actually needed, due to the high degree of self-regulation in the plant-soil-water system [27]. The new recommendations recognize that plants do not respond to the average root zone salinity, as was assumed in the original recommendations, but instead use water from the lowest-salinity portion of the root zone, which is near the soil surface for flood-irrigated plants. This is fortuitous, as fresh water supplies are under increasing pressure for multiple uses, and disposal of large volumes of agricultural irrigation drainage water has become problematic due to environmental concerns. Hence, a paradigm shift is occurring in many elements of the agricultural community towards the potential use of saline water for crop production.

A number of multi-year plot trials have been conducted with halophytes with no reported decrease in yield or negative impacts in soil structure due to saline water irrigation [16–18, 20, 21, 28]. Perhaps the longest continually operated halophyte trials were conducted at Kino Bay, Mexico [29]. This 20-ha farm was flood-irrigated with 2–3 m $year^{-1}$ of seawater from 1986 to 2010 to produce *Salicornia bigelovii* as an experimental oilseed crop. Crop yields obtained in yield trials in 2007–2008 showed biomass and seeds yields were still within the range of conventional crops [30].

There was also concern that extreme (and uneconomical) agronomic practices would be required to produce halophytes on high salinity water. Seawater along coastal deserts typically contains 38–42 g L^{-1} TDS, whereas optimal growth is obtained at half this salinity [14]. At seawater salinities, frequent irrigation and a generous leaching fraction are required to maintain halophyte productivity. In lysimeter studies, maximum productivity of *S. bigelovii* required 3 m $year^{-1}$ of seawater in a coastal desert environment in Mexico [31]. Approximately 35 % of this was the leaching fraction, required to maintain the soil solution in the root zone at 80 g L^{-1} TDS or lower. This is at the high end of water application rates for conventional crops in arid zone irrigation districts. However, in large flood-irrigated plantings, irrigated at 3–5 day intervals, as much as 5 m of water can be applied over a cropping season [30, 31].

Analysis of pumping costs supports the use of seawater for irrigation, even in large quantities under certain circumstances. Pumping costs, whether expressed as dollar costs for electricity or liquid fuel, or as carbon equivalents to take into consideration the carbon balance, are a function of the volume of water pumped and the lift of the well. Typical agricultural wells lift water

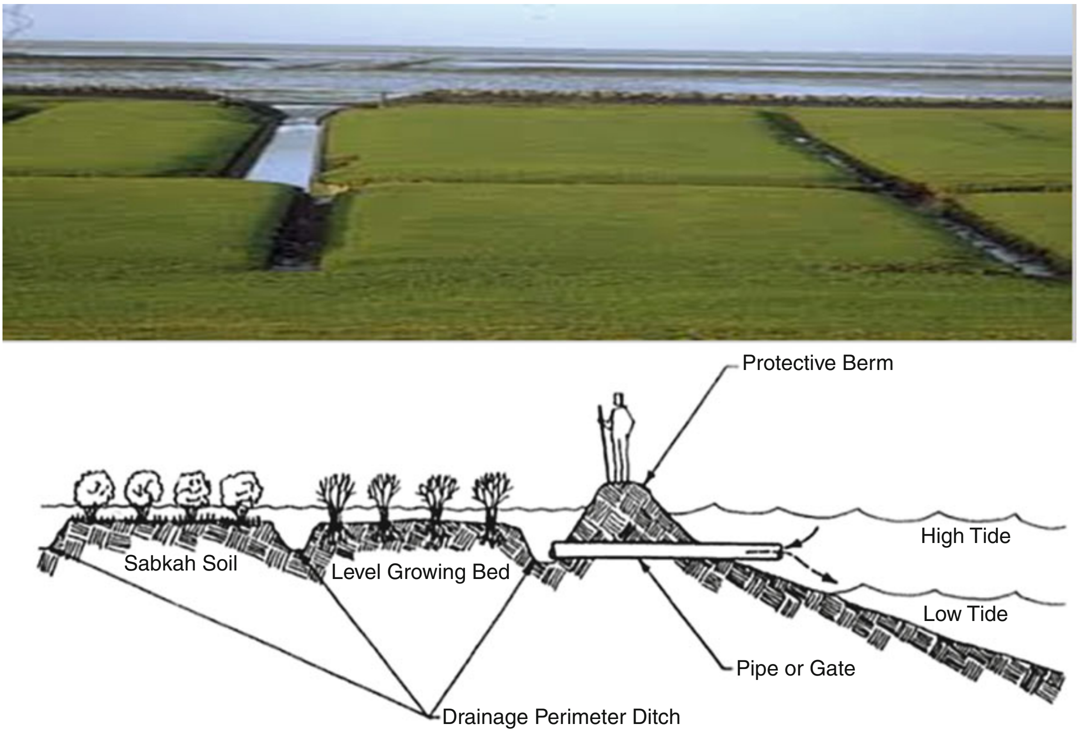

Fig. 2 Tidally irrigated *Salicornia bigelovii* beds at Jubail, Saudi Arabia

from 20 m to as deep as 100 m, whereas the lift of typical coastal seawater wells is only 3–10 m. Furthermore, tides can be used to irrigate crops without the need for pumping in some locations (Fig. 2) [28]. A demonstration project conducted for the Electric Power Research Institute concluded that the total carbon expenses of producing, harvesting, baling and delivering to roadside a halophyte crop on seawater was one-third the amount of carbon fixed and similar to conventional proposed biofuel crops [28].

4 Considerations for Domestication

Perhaps the greatest impediment to uses of halophytes as cultivated plants has been undesirable crop characteristics in these wild species. Traits such as uneven germination, lack of seed retention, and toxic substances in tissues, while adaptive for wild plants, are not typically desirable in crop plants. Genetic modification, whether conscious or natural, during long periods of domestication has been responsible for affecting such traits in most crop plants [32]. Very little has been reported on selective breeding of halophytes, with the exception of a preliminary study on *Salicornia bigelovii* [33]. Hence, the following sections outline a strategy for improving halophytes similar to what has been accomplished with other wild plants, with the goal of determining if halophytes might offer special challenges not presented by the numerous species of wild plants previously domesticated.

4.1 Basic Considerations

Here we define domestication as consistent successful cultivation and harvest of a formerly wild plant under commercial agricultural conditions. Domestication is typically a long-term process and the timeframe to domesticate a crop can be on the order of decades [32, 34].

Before undertaking any experimentation, the first obvious steps are to consider the desired product(s) within the context of available botanical and agronomic resources. Halophytes can been grown to produce oilseeds, grains, forage, fuel, food, medicine, chemicals, timber and fiber [30, 35] or be used for soil or water conservation or remediation [36, 37]. Economic assessments should be conducted to ensure that there will be a market for products and that they may be produced at a cost that is competitive with conventional crops, although this can be difficult given the agronomic unknowns associated with halophyte culture. Additionally, the desired crop should not adversely affect water supplies or land that could support conventional agriculture.

A primary consideration is where the crop might be grown. For example, if one is considering growing a crop in coastal land using seawater, then one is limited to halophytes with high salinity tolerance (euhalophytes), and thus there are fewer species from which to sample. For growing crops in inland brackish water of lower salinity, then there are a greater number of species to consider. It advantageous to examine species from climate regimes and perhaps latitudes similar to those where the potential crop is being planted, as the candidate species will be better adapted to local environmental conditions. More generally, consideration of plant growth and development including the plant's life cycle in nature is critical in identifying candidate species for evaluation and in developing agronomic practices for their production. There are both annual and perennial halophytes that under consideration for domestication, as well as monocots and dicots, and monecious and dioecious species [30].

4.2 Domestication Syndrome

The domestication syndrome is defined as the suite of traits whose expression indicates that a recent domesticate has diverged from its wild ancestors and is adapted to cultivation [38, 39]. These traits may include seed retention (loss of seed shattering), loss of seed germination inhibitors, synchrony of germination, flowering and fruit development, and increase in fruit or seed size; changes in secondary metabolites (e.g., loss of bitter or toxic compounds) [39, 40].

Many wild halophyte species are known to have various seed dormancy mechanisms to allow them to germinate under ideal conditions in nature [41]. Seed ripening and retention may also be a major factor limiting halophyte domestication. For example, although seed yields of *S. bigelovii* under seawater irrigation can approach conven-tional oilseed crops under optimal conditions, yields are reduced under mechanical harvest due to uneven seed ripening and shattering of seeds [30]. Similarly, the seeds of *S. bigelovii* contain saponins, which can have deleterious effects on animal growth limiting the use of oilseed meal in animal diets [21, 30]. However, a 25 % larger seed size in populations was reported in plants that had been cultivated for several crop cycles and harvested with mechanical equipment, suggesting that at least this species is subject to improvement through mass selection [33].

4.3 Development of Crop-Appropriate Production Regimes

A critical element in many crop domestication strategies involves the development agronomic systems that are appropriate for the new domesticate and the target environments in which its use is proposed. In the case of most crop plants, this process occurred mostly via cultivator empiricism, often with significant trial and error over hundreds of years [39]. Modern crop domestication aims to greatly accelerate this process and to replace unsystematic cultivator activity with deterministic planned experimentation. In most cases of modern crop domestication, an existing agronomic system is modified for a new crop. This might not hold for halophytes, however, as there are constraints of the use of highly saline water that do not exist for conventional crops.

4.4 Plant Breeding

In some cases, heritable genetic variation may exist in domestication syndrome traits within wild plants that could be efficiently exploited within plant breeding programs [32]. Indeed, some modern crops exist in various states of domestication and some such as the cranberry (*Vaccinium* spp.) are commercially viable with very little domestication [40], indicating that it may be feasible to grow some crops without complete control of reproduction. However, it is important to note that near domesticates like cranberry or many forage plants are successful as crops because they can be grown in environments that are very similar to those in which the plant occurs in nature [32].

Plant breeding tactics within halophytic species could vary from traditional mass selection and progeny testing to marker - assisted breeding, to using deterministic genetic modification approaches [34, 42]. As in all crop improvement through plant breeding [43], affecting the domestication syndrome or productivity characteristics in halophytes will depend on the existence of (1) heritable and useful genetic variation for traits of interest, (2) a means to consistently identify this variation, and (3) an ability to regularly replicate agronomically acceptable phenotypes within target environments. Experiences with food crop domestication [32, 39] have shown that meeting each of these requirements is by no means trivial, and genetic improvements have often have been based on hundreds of experiments, often conducted over decades, and with many failures. For the vast majority of halophytes we are just at the beginning of this process and we know very little about each of the key foundations required for significant crop improvement.

5 Conclusions

In order to manage the growing demand for agricultural products, utilization of marginal lands and water sources should be considered. We believe that halophytes can be grown using high salinity water in soils that could not support conventional crops. Halophyte crop yields can equal yields of conventional crops grown on freshwater. Additional steps toward domestication will require identifying the correct plant species for the target environment and application and eventually improving wild plants though crop breeding.

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The Gypsum Dunes of Cuatrociénegas Valley, Mexico – A Secondary Sabkha Ecosystem with Gypsophytes

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Abstract

Mexico is known for its great diversity and high endemism of plants. The geographic positions of the country as well as the complex geological history, geomorphology, and weather patterns within the territory, among other factors, have resulted in diverse landscapes and soil types. Under xerophytic conditions in the Chihuahuan Desert, a complex mix of soil types occurs, including saline, gypsum and saline-gypsum outcrops. These soils are characterized by plant communities that contain species of diverse ecological affinities, named halophilic, gypsophilic, and halophites-gypsophilic, which are either endemic to one of those soils or widespread. One important location under study is the Cuatrociénegas Valley, Coahuila, Mexico, with its dunes of gypsum where ancient lakes (*paleolagos*) once were. This paper gives an overview of the continental secondary sabkha ecosystem with gypsum dunes and proposes a new hypothesis for the evolution of this extreme habitat and its gypsophilic flora.

1 Introduction

While halophytes developed mechanisms of adaptation to soils with sodium chloride salts, another group of edaphic experts, the gypsophytes, took another path and a different evolutionary strategy to conquer habitats with high levels of calcium sulfate. The gypsophytes are an ecological group of plants that live in gypsum soils and are usually divided into two groups (similar to the halophytes): The gypsophiles that live exclusively in gypsum soils and the gypsovags that live both in gypsum substrates and in soils without gypsum. Given that gypsum is chemically a salt, gypsophytes can be considered a subgroup of halo-

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_6, © Springer Science+Business Media Dordrecht 2014

phytes. There has recently been a great deal of controversy with respect to the definition of the limits of gypsophily, and this has caused many conflicts in recent years between the obligation to protect gypsophytic flora on one hand and the gypsum industry on the other hand [1, 2]. Especially in the European Union, gypsum communities are considered to be extremely fragile ecosystems and enjoy special protection [3]. In addition to these aspects of conservation, gypsophytes have been the focus of interest in recent years due to possible implications in agriculture because of their special adaptation mechanisms (stress tolerance) [4].

1.1 Soils with Gypsophytic Vegetation

Just as with all saline soils, gypsum soils represent a significant challenge to the capacity of the adaptation of plants with respect to the frequent lack of important minerals such as nitrogen and phosphorus, the high sulfur content, and especially the recrystallization of the gypsum that causes hardening and the formation of the characteristic hard surface crusts. Several authors consider precisely this ability of some plants to penetrate this hard crust with their seeds to most likely be the most important feature of gypsophytes. Previously authors consider gypsophytes and metallophytes (plants adapted to soils contaminated with heavy metals) to be the most interesting group of plants among the edaphic specialists, although up until now there has been very little research done on the mechanisms of these types of adaptation [5].

Like halophytes, gypsophytes also belong to different families of angiosperms, gymnosperms and even pteridophytes, apparently indicating not a common evolution, but rather, several adaptive strategies (convergent evolution). There are 14 known species of pteridophytes in saline and gypsum soils of Mexico with genera such as *Acrostichum*, *Adiantum*, *Ophioglossum*, *Notholaena*, *Pityrogramma,* and *Selaginella,* of which only *Notholaena bryopoda* Mason is restricted to the gypsum soils of the Chihuahuan Desert [6]. Of the gymnosperms, there are 12 known species of the genera *Ephedra*, *Juniperus* and *Pinus*, none of which is restricted in distribution by soil salinity, while six species of *Ephedra* are common in the gypsum soils of the Chihuahuan Desert [7]. Angiosperms have a greater diversity with approximately 1,200 species of 500 genera in 106 families, among which some families are noteworthy because of their diversity and endemism, including: *Asteraceae*, *Poaceae*, *Leguminosae*, *Euphorbiaceae*, *Amaranthaceae sensu lato*, and *Cyperaceae*. In Mexico, there is more diversity of variation in halophytes due to the great diversity of saline environments that multiplies when considering the Pacific Ocean, the Gulf of Mexico and the Caribbean Sea, with coastal lagoons, salt marshes and inland endorheic basins all along and around the country.

Much of the gypsum soils of the world are found in arid and semiarid zones where poor precipitation does not leach calcium sulfate to lower horizons. According to the FAO [8] there are more than 100 million hectares of gypsum soils in the world. In many regions, the gypsum soils are connected or directly interspersed with sodium chloride soils and the differentiation between the two types is very difficult and sometimes only possible through the vegetation [9].

In Mexico, the types of vegetation that are most abundant in gypsum soils are gypsophytic grasslands (*Pastizales*) and shrublands (*Matorrales*), gypsophiles that primarily cover the northern states from Coahuila and Chihuahua in the north to San Luis Potosi State in the center of the country. However, temperate forests of *Pinus* and *Juniperus* also develop in gypsum soils. The gypsum areas are not very extensive and form a mosaic of small islands isolated from each other and often with large numbers of endemic species. These “soil islands” [1] are certainly a major cause of the large number of endemic species found in the gypsum soils of Mexico. Four decades ago, 65 species of gypsum plants were cited [10] and since then new records have been added to this list each year [11–14]. Although there is still no complete record of the gypsophytes of Mexico,[1] it is estimated that there are more than 200 species of gypsum plants in Mexico’s Chihuahuan Desert alone [15].

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[1] To date, only the families of Boraginaceae, Brassicaceae and Amaranthaceae.

Grasslands (*pastizales*) are herbaceous gypsophytic communities where species of the genera *Poaceae*, *Bouteloua*, *Muhlenbergia,* and *Sporobolus* dominate, as well as various genera such as *Condalia*, *Dicronocarpus*, *Drymaria, Flaveria, Frankenia, Fouquieria, Gypsophila, Helianthemum*, *Haploesthes*, *Lycium, Notholaena, Petalonyx, Sartwellia, Scleropogon*, *Selinocarpus, Zinnia* and others [9].

2 The Valley of Cuatrociénegas and its Gypsum Dunes

An even more extreme habitat for plants than the gypsofilous grass and shrublands are gypsum dunes where the substrate is composed almost entirely of this mineral (Fig. 1). There are very few places in the world where ecosystems are found made up of eolic sediments formed by gypsum. In the American continent, in the Chihuahuan Desert, the four largest gypsum dune areas in the world are found: The famous White Sands in New Mexico (United States), The Estancia in New Mexico (United States), Guadalupe in Texas (United States) and the gypsum dunes of Cuatrociénegas Valley in Coahuila (Mexico). While the three places in United States are known for their large dimensions and for the beauty of their landscapes, the Cuatrociénegas Valley is unique for its rich endemic flora and fauna which includes more than 70 species of reptiles, fish, mollusks, crustaceans, insects and plants [16].

The Valley of Cuatrociénegas is located in the eastern part of the great Chihuahuan Desert, the largest desert in North America, in the State of Coahuila in northern Mexico (Fig. 2). It is an intermontane valley of only 2,000 km^2 enclosed in high mountains of over 3,000 m. Because of its orogenic location, Cuatrociénegas has a semiarid climate with a precipitation of less than 200 mm/a, an average temperature of 21 °C, and a maximum temperature of up to 44 °C. Within the valley there is a particular system of marshes, wells, rivers, tunnels, and springs interconnected to each other underground. This geomorphologic diversity of habitats in a relatively small area makes Cuatrociénegas a unique place in the world and the richest in endemic species in North America.

Since the beginning of scientific research in the middle of last century, several authors have compared the ecosystem of Cuatrociénegas with ecosystems at the level of the Galapagos

Fig. 1 Extreme habitat for plants: the gypsum dunes of the valley of Cuatrociénegas, Coahuila, Mexico

Fig. 2 Map showing location of the Chihuahuan Desert and the valley of Cuatrociénegas in Mexico (Modified from Emerson Kent 2012 [39])

Islands, including it in the group of so-called **Biodiversity Hotspots** on the planet. Although the Cuatrociénegas Valley, also often called the "Mexican Galapagos", was declared a Protected Area of Flora and Fauna by the Government of Mexico in 1994, the ecosystem is, despite international protests, in extreme danger of extinction, mainly due to irresponsible overexploitation of water in neighboring basins for the cultivation of fodder (dairy industry).

The dunes are located in the SE part of the valley (Fig. 3) and are composed of almost 100 % (ca. 98 %) calcium sulfate crystals (gypsum). It is estimated that the area of recent dunes forms only approximately 20 % of the original area, because of sulfate extraction for the gypsum industry in the twentieth century. The active dunes are generally not very high, but in the center of the area reach up to 9 m high. Acting as stabilizers for the dunes are *Prosopis glandulosa* (mezquite), which often accumulates in groups of several individuals, *Dasylirion palmeri* (sotol) and *Yucca treculeana*. Another important stabilizing factor for dunes are the surface crusts caused by contact between the gypsum and rainwater. The species present are in addition to the aforementioned stabilizer especially endemic forms like *Tiquilia turneri* (Fig. 4), *Machaeranthera restiformis*, *Nerysirenia incana, Gaillardia gypsophila*, *Ephedra* spp., *Fouquieria splendens*, *Varilla mexicana* or the non-endemic species *Petalonyx crenatus* (Fig. 5). They often form islands or groups of several individuals.

Pinkava [17] who elaborated the first *Catalogue of Vascular Plants*, divided the vegetation of the Cuatrociénegas Valley in eight major zones:

1. Basin sacaton grasslands
2. Aquatic and semi-aquatic habitats
3. Gypsum dunes
4. Transition zones (between grasslands and the "bajadas")

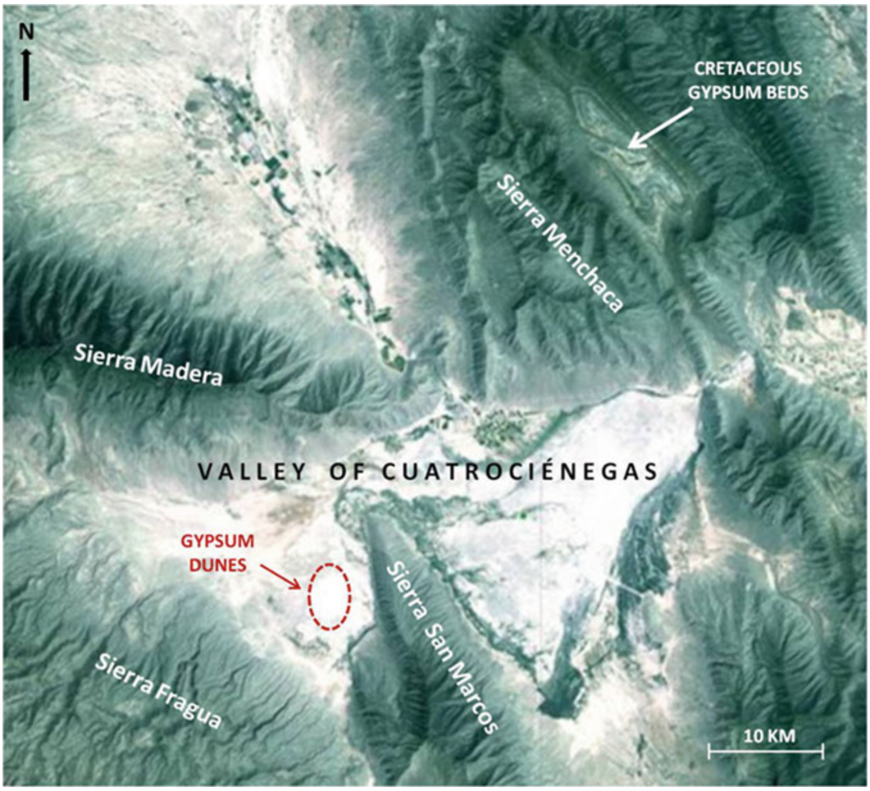

Fig. 3 Location of the gypsum dunes and the Cretaceous gypsum beds in the valley of Cuatrociénegas (Map from [40])

Fig. 4 *Tiquilia turneri* Richardson (Boraginaceae), endemic species of the gypsum dunes of Cuatrociénegas

Fig. 5 *Petalonyx crenatus* Gray ex S. Watson (Loasaceae), gypsophyte species of the valley of Cuatrociénegas

5. Desert scrub (rich in cacti)
6. Chaparral
7. Oak-pine and oak woodlands
8. Montane conifer forests

The Valley of Cuatrociénegas and the mountain ranges around it contain no less than 889 vascular plant species distributed among 112 families and 466 genera, of which 32 species are endemic [14, 17–19].

Of this large number of species, approx. 60 live exclusively on the gypsum dunes and its immediately surrounding gypsum soils (Table 1). Fourteen species are present only in the dunes, and eight are endemic species:

Except *Samolus ebracteatus* and *Sesuvium verrucosum,* which live in the West Indies and South America, none of the 63 species in the dunes of Cuatrociénegas is distributed outside of North America, and most of those are limited to the Chihuahuan Desert. Both species live apart from the continental desert playa lakes as well as in coastal wetlands, dunes and salt marshes.

With 16 species, the Asteraceae family is notable, of which two, *Machaeranthera restiformis* and *Gaillardia gypsophila* are endemic to the Valley. Seven of the Asteraceae have a limited distribution around the Valley of Cuatrociénegas and are endemic to the state of Coahuila.

The degree of adaptation of the plants to the hostile habitat is surprising, especially the ability of roots to extract the capillary water between the fine crystal grains of the gypsum dunes. The ability of the seeds to break the hard gypsum surface crust after germination is also unique [4]. For some authors, it is precisely this ability that represents a major limitation for many other species to colonize gypsum soil environments. The dunes themselves receive much of their moisture from groundwater and the overexploitation of the aquifers in the Valley and its neighboring regions put not only the flora and fauna of Cuatrociénegas, but also, in the end, the very existence of the dunes themselves at risk.

3 Origin of the Cuatrociénegas Dunes Ecosystems

Although since the middle of the last century, hundreds of scientific papers have been written on the fauna and flora of Cuatrociénegas, to date no research has been done on the origin and age

Table 1 Species that live on gypsum dunes and their surrounding areas (From [17] and own researches). (In bold = species present only in the dunes, species market with "+" = endemic forms)

Ephedra trifurca Torr. ex Watson	EPHEDRACEAE
Ephedra compacta Rose	EPHEDRACEAE
Selinocarpus purpusianus Heimerl	NYCTAGINACEAE
Ancistrocactus scheeri (Salm-Dyck) Britt. & Rose	CACTACEAE
Coryphantha macromeris (Engelm.) Britt. & Rose	CACTACEAE
Coryphantha poselgeriana (Dietrich) Britt. & Rose	CACTACEAE
Coryphantha vivipara (Nutt.) Britt. & Rose	CACTACEAE
Opuntia anteojoensis Pinkava	CACTACEAE
Opuntia leptocaulis DC.	CACTACEAE
Opuntia moelleri Berger	CACTACEAE
Atriplex canescens (Pursh) Nutt.	CHENOPODIACEAE
Atriplex prosopidium I.M. Johnston	CHENOPODIACEAE
Suaeda palmeri (Standl.) Standl.	CHENOPODIACEAE
Drymaria coahuiliana (I. M. Johnston) B.L. Turner	CARYOPHYLACEAE
+_Tidestromia rhizomatosa_ I.M. Johnston	AMARANTHACEAE
Allenrolfea occidentalis (S. Watson) Kuntze	AMARANTHACEAE
Sida longipes Gray	MALVACEAE
Fouquieria splendens Engelm.	FOUQUIERIACEAE
Fouquieria shrevi I.M. Johnston	FOUQUIERIACEAE
Ibervillea tenuisecta (Gray) Gray	CUCURBITACEAE
Cevallia sinuata Lag.	LOASACEAE
Mentzelia mexicana Thompson & Zavortnik	LOASACEAE
Petalonyx crenatus Gray ex S. Watson	LOASACEAE
Nerisyrenia castillonii Rollins	BRASSICACEAE
Nerisyrenia incana Rollins	BRASSICACEAE
Oenothera macroscelens Gray	ONAGRACEAE
Euphorbia astyla Boiss.	EUPHORBIACEAE
Euphorbia fruticulosa Boiss	EUPHORBIACEAE
Toxicodendron radicans (L.) Kuntze ssp. _eximium_ (Greene)	ANACARDIACEAE
Fagonia scoparia Brandegee	ZYGOPHYLACEAE
Lycium parishii Gray var. _modestum_ (I.M. Johnson) F. Chiang	SOLANACEAE
+_Phacelia marshall-johnstonii_ N.D. Atwood & Pinkava	BORANGINACEAE
Tiquilia gosspypina (Woot. & Standl.) Richardson	BORANGINACEAE
Tiquilia gregii (Torrey & Gray) Richardson	BORANGINACEAE
+_Tiquilia turneri_ Richardson	BORANGINACEAE
Orobanche ludoviciana Nutt. var. _ludoviciana_	OROBANCHACEAE
Chilopsis lineraris (Cav.) Sweet	BIGNONIACEAE
Baccharis neglecta Britt.	ASTERACEAE
Bahia absinthifolia Benth. var. _dealbata_ Gray	ASTERACEAE
+_Erigeron cuatrocienegensis_ Nesom	ASTERACEAE
Erigeron pinkavii Turner	ASTERACEAE
+_Gaillardia gypsophila_ B.L. Turner	ASTERACEAE
+_Haploesthes robusta_ I.M. Johnston	ASTERACEAE
Isocoma coronopifolia (Gray) Greene	ASTERACEAE
Isocoma drummondii (Torrey & Gray) Greene	ASTERACEAE
Machaeranthera gypsophila Turner	ASTERACEAE
+_Machaeranthera restiformis_ Turner	ASTERACEAE

(continued)

Table 1 (continued)

***Pseudoclappia arenaria* Rydb.**	ASTERACEAE
Sartwellia mexicana Gray	ASTERACEAE
Solidago gypsophila G.L. Nesom.	ASTERACEAE
Thymophylla gypsophila (B.L. Turner) Strother	ASTERACEAE
***Varilla mexicana* Gray var. *gypsophila* B.L. Turner**	ASTERACEAE
Xylothamia truncata G.L. Nesom	ASTERACEAE
Yucca treculeana Carr.	AGAVACEAE
Prosopis glandulosa Torrey var. *torreyana* (Benson) M.C. Johnston	FABACEAE
Nama cuatrocienegensis G.L. Nesom	HYDROPHYLACEAE
Nama serpylloides Hemsl.	HYDROPHYLACEAE
Sesuvium verrucosum Raf.	AIZOACEAE
Dasylirion palmeri Trel.	AGAVACEAE
+*Sabatia tuberculata* J.E. Williams	GENTIANACEAE
Samolus ebracteatus Kunth .var. *coahuilensis* Henr.	PRIMULACEAE
Tetraclea subinclusa I.M. Johnston	VERBENACEAE
Sporobolus coahuilensis Valdés-Reyna	POACEAE

of its gypsum dunes ecosystem. The existence of stromatolites, as well as several very ancient and systematically isolated groups of microorganisms in the wells of the Valley has given and still gives the impression of vast antiquity of the ecosystems of Cuatrociénegas. In terms of flora as well, famous botanists such as [9–11, 20, 21] refer to the high endemism of gypsum soil communities of the flora of Cuatrociénegas postulating an ancient evolutionary history (tertiary) spanning several million years. The argument was usually based on the cause of the large number of endemic species, many genera with all gypsophytic species and several species "isolated", characterizing them as "paleo-endemism" [11].

However, all of the arguments in favor of a long evolutionary history contrasted with the fact that the gypsum dunes are bodies or eolian systems, and for this reason of very recent origin. There is no evidence of the existence of gypsum dunes or a fossil record of gypsum plants before the Holocene in Cuatrociénegas Valley, nor throughout the Chihuahuan Desert region. It is likely that the dunes of Cuatrociénegas age less than 20,000 years or even belong to the Holocene age (see below). A Pleistocene (or earlier) origin of the dunes and their vegetation is unlikely considering the much more humid climatic conditions in those periods and in the consequential existence of paleolakes in the majority of the valleys and basins of the Chihuahuan Desert.

In recent years, a large number of these paleolakes have been found in the places now occupied by the valleys of the North American deserts [22–26]. Recently, research is being done on the malacofauna of two paleolakes in the neighborhood of the Valley of Cuatrociénegas (in prep.).

Previously reported that the paleolake that predated the gypsum dunes of the Estancia Valley (Chihuahuan Desert, New Mexico) occupied the valley from late Pleistocene (ca. 24,000 BP) to early Holocene (ca. 10,500 years) [22]. A significant change in the early Holocene towards drier conditions caused the evaporation of the body of water and the precipitation of gypsum crystals, which were later deposited as dunes. In Cuatrociénegas the existence of a paleolake has so far been denied [27, 28], but apart from the few geological investigations in the Valley, the gypsum dunes themselves are clear and undeniable evidence of the presence of a large body of water in the geological past!

3.1 The Habitat – Geological Evolution of the Dunes of Cuatrociénegas

In the Chihuahuan Desert region in the mountain ranges of the Sierra Madre Oriental, Permian, Jurassic and Cretaceous strata are present that contain sediments of gypsum and other evaporates.

Especially during periods of regression in the Lower Cretaceous (La *Virgen* and *Acatita* Formation), reef lagoons formed several times that were separate from the deep waters that formed systems of sabkhas [29]. One of these primary early Mesozoic sabkhas remains, which, subsequently supplying the raw material for the dunes of Cuatrociénegas, is located in direct proximity to the Valley in the Sierra de Menchaca, where powerful strata of gypsum are found (Fig. 3).

These surface layers of several meters of gypsum suffered during the Pleistocene under a humid climate, a strong weathering and erosion depositing gypsum in the paleolake in the Valley of Cuatrociénegas during thousands of years. This process of weathering and erosion of the gypsum is still active, but under current climatic conditions on a much smaller scale than in the Pleistocene. First during the Holocene under an increasingly dry climate, the body of water evaporated, leaving large quantities of gypsum precipitated on the surface of the valley. Then the gypsum was deposited by wind, forming a dune ecosystem that we can call a *Secondary Sabkha Ecosystem*.

A geological origin of the gypsum cycle similar to the Valley of Cuatrociénegas was previously reported [30] based on the extensively investigated White Sands Dunes (New Mexico), in which the author considers the age of the dunes to be between 7,000 and 4,000 years B.P. An analogous geological history can also be observed in the gypsum dunes of Lake Estancia (New Mexico), with the formation of the dunes beginning 8,000 years ago, in the Holocene [31, 32]. In both cases, the geological situation (endorheic basins) is very similar to that of the Valley of Cuatrociénegas.

In all the above-mentioned sites in the Chihuahuan Desert, there is no geologic evidence of dunes or large deposits of gypsum in the basins before the Holocene. From this perspective, the lack of fossil evidence of gypsophytes (as with cacti and most other succulents) probably is not a result of supposed reduced chances of preservation but rather the absence of such communities before the late Pleistocene.

The regional, geological, and geomorphologic evidence indicate that the gypsum dunes of Cuatrociénegas and other neighboring dunes of the Chihuahuan Desert, such as the Dunes of Bilbao and the Dunes of Acatita, are modern wind systems established during the Holocene after the disappearance of the paleolakes.

3.2 The Vegetation of the Dunes of Cuatrociénegas

Was an adaptation of plants to the habitat of the gypsum dunes of Cuatrociénegas possible in just 10,000 years? The gypsophytic vegetation of Cuatrociénegas being part of the older general problem of the origin of the North American deserts. The lack of fossil records forces us to look for possible answers and hypotheses in different disciplines, such as evolutionary ecology, geobotany, geomorphology, geology, climatology, systematic and others.

The key point was the erroneous consideration of the Cuatrociénegas gypsophytes *a priori* as “paleoendemism” with a long evolutionary history [11] instead of neo-endemism. A large number of endemic plants by itself do not speak for an old age of these communities nor of all the species that form them. There are several investigations on rapid or even explosive diversification of species in magnitude in just a few thousand years, typical for neo-endemic forms.

The most peculiar case of a rapid adaptive radiation is undoubtedly that of the cichlids of Lake Victoria in the African Rift, from which about 500 species emerged in just 15,000 years[2] [33, 34]. Several similar examples exist in the area of flora, such as the well-researched case of the species *Armeria maritima* s. l. (Plumbaginaceae) in Europe with its various post-glacial adaptations [35], or the genus *Nepenthes* (Nepenthaceae) in SW Asia [36]. Triggers for rapid adaptive radiation are abrupt changes in climate and geomorphology, both typical of the Pleistocene, with its sudden changes during the glacial/interglacial-cycle. These environmental and climatic changes drive the explosive diversification of the groups into

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[2] Others authors mention 100,000 years but it also would be surprisingly short time.

new habitats by genetic drift in very short time. The creation of small populations (metapopulations) with different phenotypes separated from the parent population within a few generations was reported in literature [36].

In some cases these rapid diversification do not match the data obtained with modern molecular techniques (DNA sequences) because they take gradual evolution as a basis and a constant rate of mutations per time unit [36]. Other evolutionary concepts (punctualism) put exactly this constant of mutations in question.

Suitable sites for rapid diversification are islands and high mountains. In the case of the Chihuahuan Desert in general and of Cuatrociénegas in particular, the soils are "edaphic islands", special habitats with different types of soils where, processes of formation of ecotypes and later of (neo-) endemics took place during the Pleistocene and Holocene. The "extreme" gypsophily of the plants of the dunes was probably a key innovation (mutation) as the plants' response to extreme environmental stress for the colonization of a new space.

The earliest researchers of the gypsophytes, such as Johnston [20], for example, already postulated that the gypsum in the soil should be very encouraging with respect to the diversification of species and this is reflected in the high degree of endemism. Ecosystems of gypsum substrates do not contain a large number of species, but are very unique because of their endemism. The gypsum itself is probably not the main stimulant, but a new niche "free" to be taken on as a challenge for the few species already well adapted to xeric environments. Some authors consider the gypsophily generally as a possible form of xerophytic adaptations [3, 37]. The different ecological strategies of the gypsophylic species seem to support this argument. In Cuatrociénegas, various forms were able to colonize the gypsum dunes that are not usually related to gypsophily, but are related to xerophily (*Coriphantha*, *Yucca*, *Prosopis* and others). For Nyctaginaceae, a family with known tolerance to gypsum with seven genera and 28 species, it was suggest that the gypsum tolerance was derived multiple times [38].

Characteristic of the neo-endemits are genera with a large number of species in the process of speciation [36]. Within the Cuatrociénegas Valley, most endemic genera are present with three or four species, and some, such as *Euphorbia* or *Coryphantha* with even more than ten! Many of the sister species are halophytes. Speciation that is still in process is also very common and is manifested as subspecies or varieties. None of the endemics gypsophytes of Cuatrociénegas Valley are at the level of genus or family, characteristic for the relict or paleo-endemic forms.

4 Conclusion

The ecosystem of the gypsum dunes of Cuatrociénegas and its several endemic species is, contrary to previous concepts, geologically young and was supposedly established in the Holocene after evaporation of the paleolakes. This new hypothesis of a rapid adaptation of the species that now form the gypsum dune community agrees well with the observations and geological evidences.

Like all ecosystems with highly specialized members, the Cuatrociénegas Valley and specifically the gypsum dunes with their flora rich in endemism are very fragile ecosystems and require special protection. Despite major national and international efforts, protection has not yet been given.

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Effects of Seed Storage on Germination of Desert Halophytes with Transient Seed Bank

Ali El-Keblawy

Abstract

Some halophytes of the subtropical arid deserts produce fruits have a transient seed bank. The time of fruit ripening and shedding in these plants coincides with the onset of suitable conditions for germination and seedling establishment. Economic uses of plants with transient seed bank necessitate understanding environmental factors that would affect seed longevity under different storage conditions. Fresh seeds of both *Salsola imbricata* and *Haloxylon salicornicum* have high germination level and germination speed, and form a transient seed bank in nature. The impacts of storage period and condition on germination level and speed were assessed in the two species. In both species, 9 months storage did not affect germination percentage of seeds in fridge, but completely inhibited it in field seeds. The impacts of room and warm temperatures were in between cold and field storage. Storage significantly increased germinate rate index of seeds stored in all conditions till 17 months in *S. imbricata* and till 12 months in *H. salicornicum*. In both species, fridge storage had little effects on final germination and germination speed of seeds incubated at the different temperatures, compared to fresh seeds. However, room temperature and warm storages significantly reduced final germination and germination speed at the different temperatures, so the reduction was more pronounced at 35 °C, especially in *H. salicornicum.*

Keywords

Dormancy • Germination • Desert halophytes • Seed storage • Transient seed bank

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_7,

1 Introduction

Salinity is one of the most severe environmental factors limiting the productivity of agricultural crops. It is especially an important problem in arid and semi-arid regions because of low rainfall and high rates of evaporation [1]. Soil salinity is a major constraint to the economic exploitation of land for agriculture and forestry and increasing in these regions. One of the most important issues in water management is the maximization of the profitability from water use in agriculture and adoption of potential native halophytes that could be grown in salt affected lands or irrigated with brackish water [2]. In dry regions where fresh water becomes a scarce commodity, the irrigation of economically important salt tolerant native plants with brackish water could help in the sustainable use of natural resources in these regions [3].

Saline environments are often wet and so the seeds of halophytes may remain un-germinated over extended periods even after imbibition if the external environment does not favour germination and seedling survival [4]. The survival of halophytes seeds in soil seed bank depends on the salinity tolerance of seeds at the germination stage and the seeds ability to tolerate hyper saline conditions during storage in the soil [5]. In the subtropical region, many perennial halophytes do not possess elaborate dormancy systems. Instead, halophytes could propagate through vegetative means, such as ramets and have no ecological compulsions for seed germination [4].

In the subtropical region of Pakistan, monsoon rains (July and August) decrease soil salinity as well as lower the ambient and soil temperatures along with providing appropriate photoperiod. This stimulate seeds of most halophytes to germinate and consequently do not maintain a persistent seed bank [4]. The subtropical region of the Arabian Peninsula, however, does not receive monsoon rains. Many halophytes of this region adopt another strategy, which enable them to germinate immediately after seed maturation, especially if the environmental conditions are suitable for germination and seedling recruitment [6, 7].

Several species of halophytes in the subtropical region produce seeds that germinate very fast and to high levels immediately after maturation. Typically, the time of maturation of these seeds coincides with the favorable time of seed germination and seedling recruitment. In many cases, such seeds form a transient seed bank. For example, perennial halophytic shrubs, such as *Cressa cretica*, *Haloxylon stocksii*, *Salsola imbricata*, and *Sporobolus ioclados*, have a transient seed bank and depleted gradually in few months after dispersal [8, 9]. Similarly, seeds of *Aeluropus lagopoides* seeds are not dormant and showed 100 % germination at the optimal temperature at the time of seed maturation and maintained a transient seed bank [10].

Haloxylon salicornicum and *Salsola imbricata* (Chenopodiaceae) are perennial shrubs widely distributed in sandy habitats of the Arabian deserts. Both species are succulent halophytes and well-adapted to endure severe environmental stresses and human disturbances in the deserts. *H. salicornicum* has been considered one of the most promising species for re-seeding deteriorating desert range vegetation and for sand dune fixation [11]. In addition, *S. imbricata* has the ability to stabilize sand dunes and to restore degraded, oil-polluted soils [12, 13].

Both *H. salicornicum* and *S. imbricata* ripen and shed their seeds early in the growing season (early winter). This coincides with the onset of suitable conditions for germination and seedling establishment (e.g., availability of rainfall and lower temperatures). Shortly after effective rainfalls, many seedlings appear under and around the maternal plants (Ali El-Keblawy, unpublished data). Under laboratory conditions, fresh harvested seeds of both species germinate to a very high level with high speed [6, 7]. Seed bank studies indicated that a transient nature of the seed bank both in *S. imbricata* [14, 15] and *H. salicornicum* [16, 17].

Dry storage usually results in the decrease in germination requirements in seeds of many species of arid and semiarid lands. Generally, germination requirements usually become less specific after seed dry storage [18]. For example, the need for high temperature and light to achieve greater germination in fresh seeds of *Prosopis juliflora* was significantly reduced after seed stored dry at room temperatures for 8 months [19]. Similarly, seeds of the desert herb *Plantago coronopus* stored for 2 months germinated under narrow range of temperatures, but germinated under wider range of temperatures when stored in their inflorescences under natural desert habitats for 1 year [20]. These species developed innate dormancy and form persistent seed bank. However, few studies have assessed the impact of different storage conditions on temperature requirement for desert shrubs with a transient seed bank [11, 21, 22]. The aim of this study was to assess the impact of different storage periods and conditions (e.g., cold, warm, room temperatures and natural field conditions) on germination level and speed of the two desert shrubs *Haloxylon salicornicum* and *Salsola imbricata*, which have a transient seed bank. In addition, the study also aimed at assessing the impact of the different storage conditions for a period of 1 year on the temperature requirement during germination in the two species.

2 Materials and Methods

Fresh seeds of *H. salicornicum* and *S. imbricata* were collected during December from large populations in the inland desert of the United Arab Emirates (UAE), near Al-Ain. Seeds were randomly collected from about 50 plants of each species that represent the genetic diversity of the populations. Seeds of each species were divided into five groups. Seeds of one group were germinated immediately after collection (within 5 days, hereafter referred as fresh seeds). Seeds of the other four groups were put into 4 × 6 cm mesh bags. The bags were stored in room temperatures, at freezer (−4 °C, hereafter referred as cold storage), in oven adjusted at 40 ± 2 °C (hereafter referred as warm storage) and on soil surface of a natural habitat, where the two species are naturally grown. When the local weather forecast expected a rain, seeds of the natural habitats were removed and returned back shortly after improvement of the weather. The site of natural seed storage received only one effective rain during the study period.

Seeds of the two species were tested for germination after 3, 9, 12 and 17 months of storage. Seeds were germinated in incubators adjusted to 15 °C for *H. salicornicum* and 20 °C for *S. imbricata* under continuous illumination with daylight fluorescent tubes (110 μmol photons/m^2/s, 400–700 nm). The highest germination in light was recorded at these temperatures in *H. salicornicum* (6) and *S. imbricata* [7].

In order to assess the impact of different storage conditions on temperature requirements, seeds stored in room temperature, freezer and oven were tested for germination in four incubators adjusted at 15, 20, 25 and 30 °C under continuous illumination with daylight fluorescent tubes. The germination was conducted in 9-cm Petri-dishes containing one disk of Whatman No. 1 filter paper, with 10 ml of distilled water. Four replicate dishes, each with 20 seeds, were used for each treatment. Seeds were considered to be germinated with the emergence of the radicles. Germinated seedlings were counted and removed every alternative day for 14 days following sowing.

The rate of germination was estimated using a modified Timson's index of germination velocity = $\Sigma G/t$, where G is the percentage of seed germination at 2 d intervals and t is the total germination period [23]. The maximum value possible using this index with these experiments was 700/14 = 50. The higher the value, the more rapid is the germination.

Two way-ANOVAs were used to assess the impact of storage condition and seed storage period or temperature of incubation on final germination percentage and germination rate. Tukey's test (Honestly significant differences, HSD) was used to estimate least significant range between means. The germination percentages were arcsine transformed to meet the assumptions of ANOVA. The transformation improved normality of distribution of data. All statistical methods were performed using SYSTAT, version 11.0.

3 Results

3.1 Effect of Storage Period and Storage Condition

3.1.1 Effect on Final Germination

Both storage period and storage conditions and their interactions significantly affected final germination percentage of the two species ($P<0.001$, Table 1). Generally, storage in freezer didn't affect the level of final germination, compared to the other storage conditions, especially seeds stored under natural field conditions.

The germination of fresh seeds was 76 and 68.3 % in *H. salicornicum* and *S. imbricata*, respectively. Storage for 3 months significantly increased germination of seeds stored under different conditions, compared to germination of fresh seeds. The range of the germination increase was between 10.5 % for seeds stored under warm conditions and 22.8 % for seeds stored in field conditions in *H. salicornicum* and between 18.9 % for seeds stored in freezer and 37.4 % for seeds stored under warm conditions in *S. imbricata*.

In *H. salicornicum*, storage for 9 and 12 months completely inhibited germination of seeds stored in the field and significantly reduced germination of seeds stored in warm and room temperature conditions, but not affected germination of seeds stored in freezer, compared to fresh seeds. Further storage for 17 months led for almost complete inhibition in germination of seeds stored in warm and room temperature conditions and to a significant reduction for the germination of seeds stored in the freezer (Fig. 1a).

For *S. imbricata*, 9 months storage inhibited germination of field seeds, but not affect it for seeds stored under the other conditions. Storage for 12 and 17 months significantly reduced final germination of cold, room and warm storage seeds, but did not completely deteriorate it. The deteriorations in final germination, compared to fresh seeds, under warm, room temperature and cold conditions were 32.6 %, 21.1 % and 17.2 %, respectively, after 12 months and 60 %, 55.4 % and 27.7 %, respectively, after 17 months (Fig. 1b).

Table 1 Two-way ANOVA showing the effect of storage period and storage condition on final germination percentage and germination rate index of *Haloxylon salicornicum* and *Salsola imbricata* seeds

Source of variation	df	Mean-square	F-ratio	P
Final germination percentage				
A: *Haloxylon salicornicum*				
Storage period (SP)	3	2.363	112.4	<0.001
Storage condition (SC)	3	0.633	30.1	<0.001
SP*SC	9	0.165	7.8	<0.001
Error	40	0.021		
B: *Salsola imbricata*				
Storage period (SP)	3	1.162	75.2	<0.001
Storage condition (SC)	3	0.445	28.8	<0.001
SP*SC	9	0.088	5.7	<0.001
Error	40	0.015		
Germination rate index				
A: *Haloxylon salicornicum*				
Storage period (SP)	3	12.806	48.3	<0.001
Storage condition (SC)	3	18.546	69.9	<0.001
SP*SC	9	4.985	18.8	<0.001
Error	40	0.265		
B: *Salsola imbricata*				
Storage period (SP)	3	2.332	3218.6	<0.001
Storage condition (SC)	3	23.394	32281.8	<0.001
SP*SC	9	2.840	3919.1	<0.01
Error	40	0.001		

3.1.2 Effect on Germination Rate

Similar to the impact on final germination, both storage period and storage conditions and their interactions significantly affected final germination rate of the two species ($P<0.001$, Table 1). There was no significant difference in germination rate index between fresh seeds and those stored for 3 months under different conditions. Storage significantly increased germinate rate index of seeds stored for 9 months in all storage conditions, except field seeds, which did not germinate. After 12 and 17 months, the increase in germination rate, compare to fresh seeds, was significant for *S. imbricata*

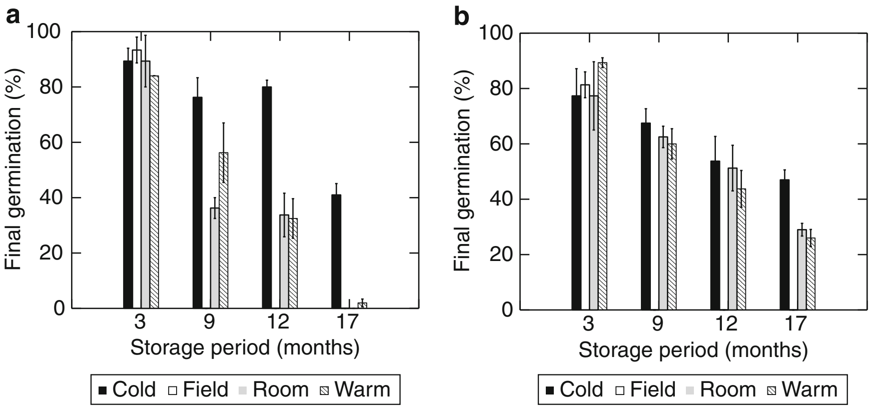

Fig. 1 Effect of storage period and storage conditions on final germination percentage of *Haloxylon salicornicum* and *Salsola imbricata* seeds. (**a**) *Haloxylon salicornicum* (**b**) *Salsola imbricata*

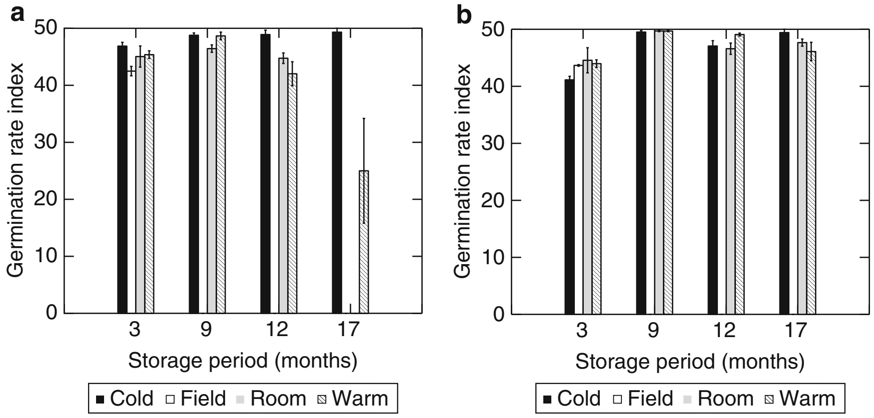

Fig. 2 Effect of storage period and storage conditions on germination rate index of *Haloxylon salicornicum* and *Salsola imbricata* seeds. (**a**) *Haloxylon salicornicum* (**b**) *Salsola imbricata*

stored at the different conditions, but was significant only for seeds of *H. salicornicum* stored in freezer (Fig. 2). After 17 months, the germination rate index of *H. salicornicum* seeds stored in room temperatures and warm conditions was significantly low, compared to that of fresh seeds (Fig. 2a).

3.2 Effects of Storage Condition and Temperature of Incubation

3.2.1 Effect on Final Germination

The effects of storage condition and temperature of incubation and their interaction on final germination were significant in both *H. salicornicum* and *S. imbricata* ($P<0.01$, Table 2). Germination of the fresh and stored seeds was significantly greater at 15, 20 and 25 °C, compared to 35 °C.

Final germination of *H. salicornicum* seeds at the different temperatures didn't differ significantly ($P>0.05$) between fresh seeds and seeds stored at freezer. However, the final germination of both room and warm stored seeds of *H. salicornicum* was significantly reduced at 15, 20 and 25 °C, and was almost inhibited at 35 °C (Fig. 3a).

In *S. imbricata,* final germination at 15 °C was less affected by storage in room and warm conditions and significantly increased by storage in freezer, compared to that of fresh seeds.

Table 2 Two-way ANOVA showing the effect of storage condition and temperature of incubation on final germination percentage and germination rate index of *Haloxylon salicornicum* and *Salsola imbricata* seeds. Ns: insignificant at F equal or less than 0.05

Source of variation	df	Mean-square	F-ratio	P
Final germination percentage				
A: *Haloxylon salicornicum*				
Storage condition (S)	3	1.404	184.3	<0.001
Incubation temperature (T)	3	0.763	100.2	<0.001
S*T	9	0.040	5.29	<0.001
Error	44	0.008		
B: *Salsola imbricata*				
Storage condition (S)	3	0.078	11.4	<0.001
Incubation temperature (T)	3	0.482	71.1	<0.001
S*T	9	0.024	3.6	<0.01
Error	44	0.007		
Germination rate index				
A: *Haloxylon salicornicum*				
Storage condition (S)	3	2.058	3.8	<0.05
Incubation temperature (T)	3	5.787	10.6	<0.001
S*T	9	1.873	3.45	<0.01
Error	44	0.543		
B: *Salsola imbricata*				
Storage condition (S)	3	0.213	0.957	Ns
Incubation temperature (T)	3	0.420	1.87	Ns
S*T	9	0.313	1.39	Ns
Error	44	0.225		

At 35 °C, there was no significant difference between final germination of fresh seeds and that of seeds stored in the different conditions (Fig. 3b).

3.2.2 Effect on Germination Rate

The effects of storage condition and temperature of incubation and their interaction on germination rate was significant ($P<0.05$) in *H. salicornicum*, but not for *S. imbricata* seeds ($P>0.05$). In *H. salicornicum*, storage in freezer, but not in room and warm conditions, significantly increased germination rate index, compared to fresh seeds. There were no significant differences between the germination rates at the different temperature for fresh seeds, but germination speed was significantly reduced at 35 °C, compared to other temperatures, for stored seeds (Fig. 4).

Cold storage significantly increased germination speed at 15, 20 and 25 °C, but not at 35 °C. In addition, warm storage and storage at room temperatures did not affect germination speed at 15, 20 and 25 °C, but significantly reduced it at 35 °C. The ecological advantage of this is to ensure that seeds of *H. salicornicum* stored on soil surface or under the shade of vegetation will not germinate easily under high temperatures of summer, even if rainfall is enough for seedling emergence (Fig. 4).

4 Discussion

Seed dormancy has been hypothesized to be evolved as an adaptation for survival during a season when environmental conditions are unfavourable for seedling establishment [24, 25]. Dormancy can influence patterns of plant distribution, recruitment dynamics, and persistence in the plant community [26]. Consequently, dormancy is very crucial in formation of soil seed banks, which play important roles in maintaining plant populations and also in restoring vegetation after destruction [27]. The results of the present study, however, indicated that both *S. imbricata* and *H. articulata* have transient seed bank; seeds germinate immediately after ripening and lost their viability after 9 months under natural field conditions. This result is consistent with those of the earlier studies about *S. imbricata* [14, 15] and *H. salicornicum* [16, 17]. In some species, maintenance of seed dormancy when conditions are optimal for germination can be disadvantage, as seeds are exposed to lethal environmental factors such as granivory and extreme temperatures for longer periods [21]. In addition, species with non-dormant seeds might be expected to benefit from earlier germination more than those with dormant seeds, because such a response might reduce mortality, due to factors such as seed predation, sibling competition or shade intolerance [28]. Furthermore, storage of the seeds reduce germination

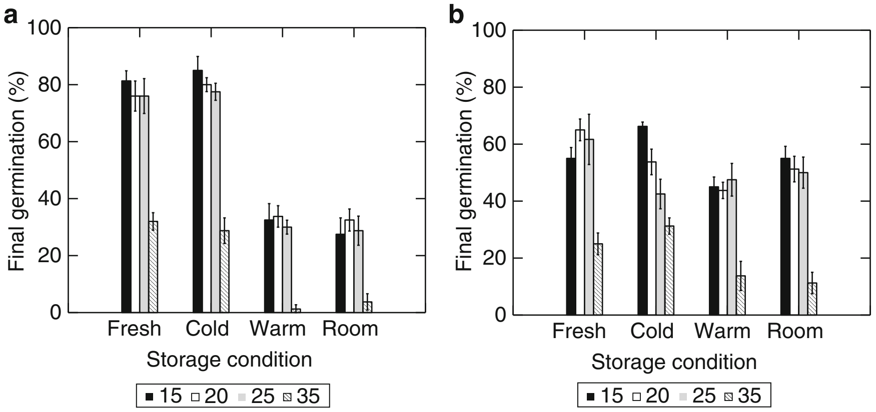

Fig. 3 Effect of storage condition and incubation temperature on final germination percentage of *Haloxylon salicornicum* and *Salsola imbricata* seeds. (**a**) *Haloxylon salicornicum* (**b**) *Salsola imbricata*

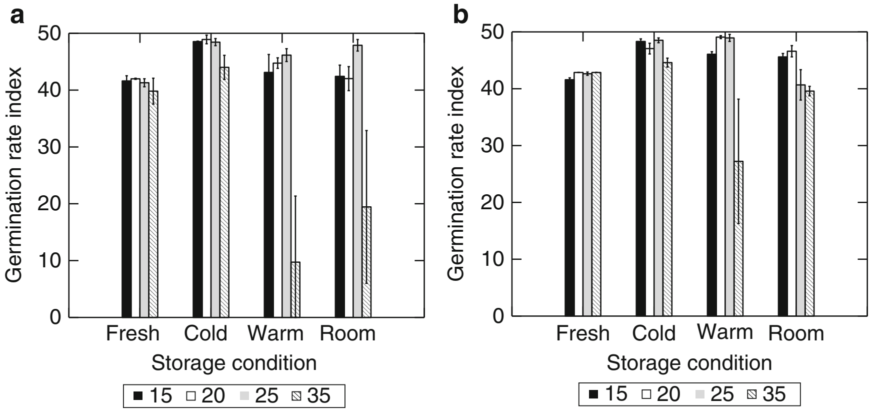

Fig. 4 Effect of storage condition and incubation temperature on germination rate index of *Haloxylon salicornicum* and *Salsola imbricata* seeds. (**a**) *Haloxylon salicornicum* (**b**) *Salsola imbricata*

speed, which usually reduce the competitive ability of the seedlings, as they emerge later in the season, compared to other species [29–31].

Seed dormancy respond to diurnal fluctuations in temperature [32], but the response differs according to the level and kind of dormancy [24]. Several researchers have reported that high temperatures and wide daily temperature fluctuations break seed dormancy in many species [24]. For example, seeds with physical seed-coat dormancy require temperature fluctuations, such as that on soil surface, to break their dormancy [33]. Seeds with low dormancy, however, would lose their viability faster when stored on soil surface, compared with seeds with physical dormancy [21]. For example, seeds of *Acacia berlandieri* with no dormancy deteriorated faster on soil surface compared to seeds of *Leucaena pulverulenta*, which have physical seed coat dormancy [21]. In the two species of the present study, which have little seed dormancy, 9 months of storage under field conditions resulted in complete inhibition for the seed germination.

Seeds in soils undergo hydration–dehydration cycles in concert with fluctuations in the humidity of their surroundings [34]. In the coastal and inland areas of the UAE deserts, dew and morning dense fogs are frequent events that result in moistening the fruits of both *S. imbricata* and *H. salicornicum*;

especially the winged structures of their fruits keep them exposed on the soil surface. During dew formation, soil surfaces can become saturated, and seeds with permeable seed coats imbibe water [22]. The effect of hydration – dehydration cycles on seed germination rate and level are important in natural plant populations. These cycles had resulted in an earlier germination of desert cacti [35], but led to loss of seed viability in *Acacia tortilis* and *A. nilotica* [36]. The hydration – dehydration cycles would be responsible for the complete deterioration of the field-stored seeds of the studied species. Such deterioration was attributed to the accumulation of reactive oxygen species, which lead to oxidative stress and cellular damage [37]. In addition, both membrane permeability, measured by ion conductivity, and the seed respiratory activity were significantly increased following the hydration-dehydration cycles [38, 41].

The interactions between temperature and moisture can significantly affect seed germination of a wide range of desert species [21, 39] Seeds of Australian *Acacia* species were not affected by long-term exposure to high temperatures (>50 °C) under dry conditions, but germinated to high levels when high temperatures coupled with moisture [40]. In the present study, storage for 9 months completely inhibited germination for field seeds of the two species, but not affected it for *S. imbricata* seeds stored dry in room temperatures and in warm conditions. A similar result has been reported in the desert shrubs *Acacia berlandieri* that also has seeds with little dormancy [21]. This was attributed to the greater interaction effect between moisture and fluctuating temperatures under field conditions, compared to dry fluctuating temperatures in the lab. Seed survival is more affected under moist heat than dry heat [21, 42]. In addition, greater loss in viability of *Galium aparine* and *Bifora radians* seeds on soil surface, compared to dry-stored seeds, could be attributed to greater diurnal soil temperatures fluctuations, different wavelength of light, microbial activity and other soil factors [43]. Storage of *H. salicornicum* and *S. imbricata* fruits on the soil surface expose them to great diurnal day/night temperatures fluctuate that ranged 25–65 °C during summer and 5–40 °C during winter (Ali El-Keblawy, unpublished data). On the other hand, the little effect of warm and room temperature storage could be attributed to the smaller amplitudes and/or lower temperature, compared to that in natural field conditions.

Maintenance of seed viability requires relatively both low moisture content by drying and a lower temperature environment [44, 45]. In the present study, storage for 12 and 17 months maintained the high germination percentage for seeds stored in refrigerator in both *S. imbricata* and *H. salicornicum*. This result is in agreement to the seeds of *S. imbricata* stored at −18 and 4 °C for 24 months where 80–100 % germination was observed compared to 0 % for those stored at ambient temperature and at 50 °C [15]. This result also coincides with seeds of *H. salicornicum* from Iraqi deserts which maintained their viability for 1 year when stored at 5 °C, but lost it at room temperatures [11]. However, seeds of eight out of nine annual plant species from the Mojave and Sonoran Deserts of North America germinated to high percentages after dry storage for 1–5 weeks at 50 °C, but they gave poor germination when stored at 4 °C [46]. Similarly, less than 18 months storage at cool temperatures increased seed moisture content, reduced viability and did not promote germination in three Australian everlasting daisy species, but storage at high temperatures decreased seed moisture content, maintained viability and improved germination [47]. The difference in the response to cold storage between *S. imbricata* and *H. salicornicum* and the other mentioned species could be attributed to the degree of seed development and consequently the need for after-ripening. Seeds of *S. imbricata* and *H. salicornicum* are fully developed and germinated to high level immediately following dispersal, but seeds of the other species require high temperatures following seed dispersal to promote seed maturation [46]. In another shrubby chenopod, *Haloxylon ammodendron*, with fully developed seeds and only 10-months longevity, seeds survived for longer period during storage at low temperatures, but lost their viability sharply in natural conditions [22].

It has been reported that fresh seeds usually germinate under specific narrow range of conditions, but such conditions gradually become wider as a result of seed storage [20, 48, 49]. In the annual desert herb *Plantago coronopus* of the Negev Desert, greater and faster germination was observed at a wide range of temperatures when the seeds were stored at naturally fluctuating daily temperatures of 13/55 °C or at constant 40 °C [20]. Similarly, dry storage at high temperatures reduced seed dormancy and widened the germination temperature requirements in *Bromus tectorum* [50] and light and GA_3 requirements in *Arabidopsis thaliana* [51]. In addition, the proportion of *Dactylis glomerata* seeds which require light and/or alternating temperatures to trigger germination declines during dry storage [52]. After prolonged storage, non-dormant seeds of *D. glomerata* are capable of maximum germination, even in the dark, at constant temperatures [52]. In the present study, however, fridge storage had little effect on the temperature requirement during seed germination of both *H. salicornicum* and *S. imbricata*. In addition, room temperature and warm storages significantly reduced final germination and germination speed at the different temperatures; the reduction was more pronounced at 35 °C. The ecological advantage of narrowing the germination window at 35 °C is to ensure that seeds stored on soil surface or under the shade of vegetation will not germinate easily under high temperatures of summer, even if rainfall is enough for seedling emergence.

Repeated environmental stresses facing desert plants coupled with great human disturbances in the Arabian Gulf deserts increase the chance of the shrubs mortality [53]. In addition, the inability of the two shrubs *S. imbricata* and *H. salicornicum* to produce persistent seed bank would threaten their life under repeated drought stress and human disturbances in the deserts. In order to ensure annual seedling recruitment, high annual fruit production should compensate the high mortality rate of the seeds and plants of both *S. imbricata* and *H. salicornicum*. Both species produce enormous amount of highly dispersed fruits every year, even in the dry seasons. These plants mainly rely on atmospheric moisture and fog as main sources of water for their growth [6, 7]. The high annual fruit production, even in the dry years, would compensate for the depletion of the transient seed bank, and consequently could ensure the regeneration of the two species in the harsh deserts. In addition, the greater dispersal ability of the fruits would enhance their ability in exploring the unpredictable deserts for more safe sites for germination and establishment [25].

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Halophytes of Southwest Asia

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Abstract

In general, saline and arid environments are poor in species. A total of 728 taxa of halophytes are recorded for SW Asia belonging to 68 families (compared to 117 plant families worldwide). The majority of halophytes belong to the families Chenopodiaceae, Poaceae, Leguminosae (Papiliondeae), Asteraceae and Cyperaceae. Chenopodiaceae has the largest number of species and genera of all families only exceeded by Poaceae which has more genera but fewer species. These numbers are in accordance with those found for halophytes of the world. From the data available, Turkey has the most halophytes (±600 taxa), followed by Pakistan (±361 taxa), Iran ± 350 taxa), Afghanistan, Saudi Arabia, Oman and Yemen (±120 taxa). Halophytes in SW Asia constitute about half the number of halophyte taxa (and families) recorded for the world.

Information on halophytes is collated from published sources, and names of accepted taxa (and synonyms) are compiled in the database BRAHMS. A preliminary checklist (of names only) produced from this database is provided in this chapter.

1 Introduction

Halophytes are plants that are specially adapted to live in saline environments. Salt affected areas amount to about 955 million ha worldwide, with the tropical African and SW Asian deserts constituting a major part of this area. In semi arid areas about 30 % of all irrigated land suffers from salinization, and with the present trend in global warming and climate change towards aridity, more and more land will eventually fall to salinity.

The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_8, © Springer Science+Business Media Dordrecht 2014

Fig. 1 Countries of SW Asia included in the study. Turkey, Lebanon, Israel, Palestine, Jordan, all countries of the Arabian Peninsula, Iraq, Iran, Afghanistan and Pakistan (From Google maps)

Information on saline ecosystems, correct identification of halophytes and their potential uses is scattered or lacking, especially in parts of SW Asia. This chapter is aimed towards understanding and identifying the plants that tolerate saline conditions in SW Asia; it collates the information that is available at present, and aims towards updating the nomenclature of this group of salt tolerant plants. This information is necessary for any research on biosaline agriculture, rangeland and coastal management and restoration of degraded arid and saline habitats.

1.1 Geographical Scope

For the purpose of this chapter, Southwest Asia is taken to include Turkey, Lebanon, Israel, Palestine, Jordan, all countries of the Arabian Peninsula (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, Yemen, and the United Arab Emirates), Iraq, Iran, Afghanistan and Pakistan (Fig. 1).

Southwest Asia is mostly arid with large gravel and sandy desert areas. The region lies at the edge of a large tectonic plate such that the Arabian Peninsula is pulling away from Africa, and parts of the Anatolian Peninsula (Turkey) are sliding past parts of Asia. Continental rifting has caused some areas to be below sea level, such as the Dead Sea located between Israel and Jordan.

The Arabian Peninsula lies between the Red Sea and Persian Gulf and the Anatolian Peninsula lies between the Black Sea and Mediterranean Sea. In the north, the Zagros, Elbruz and Taurus mountains are present. The Arabian Peninsula is mostly covered by sandy and gravelly plains with escarpment mountains in the southwest, and Rub' al Khali, one of the world's largest sand deserts, spanning the southern third. In Yemen, the mountains reach up to 3,700 m and the highlands extend north along the Red Sea coast and north into Lebanon. The Zagros Mountains located in Iran also border with parts of northern Iraq. The central plateau of Iran, a hyper arid area, is divided into two drainage basins, Dasht-e-Kavir (Great Salt Desert) in the north and Dasht-e-Lut in the south.

Though surrounded by water, the region of Southwest Asia is arid and lacks water resources. The few rivers, such as the Tigris and Euphrates which flow through Turkey, Syria and Iraq and the Jordan River (which flows from Mt. Hermon in Lebanon through Jordan into the Dead Sea) are critical for agriculture.

Climatically most areas in the plains receive less than 400 mm of precipitation a year (Fig. 2). Large areas of deserts are saline with inland sabkhas (salt flats). Some of the largest salt areas lie in the central plateau of Iran, and Umm as Samim, a big inland salt plain (a former lake) lies in western Oman.

1.2 What Are Halophytes

Halphytes can be defined in various ways, but for our purpose, we have taken halophytes as those plants that are able to complete their life cycle under saline conditions, where salt concentration is at least 200 mM NaCl [1]. Plants that are classified as "true" or "obligate" halophytes such as mangroves, seagrasses or some species of Amaranthaceae (in the former Chenopodiaceae) are not able to exist in non saline habitats, while "facultative" halophytes can live in non saline habitats. The majority of halophytes depend on rain for seed to germinate, but can flower and fruit in saline environments, and seeds of halophytes can survive long periods in saline conditions.

Many eudicot halophytes do not show optimum growth in salinity concentrations of 50–250 mM NaCl, while monocot halophytes generally grow optimally in the absence of salt, or if growth is stimulated, it is by a low concentration of NaCl (50 mM or less) [2]. All halophytes need to regulate their cellular Na^+, Cl^- and K^+ concentrations as they adjust to the external water potential. However species differ in the succulence (water content per unit area of leaf); [1] and in the solutes accumulated. Detailed account of salinity tolerance in flowering plants is given in [3].

Nearly all salt-tolerant plants belong to the angiosperms, although a few are ferns (in families Pteridaceae and Ophioglossaceae). Halophytes are widely distributed among the families of flowering plants, and are found in about a third of the total plant families [4]. There are about 500 genera of halophytes worldwide, of which about half belong to only 20 families (Table 1). Amongst monocotyledons, the Poaceae contain more halophytic genera than any other family (7 % of the family), in Cyperaceae 14 % of the genera are halophytic. Amongst the eudicots, Chenopodiaceae has the highest proportion of halophytic genera followed by Asteraceae, Aizoaceae, Leguminosae, Apiaceae, Euphorbiaceae, Brassicaceae, Plantaginaceae and Caryophyllaceae [1]. [In the APG III (2009) classification Chenopodiaceae is included in the Amaranthaceae. In this chapter, for the sake of convenience, we have kept the name Chenopodiaceae as used earlier.]

2 Distribution and Biogeography of the SW Asia Halophytic Flora

A fair amount of literature exists on halophytes of the countries of SW Asia and a number of papers are present on the physiology and germination

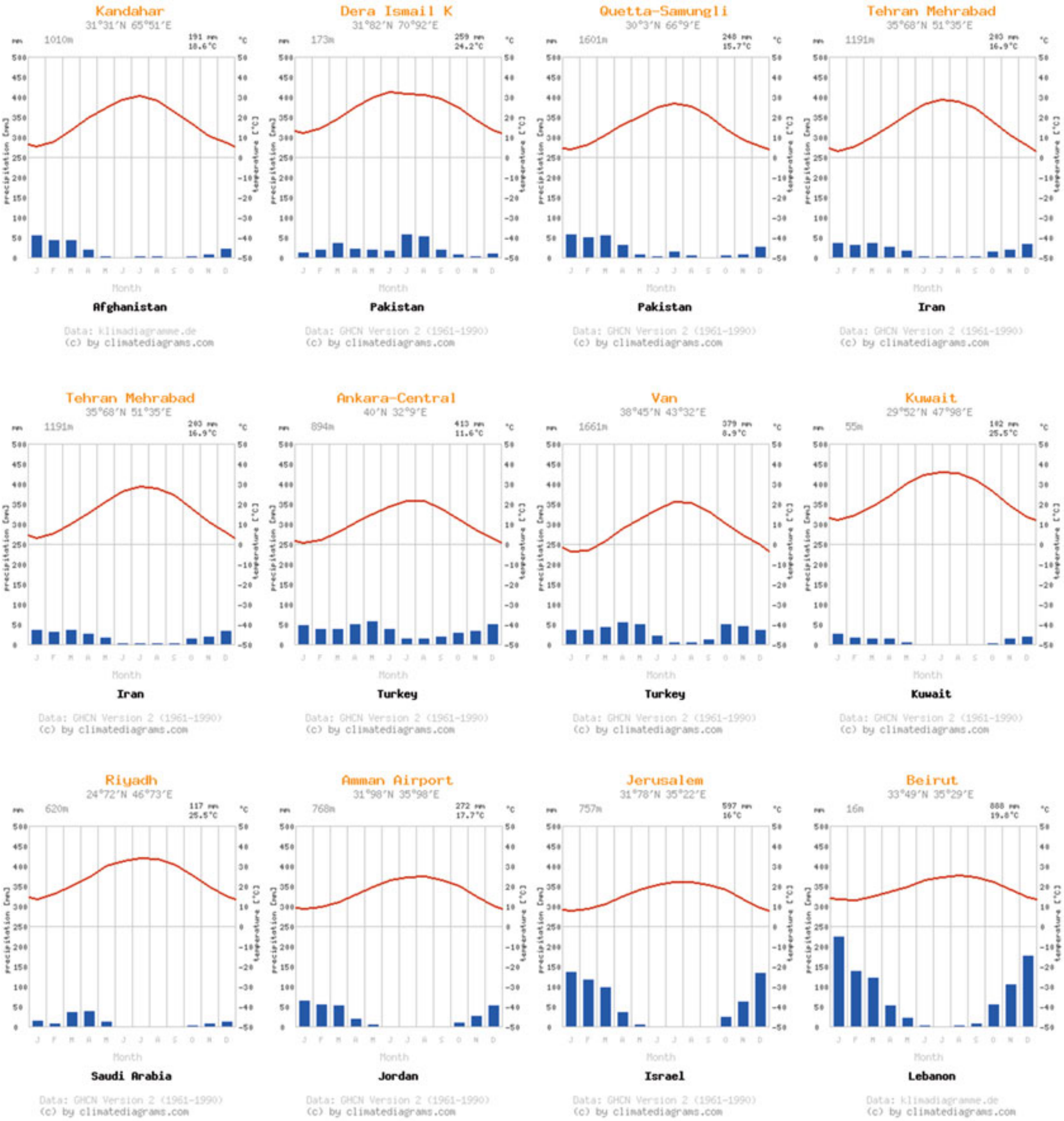

Fig. 2 Climate diagrams of nine countries of SW Asia

studies of halophytes [1, 3]. More recently, several studies have concentrated on the phylogeny of halophytes mainly in the Family Chenopodiaceae leading to revised classifications and changes in the nomenclature of species [5].

A total of 728 taxa of halophytes are recorded for SW Asia. This information has been collated from Published sources of which the main ones are: Pakistan: [6]; Turkey: [7–14]; Iran: [15]; Arabian Peninsula: [16–18]; Jordan: [17] (Fig. 3). Nomenclature of taxa (especially those in the Chenopodiaceae) are updated to the accepted names as provided in various publications [5, 20–25].

Names of taxa are databased in [26] used at the Royal Botanic Gardens Kew. This data base will be updated as and when new information becomes available. A preliminary checklist (of

Table 1 Families, genera and species in the halophytic families of SW Asia

Family	Genera	Species
Chenopodiaceae s.str.	49	183
Poaceae	55	112
Asteraceae	26	55
Leguminosae: Papilionoideae	27	48
Cyperaceae	10	44
Zygophyllaceae	8	17
Caryophyllaceae	8	16
Tamaricaceae	2	16
Juncaceae	1	15
Boraginaceae	9	14
Apiaceae	7	13
Brassicaceae	9	12
Polygonaceae	4	10
Liliaceae	3	10
Apocynaceae	8	9
Euphorbiaceae	2	9
Aizoaceae	5	8
Lamiaceae	5	8
Leguminosae: Mimosoideae	2	8
Plantaginaceae	2	7
Gentianaceae	3	7
Plumbaginaceae	3	6
Solanaceae	3	6
Ranunculaceae	4	5
Primulaceae	4	4
Arecaceae	2	4
Cymodoceaceae	2	4
Iridaceae	2	4
Rosaceae	1	4
Typhaceae	1	4
Malvaceae	3	3
Rhizophoraceae	3	3
Verbenaceae	3	3
Convolvulaceae	2	3
Hydrocharitaceae	2	3
Frankeniaceae	1	3
Juncaginaceae	1	3
Amaranthaceae s.str.	2	2
Orchidaceae	2	2
Rubiaceae	2	2
Valerianaceae	2	2
Elatinaceae	1	2
Goodeniaceae	1	2
Linaceae	1	2
Myrsinaceae	1	2
Najadaceae	1	2
Orobanchaceae	1	2
Portulacaceae	1	2
Thymelaeaceae	1	2
Leguminosae: Caesalpinioideae	2	2
Scrophulariaceae	2	1
Avicenniaceae	1	1
Cistaceae	1	1
Combretaceae	1	1
Cynomoriaceae	1	1
Molluginaceae	1	1
Moraceae	1	1
Nyctaginaceae	1	1
Pandanaceae	1	1
Pedaliaceae	1	1
Resedaceae	1	1
Rhamnaceae	1	1
Ruppiaceae	1	1
Salicaceae	1	1
Sonneratiaceae	1	1
Sterculiaceae	1	1
Tiliaceae	1	1

names only) is produced from this database which is given in the Appendix.

From the data available, Turkey has the most halophytes (±600 taxa), followed by Pakistan (± 361 taxa), (Iran ± 350 taxa), Afghanistan, Saudi Arabia, Oman and Yemen (±120 taxa). Halophytes in SW Asia constitute about half the number of halophyte taxa (and families) recorded for the world by [27].

In general, saline and arid environments are poor in species. Of the total 415 plant families [28] halophytes of SW Asia are recorded in 68 families (117 families worldwide as recorded [27]). The majority of halophytes belong to the families Chenopodiaceae, Poaceae, Leguminosae: Papiliondeae, Asteraceae and Cyperaceae. Chenopodiaceae has the largest number of species and genera of all families only exceeded by Poaceae which has more genera (but fewer species) than Chenopodiaceae (Table 1). These data are in accordance with that found for halophytes of the world [1] (Table 2).

The SW Asian flora mainly falls within the Saharo-Sindian and Irano-Turanian floristic

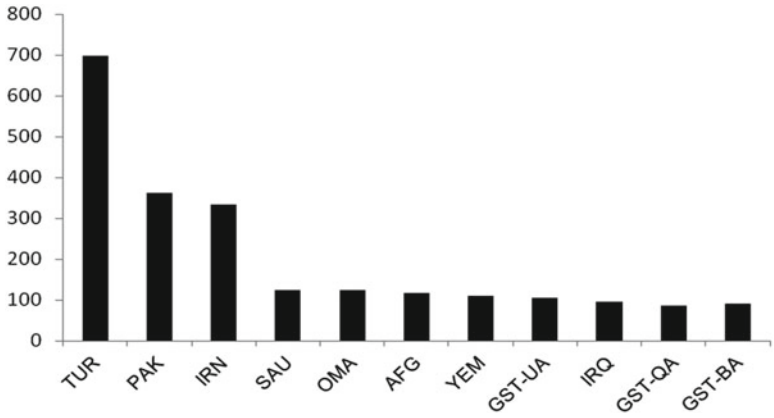

Fig. 3 Number of halophytic species in countries of SW Asia. *TUR* Turkey, *PAK* Pakistan, *IRN* Iran, *SAU* Saudi Arabia, *OMA* Oman, *AFG* Afghanistan, *YEM* Yemen, *GST-UA* United Arab Emirates, *IRQ* Iraq, *GST-QA* Qatar, *GST-BA* Bahrain (Data from published sources – see references)

Table 2 Families of flowering plants in which halophytic genera worldwide occur most frequently

Family	Percentage of halophytic genera
Chenopodiaceae	44
Aizoaceae	15
Cyperaceae	14
Caryophyllaceae	11
Poaceae	7
Arecaceae	6
Asteraceae	3
Fabaceae	3

Adapted from [1]

regions [29, 30], to which the majority of the halophytic communities belong.

Biogeographically, the Irano-Turanian region, including the area around Persian Gulf and western Pakistan (Makran and Baluchistan) can be considered as a centre of diversity of many halophytic genera of Chenopodiaceae such as *Bienertia*, *Caroxylon*, *Climacoptera*, *Gamanthus*, *Halanthium*, *Halimocnemis*, *Halostachys*, *Kalidium*, *Piptoptera*, *Petrosimonia*, *Salsola* and *Suaeda*. Except the cosmopolitan genus *Suaeda* s.lat. and Eurasian and African genus *Salsola* s.lat., all other genera are exclusively Irano-Turanian endemics [15, 31]. The largest diversity both in quantity and sections in the *Salsola* can be seen in SW and Central Asia. The genus *Tamarix*, as a second important halophytic genus in SW Asia is similar in its diversity to *Salsola* such that most are found in the Irano-Turanian region and a few species in the Mediterranean area, North and South Africa [32]. *Halocnemum strobilaceum* is the most salt tolerant and common halophyte in northern Iran, Afghanistan and Central Asia, but less common in southern Iran and the Arabian Peninsula.

2.1 Turkey

In Turkey there are about 300 species that are true halophytes with Chenopodiaceae, Asteraceae and Fabaceae at the top of the list [7]. There are coastal and inland halophytic habitats in Turkey, coastal halophytic habitats are mainly distributed in Mediterranean and Aegean Sea coasts, and there are also a few in Black Sea and Marmara Sea coasts. The most common coastal halophytic species in Turkey are *Cakile maritima, Salicornia emerici, Sarcocornia perennis, Sarcocornia obclavata, Arthrocnemum macrostachyum* and *Atriplex portulacoides*. Inland halophytic habitats are mainly distributed in Central and Eastern Anatolia. Species composition of Eastern Anatolian salt marshes and salt stepes is quite similar to North western Iranian salt marshes and salt steppes. Central Anatolia is the richest region in terms of halophytic species as several salt and brackish water lakes are present there with Tuz Lake (Konya-Ankara-Aksaray), Seyfe Lake (Kırşehir) and Sultansazlığı (Kayseri) as some of the largest ones surrounded by salt marshes [9]. Tuz Lake is a special case as it also has the highest endemism of halophytes in Turkey. Detailed studies on the vegetation are given by [33–37]. Halophytic vegetation usually forms zones depending on the salinity of the soils. Aksoy and Hamzaoğlu [37] give the zonation of the halophytic vegetation of Central Anatolia. In the first zone where salt density is maximum (Tuz Lake, Seyfe Lake and Sultansazlığı), *Salicornia freitagii, S. perennas* and *Halocnemum strobilaceum* are dominant. The general cover in this zone ranges between 10 and 80 % and depends on the concentration of salt. The width of this zone also differs and depends on the topography of the area. It is narrower in areas where the slopes are steeper, but can continue for kilometers where the slopes are low. Because of its high and fluctuating salinity, this zone is poor in terms of species richness, with one to ten species occurring and no endemics. *Halocnemum strobilaceum*, one of the dominant species in this zone can also be found in the second zone where the salt concentration is less. Depending on the gradually decreasing salinity a second zone can be recognised with an increase in the number of species. Where a water source is not present, succulents and hemicryptophyts are dominant and the species richness ranges between 65 and 80 species, and endemism between 16 and 21 %. The most common species in this zone are *Limonium iconicum*, *Frankenia hirsuta*, *Lepidium cartilagineum*, *Atriplex verrucifera*, *Caroxylon stenopterum* (*Salsola stenoptera*), *Puccinellia convoluta* and *Halocnemum strobilaceum. Limonium iconicum*, *Lepidium cartilagineum* and *Caroxylon stenopterum* are endemic to the salt marshes of Central Anatolia.

Where a water source feeding the marsh is present, tall herbaceous hemicryptophyts are dominant. Amongst these, *Elymus elongatus*, *Puccinellia koeieana* subsp. *anatolica*, *Inula aucherana*, *Juncus maritimus*, *Juncus heldreichianus* subsp. *orientalis* and *Puccinellia convoluta* are dominant. The number of species ranges between 45 and 60 and endemism between 26 and 32 %. Generally speaking families Chenopodiaceae and Plumbaginaceae are dominant where the salt marshes are not fed by a water source, while *Poaceae* and Juncaceae are dominant where water is available and feeds the salt marshes [35, 38, 39].

The outermost zone of the salt marshes of Central Anatolia is characterized by *Artemisia santonicum*. This zone, called the "salty steppe", borders with the non-halophytic communities. Succulent species are mostly absent; *Artemisia santonicum* is dominant sometimes with a cover of 70 %. Other common species of this zone are *Peganum harmala*, *Alhagi pseudalhagi*, *Achillea santolinoides* subsp. *wilhelmsii*, *Noaea mucronata* subsp. *mucronata* and *Apera intermedia*. The number of species ranges between 70 and 95 and endemism is between 17 and 23 %.

2.2 The Arabian Peninsula

About 140 taxa are recorded as halophytes in the Arabian Peninsula. This constitutes about 4 % of the total flora of the Arabian Peninsula (± 3500 taxa). Not surprisingly the majority of halophytes belong to the families Chenopodiaceae, Poaceae, Zygophyllaceae, Fabaceae and Plumbaginaceae. Table 3 shows the distribution of halophytic taxa and their families in the Arabian Peninsula [16, 17, 19, 40–50].

Key species in saline habitats of Arabia are nearly always perennial. The predominant life-forms are succulent, semi-woody dwarf shrubs belonging to the families Chenopodiaceae, Zygophyllaceae and Plumbaginaceae, and hemicryptophytes with runners and spiny leaves belonging to the families Poaceae and Juncaceae. Annual succulents such as *Bienertia cycloptera* and *Tetraena simplex* are exceptions. Coastal species are either obligate halophytes like the representatives of the families Chenopodiaceae, Frankeniaceae and Plumbaginaceae, or salt tolerant genera from unspecialized families, such as *Sporobolus* and

Table 3 Number of halophytic taxa in plant families in the Arabian Peninsula [18]

Family	No. halophytic species	Family	No. halophytic species
Acanthaceae	1	Juncaceae	2
Aizoaceae	4	Liliaceae	1
Apocynaceae	2	Mimosaceae	2
Arecaceae	1	Najadaceae	1
Asteraceae	2	Orobanchaceae	1
Boraginaceae	2	Plumbaginaceae	6
Chenopodiaceae	41	Poaceae	17
Caryophyllacae	8	Portulacaceae	1
Ceratophyllaceae	1	Potamogetonaceae	1
Convolvulaceae	2	Rhizophoraceae	2
Cymodoceaceae	3	Ruppiaceae	1
Cynomoriaceae	1	Salvadoraceae	1
Cyperaceae	4	Tamaricaceae	3
Fabaceae	5	Typhaceae	1
Frankeniaceae	1	Zygophyllaceae	11
Hydrocharitaceae	2		

Aeluropus (Poaceae), or salt secreting species such as *Avicennia* (Acanthaceae) and *Limonium* (Plumbaginaceae). The most common coastal and salt tolerant species are *Arthrocnemum macrostachyum, Halocnemum strobilaceum, Halopeplis perfoliata, Salsola* spp., *Suaeda* spp., (Chenopodiaceae); *Aeluropus lagopoides, Odyssea mucronata, Sporobolus spicatus, S. consimilis* (Poaceae); *Juncus rigidus* (Juncaceae), *Tetraena* spp. (Zygophyllaceae); *Limonium* spp. (Plumbaginaceae) and *Avicennia marina* (Acanthaceae) [18, 50].

The submerged coastal vegetation of the Arabian Peninsula especially that of the Gulf, has been particularly well studied owing to the rapid coastal development. The submerged seagrass beds are one of the most important vegetation types and highly productive ecosystems of great importance to the marine fauna especially the marine turtles, shrimps and numerous species of fish. Sheppard et al. [51] report four species of seagrasses from the Gulf, *Halodule uninervis*, *H. wrightii*, *Halophila stipulacea*, *H. ovalis* and *Syringodium isoetifolium. Ruppia maritima* is also reported in several coastal lagoons [52]. *Halodule uninervis*, *Halophila stipulacea*, *H. ovalis* are most widespread and the most common.

2.3 Iran

The halophytic and salt tolerant flora of Iran is very diverse compared to other countries of SW Asia. About 365 species in 51 genera and 44 families of vascular plants are recorded as true halophytes [15]. Akhani [15] lists 12 halophytic plant communities for Iran: (1) Mangrove communities (Avicennio Sonneratietea); (2) Submerged aquatic plant communities (Ruppietea maritimae); (3) Annual obligatory hygro-halophytic communities on sea, lake and river marshes dominated by stem or leaf succulent C3 chenopods (Thero-Salicornietea); (4) Semi-woody or perennial halophytic communities on muddy or coastal salt flats dominated by stem succulent C3 chenopods (Salicornietea fruticosae); (5) Hydrophilous euryhalophytic rush communities, Phragmitetea australis; (6) Halophytic grassland and herbaceous perennial sedge communities belonging to genera *Puccinellia* and *Juncus* (Juncetea maritimi); (7) Salt marsh and riverine brushwood communities dominated by salt-excreting halophytes (Tamaricetea ramosissimae, prov.); (8): Annual halophytic communities dominated by C4 chenopods in temporary moist and inundated, or disturbed salty soils (Climacopteretea crassae, prov.); (9) Halophytic shrubby, semi-woody or hemicrytophytic communities on salty and dry soils dominated by leaf or stem succulent C4 chenopods (Haloxylo-Salsoletea tomentosae, prov.); (10) Halophytic shrub communities on salty and sandy coastal or margin of sabkhas with high water table dominated by *Nitraria schoberi* and *Reaumuria fruticosa*; (11) Psamohalophytic shrub communities along sandy coasts of Persian Gulf and Oman sea (Sphaerocomion aucheri and communities of *Tetraena qatarense* and *Heliotropium bacciferum* s.lat.; (12) Unclassified halophytic communities of herbaceous perennial and hemicryptophyte halophytic communities of secondary origin.

Four distribution patterns are distinguished amongst the halophytes in the Irano-Turanian floristic region of Iran [15]: (1) The Aralo-Caspian/Central Iranian species which contains the highest number of taxa. Examples of this group are *Suaeda arcuata, Suaeda linifolia, Nitraria schoberi, Climacoptera turcomanica, Halimocnemis pilifera, H. mollissima, H. longifolia, Bassia eriantha, Gamanthus gamocarpus, Bienertia cycloptera, Petrosimonia glaucescens, Halothamnus subaphyllus, Haloxylon ammodendron, Xylosalsola arbuscula, S. arbusculiformis, Caroxylon incanescens*; (2) The Central Iranian endemics such as *Caroxylon abarghuensis, Anabasis haussknechtii, A. calcarea, Hypocylix kerneri* (*Salsola kerneri*), *Salicornia persica, Hypericopsis persica, Limonium perfoliatum* and *Halimocnemis occulta* (3) Endemic species in Azerbaijan or linking species between Iran, Turkey, Armenia and Azerbaijan. Examples are *Gamanthus pilosus, Kali tamamschjanae* (*Salsola tamamschjanae*), *Salsola ericoides, Salsola dendroides, Caroxylon persicum* (*Salsola persica*), *Suaeda dendroides* and *Suaeda gracilis*. The discovery of two extremely endangered disjunct species *Asparagus lycaonicus* and *Microcnemum corralloides* in West Iran and Central Anatolia are interesting phytogeographical links between these areas [53, 54]; (4) The fourth group are those species distributed around and along the Persian Gulf area and further East into Balochistan of Pakistan. Examples are *Bienertia sinuspersici*, *Salsola drummondii* [26], *Kali griffithii* (*Salsola griffithii*), *Suaeda fruticosa, Halothamnus iranicus, Halanthium purpureum, Salicornia* sp., *Suaeda* sp., *Tamarix kermanensis*, *Limonium stocksii, Indigofera stricta* and *Tetraena qatarense*. In southern Iran there are some Saharo-Arabian, Somalia-Masai and tropical species such as *Avicennia marina, Suaeda monoica, Juncus socotranus* or Saharan-Arabian/Mediterranean species such as *Arthrocnemum macrostachyum.*

2.4 Afghanistan

The saline vegetation of Afghanistan is comparable to that of Iran. The large arid and saline regions of Afghanistan (Seistan, Dasht-e-Margo and Registan) lie in the southwest and southeast of the country and the vegetation falls under the influence of the Irano-Turanian floristic elements that overlaps with that of Iran and to some extent that of northern Pakistan. Amongst the halophytic communities, *Halocnemum strobilaceum* with *Salsola rosmarinus* (*Seidlitzia rosmarinus*) is dominant in most of the saline areas. *Halocnemum strobilaceum* is the most abundant halophyte in northern Iran, Afghanistan and Central Asia. Other species include those of *Haloxylon*, *Anabasis*, *Aeluropus lagopoides*, *Atriplex*, *Limonium*, *Lycium*, *Fortuynia*, *Alhagi*, *Salsola* and *Tetraena* spp. (*Zygophyllum*) [55, 56].

2.5 Iraq

The halophytic vegetation in Iraq is present in the large desert areas of southwest Iraq. As for most arid regions, the flora of Iraq is poor in species, with the majority of the perennial plants in saline areas belonging to the family Chenopodiaceae [57].

The following account is adapted from [57] and [58]. The most characteristic plant communities with halophytic flora are: (1) *Haloxyletum ammodendri*. The main component of this association is *Haloxylon ammodendron* (= *H. aphylla*), which is found only in the sandy desert with unstabilized sand dunes, also prevalent in southern Palestine and northern Arabia. In Iraq this community stretches along the Euphrates sand-belt. It is evident that this community was once much more widespread and closed than it is perhaps in recent times due to degradation from fuel gatherers who use it for making charcoal. The dominant species is *Haloxylon ammodendron*, common associates are *Panicum turgidum* and *Calligonum comosum*; other members of this community include species such as *Haloxylon salicornicum*, *Salsola* spp., *Aristida plumosa*, *Salsola rosmarinus*, *Moltkiopsis ciliata*, *Neurada procumbens*, *Plantago* spp., *Cyperus conglomeratus*, *Silene villosa*, *Anisosciadium lanatum*, *Eremobium aegyptiacum*, *Cutandia memphitica*, *Bassia muricata* and *Astragalus gyzensis. Cistanche* is parasitic on the saline shrubs especially *Haloxylon*; (2) *Haloxyletum salicornici*. This is the most characteristic and important community of the desert region of Iraq and is widespread throughout the deserts of the Arabian Peninsula [44, 59]. This community is found on calcareous substrate with a gypsophilous underlying substrate. The dominant species of this community is *Haloxylon salicornicum* which usually grows in small mounds made from aeolian sand. Major associates of *Haloxylon salicornicum* are *Salsola setifera* (*Anabasis setifera*), *Caroxylon jordanicola* (*Salsola jordanicola*), *Salsola rosmarinus*, *Cornulaca aucheri*, *Cymbopogon olivieri*, *Aristida plumosa*, and *Annothamnus gibbous. Salsola rosmarinus* is found on higher ground at the edges of saline mud flats as opposed to the halophyte *Halopeplis perfoliata* found in the sabkhas of the Sultanate of Oman [60]. Other associates are *Heliotropium ramosissimum* s.lat., *Farsetia aegytiaca*, *Plantago ciliata*, *Teucrium oliverianum* and *Neurada procumbens*; (3) *Zygophylletum coccinei*. This community is usually found on sandy soil overlying saline flats. The shrub, *Tetraena coccinea* (*Zygophyllum coccineum*) grows on small hummocks made from wind-blown sand. In Iraq often found in the southern desert, this species often occurs near the sea in Kuwait and southern Arabia; (4) *Seidlitzietum rosmarini*. This is another halophytic or semi-halophytic community often found on fringes of saline or brackish water pools. Other *Salsola* species are often associated with *Salsola rosmarinus* in this community; (5) *Halocnemum strobilacei*. This is the most characteristic community of sabkha areas and is prevalent on the saline mud-flats in south western Iraq. *Halocnemum strobilaceum* is the dominant species, with occasional associates of *Aeluropus lagopoides* and *Cressa cretica*; (6) *Bienertietum cyclopterae*. This community consisting of a single species, *Bienertia cycloptera*, is found on margins of small saline depressions in sandy areas. Associated with it in some areas, such as at the margins of Bahr al Milh in the western desert, are *Frankenia pulverulenta* and *Aleuropus lagopoides*. In addition to these communities, scattered plants of *Tamarix passerinoides*, and *Peganum harmala* are often found in saline habitats. In particular *Peganum harmala* is present often on disturbed and waste ground where there is a high level of soil nitrates. *Ziziphus nummularia* is a constant species of sandy depressions.

2.6 Pakistan

The halophytic flora of Pakistan has been summarised by [6]. They list the distribution, life form and potential economic uses of about 410 taxa. As with most halophytes, the family Chenopodiaceae has the highest number of species (90 spp.) followed by Poaceae (68 spp.), Cyperaceae (30 spp.), Fabaceae (29 spp.), Asteraceae (24 spp.) and Tamaricaceae (23 spp.). Most of the halophytes are found in the Balochistan plains and Sind (especially coastal); fewer halophytes are found in the mountains, Potwar plateau and the deserts of Punjab [6]. Balochistan is the most species rich in halophytic diversity. There are several brackish lakes in the Salt Range in the Punjab (Kalar Kahar in Chakwal District, Khabikki Lake in Soan Sakesar valley) and Hadero Lake in Sind (which is also a wildlife bird sanctuary) that show a range of halophytes.

The most distinctive halophytic flora is found in the mangroves of the coastal tidal zone in Sind and Balochistan with *Avicennia*, *Sonneratia*, *Rhizophora*, *Ceriops*, *Aegicerus* and *Scaveola*. The inland, saline desert areas and plains of Balochistan are poor in species and are dominated by *Tamarix*, with *Haloxylon*, *Atriplex*, *Salsola*, and other halophytes as associates.

3 Economic Uses

Halophytes have their greatest potential in their utilization in restoration of degraded saline locations, coastal stabilization, production of cheap biomass for renewable energy, cash crops for fodder, medicine, building materials and other utilitarian objects and for sequestering CO_2.

The use of halophytes as fodder, food plants, medicinals and fuel wood has been documented extensively for most regions of SW Asia [6, 61–63]. Ghazanfar in her works on the medicinal plants of the Arabian Peninsula [64] and The Middle East [60] lists uses of several halophytes. Species such as *Portulaca oleracea*, *Aerva javanica*, *Vernonia cinerea* and *Heliotropium* have been used traditionally in the treatment of skin disorders, burns, stings and insect bites; *Apium graveolens* and *Centella asiatica* have been used as diuretics; *Artemesia* as an antihelmintic, *Teucrium* spp. for abdominal pain and colic, and *Salvadora persica* as tooth cleaner. The multiple uses of *Cocos nucifera* and *Phoenix dactylifera* have been known since ancient times, as have the uses of species of *Typha* and *Phragmites* for making thatching, mats and boats.

The use of halophytes is also studied as potential biomass crops to directly sequester up to 0.7 Gt C, similar to tree plantations [66]. Halophytes can play a role in absorbing C from the atmosphere while providing food, fodder and energy crops on previously unused saline land. Thus, through halophyte plantations, unused saline land can be restored and become productive.

Appendix: A Preliminary List of the Halophytes of SW Asia

Several names in the Che nopodiaceae are still unresolved. Only critical synonyms are provided.

AIZOACEAE

Aizoon canariense L.
Mesembryanthemum crystillinum L.
Mesembryanthemum nodiflorum L.
Sesuvium verrucosum Raf.
Sesuvium sesuvioides (Fenzl) Verdc.
Sesuviumportulacastrum (L.) L.
Trianthema portulacastrum L.
Trianthema triquetra Rott. ex Willd.
Zaleya pentandara (L.) Jeffrey

ACANTHACEAE

Avicennia marina (Forssk.) Vierh.
Syn.: *Sceura marina* Forssk**.** (formerly in Avicenniaceae)

AMARANTHACEAE s.str.

Aerva javanica (Brum.f.) Juss. ex J.A. Schultes
Amaranthus retroflexus L.

APIACEAE

Ammi visnaga (L.) Lam.
Apium graveolens L.
Apium nodiflorum (L.) Lag.
Bupleurum euboeum Beauverd
Syn.: *Bupleurum gracile* auct. mult. non (M.Bieb.) DC. non *Odontites gracilis* Bie;
Bupleurum heldreichii Boiss. & Bal.
Bupleurum semicompotisum L.
Syn.: *Bupleurum glaucum* Ledeb.
Bupleurum tenuissimum L.
Bupleurum turcicum Snogerup
Centella asiatica (L.) Urban
Echinophora orientalis Hedge & Lamond
Syn.: *Echinophora trichophylla* J.E. Smith
Falcaria falcarioides (Bornm. & Wolff) Wolff
Syn.: *Pimpinella falcarioides* Bornm. & Wolff
Ferula caspica M. Bieb.
Syn.: *Ferula aciphylla* M. Bieb. ex Ledeb.; *Ferula orientalis* Eichw.; *Peucedanum caspicum* (M. Bieb.) Link
Ferula halophila Pesmen

APOCYNACEAE (incl. Asclepiadaceae)

Calotropis procera (Ait.) Ait.
Cionura erecta (L.) Griseb.
Syn.: *Cionura erectum* (L.) Griseb.
Cynanchum acutum L. subsp. **acutum**
Syn.: *Cynanchum monspeliacum* L.
Glossonema varians (Stocks.) Hook. f.
Leptadenia pyrotechnica (Forssk.) Decne.
Oxystelma esculentum (Linn. f.) R. Brown
Pentatropis nivalis (J.F. Gmel.) D.V. Field & J.R.I. Wood
Pergularia daemia (Forssk.) Chiov.
Pergularia tomentosa L.

ARECACEAE

Cocos nucifera L.
Phoenix caespitosa Chiov.
Syn.: *Phoenix comorensis* Becc.
Phoenix dactylifera L.
Phoenix reclinata Jacq.

ASTERACEAE

Achillea millefolium L. subsp. **millefolium**
Achillea santolinoides subsp. **wilhelmsii** (K. Koch) Greuter
Syn.: *Achillea wilhelmsii* K. Koch
Achillea schischkinii Sosn.
Syn.: *Achillea muschensis* Bornm.
Achillea sieheana Stapf
Syn.: *Achillea salsuginea* Bornm.
Anthemis halophila Boiss. & Bal.
Syn.: *Anthemis alexandrettae* Eig
Artemisia campestris L.
Artemisia herba-alba Asso
Syn.: *Artemisia arragonensis* Lam.; *Artemisia herba-alba* Asso var. *tenuifolia* Boiss.
Artemisia santonicum L.
Syn.: *Artemisia maritima* (Waldst. & Kit) Gams subsp. *monogyna*; *Artemisia monogyna* Waldst. & Kit.
Artemisia scoparia Waldst. & Kit.
Aster tripolium L.
Syn.: *Tripolium vulgare* Nees
Bellis annua L.
Bellis perennis L.
Syn.: *Bellis armena* Boiss.
Bellis sylvestris Cyr.
Bidens cernua L.
Centaurea balsamita Lam.
Centaurea halophila Hub.-Mor.
Centaurea tuzgoluensis Aytaç & Duman
Centaurea virgata Lam.
Cirsium alatum (Gmelin) Bobrov subsp. **alatum**
Syn.: Serratula alata Gmelin
Cousinia birandiana Hub.-Mor.
Cousinia humilis Boiss.
Syn.: *Arctium humile* (Boiss.) O. Kuntze
Crepis foetida L. subsp. **rhoeadifoli** (M. Bieb.) Celak.
Syn.: Crepis foetida L. var. *rhoeadifoli* Boiss.; *Crepis nemetzii* Rech.f.; *Crepis nestmeiri* Herro. & Degen; *Crepis rhoeadifoli* M. Bieb.
Crepis sancta (L.) Babcock
Syn.: *Crepinia marschalliana* Reichb.; *Crepis kochiana* Boiss.; *Crepis sancta* subsp. *bifida* (Vis.) Babcock; *Crepis sancta* subsp. *nemausensis* (Gouan) Babcock; *Crepis sancta* subsp. *obovata* (Boiss. & Noe) Babcock; *Hieracium sanctum* L.; *Lagoseris orientalis* Boiss.
Cymbolaena griffithii (A. Gray) Wagenitz
Handelia tricophylla (Schrenk.) Heimerl
Inula aucherana DC.
Syn.: *Inula armena* Bordz.; *Inula seidlitzii* Boiss.
Inula britannica L.
Inula crithmoides L.
Inula graveolens (L.) Desf.
Syn.: *Dittrichia graveolens* (L.) Greuter; *Erigeron graveolens* L.
Iphiona aucherii (Boiss.) Anderb.
Launaea procumbens (Roxb.) Ramayya & Rajagopal
Microcephala lamellate (Bunge) Pobed.
Mulgedium tataricum (L.) DC.
Pluchea arguta Boiss.
Pluchea dioscoridis (L.) DC.
Syn.: *Conyza dioscoridis* Desf.
Pseudognaphalium luteoalbum (L.) O.M. Hilliard & B.L. Burtt
Pulicaria boissieri Hook. f.
Pulicaria carnosa (Boiss.) Burkill.
Pulicaria dysenterica (L.) Bernh.
Syn.: *Inula dysenterica* L.; *Pulicaria dysenterica* var. *microcephala* Boiss.; *Pulicaria uliginosa* Stev.
Pulicaria gnaphalodes (Vent.) Boiss.

Pulicaria hadramautica E. Gmal-Eldin & Boulos

Pulicaria undulata (L.) C.A. Meyer

Senecio doriiformis DC. subsp. **orientalis** (Fenzl) Matthews

Syn.: *Senecio doriaeformis* DC. var. *megalophron*; *Senecio doriaeformis* DC. var. *orientais*; *Senecio nemorensis* L. var. *orientalis*

Senecio salsuginea H. Duman & Vural

Seriphidium quettense (Podlech) Ling

Sonchus asper (L.) Hill subsp. **asper**

Sonchus erzincanicus Matthews

Sonchus maritimus L.

Sonchus tenerrimus L.

Taraxacum bessarabicum (Hornem.) Hand.-Mazz. var. **bessarabicum**

Syn.: *Leontodon besarabicus* Hornem.; *Taraxacum fulvipile* Harv.; *Taraxacum leptocephalum* Rchb.; *Taraxacum stenocephalum* Boiss. & Kotschy ex Boiss.

Taraxacum farinosum Hausskn. & Bomm.

Taraxacum mirabile Wagenitz

Taraxacum tuzgoluensis Yildirimli & A. Dogrukoca var. **tuzgoluensis**

Taraxacum tuzgoluensis Yildirimli & A. Dogrukoca var. **eskilensis** Yildirimli & A. Dogrukoca

Tripleurospermum callosum (Fisch. & Mey.) Bornm.

Tripleurospermum decipiens (Boiss. & Heldr.) E. Hossain

Syn.: *Chamaemelum decipiens* (Fisch. & Mey.) Boiss.; *Pyrethrum decipiens* Fisch. & Mey.

Xanthium sibiricum Patrin. ex Widder

BORAGINACEAE

Caccinia macranthera (Banks & Sol.) Brafid var. **macranthera**

Syn.: *Borago macranthera* Banks & Sol.

Conringia persica Boiss.

Coronopus didymus (L.) Smith

Cynoglossum creticum Miller

Heliotropium aucheri DC.

Heliotropium bacciferum Forssk. s.lat.

Syn.: *Heliotropium undulatum* Vahl; *H. ramosissimum* (Lehm.) DC.; *H. kotschyi* Bunge nom. nud.; *H. Persicum* auct., Boiss.; *H. lignosum* Bornm.; *H. fartakense* O. Schwartz

Heliotropium curassavicum L.

Heliotropium dolosum De Not.

Syn.: *Heliotropium eichwaldii* Steud.; *Heliotropium macrocarpum* Guss.

Heliotropium lasiocarpum Fisch. & Mey.

Syn.: *Heliotropium eichwaldii* Steud. var. *lasiocarpum* (Fisch & Mey.) C. B. Clarke; *Heliotropium ellipticum* Ledeb. var. *lasiocarpum* (Fisch. & Mey.) M. Popov; *Heliotropium europaeum* L. var. *tenuiflorum* Boiss.; *Heliotropium tenuifolium* Bunge non Guss.

Heliotropium remotiflorum Rech.f. & Riedl

Moltkia coerulea (Willd.) Lehm.

Syn.: *Moltkia anatolica* Boiss.; *Moltkia punctata* Lehm.; *Onosma coeruleum* Willd.

Moltkiopsis ciliata (Forssk.) I.M. Johnst.

Onosma halophilum Boiss. & Heldr.

Tournefortia sibirica L. var. **sibirica**

Syn.: *Tournefortia sibirica* L.

BRASSICACEAE

Cakile maritima Scop.

Syn.: *Cakile euxina* Pobed. ex Grossheim

Dilophia salsa Thompson

Erysimum crassipes Fisch. & Mey.

Eutrema parvulum (Schrenk) Al-Shehbaz & Warwick

Iberis halophila Vural & H. Duman

Isatis kotschyana Boiss. & Hohen.

Lepidium latifolium L.

Lepidium cartilagineum (J. May) Thell.

Syn.: *Lepidium caespitosum* Desv.; *Lepidium cartilagineum* (J. May.) Thell. subsp. *caespitosum*; *Lepidium cartilagineum* (J. May.) Thell. subsp. *crassifolium* (Waldst. & Kit.) Thell.; *Lepidium crassifolium* Waldst. & Kit.; *Lepidium crenatifolium* Boiss. & Bal.; *Thlaspi cartilagineum* J. May.

Lobularia maritima (L.) Desv.

Raphanus raphanistrum L.

Sinapis arvensis L.

Sisymbrium loeselii L.

Syn.: *Sisymbrium glabratum* Schulz

CARYOPHYLLACEAE

Cerastium dubium (Bastard) Guepin

Syn.: *Cerastium anomalum* Waldst. & Kit.

Cerastium glomeratum Thuill.

Gypsophila oblanceolata Bark.

Gypsophila perfoliata L.

Syn.: *Gypsophila anatolica* Boiss. & Heldr.; *Gypsophila hygrophila* Post; *Gypsophila pauli* Klokov; *Gypsophila tekirae* Stef.; *Gypsophila trichotoma* Wenderoth

Minuartia urumiensis (Bornm.) Bornm.

Syn.: *Alsine urumiensis* Bornm.

Polycarpaea spicata Wight ex Arn. var. **spicata**

Polycarpaea spicata Wight ex Arn. var. **capillaris** Balf. f.

Saponaria halophila Hedge & Hub.-Mor

Saponaria karapinarensis Vural & N. Adygüzel

Silene nocturna L.

Silene salsuginea Hub.-Mor.

Spergularia diandra (Guss.) Heldr.

Syn.: *Arenaria diandra* L.; *Spergulariasalsuginea* Fenzl

Spergularia marina (L.) Gris.

Syn.: *Arenaria rubra* var. *campestris* L.; *Arenaria rubra* L. var. *marina*; *Spergula marina* (L.) Bartl. & H. L. Wendl.; *Spergularia campestris* (L.) Aschers.; *Spergularia salina* J.& C. Presl

Spergularia media (L.) C. Presl

Syn.: *Arenaria media* L.; *Spergularia marginata* (DC.) Kitt.

Spergularia rubra (L.) J. & C. Presl

Sphaerocoma aucheri Boiss.

CHENOPODIACEAE

Anabasis aphylla L.

Syn.: *Anabasis aphylla* Iljin subsp. *australis*; *Anabasis aphylla* Iljin subsp. *rubra*; *Anabasis tatarica* Pall.

Anabasis calcarea (Charif & Aellen) Bokhari & Wendelbo

Anabasis ehrenbergii Schwinf. ex Boiss.

Anabasis eugeniae Iljin

Anabasis haussknechtii Bunge ex Boiss.

Anabasis iranica Iljin

Anabasis lachnantha Allen & Rech.f.

Anabasis salsa (C.A. Mey.) Benth.

Arthrocnemum macrostachyum (Moric.) K. Koch

Syn.: Arthrocnemum fruticosum (L.) var. macrostachyum (Moric.) Moq.;

Salicornia macrostachya Moric.; *Arthrocnemem glaucum* (Delile) Ung.-Sternb.

Atriplex aucheri Moq.

Syn.: *Atriplex amblyostegia* Turcz.; *Atriplex hortensis* L. subsp. *desertorum* (Sosn.) Aellen; *Atriplex nitens* Schkuhr subsp. *aucheri* (Moq.) Takht. & A.A. Fedor.; *Atriplex nitens* Schkuhr subsp. *desertorum* Iljin

Atriplex davisii Aellen

Atriplex dimorphostegia Kar. & Kir.

Atriplex farinosa Forssk. subsp. farinosa

Atriplex flabellum Bunge ex Boiss

Atriplex halimus L.

Atriplex hortensis L.

Atriplex laevis Ledeb.

Syn.: *Atriplex littorale* Boiss.

Atriplex lasiantha Boiss.

Atriplex lehmanniana Bunge

Atriplex leucoclada Boiss. var. **inamoena** (Allen) Zohary

Syn.: *Atriplex inamoena* Allen

Atriplex micrantha Ledeb.

Syn.: *Atriplex heterosperma* Bunge

Atriplex nogalensis Friis & M.G. Gilbert

Atriplex portulacoides L.

Syn.: *Halimione portulacoides* (L.) Aellen

Atriplex prostrata Boucher ex DC.

subsp. **calotheca** (Raf.) M.A. Gust.

Syn.: *Atriplex hastata* Forssk.

Atriplex sagitata Borkh.

Syn.: *Atriplex nitens* Schkuhr, nom illegit.

Atriplex schugnanica Iljin

Atriplex stocksii Boiss.

Syn.: *Atriplex griffithii* Moq. var. *stocksii* (Boiss.) Boiss.

Atriplex tatarica L

Atriplex tatarica L. var. **pamirica** (Iljin) G.L. Chu

Syn.: *Atriplex pamirica* Iljin

Atriplex verrucifera M. Bieb.

Syn.: *Halimione verrucifera* (M. Bieb.) Aellen

Bassia crassifolia (Pall.) Soldano

Syn.: *Salsola stenoptera* Wagenitz; *Suaeda crassifolia* Pall.

Bassia dasyphylla (Fisch. & C.A. Mey.) Kuntze

Bassia eriophora (Schrad.) Asch.

Syn.: *Kochia eriophora* Schrader; *Kochia latifolia* Fresen.; *Londesia eriantha* Fisch. & C.A. Mey.

Bassia hyssopifolia (Pall.) Kuntze

Bassia odontoptera (Schrenk) Freitag & G. Kadereit

Syn.: *Kochia odontoptera* Schrenck; *Kochia stellaris* Moq.; *Kochia iranica* Litv. ex Bornm.

Bassia muricata (L.) Asch.

Syn.: *Salsola muricata* L.; *Echinopsilon muricatus* (L.) Moq.; *Kochia muricata* (L.) Schrad.

Bassia pilosa (Fisch. & C.A. Mey.) Freitag & G. Kadereit

Syn.: *Panderia pilosa* Fisch. & C.A. Mey.

Bassia prostrata (L.) Beck

Syn.: *Kochia prostrata* (L.) Schrad.; *Salsola prostrata* L.

Bassia scoparia (L.) A.J. Scott

Syn.: *Kochia scoparia* (L.) Schrad.

Bassia sedifolia (Pall.) ined.

Syn.: *Bassia sedoides* Asch. nom. illegit.

Bassia tomentosa (Lowe) Maire & Weiller

Syn.: *Chenoleoides tomentosa* (Lowe) Botsch

Beta vulgaris L.

Syn.: *Beta maritima* L.

Bienertia cycloptera Bunge ex Boiss.

Bienertia sinuspersici Akhani

Camphorosma monspeliaca L.

Syn.: *Camphorosma ruthenica* M. Bieb.

Camphorosma monspeliaca L. subsp. **lessingii** (Litv.) Aellen

Syn.: *Camphorosma lessingii* Litw.

Caroxylon abarghuense (Assadi) Akhani & Roalson

Syn.: *Salsola abarghuense* Assadi

Caroxylon canescens (Moq.) Akhani

Syn**.:** *Noaea canescens* Moq.; *Salsola canescens* (Moq.) Boiss.

Caroxylon carpatha (P.H. Davis) Akhani

Syn.: *Salsola carpatha* P.H. Davis

Caroxylon chorassanicum (Botsch.) Akhani

Syn.: *Salsola chorassanica* Botsch.

Caroxylon cyclophyllum (Baker) Akhani

Syn.: *Salsola cyclophylla* **Baker**

Caroxylon dzhungaricum (Iljin) Akhani

Syn.: *Salsola dzhungarica* Iljin

Caroxylon imbricatum (Forsskal) Akhani

Syn.: *Salsola imbricata* **Forssk.**; *Salsola foetida* Del. ex Sprengel

Caroxylon incanescens (C.A. Mey.) Akhani

Syn.: *Salsola incanescens* C.A. Mey.; *Salsola ruthenica* Iljin

Caroxylon jordanicola (Eig) Akhani & Roalson

Syn.: *Salsola jordanicola* **Eig**

Caroxylon nitrarium (Pall.) Akhani & Roalson

Syn.: *Salsola nitraria* Pall.; *Salsola macera* Litv.

Caroxylon persicum (Bunge ex Boiss.) Akhani & Roalson

Syn.: Salsola persica Bunge ex Boiss.

Caroxylon stenopterum (Wagenitz) Akhani & Roalson

Syn.: *Salsola stenoptera* Wagenitz

Caroxylon tomentosum (Moq.) Tzvelev

Syn.: *Salsola tomentosa* (Moq.) Spach

Ceratocarpus arenarius L.

Syn.: *Ceratocarpus turkestanicus* Sav.-Rycz.

Chenopodium album L. subsp. **album** var. **album**

Syn.: *Chenopodium album* var. *microphyllum* Boenn.

Chenopodium album L. subsp. **iranicum** Aellen

Chenopodium album L. subsp. **album**

var. **microphyllum** (Boenn.) Aellen

Chenopodium chenopodioides (L.) Aellen

Syn.: *Blitum chenopodoides* L.; *Chenopodium botryoides* Sm.

Chenopodium ficifolium Sm.

Chenopodium foliosum Asch.

Syn.: *Blitum virgatum* L.; *Morocarpus foliosus* Moench

Chenopodium glaucum L.

Chenopodium murale L.

Chenopodium sosnowskyi Kapeller

Choriptera semhahensis (Vierh.) Botsch.

Syn.: Salsola semhahensis Vierh.

Climacoptera brachiata (Pall.) Botsch.

Climacoptera crassa (M. Bieb.) Botsch.

Climacoptera glaberrima Botsch.

Climacoptera iranica U.P. Pratov

Climacoptera iraqensis Botsch.

Climacoptera lanata (Pall.) Botsch.

Climacoptera longipistillata Botsch.

Climacoptera turcomanica (Litv.) Botsch.

Corispermum korovinii Iljin

Cornulaca aucheri Moq.

Syn.: *Cornulaca leucacantha* Charif & Aellen

Cornulaca ehrenbergii Asch.

Cornulaca monacantha Delile

Syn.: *Cornulaca arabica* Botsch.

Cyathobasis fruticulosa (Bunge) Aellen

Syn.: *Girgensohnia fruticulosa* Bunge

Dysphania ambrosioides (L.) Mosyakin & Clemants

Syn.: *Chenopodium ambrosioides* L.

Dysphania botrys (L.) Mosyakin & Clemants

Syn.: *Chenopodium botrys* L.

Girgensohnia imbricata Bunge

Girgensohnia minima Korovin

Girgensohnia oppositiflora (Pall.) Fenzl

Halimocnemis commixtus (Bunge) Akhani

Syn: *Gamanthus commixtus* Bunge

Halimocnemis gamocarpa Moq.

Syn.: *Gamanthus gamocarpus* (Moq.) Bunge

Halimocnemis longifolia Bunge

Halimocnemis occulta (Bunge) Hedge

Syn.: *Halotis occulta* Bunge

Halimocnemis pilifera Moq.

Syn.: *Halotis pilifera* Botsch

Halimocnemis pilosa Moq.

Syn.: *Gamanthus pilosus* (Pall.) Bunge; *Halimocnemis pilosa* (Pall.) Akhani (later homonym)

Halimocnemis purpurea Moq.

Syn.: *Halanthium purpureum* Bunge

Halimocnemis pycnantha K. Koch

Syn.: *Halocharis kulpianum* K. Koch; *Halanthium kulpianum* (K. Koch) Bunge

Halimocnemis rarifolia (K. Koch.) Akhani

Syn.: *Halanthium rarifolium* K. Koch; *Halanthium roseum* Iljin

Halocharis hispida (Schrenk ex C.A. Mey.) Bunge

Halocharis sulphurea (Moq.) Moq.

Halocnemum strobilaceum (Pallas) M. Bieb

Syn.: Salicornia strobilacea Pallas

Halocnemum yurdakulolii Yaprak

Halogeton alopecuroides (Del.) Moq.

Syn.: *Agathophora alopecuroides* (Del.) Fenzl ex Bunge var. *alopecuroides*; *Agathophora algeriensis* Botsch.; *Agathophora alopecuroides* (Eig) Botsch.; *Agathophora galalensis* Botsch.; *Agathophora iraqensis* Botsch.

Halogeton glomeratus (M. Bieb.) Ledeb.

Syn.: *Anabasis glomerata* M. Bieb.

Halogeton glomeratus (M. Bieb.) Ledeb. var. **tibeticus** (Bunge) Grubov

Halopeplis nodulosa (Del.) Bunge ex Ung.-Sternb.

Syn.: *Halopeplis amplexicaulis* (Vahl.) Bunge ex Ung.-Sternb.; *Salicornia amplexicaulis* Vahl.

Halopeplis perfoliata (Forssk.) Bunge ex Schweinf.

Syn.: Salicornia perfoliata Forssk.

Halopeplis pygmaea (Pall.) Bunge ex Ung.-Sternb.

Halosarcia indica (Willd.) Paul G. Wilson

Halostachys caspica (M. Bieb.) C.A. Mey. ex Schrenk.

Syn.: *Arthrocnemum belangerianum* Moq.; *Halostachys belangeriana* (Moq.) Botsch *Halostachys caspica* (Moq.) Moq. var. *belangeriana*; *Salicornia caspica* Pall.

Halothamnus auriculus (C.A. Mey.) Botch. subsp. **acutifolius** (Moq.) Kothe-Heinr.

Halothamnus glaucus (M. Bieb.) Botsch.

Syn.: *Caroxylon glaucum* (M. Bieb.) Moq.; *Salsola brachyphylla* Boiss. & Hausskn.; *Salsola glauca* M. Bieb.

Halothamnus iranicus Botsch.

Halothamnus subaphyllus (C.A. Mey.) Botsch.

Haloxylon ammodendron (C.A. Mey.) Bunge ex Fenzl

Syn.: *Haloxylon aphyllum* (Minkw.) IIjin

Haloxylon griffithii (Moq.) Boiss. subsp. **griffithii**

Syn.: *Hammada griffithii* (Moq.) Iljin

Haloxylon griffithii (Moq.) Boiss. subsp. **wakhanicum** (Paulsen) Hedge

Haloxylon persicum Bunge ex Boiss. & Buhse

Haloxylon salicornicum (Moq.) Bunge ex Boiss.

Syn.: Caroxylon salicornicum Moq.; *Hammada salicornica* (Moq.) Iljin;

Haloxylon stocksii (Boiss.) Benth. & Hook. f.

Syn.: *Haloxylon recurvum* (Wall.) Bunge ex Boiss.

Hammada scoparia (Pomel) Iljin.

Horaninovia ulicina Fisch. & C.A. Mey.

Kali australis (R.Br.) Akhani & Roalson

Syn*.: Salsola kali* L.; *Salsola australis* R.Br.

Kali griffithi (Bunge) Akhani & Roalson

Syn.: *Noaea griffithii* Bunge; *Salsola griffithii* (Bunge) Freitag & Akhani

Kali paulsenii (Litv.) Akhani

Syn.: *Salsola paulsenii* Litv.

Kali tamamschjanae (Iljin) Akhani & Roalson

Syn: *Salsola tamamschjanae* Iljin

Kali tragus (L.) Scop.

Syn: *Salsola tragus* L.

Kalidium caspicum (L.) Ung.-Sternb.
Syn.: *Salicornia caspia* L.
Kalidium wagenitzii (Aellen) Freitag & G. Kadereit
Syn.: *Kalidiopsis wagenitzii* Aellen
Kaviria rubescens (Franch.) Akhani
Syn.: *Salsola rubescens* Franch.; *Salsola hadramautica* Baker; *Salsola leucophylla* Baker.
Kirilowia eriantha Bunge
Krascheninnikovia ceratoides (L.) Guldenst.
Lagenantha cycloptera (Stapf) M.G. Gilbert & Friis
Syn.: *Salsola cycloptera* Stapf; *Gyroptera cycloptera* (Stapf) Botsch.
Maireana coronata (J.M. Black) Paul G. Wilson
Micronemum fastigiatum Ung.-Sternb.
Microcnemum coralloides (Loscos & Pardo) Font-Quer subsp. **anatolicum** Wagenitz
Syn.: *Micronemum fastigiatum* Ung.-Sternb.; *Arthrocnemum corraloides* (Loscos & Pardo) Font-Quer
Nanophyton erinaceum (Pall.) Bunge
Noaea minuta Boiss. & Balansa
Noaea mucronata (Forssk.) Asch. & Schweinf.
Syn.: *Noaea spinosissima* (L. F.) Moq.; *Salsola mucronata* Forssk.
Petrosimonia brachiata (Pall.) Bunge
Syn.: *Polycnemum brachiatum* Pall
Petrosimonia glaucescens (Bunge) Iljin
Syn.: *Polycnemum glaucum* Pall.
Petrosimonia nigdeensis Aellen
Petrosimonia squarrosa (Schrenk) Bunge
Syn.: *Halocnemis squarrosa* Schrenk
Pyankovia brachiata (Pall.) Akhani & Roalson
Syn.: *Salsola brachiata* Pall.
Salicornia bigelovii Torr.
Salicornia dolichostachya Moss
Syn.: *Salicornia stricta* D. König
Salicornia emerici Duval-Jouve
Salicornia iranica Akhani
Salicornia persica Akhani
Salicornia persica subsp. **rudshurensis** Akhani
Salicornia perspolitana Akhani
Salicornia perennas Wild.
Syn.: *Salicornia prostrata* Pall.
Salicornia sinus-persica Akhani
Salicornia ramosissima J. Woods
Salicornia × **tashkensis** Akhani
Salsola arbusculiformis Drobov.
Salsola anatolica Aellen
Salsola baryosma (Schult.) Dandy
Syn.: *Chenopodium baryosmon* Roemer & Schultes
Salsola crassa M. Bieb.
Salsola cyrenaica (Maire & Weiller) Brullo subsp. **antalyensis** Freitag & H. Duman
Salsola dendroides Pall.
Syn.: *Salsola verrucosa* M. Bieb.
Salsola drummondii Ulbr.
Syn.: *Salsola obpyrifolia* Botsch & Akhani
Salsola ericoides M. Bieb
Salsola grandis Freitag, Vural & N. Adigüzel
Salsola foliosa (L.) Schrad. ex Schult.
Salsola kerneri (Wol.) Botsch.
Syn.: *Hypocylix kerneri* Wol.
Salsola laricina Pall.
Salsola leptoclada Gand.
Salsola makranica Freitag
Salsola montana Litv.
Syn.: *Salsola masenderanica* Botsch.
Salsola nodulosa (Moq.) Iljin
Syn.: *Caroxylon nodulosum* Moq.
Salsola orientalis S.G. Gmel.
Salsola praecox (Litv.) Iljin
Salsola rosmarinus (Ehrenb. ex Boiss.) Akhani
Syn: *Seidlitzia rosmarinus* Ehrenb. ex Boiss.
Salsola richteri (Moq.) Karel. ex Litv.
Salsola schweinfurthii Solms-Laub.
Syn.: *Darniella schweinfurthii* (Solms-Laub.) Brullo;
Salsola sclerantha C.A. Mey
Salsola setifera (Moq.) Akhani
Syn.: *Anabasis setifera* Moq.
Salsola soda L.
Salsola turcica Yild.
Salsola turcomanica Litv.
Syn.: *Salsola crassa* subsp. *turcomanica* (Litv.) Freitag
Salsola vermiculata L.
Salsola zygophylla Batt. & Trab.
Salsola zygophylloides (Aellen & Townsend) Akhani
Syn.: *Fadenia zygophylloides* Aellen & Townsend
Sarcocornia fruticosa (L.) A.J. Scott
Syn.: *Arthrocnemum fruticosum* (L.) Moq.; *Salicornia europaea* L. var. *fruticosa*;

Salicornia fruticosa (L.) L.; *Salicornia patula* Duval-Jouve
Sarcocornia perennis (Mill.) A.J. Scott
Syn.: *Arthrocnemum perenne* (Mill.) Moss ex Fourcade; *Salicornia perennis* Mill.; *Salicornia radicans* Sm.
Sarcocornia obclavata Yaprak
Seidlitzia florida (M. Bieb.) Bunge
Syn.: *Anabasis florida* M. Bieb.
Sevada schimperi Moq.
Syn.: *Suaeda schimperi* (Moq.) Martelli
Suaeda aegyptiaca (Hasselq.) Zohary
Syn.: *Chenopodium aegyptiacum* Hasselq.; *Schanginia aegyptiaca* (Hasselq.) Aellen; *Suaeda maris-mortui* Post; *Schanginia baccata* (Forsskal ex Gmelin) Moq.; *Suaeda hortensis* Forsskal ex Gmelin
Suaeda acuminata (C.A. Mey) Moq.
(incl. *S. baccifera* Pall., *S. confusa* Iljin & ***S. pterantha*** (Kar. & Kir.) Bunge
Suaeda altissima (L.) Pall. ex J.F. Gmel.
Syn.: *Chenopodium altissimum* L.
Suaeda arcuata Bunge
Suaeda carnosissima Post
Suaeda corniculata (C.A. Mey.) Bunge var. **olufsenii** (Paulsen) G.L. Chu
Syn.: *Suaeda olufensii* Paulsen
Suaeda cucullata Aellen
Suaeda dendroides (C.A. May.) Moq.
Suaeda eltonica Iljin
Suaeda fruticosa Forssk. ex J.F. Gmel.
Syn: *Suaeda baluchestanica* Akhani & Podlech
Suaeda gracilis Moq.
Suaeda heterophylla Bunge ex Boiss.
Suaeda linifolia Pall. Ex J.F. Gmel.
Suaeda maritima (L.) Dumort
Syn.: *Chenopodium maritimum* L.; *Suaeda prostrata* Pall; *Suaeda indica* Willd.; *Kochia indica* Wight
Suaeda microphylla Pall.
Suaeda monoica Forssk. ex J.F. Gmel.
Suaeda moschata A.J. Scott
Suaeda physophora Pall.
Suaeda prostrata Pall. subsp. **anatolica** Aellen
Suaeda splendens (Pourr.) Gren. & Godr.
Syn.: *Chenopodium setigerum* DC.; *Salsola splendens* Pourr.; *Suaeda setigera* (DC.) Moq.
Suaeda vermiculata Forssk. ex J. F. Gmel.
Syn.: *Suaeda pruinosa* Willk. & Lange
Suaeda vermiculata Forssk. ex J. F. Gmel. var. **puberula** C.B. Clarke
Traganum nudatum Delile
Xylosalsola arbuscula (Pall.) Tzvelev.
Syn.: *Salsola arbuscula* Pall.

CISTACEAE

Helianthemum ledifolium (L.) Miller var. **mucrocarpum** Willk.

COMBRETACEAE

Conocarpus lancifolius Engl. & Diels

CONVOLVULACEAE

Cressa cretica L.
Evolvulus alsinoides (L.) L.
Ipomoea alba L.
Ipomoea fistulosa Mart. ex Choisy
Ipomoea pes-caprae Roth

CYMODOCEACEAE

Halodule uninervis (Forssk.) Boiss.
Halodule wrightii Asch.
Syringodium isoetifolium (Asch.) Dandy
Thalassodendron ciliatum (Forssk.) Hartog

CYNOMORIACEAE

Cynomorium coccineum L.

CYPERACEAE

Blysmus rufus (Huds.) Link.
Bolboschoenus glaucus (Lam.) S.G. Sm.
Bolboschoenus maritimus (L.) Palla var. **maritimus**
Syn.: Scirpus maritimus L.
Bolboschoenus maritimus (L.) Palla var. **affinis** (Roth) T. Koyama
Carex capitellata Boiss. & Bal.
Carex diluta M. Bieb.
Carex distans L.
Carex divisa Huds.
Carex extensa Good.
Carex heterostachya Bunge
Carex medwedewii Leskov
Syn.: *Carex atrata* Boiss.; *Carex kukkonenii* O. Nilsson

Carex stenophylla Wahlenb. subsp. **stenophylloides** (V.I. Krecz.) T.V. Egorova

Carex vesicaria L.

Cladium mariscus (L.) Pohl

Syn.: *Schoenus mariscus* L.; *Mariscus cladium* Kuntze;

Cyperus noeanus Boiss.

Cyperus alopecuroides Rottb.

Cyperus arenarius Retz.

Cyperus atkinsonii C.B. Clarke

Cyperus aucheri Jaub. & Spach

Cyperus bulbosus Vahl

Cyperus capitatus Vandelli

Syn.: *Cyperus schoenoides* Griseb.; *Galilaea mucronata* (L.) Parl.

Cyperus conglomeratus Rottb. subsp. **conglomeratus**

Cyperus conglomeratus Rottb. subsp. **curvulus** (Boeckeler) Kukkonen

Cyperus conglomeratus Rottb. subsp. **pachyrrhizus** (Nees) T. Koyama

Cyperus laevigatus L.

Cyperus longus L.

Syn.: *Cyperus longus* subsp. *badius* (Desf.) Murb; *Pycreus longus* (L.) Hayek

Cyperus malaccensis Lam.

Cyperus niveus Retz.

Cyperus pangorei Rottb.

Cyperus rotundus L.

Cyperus stoloniferus Retz.

Eleocharis mitracarpa Steudel

Syn.: *Eleocharis argyrolepidoides* Zinserl.

Eleocharis palustris (L.) Roemer & Schultes

Syn.: *Eleocharis crassa* Fisch. & Mey. ex A. Becker; *Eleocharis crassa* Fisch. & Mey. ex A. Becker var. *glaucescens* Zinserl.; *Eleocharis gracilis* Hayek non R. Br.(1810); *Eleocharis intersita* Zinserl.; *Eleocharis palustris* (L.) Roemer & Schultes subsp. *microcarpa* Walters; *Eleocharis palustris* (L.) Roemer & Schultes var. *communis* Schmalh. f. *eupalustris* (Lindb. fil.) Krylov; *Eleocharis palustris* (L.) Roemer & Schultes var. *eupalustris* (Lindb. fil.) Syreish.; *Eleocharis palustris* (L.) Roemer & Schultes *var. gracilis* Suesseng.; *Heleocharis eupaluster* Lindb.f.; *Scirpus palustris* L.

Eleocharis quinqueflora (Hartmann) O. Schwarz

Eleocharis uniglumis (Link.) Schult.

Fimbristylis complanata (Retz.) Link

Fimbristylis cymosa R.Br.

Cyperus pannonicus Jacq.

Syn.: *Acorellus pannonicus* (Jacq.) Palla; *Juncellus pannonicus* (Jacq.) C.B. Clarke

Schoenoplectus lacustris (Schrad.) Palla subsp. **hippolyti** (V.I. Krecz.) Kukkonen

Syn.: *Schoenoplectus tabernaemontani* (C.C. Gmel.) Palla; *Scirpus glaucus* Sm. Non Lam. (179I); *Scirpus lacustris* L. subsp. *glaucus* (Sm.) Hartman; *Scirpus lacustris* L. subsp. *tabernamontanae* (C.C. Gmelin) Syme; *Scirpus lacustris* L. var. *digynus* Godron; *Scirpus lacustris* L. var. *tabernaemontani* (C.C. Gmelin) Doll

Schoenoplectus litoralis (Schrad.) Palla

Syn.: *Heleogiton litorale* (Schrad.) Rchb.; *Scirpus aegyptiacus* Decne.; *Scirpus litoralis* Schrad.

Schoenoplectus triqueter (L.) Palla

Schoenus nigricans L.

Syn.: *Chaetospora nigricans* (L.) Kunth

Scirpoides holoschoenus (L.) Sojak

Syn.: *Holoschoenus australis* (Murray) Reichb.; *Holoschoenus romanus* (L.) Fritsch; *Holoschoenus vulgaris* Link; *Holoschoenus vulgaris* Link subsp. *australis* (Murray) Hayek; *Holoschoenus vulgaris* Link subsp. *eu-vulgaris* Hayek; *Isolepis holoschoenus* (L.) Roemer & Schultes; *Scirpus australis* Murray; *Scirpus holoschoenus* L.; *Scirpus holoschoenus* L. var. *australis* (Murray) W.D.J. Koch; *Scirpus holoschoenus* L. var. *genuinus* Boiss.; *Scirpus holoschoenus* L. var. *romanus* (L.) W.D.J. Koch; *Scirpus romanus* L.; *Scirpus tabernaemontani* C.C. Gmelin; *Scirpus uliginosus* Kar. & Kir.

ELATINACEAE

Bergia aestivosa (Wight) Steud.

Bergia ammannioides Roxb. ex Roth.

EUPHORBIACEAE

Andrachne telephioides L.

Euphorbia boissieriana (Woronow) Prokh.

Euphorbia falcata L. subsp. **falcata** var. **falcata**

Syn.: *Euphorbia falcata* L. var. *falciformis* Griseb.; *Euphorbia falcata* L. var. *rubra* (Cav.) Boiss.

Euphorbia granulata Forssk.

Euphorbia hirsuta L.

Syn.: *Euphorbia pubescens* Vahl

Euphorbia indica Lam.

Euphorbia macroclada Boiss.

Syn.: *Euphorbia macroclada* Boiss. var. *aceras* Hand.-Mazz.; *Euphorbia schizoceras* Boiss. & Hohen.; *Euphorbia syspirensis* C. Koch; *Euphorbia tinctoria* Boiss. & Huet ex Boiss.

Euphorbia paralias L.

Euphorbia repens K. Koch

Euphorbia thymifolia L.

Euphorbia verrucosa L.

FRANKENIACEAE

Frankenia hirsuta L.

Syn.: *Frankenia hispida* DC.; *Frankenia intermedia* DC.; *Frankenia revoluta* Forssk.

Frankenia pulverulenta L.

Frankenia salsuginea Adilguzel & Aytac

Hypericopsis persica Boiss.

GENTIANACEAE

Blackstonia perfoliata (L.) Hudson subsp. **serotina** (W. Koch ex Reichb.) Vollmann

Syn.: *Chlora acuminata* W. Koch & Ziz.; *Chlora serotina* W. Koch ex Reichb.

Blackstonia perfoliata (L.) Hudson subsp. **perfoliata**

Syn.: *Chlora perfoliata* (L.)L.; *Gentiana perfoliata* L.

Centaurium erythraea Rafn subsp. **erythraea**

Syn.: *Erythraea centaurium* Boiss.

Centaurium pulchellum (Swartz) Druce

Syn.: *Erythraea anatolica* C. Koch; *Erythraea caspica* Fischer; *Erythraea pulchella* (Swartz) Fries; *Erythraea ramosissima* (Viii.) Pers.; *Gentiana pulchella* Swartz

Centaurium spicatum (L.) Fritsch

Centaurium tenuiflorum (Hotfmanns. & Link) Fritsch subsp. **tenuiflorum**

Enicostema axillare (Poir. ex Lam.) A. Raynal

GOODENIACEAE

Scaevola plumieri (L.) Vahl.

Scaevola taccada (Gaertn.) Roxb.

GUTTIFERAE

Hypericum salsugineum Rabson & Hub.-Mor.

HYDROCHARITACEAE

Halophila ovalis (R.Br.) Hook f.

Halophila stipulacea (Forssk.) Asch.

Thalassia hemprechii (Ehrenb. ex Solms.) Asch.

IRIDACEAE

Gladiolus halophilus Boiss. & Heldr.

Gladiolus italicus Mill.

Iris orientalis Miller

Syn.: *Iris longipedicellata* Czecz.

Iris paradoxa Steven

Iris spuria L. subsp. **musulmanica** (Fomin) Takht.

JUNCACEAE

Juncus acutus L.

Juncus articulatus L.

Juncus bufonius L.

Juncus fontanesii J. Gay apud Laharpe subsp. **pyramidatus** (Laharpe) Snog.

Syn.: *Juncus camptotropus* V. Krecz.; *Juncus pyramidatus* Laharpe

Juncus persicus Boiss. subsp. **libanoticus** (Thieb.) Snog.

Syn.: *Juncus gerardii* Loisel. subsp. *libanoticus* (Thieb.) Snog.

Juncus gerardii Loisel.

Syn.: *Juncus libanoticus* Thieb.

Juncus heldreichianus Marsson ex Parl. subsp. **heldreichianus**

Juncus heldreichianus Marsson ex Parl. subsp. **orientalis** Snog.

Juncus littoralis C.A. Meyer

Syn.: *Juncus acutus* L. subsp. *tyraicus* Paczoski; *Juncus tommasinii* Parl.; *Juncus tyraicus* (Paczoski) V. Krecz. & Gontsch.

Juncus maritimus Lam.

Juncus punctorius L.f.

Juncus rigidus Desf.

Juncus subnodulosus Schrank

Syn.: *Juncus nodosus* Weber non L.(1762); *Juncus obtusiflorus* Ehrh. ex Hoffm.; *Juncus sylvaticus* Reichard non Hudson(1762)

Juncus subulatus Forssk.

Syn.: *Juncus multiflorus* Desf.

JUNCAGINACEAE

Triglochin bulbosa L. subsp. **barrelieri** (Loisel.) Rouy

Syn.: *Triglochin barrelieri* Loisel.

Triglochin maritima L.

Syn.: *Triglochin ani* C. Koch

Triglochin palustris L.

LAMIACEAE

Mentha aquatica L.

Syn.: *Mentha hirsuta* Hudson; *Mentha stricta* L. var. *stricta* C. Koch in

Phlomis armeniaca Willd.

Syn.: *Phlomis linearis* Boiss. & Bal. subsp. *anticragi* P.H. Davis; *Phlomis nympharum* O. Schwarz

Salvia syriaca L.

Salvia halophila Hedge

Salvia staminea Montbret & Aucher ex Bentham

Syn.: *Salvia armeniaca* (Bordz.) Grossh.; *Salvia staminea* Montbret & Aucher ex Bentham subsp. *armeniaca* Bordz.; *Salvia staminea* Montbret & Aucher ex Bentham var. *latifolia* Bornm.; *Salvia staminea* Montbret & Aucher ex Bentham var. *persica* Bornm.; *Salvia transcaucasica* Pobed.

Scutellaria orientalis L. subsp. **orientalis**

Syn.: *Scutellaria caucasica* A. Ham.; *Scutellaria taurica* Juz.

Teucrium polium L.

Teucrium scordium L. subsp. **scordioides** (Schreber) Maire & Petitmengin

Syn.: *Teucrium lanuginosum* Hoffmanns. & Link; *Teucrium petkovii* Urumov; *Teucrium scordioides* Schreber

LEGUMINOSAE: CAESALPINIOIDEA

Caesalpinia bonduc (L.) Roxb.

Senna italica Mill.

LEGUMINOSAE: MIMOSIOIDEAE

Acacia leucophloea (Roxb.) Willd.

Acacia nilotica (L.) Delile subsp. **nilotica**

Acacia sphaerocephala Schltdl. & Cham.

Acacia tortilis (Forssk.) Hayne

Syn.: *Acacia raddiana* Savi

Prosopis cineraria (L.) Druce

Prosopis farcta (Banks & Sol.) J.F. Macbr.

Prosopis juliflora (Sw.) DC.

Prosopis koelziana Burk.

LEGUMINOSAE: PAPILIONOIDEAE

Aeschynomene indica L.

Alhagi graecorum Boiss.

Syn.: *Alhagi maurorum* Medik.

Alhagi pseudalhagi (M. Bieb.) Desv.

Astragalus ovalis Boiss. & Ball.

Astragalus shelkovnikovii Grossh.

Astragalus tribuloides Delile

Syn.: *Astragalus kirghisicus* Schtschegleev; *Oxyglottis tribuloides* (Delile) Nevski

Astragalus vogelii (Webb) Bornm.

Crotalaria persica (Burm. f.) Merr.

Crotalaria saltiana T. Anders

Dalbergia sissoo DC.

Dorycnium strictum (Fisch. & Mey.) Lassen

Syn.: *Lotus albus* Janka; *Lotus strictus* Fisch. & Mey.; *Lotus strictus* Fisch. & Mey. var. *rotundifolius* Boiss.; *Lotus thermalis* Boiss.

Erythrina herbacea L.

Indigofera argentea Burm. f.

Indigofera cordifolia Roth

Indigofera intricata Boiss.

Indigofera linifolia (L.f.) Retz.

Indigofera oblongifolia Forsk.

Lespedeza juncea (Linn.f.) Pers. var. **sericea** (Thunb.) Lace & Hauech

Lotus corniculatus L. var. **tenuifolius** L.

Lotus garcinii DC.

Syn.: *Lotus stocksii* Boiss.

Lotus halophilus Boiss. & Spruner

Syn.: *Lotus villosus* Forssk.

Macroptilium lathyroides (L.) Urb.

Medicago lupulina L.

Medicago minima (L.) Bart. var. **minima**

Medicago falcata L.

Melilotus indicus (L.) All.

Syn.: *Melilotus indica* (L.)

Melilotus messanensis (L.) All.

Syn.: *Trifolium messanense* L.

Melilotus officinalis (L.) Desr.

Syn.: *Trifolium officinalis* L.

Pongamia pinnata (L.) Merrill

Prosopis farcta (Banks & Sol.)

Sesbania grandiflora (L.) Pers.

Sesbania sesban (L.) Merr.
Sophora alopecuroides L. var. **alopecuroides**
Syn.: *Goebelia alopecuroides* (L.) Bunge
Sphaerophysa kotschyana Boiss.
Taverniera cuneifolia (Roth) Arn.
Taverniera spartea (Burm. f.) DC.
Tephrosia apollinea (Delile) DC.
Tephrosia purpurea (L.) Pers.
Lotus maritimus L.
Syn.: *Lotus siliquosus* L.;
Trifolium fragiferum L.
Trifolium repens L
Trifolium resupinatum L.
Trifolium tomentosum L.
Medicago orthoceras (Kar. & Kir.) Trautv.
Syn.: *Trigonella orthoceras* Kar. & Kir.; *Trigonella orthoceras* Kar. & Kir. var. *anatolica* (Boiss. & Bal.) Boiss.; *Trigonella polycerata* M. Bieb. non L.
Vicia sativa L.
Vigna trilobata (L.) Verdc.

LILIACEAE

Allium cupani Rafin. subsp. **hirtovaginatum** (Kunth) Stearn
Syn.: *Allium hirtovaginatum* Kunth; *Allium moschatum* d'Urv. non L.(1753)
Allium macrochaetum Boiss. & Hausskn. subsp. **macrochaetum**
Syn.: *Allium laeve* Wendelbo & von Bothmer
Allium nevsehirense Koyuncu & Kollmann
Allium sieheanum (Hausskn. ex) Kollmann
Allium scabriflorum Boiss.
Syn.: *Allium vuralii* Kit Tan
Asparagus gharoensis Blatt.
Asparagus lycaonicus P. H. Davis
Asparagus persicus Baker
Syn.: *Asparagus leptophyllus* Schischkin; *Asparagus oligophyllus* Baker
Dipcadi biflorum Ghaz.
Drimia indica (Roxb.) Jessop

LINACEAE

Linum bienne Miller
Syn.: *Linum angustifolium* Hud.
Linum seljukorum Davis

LYTHRACEAE

Lythrum salicaria L.
Syn.: *Lythrum cinereum* Gris.; *Lythrum tomentosum* DC.

MALVACEAE

Alcea calvertii (Boiss.) Boiss.
Syn.: *Althaea calvertii* Boiss.
Gossypium stocksii Mast.
Thespesia populneoides (Roxb.) Kostel.

MOLLUGINACEAE

Glinus lotoides L.

MORACEAE

Ficus microcarpa L.f.

MYRSINACEAE

Aegiceras corniculatum (L.) Blanco
Ardisia solanacea (Poir.) Roxb.

NAJADACEAE

Najas graminea Delile
Najas marina L.
Najas minor All.

NYCTAGINACEAE

Pisonia grandis R.Br.

ORCHIDACEAE

Epipactis palustris (L.) Crantz
Orchis palustris Jacq.
Syn.: *Orchis elegans* Heuffel; *Orchis laxiflora* Lam. subsp. *dielsianus* Soo; *Orchis laxiflora* Lam. subsp. *paluster* (Jacq.) Aschers. & Graebn; *Orchis laxiflora* Lam. subsp. *palustris* (Jacq.) Bonnier & Layens; *Orchis pseudolaxiflora* Czernjak.

OROBANCHACEAE

Cistanche salsa (C. A. Mey.) Beck
Cistanche tubulosa (Schenk) Wight
The generic name *Phelypaea is unresolved.*

PANDANACEAE

Pandanus odorifer (Forssk.) Kuntze

PEDALIACEAE

Pedalium murex L.

PLANTAGINACEAE

Bacopa monnieri (L.) Wettst. (formerly in Scrophulariaceae)

Plantago coronopus L. subsp. **coronopus**

Plantago coronopus L. subsp. **commutata** (Guss.) Pilger

Syn.: *Plantago commutata* Guss.;

Plantago lanceolata L.

Plantago major L. subsp. **intermedia** (Gilib.) Lange

Syn.: *Plantago intermedia* Glib.; *Plantago major* L. subsp. *pleiosperma* Pilger

Plantago maritima L.

Plantago scabra Moench

Syn.: *Plantago arenaria* Waldst. & Kit.; *Plantago indica* L.; *Plantago psyllium* L. non L.(1759) nee L.(1762) nom. ambig; *Plantago ramosa* Ascherson

PLUMBAGINACEAE

Acantholimon halophilum Bokhari

Limonium axillare (Forssk.) Kuntze

Syn.: *Statice axillaris* Forssk.

Limonium carnosum (Boiss.) O. Kuntze

Limonium cylindrifolium Verdc.

Limonium gmelinii (Willd.) Kuntze

Syn.: *Limonium hirsuticalyx* Pignatti; *Limonium pycnanthum* (C. Koch) Kuntze; *Statice gmelini* Willd.; *Statice*

pychnantha C. Koch

Limonium graceum (Poiret) Rech.f.

Syn.: *Statice graeca* Poiret; *Statice prolifera* d'Urv.; *Statice rorida* Sibth. & Sm.

Limonium iconicum Kuntze

Limonium milleri Ghaz. & J.R. Edm.

Limonium sarcophyllum Ghaz. & J.R. Edm.

Limonium sinuatum (L.) Miller

Syn.: *Statice sinuata* L.

Limonium stocksii Kuntze

Limonium suffruticosum (L.) Kuntze

Limonium perfoliatum (Kar. ex Boiss.) Kuntze

Psylliostachys spicata (Willd.) Nevski

POACEAE

Aeluropus lagopoides (L.) Thwaites

Syn.: Aeluropus littoralis (Gouan) Parl. var. *repens* (Desf.) Casson & Dur.; *Aeluropus massauensis* (Fresen.) Mattei;

Aeluropus littoralis (Gouan) Parl.

Syn.: *Aeluropus intermedius* Regel; *Aeluropus laevis* Trin. var. *dasyphyllum* Trautv.; *Aeluropus littoralis* (Gouan) Parl. subsp. *intermedius* (Regel) Tzvelev; *Aeluropus littoralis* (Gouan) Parl. subsp. *kuschkensis* Tzvelev; *Aeluropus littoralis* (Gouan) Parl. subsp. *pungens* (M. Bieb.) Tzvelev; *Aeluropus pungens* (M. Bieb.) C. Koch; *Calotheca littoralis* (Gouan) Sprengel; *Dactylis littoralis* (Gouan) Willd.; *Poa littoralis* Gouan

Aeluropus macrostachyus Hack.

Agrostis stolonifera L.

Aira elegantissima Schur var. **elegantissima**

Syn.: *Aira capillaris* Host; *Fussia capillaris* (Host) Schur var. *elegantissima* (Schur) Schur

Alopecurus myosuroides Hudson var. **myosuroides**

Syn.: *Aira agrestis* L.

Alopecurus myosuroides Hudson var. **latialatus** M. Dogan

Ammophila arenaria (L.) Link subsp. **arundinaea** H. Lindb.fil.

Syn.: *Arundo arenaria* L.; *Psamma arenaria* (L.) Roemer & Schultes

Apera intermedia Hackel

Syn.: *Apera spica-venti* (L.) P. Beauv. subsp. *intermedia* (Hackel) Hackel ex Bornm.

Aristida abnormis Chiov.

Aristida adscensionis L.

Aristida mutabilis Trin. & Rupr.

Arundo donax L.

Bromus arvensis L.

Bromus inermis Leyss.

Syn.: *Zerna inermis* (Leyss.) Lindm.

Bromus rubens L.

Bromus tectorum L.

Calamagrostis pseudophragmites (Haller fil.) Koeler

Syn.: *Arundo glauca* M. Bieb.; *Arundo pseudophragmites* Haller fil.; *Calamagrostis littorea*

(Schrader) P. Beauv. var. *persica* (Boiss.) Boiss.; *Calamagrostis persica* Boiss.

Catabrosa aquatica (L.) P. Beauv.

Cenchrus biflorus Roxb.

Cenchrus ciliaris L.

Cenchrus pennisetiformis Steud.

Chloris gayana Kunth

Chloris quinquesetica Bhide

Chloris virgata Sw.

Coelachyrum piercei (Benth.) Bor

Crypsis aculeata (L.) Aiton

Crypsis faktorovskyi Eig

Syn.: *Heleochloa faktorovskyi* (Eig) Pilger

Cynodon dactylon (L.) Pers. var. **dactylon**

Syn.: *Panicum dactylon* L.

Cynodon dactylon (L.) Pers. var. **villosus** Regel

Syn.: *Cynodon dactylon* (L.) Pers. var. *villosum* Roshev. ex Grossh.

Dactyloctenium aegyptium (L.) Willd.

Dactyloctenium aristatum Link

Dactyloctenium scindicum Boiss.

Desmostachya bipinnata (L.) Stapf

Dichanthium annulatum (Forssk.) Stapf

Digitaria longiflora (Retz.) Pers.

Echinochloa colona (L.) Link

Eleusine indica (L.) Gaertn.

Elymus elongatus (Host) Runemark

Syn.: *Triticum obtusiflorum* DC.; *Triticum ponticum* Podp.

Elymus farctus Viv.Runemark ex Melderis

Syn.: *Agropyron junceum* (L.) P. Beauv.; *Elytrigia juncea* (L.) Nevski subsp. *juncea*; *Triticum farctum* Viv.; *Triticum junceum* L.

Elymus hispidus (Opiz) Melderis subsp. **hispidus**

Syn.: *Agropyron glaucum* (Desf. ex DC.) Roemer & Schultes; *Agropyron hispidum* Opiz; *Agropyron laevifolium* Opiz; *Agropyron latronum* (Godron) Cand.; *Agropyron validum* Opiz; *Elytrigia intermedia* (Host) Nevski; *Triticum glaucum* Desf.; *Triticum intermedium* Host; *Triticum latronum* Godron; *Triticum truncatum* Wallr.

Eragrostis collina Trin.

Syn.: *Eragrostis arundinacea* (L.) Roshev.; *Eragrostis tatarica* (Fischer ex Griseb.) Nevski; *Poa tatarica* Fischer ex Bess.

Eragrostis curvula (Schrad.) Nees

Eragrostis japonica (Thunb.) Trin.

Eragrostis superba Peyr.

Syn.: *Aira aquatica* L.

Festuca arundinacea Schreber subsp. **arundinacea**

Syn.: *Festuca elatior* L. subsp. *arundinacea* (Schreber) Hackel

Festuca rubra L.

Halopyrum mucronatum (L.) Stapf

Holcus lanatus L.

Hordeum bogdanii Wilensky

Hordeum brevisubulatum (Trin.) Link

Hordeum marinum Huds.

Imperata cylindrica (L.) Raeusch.

Lagurus ovatus L.

Lasiurus scindicus Henrard

Leptochloa fusca (L.) Kunth

Leymus cappadocicus (Boiss. et Bal.) Melderis

Syn.: *Elymus cappadocicus* Boiss. & Bal.

Leymus secalinus (Georgi) Tzvelev

Lolium rigidum Gaudin

Syn.: *Lolium subulatum* Vis.

Lolium multiflorum Lam.

Molinia caerulea (L.) Moench

Syn.: *Aira caerulea* L.

Ochthochloa compressa (Forssk.) Hilu

Panicum antidotale Retz.

Panicum turgidum Forssk.

Parapholis filiformis (Roth) C.E. Hubbard

Syn.: *Lepturus filiformis* (Roth) Trin.; *Ophiurus filiformis* (Roth) Roemer & Schultes; *Pholiurus filiformis* (Roth) Schinz & Thell.; *Rottboellia erecta* Savi; *Rottboellia filiformis* Roth; *Rottboellia incurvata* (L.) L. fil.

Parapholis incurva (L.) C.E. Hubbard

Syn.: *Aegilops incurva* L.; *Aegilops incurvata* L.; *Lepturus incurvatus* (L.) Trin.; *Lepturus incurvatus* (L.) Trin. subsp. *curvatissimus* (Aschers. & Graebn.) Rouy; *Pholiurus incurvatus* (L.) Hitchc.

Paspalidium desertorum (A. Rich.) Staph

Paspalum distichum L.

Paspalum vaginatum Sw.

Phalaris arundinacea L.

Syn.: *Digraphis arundinaceae* (L.) Trin.; *Phalaroides arundinaceae* (L.) Rauschaert; *Typhoides arundinaceae* (L.) Moench

Phalaris canariensis L.

Phalaris minor Retz.

Phleum exaratum Hochst. ex Griseb. subsp. **exaratum**

Syn.: *Phleum arenarium* L. var. *breviglume* Bornm.; *Phleum cornutum* Mez; *Phleum graecum* Boiss. & Heldr. ex Boiss.

Phragmites australis (Cav.) Trin. ex Steud. **Phragmites karka** (Retz.) Trin. ex Steud.

Poa annua L.

Poa bulbosa L.

Poa pratensis L.

Poa trivialis L.

Polypogon maritimus Willd. subsp. **maritimus**

Syn.: *Polypogon monspeliensis* (L.) Desf. var. *maritimus* (Willd.) Casson & Durieu

Polypogon monspeliensis (L.) Desf.

Syn.: *Alopecurus monspeliensis* L.

Porteresia coarctata (Roxb.) Tateoka

Puccinellia bulbosa (Grossh.) Grossh. subsp. **caesarea** Kit Tan

Puccinellia bulbosa (Grossh.) Grossh. subsp. **bulbosa** (Grossh.) Grossh.

Syn.: *Atropis bulbosa* Grossh.; *Puccinellia gigantea* (Grossh.) Tzvelev subsp. *bulbosa*

Puccinellia convoluta (Hornem.) Fourr.

Syn.: *Atropis convoluta* (Hornem.) Griseb.; *Festuca convoluta* (Hornem.) Kunth; *Glyceria convoluta* (Hornem.) Fries; *Glyceria distans* (L.) Wahlenb. var. *convulata* (Hornem.) Regel non Boiss. ex Hooker fil.(1896); *Poa convoluta* Hornem. non Hartm. ex Reichb.(1830); *Puccinellia anisoclada* V. Krecz.; *Puccinellia festuciformis* (Host) Parl. subsp. *convoluta* (Hornem.) W.E. Hughes; *Puccunellia convoluta* (Hornem.) Hayek

Puccinellia distans (Jacq.) Parl. subsp. **distans** (Jacq.) Parl.

Syn.: *Atropis distans* (Jacq.) Griseb.; *Glyceria distans* (Jacq.) Wahlenb.; *Poa distans* Jacq.; *Puccinellia pseudoconvoluta* Klokov

Puccinellia festuciformis (Host) Parl.

Syn.: *Atropis festucaeformis* (Host) K. Richter; *Festuca hostii* Kunth non Schott. ex Roemer & Schultes(1817); *Festuca palustris* Seenus; *Glyceria convulata* (Hornem.) Fries subsp. *festucaeformis* (Host) Douin; *Glyceria festucaeformis* (Host) Heynh. ex Reichb.; *Poa festuciformis* Host; *Puccinellia palustris* (Seenus) Podp. non(Seenus) Grossh.(1928); *Puccinellia palustris* (Seenus) Podp. subsp. *festucaeformis* (Host) Maire

Puccinellia gigantea (Grossh.) Grossh.

Syn.: *Puccinellia anisoclada* (V.I. Krecz.) V.I. Krecz. subsp. *melderisiana* Kit Tan

Puccinellia intermedia (Schur) Janch.

Syn.: *Atropis festucaeformis* (Schur) Hack. var. *intermedia* (Schur) Hackel; *Atropis intermedia* Schur; *Puccinellia festuciformis* (Host) Parl. subsp. *intermedia* (Schur) W.E. Hughes

Puccinellia koeieana Melderis subsp. **anatolica** Kit Tan

Rostraria cristata (L.) Tzvelev var. **cristata**

Syn.: *Festuca cristata* L.

Sacchraum bengalense Retz.

Sacchraum spontaneum L.

Setaria viridis (L.) P. Beauv.

Sphenopus divaricatus (Gouan) Rchb.

Sporobolus coromandelianus (Retz.) Kunth

Sporobolus helvolus (Trin.) Durand & Schinz

Sporobolus ioclados (Nees ex Trin.) Nees

Syn.: *Sporobolus arabicus* Boiss.; *Sporobolus jemenicus* Pilg. ex Schwartz; *Sporobolus kentrophyllus* (K. Schum.) Clayton; *Sporobolus marginatus* Hochst. ex A. Rich.

Sporobolus robustus Kunth.

Sporobolus tourneuxii Coss.

Sporobolus virginicus (L.) Kunth

Syn.: *Agrostis arenaria* Gouan; *Agrostis congener* Schumach.; *Agrostis virginica* Forssk.; *Sporobolus arenarius* (Gouan) Duval-Jouve; *Sporobolus confertus* J. A. Schmidt; *Sporobolus pungens* (Shreb.) Kunth

Sporobolus spicatus (Vahl) Kunth

Stipa himalaica Roshev.

Stipa splendens Trin.

Urochondra setulosa (Trin.) C.E. Hubb.

POLYGONACEAE

Atraphaxis spinosa L.

Persicaria vivipara (L.) Ronse Decr.

Polygonum arenastrum Bor.

Syn.: *Polygonum aequale* Lindm.; *Polygonum aviculare* subsp. *aequale* (Lindm.) Asch. & Graebn.

Polygonum aviculare L.

Syn.: *Polygonum heterophyllum* Lindman

Polygonum bellardii All.
Polygonum effusum Meisn.
Polygonum maritimum L.
Polygonum plebeium R.Br.
Polygonum sibiricum Laxm. var. **thomsonii** Meisn.
Rumex vesicarius L.

PORTULACACEAE

Portulaca oleracea L.
Portulaca quadrifida L.

PRIMULACEAE

Anagallis arvensis L. var. **arvensis**
Glaux maritima L.
Lysimachia maritima (L.) Galasso, Banfi & Soldano
Primula algida Weber & Mohr
Syn.: *Primula hookeri* Freyn & Sint.
Samolus valerandi L.

RANUNCULACEAE

Consolida anthoroidea (Boiss.) Schrod.
Nigella turcica Dönmez & Mutlu
Pseudodelphinium turcicum H. Duman, Vural, Aytaç & Adıgüzel
Ranunculus marginatus d'Urv. var. **marginatus**
Thalictrum lucidum L.
Thalictrum simplex L.

RESEDACEAE

Oligomeris linifolia (Vahl) J.F. Macbr.

RHAMNACEAE

Zizyphus nummularia (Burm. f.) Wight & Arn.

RHIZOPHORACEAE

Bruguiera gymnorrhiza (L.) Lam.
Ceriops tagal (Perr.) C.B. Rob.
Rhizophora mucronata Lam.

ROSACEAE

Potentilla anserina L.
Potentilla bifurca L. subsp. **orientalis** (Juz.) Sojak
Potentilla reptans Laicharding
Syn.: *Potentilla nemoralis* Nestler; *Potentilla procumbens* Sibth.
Potentilla supina L.

RUBIACEAE

Cruciata taurica (Pallas ex Willd.) Ehrend.
Syn.: *Valantia taurica* Pallas ex Willd.
Galium verum L.

RUPPIACEAE

Ruppia maritima L.

SALICACEAE

Populus euphratica Olivier

SANTALACEAE

Thesium compressum Boiss. & Heldr.

SCROPHULARIACEAE

Scrophularia bicolor Sibht. & Sm.
Verbascum helianthemoides Hub.-Mor.
Verbascum pyroliforme Kuntze
Verbascum sinuatum L.

SOLANACEAE

Lycium depressum Stocks
Lycium ruthenicum Murray
Lycium shawii Roem. & Schult.
Solanum incanum L.
Solanum virginianum L.
Withania somnifera (L.) Dunal

SONNERATIACEAE

Sonneratia caseolaris (L.) Engl.

STERCULACEAE

Melhania denhamii R.Br.

TAMARICACEAE

Reaumuria alternifolia Britten
Syn.: *Hypericum alternifolium* Labill.; *Reumuria cistoides* Adam; *Reumuria hypericoides* Willd.
Reaumuria fruticosa Boiss.
Tamarix androssowii Litv. subsp. **androssowii**
Tamarix aphylla (L.) H. Karst.
Tamarix aralensis Bunge
Tamarix arceuthoides Bunge
Tamarix gallica L. var. **indica** (Willd.) Ehrenb.
Tamarix hampeana Boiss. & Heldr.
Tamarix hispida Willd.
Tamarix kermanensis Baum.
Tamarix karelinii Bunge

Tamarix kotschyi Bunge
Tamarix leptostachya Bunge
Tamarix parviflora DC.
Syn.: *Tamarix cretica* Bunge
Tamarix passerinoides *Delile*
Tamarix rosea Bunge
Tamarix smyrnensis Bunge
Syn.: *Tamarix pallasii* Desv. var. *smyrnensis* (Bunge) Boiss.; *Tamarix ramosissima* Ledeb.
Tamarix tetragyna (Boiss.) Boiss. var. **meyeri**

THYMELAEACEAE

Thymelaea hirsuta (L.) Endl.
Thymelaea passerina (L.) Casson & Germ.

TILIACEAE

Corchorus depressus (L.) Stocks

TYPHACEAE

Typha australis K. Schum. & Thonner
Typha domingensis Pers.
Typha latifolia L.
Typha laxmannii Lepechin
Syn.: *Typha stenophylla* Fisch. & Mey.
Typha minima Funck var. **gracilis** Ducomm.
Syn.: *Typha gracilis* Jordan non Rafin.(1836); *Typha lugdunensis* Chabert; *Typha martini* Jordan

VALERIANACEAE

Centranthus longiflorus Stev. subsp. **longiflorus**
Valerianella vesicaria (L.) Moench

VERBENACEAE

Clerodendrum inerme (L.) Gaertn.
Phyla nodiflora (L.) Greene
Verbena officinalis L.
Globularia trichosantha Fisch. & Mey.
(Formerly in Globulariaceae)

ZYGOPHYLLACEAE

Fagonia bruguieri DC.
Fagonia indica Burm. f.
Fagonia ovalifolia Hadidi
Malacocarpus crithmifolius (Retz.) C.A. Mey.
Nitraria retusa (Forssk.) Asch.
Nitraria schoberi L.
Syn.: *Nitraria olivieri* Jaub. & Spach
Seetzenia lanata (Willd.) Bullock
Tetradiclis tenella (Ehrenb.) Litv.
Syn.: *Anatropa tenella* Ehrenb.; *Tetradiclis caspia* Lindl. in Chesney; *Tetradiclis salsa* C.A. Mey.
Tetraena alba (L.f.) Beier & Thulin
Syn.: *Zygophyllum album* L.f.
Tetraena simplex (L.) Beier & Thulin
Syn**.** *Zygophyllum simplex* L
Tetraena coccinea (L.) Beier & Thulin
Syn.: *Zygophyllum coccineum* L.
Tetraena qatarensis (Hadidi) Beier & Thulin
Syn.: *Zygophyllum qatarense* Hadidi
Tribulus arabicus Hosni
Syn.: *Tribulus omanensis* Hosni
Tribulus terrestris L.

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From Halophyte Research to Halophytes Farming

K. Ben Hamed, C. Magné, and C. Abdelly

Abstract

The need for halophytes in saline agriculture is rising, as the increasing population seeks to feed itself with ever-decreasing soil sources and dwindling freshwater supplies. Two main steps are needed to establish sustainable halophyte farming: (i) the selection of an economically important and ecologically relevant halophyte and (ii) the development of good management practices for irrigation. The success of both steps will depend on the efforts of many actors in science, technology, environment, agronomy, industry and farming.

Crucial halophyte scientific missions are to work on the multiple uses of halophytes and their salt tolerance limits. Those investigations should also contribute to the understanding of salt mechanisms in halophytes.

In this chapter, we will show recent findings on the use of halophytes and their behavior under saline conditions, and discuss how the farmers, the industrials and consumers can benefit from such scientific knowledge to enhance the development of halophyte farming.

Keywords

Agriculture • Environment • Halophytes • Salinity • Science • Technology

1 Introduction

At present over one billion hectares of land are salinized globally. Each year an increase of ten million hectares is observed. Climate change will speed the salinisation process in coastal areas as a result of seawater intrusion. The melting of glaciers will influence the availability of fresh water in arid areas in a negative way. We do not have a choice but to find ways to use

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_9, © Springer Science+Business Media Dordrecht 2014

saline resources (soil, water and plants) due to increasing world population and growing demands for prosperity the world over,

Agriculture sector is still the largest fresh water consumer globally, although differences can be observed between countries and continents. Agriculture will be more and more out-competed on the freshwater market by industrial and urban users, who bring apparently more economic value for the same amount of water. Rising prices for energy and raw materials are caused by population growth and even more by the rising living standards of the population of countries like Brazil and China. This creates more and more a level playing field for saline resources.

The farming of halophytes emerged as a solutions to the problems the traditional agriculture is facing. Halophytes can be used in saline areas to feed people, graze livestock and develop edible oil, and bio-fuel. The only major difference is that saline or brackish water is used instead of fresh water. But, farming of halophytes will absolutely necessitate the availability of correct scientific knowledge and sustainable technologies. Scientists through their new ideas can convince farmers with the use of halophytes.

2 Halophyte-Glycophyte Associations: The Evidence for Highly Productive Agriculture

The soils in many arid and semi-arid regions are saline and are not thus proper for the cultivation of traditional crops. In these soils, two major vegetation types can coexist (i) a halophytic vegetation, naturally salt-tolerant and (ii) a glycophytic vegetation, generally salt sensitive, but capable of growing in association with halophytes (Fig. 1). The coexistence of both types of vegetation (halophytes and glycophytes) can be explained by the stratification of root systems of perennial halophytes, to exploit only the deepest and salty horizons, and root systems of annuals, which thrive in the less saline surface areas [1]. Several hypotheses can explain the low salinity of the higher horizon. The upper layer can be washed away by a lateral flow of water lightly loaded to the center of the depression. Halophytes, by exploiting the saline deep horizons, may limit the rise of saline groundwater to the surface allowing rainwater to penetrate the upper horizon of the profile. Finally, the halo-

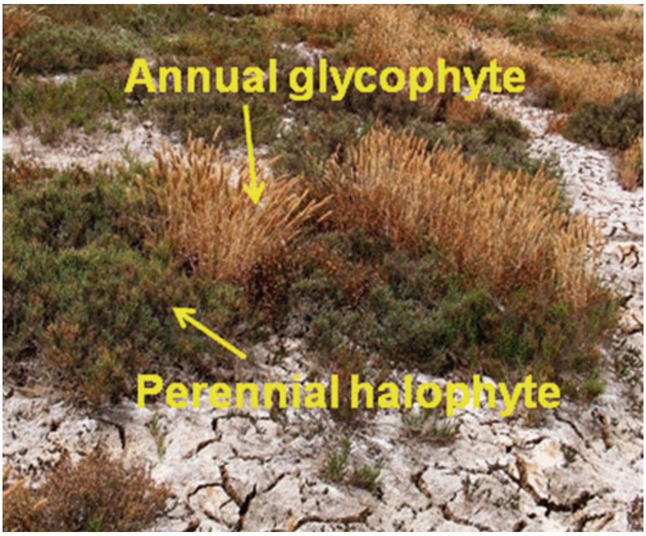

Fig. 1 Perennial halophytes in Sabkhas favouring the growth of annuals (Leguminous, Poaceae) through efficient salt removal from the soil, N and P fertilization

phytes, through their shallow roots, can help maintaining low levels of salt in surface horizon. These factors favor the rapid development of a carpet of annuals less resistant to salt stress but very efficient in the acquisition of mineral resources as soon as the water resources permit [1]. These data clearly show that some halophytes are capable of desalinizing and fertilizing soils, thus creating micro-habitats favorable for the development of several salt-sensitive annual plants. The latter are represented mainly by *Medicago* species that are highly preferred by livestock [2]. Other halophytes are well grazed and contribute directly to the pastoral value of marginal zones. Many of these species are capable of maintaining high growth potentials, under a wide range of salinities, and in the case of the Poaceae to produce plant biomass with low salt concentrations [2].

Such highly interesting findings, when properly and explicitly explained to farmers, may encourage using saline soils and plants in agricultural systems. Farmers will also need to know more about the different kinds of halophytes, their requirement, the mechanisms of their salt tolerance and especially their potential interests.

3 Which Kinds of Halophytes Should the Farmers Recognize?

Halophytes can survive in a number of environments. Many are adapted to grow in salt marshes and estuaries, where there is a high concentration of salty water. Others can live on cliffs and dunes near the ocean, and some are adapted for near-desert environments where water supplies may be limited and highly saline. A halophyte which lives in the desert is typically a succulent, so that it can store water to ensure that it has an ample supply [3].

Researchers distinguish between facultative halophytes and obligate halophytes. A facultative halophyte is a plant which can live in salty conditions, but would prefer to avoid salt, if possible. For example, plants which thrive during the rainy season, when salt concentrations are diluted, are usually facultative halophytes which tolerate the salt, but do not particularly enjoy it. An obligate halophyte, on the other hand, actually needs salt to survive.

Halophytes can also be divided into hydro-halophytes and xero-halophytes. Hydro-halophytes grow in aquatic conditions or on wet soil such as mangroves, saltmarsh species along coastlines. Xerohalophytes may grow in habitats where the soil is always saline but may dry out so much that water becomes less available for the plant. Most species in sabkhat of desert areas are xero-halophytes. We can also distinguish succulent halophytes, halophytes with salt bladders on the leaf surface, and those which excrete the salt with evaporation water, where the salt crystals remain visible on the leaf surface. Under lower salinity levels some plants are able to exclude the salt otherwise taken up by the roots. A plant may belong to several of the above listed categories.

4 Requirements of Halophytes

4.1 Halophytes and Climates

Halophytes are distributed in variety of climatic conditions. Halophytes were investigated in hot desert climates with low seasonality as well as in more moderate or even cool and moist climates with strong seasonality. The plants are adapted to temperate levels as well as to seasonal patterns. It is important, therefore, to compare the climate of natural occurrence of a species with the climate where a species is intended to be used. In climates with strong seasonality it might well be that an annual plant can be used during that part of the year where the temperature range is nearly equal to the temperature of the growing season where the plant occurs naturally. As an example the experiments conducted in Pakistan with *Aster tripolium* which he imported from the Netherlands and grew it successfully near Faisalabad [4]. The two climates differ substantially in temperature, seasonality as well as in their precipitation pattern. One can see that the winter season will allow the species to grow in Pakistan, whereas the growing season in the Netherlands is the summer. The lack of precipitation in Pakistan during that time can be compensated for by irrigation with saline water, since *Aster tripolium* tolerates salinity up to seawater strength. Another example, *Atriplex undulata* (from central western Argentina) grows well in a Mediterranean climate in south western Australia and on the Persian Gulf in Saudi Arabia; *A. amnicola* from north western Australia grows well in south western Australia and on the Persian Gulf; *A. canescens* from the south western United States of America grows well on the Persian Gulf but poorly in south western Australia. It has been observed that species unaccustomed to frost are winterkilled in colder climates; There is an urgent need for a coordinated programme to exchange seeds, conduct adaptation tests, describe site conditions and develop a data bank on species adaptation to saline environments.

4.2 Halophytes and Soils

Halophytes occur naturally on soils with elevated salinities. The salinity is usually dominated by sodium chloride (NaCl). The adaptation to NaCl is apparently easier than the adaptation to $MgCl_2$, $NaHCO_3$. The texture of the soil is also important. On the seashore stretches of coarse sand which moves with the waves exerts additional force upon the plants. Its water holding capacity is very low and gets full aeration twice a day with the tides. Fine sediments at the coasts are either silt or clay which holds the water much longer than the sandy soils [5].

The roots of halophytes grow more easily into coarse-textured soils than massive or weakly structured clayey sub-soils, resulting in the development of a more extensive root system. This, and leaching of salts in winter, would explain why production from saltbush pasture can be higher on coarse-textured soils or deep sandy duplex soils. Deep-ripping can increase production on coarse-textured soils [6].

4.3 Halophytes and Water Resources

The short description of climate and soil parameters of the halophyte environment demonstrates that under any favorable temperature regime the water supply and its quality requires foremost attention. As far as farming, cropping or feed production is concerned, the choice of the best irrigation method is as important as choosing the optimal fertilizing technique. There is a wide span of halophyte utilization. In most cases amount and quality of the irrigation water as well as economic parameters control any possible utilization. The key point for irrigation is the demand on salinity of each species chosen. There are wide ranges of salinity tolerances among species and even within species wide margins of salinity tolerance and their requirements are given for some species out of 2,600 [7]. For practical applications of halophyte utilization we need to pay attention to the quality of the irrigation water (e. g. the wastewater qualities from agricultural irrigation systems). Halophytes tolerate more influx of heavy metals and large organic molecules than glycophytes. Various applications of urban waste waters are reported [8]. Together with the experiences resulting from saline irrigation experiments at many places around the world we can draw the conclusion that halophyte production systems can be established in an ecologically sustainable way if surface salinity increase is prevented. This requires intermittent irrigation and good drainage. Most waste waters and even seawater usually contains a sizable amount of fertilizer. Since ion concentrations and composition are different at each site, a routine chemical analysis of water and plant material is essential.

4.4 Halophytes and Fertilizer

Growing halophytes does not use any synthetic fertilizer. NASA research laboratory working on halophytes used only fish waste, which is readily available, as a completely “green” fertilizer [9]. They are planning a halophyte farm on private land along the Mississippi river, which has abundant fish waste. Most waste waters and even seawater usually contains a sizable amount of fertilizer (11 of the 13 mineral nutrients needed by plants are present in seawater in adequate concentrations for growing crops).

5 Where Can Halophytes Be Grown?

Halophytes can be grown in:

1. Farmlands salinized by poor irrigation practices: in some developing regions, there are millions of hectares of salinized farmland resulting from poor irrigation practices ($1.5–7 \times 10^9$ ha). These lands would require large and generally unavailable amounts of water to leach away the salts before conventional crops could be grown. Instead of this water waste, appropriate halophytes can do the same work. Although the introduction of salt-tolerant plants will not necessarily restore the soil to the point that conventional crops can be grown, soil character is often improved and erosion reduced.
2. Arid or desert lands over brackish aquifers: the reservoirs of water of these areas contain too high salt levels for the irrigation of conventional, salt-sensitive crops. Many of these barren lands can become productive by growing selected crop halophytes and employing special cultural techniques using this store of brackish water for irrigation.
3. Coastal deserts: throughout the developing world, there are extensive coastal deserts where seawater is the only water available. Although growing crops in sand and salty water is not a benign prospect for most farmers, for saline agriculture they can complement each other. The disadvantages of sand for conventional crops become advantages when saline water and salt-tolerant plants are used. Sand is inherently low in the nutrients required for plant growth, has a high rate of water infiltration, and a low water-holding capacity. Therefore, agriculture on sand requires both irrigation and fertilizer. Surprisingly, 11 of the 13 mineral nutrients needed by plants are present in seawater in adequate concentrations for growing crops. In addition, the rapid infiltration of water through sand reduces salt buildup in the root zone when seawater is used for irrigation. The high aeration quality of sand is also valuable. This characteristic allows oxygen to reach the plant roots and facilitates growth. Although careful application of seawater and supplementary nutrients are necessary, the combination of sand, saltwater, sun, and salt-tolerant plants presents a valuable opportunity for many developing countries.

6 Production of Halophytes as Compared to Conventional Crops

Although halophyte agriculture is not that well understood, there have been relatively few field trials set up to simulate agronomic conditions. Ecological studies, however, have documented the high-yield potential of salt marsh species such as *Spartina alterniflora*, which produces up to 40 t/ha of biomass in the low intertidal zone of estuaries [10]. Yields ranging from 13.6 to 17.9 t/ha of dry matter for the most productive halophyte species were observed in field plots of a coastal desert environment (Puerto Penasco, Sonora, Mexico), using 40 g/l seawater as the irrigation source [11]. These are comparable to yields obtained from conventional forage crops such as alfalfa that is grown with freshwater irrigation (2 t/ha dry mass).

The list of productive species included several plant types: a succulent, annual plant (*Salicornia bigelovii*); a perennial grass (*Distichlis palmeri*); *Batis maritima*; and several species of desert saltbush (*Atriplex* spp.). Isolated field studies with *Salicornia europaea* in Mexico, Egypt, and United Arab Emirates reported a production of 20 t of total biomass per hectare, with a yield of 2 t of seeds [12]. Similar yields for *S. bigelovii* (12.7–24.6 t/ha of biomass) and 1.39–2.46 t/ha of seed over a 200-day growing cycle are reported [13]. The seed contained 31 % protein, 28 % oil, and only 5 % fiber and 5 % ash; the oil was high in polyunsaturated fatty acids, particularly linoleic acid (74 % of total). Under full seawater irrigation, *Atriplex* species produced 12.6–20.9 t/ha of biomass containing 9.9–19.5 % protein on full-strength seawater, not significantly lower than the yields on 15 % seawater [14]. Yields of 5.2–9.5 t/ha of the salt-grass *Distichlis spicata* were obtained under seawater (30 g/l) irrigation in Delaware, USA, while *Spartina patens* yielded 14.4 t/ha when harvested in July [15]. These are within the range of yields from conventional forage grasses. The herbaceous plant *Atriplex triangularis*, a potential fresh vegetable crop for human consumption, yielded the equivalent of 21.2 t/ha on a fresh-weight basis. *Inula crithomoides*, a perennial halophyte bush, was proposed as a forage plant for saline irrigation [16]. From small-scale experiments, an yield of 4 t/ha of dry biomass was found when grown in 40 dS/m (24 g/l) seawater.

These reports show that halophytes can yield as high as conventional irrigated crops even under full seawater irrigation. Biomass produced by halophytes under saline irrigation can therefore be converted into useful products: edible oils [17], food [18, 19], fodder [20, 21] and biofuels [22].

7 Halophytes and Modern Technologies

7.1 Use of Plant Biotechnology Methods

Due to their remarkable ability to tolerate and even benefit from excessive salt concentrations that kill most other plant species, halophytic plants have also attracted attention of plant biologists who consider that they may provide genes that confer salinity tolerance to crops. So, many genes are already identified in halophytes (eg. Suaeda corniculata ScV-H^+ PPase, Thellungiella halophila TsVP), and proved their ability to improve resistance of many crops [23]. Wild halophytes (like tall wheatgrass, *Thinopyrum ponticum*, *Hordeum marinum*) can be hybridized with crop plants (like wheat) with some notable examples of improved Na^+ exclusion and enhanced salt tolerance in the progeny, as compared with the wheat parent [24, 25].

The prospects of biotechnology for crop improvement [26] and their successful efforts to transfer salt tolerance from a halophyte, *Aeluropus littoralis*, to wheat via asymmetric somatic hybridization [27] have also been reported. Some promising results obtained in applying asymmetric somatic hybridization to *Triticum aestivum* and *Thinopyrum ponticum* are also reported in literature [28].

7.2 Micropropagation

In order to propagate halophytes for industrial purposes, tissue cultures and regeneration methods have been developed in some halophytes like *Crithmum maritimum* [29], *Sporobolus virgincus, Distichlis spicata* [30], *Salicornia brachiata* [31], *Sesuvium portulacastrum* and *Avicennia marina* [32]. By taking advantage of somaclonal variation which occurs during the tissue culture process, plants with desirable characteristics can be also selected for agriculture. Tissue cultures from halophytes can also provide systems for the production of valuable secondary metabolites commonly found in some halophytes. Halophyte callus and suspension cultures have already proved useful in stress-related physiological studies [33].

8 Concluding Remarks

Farming of halophytes has several advantages:

- It did not use fresh water resources. Rather, it uses unconventional saline water resources. Seawater can be used (*salicornia*, mangroves, seawater grasses), but brackish water offers a higher potential in salt tolerant species that can flourish on it.
- In the light of rising fossil fuel prices and the upcoming international measures in favor of renewables, new markets for biomass and biomaterials are developing fast. The fact that biosaline production is non-competitive with

food-production, combined with the benefits of preventing desertification, are important pushing factors for halophyte agriculture.

- Vast areas are available that potentially can produce high biomass and yield. Halophyte agriculture may therefore be able to contribute considerably to the production of CO_2 neutral bio-energy. The success of halophyte farming is based on two major components: (1) the knowledge of halophytes in various saline environments and how to improve their productivity via plant breeding, biotechnology and agronomics. (2) The knowledge of salinity management in various saline environments including infrastructure for irrigation and drainage adapted to the needs of specific halophytic crops.

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Interactive Effect of Salinity and Drought on the Germination of Dimorphic Seeds of *Suaeda salsa*

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Abstract

Suaeda salsa is an annual herbaceous halophyte in the family Chenopodiaceae which produces dimorphic seeds on the same plant under natural conditions, the seed germination is often affected by salinity as well as drought or both. The objective of this study was to determine the effects of salt, drought and their interaction on germination of dimorphic seed of *S. salsa* and the recovery when stress was removed.

The germination response of dimorphic seeds was studied under stress created by salt (NaCl) and polyethylene glycols 6000 (PEG) singly and in combination. Results showed that the seed germination decreased with an increase in the stress. The black seeds showed greater inhibition than the brown ones. Addition of moderate amount PEG (isotonic to 50 and 100 mM NaCl solutions) in the medium with high salinity (above 300 mM NaCl) increased the germination of both kinds of seeds compared with no PEG addition. This increase was greater in black seeds than in brown seeds. The rate of germination was higher in brown seeds than that in black seeds in all the treatments, while germination recovery and total germination percentage was higher in black seeds than in brown seeds after their exposure to NaCl and PEG and then transferring to distilled water. In conclusion, brown seeds might germinate better under higher salt and drought stress than black seeds, however black seeds showed higher viability under such conditions. Moderate PEG might alleviate the detrimental effect of high salinity on seed germination.

Keywords

Dimorphic seeds • Germination • Halophyte • Polyethylene glycols • Sodium chloride • *Suaeda salsa*

The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_10, © Springer Science+Business Media Dordrecht 2014

1 Introduction

Suaeda salsa, a leaf succulent annual herb of the family Chenopodiaceae, is a main halophytic species distributed widely in the saline soils of north part of China [1]. As its seeds contain approximately 30–40 % edible oil rich in unsaturated fatty acids [2] and its fresh branches are edible, this species has economic potential as a source of oil, food, vegetable and fodder [1, 3]. The species is adapted to saline soils, and it is Na^+ and Cl^- hyper-accumulating halophyte [4]. Thus, it might be useful in improving the saline soils. In order to manage *S. salsa* as a crop for industrial products or for vegetation rehabilitation in saline soils, a good understanding its of seed germination characters is essential.

Germination is a crucial stage in the life history of plants as it determines whether a plant can establish successfully in a given condition [5]. Though halophytes are salt tolerant, germination of their seeds is often inhibited by increased salinity; best germination of halophytes is obtained under non-saline conditions and their germination decreased with increase in salinity [6, 7]. High salinity inhibits seed germination through an osmotic component that affects water uptake and through an ionic component that is linked to the accumulation of Na^+ and Cl^-. For successful establishment of plants in saline environments, seeds must remain viable at high salinity and germinate when salinity in the growth medium decreases [8, 9].

Salinity concentration at the surface of the soil changes over time by continuous evaporation and occasional precipitation [10] in natural saline environment. Especially in the saline soil areas of North China in spring, high evaporation and low precipitation result in variable levels of salinity and drought stress for annual halophyte seeds germination [11]. Seed heteromorphism or dimorphism is an adaptive mechanism in many xerophyte and halophyte species to the unfavorable environment during germination [12]. The occurrence of seed heteromorphism or dimorphism is often associated with environments that are highly variable either in time or space, *e.g.*, deserts, semi-deserts, salt marshes, or human-made habitats [13, 14]. It has been demonstrated that seed polymorphism provides an adaptive advantage in saline habitats through permitting germination at different times, which increases the chances of survival of at least some seedling cohorts [9]. The two kinds of seeds in the dimorph species could provide multiple germination cohorts in saline habitats that provide several opportunities for halophytes to establish populations in new habitats [15]. Several investigators have demonstrated the dimorphic seeds had different germination behaviors and salt tolerance under saline condition in several halophytes including *Atriplex triangularis, Arthrocnemum indicum*, *Suaeda moquinii*, *Atriplex prostrata, Atriplex patula* and *Suaeda salsa* [6, 15–22]. However there is less information on the response of dimorphic seeds germination to environmental variables, especially under the combined salt and drought stress condition.

Previous studies showed that brown seeds of *S. salsa* germinated faster and appeared more tolerant than black seeds under salinity or drought stress independently [21, 22]. A recent field investigation showed that *S. salsa* grown in inland saline soils with low soil moisture produces more black seeds while grown in coastal saline soils with high soil moisture produces more brown seeds [23]. As an adaptation strategy, it may indicate that the dimorphic seeds of *S. salsa* have different response to salt and drought or combined stress. However, information on germination of dimorphic seeds of *S. salsa* under combined drought and salt stress is rare. The objective of the study was to determine the effects of salt and drought independently and in combination on germination of dimorphic seeds of *S. salsa* and recovery when stress was removed.

2 Materials and Methods

Seeds of *S. salsa* were collected from the coastal saline soil area of Haixing county of Hebei province, China, in October 2004. Black seeds and brown seeds were separated from the inflorescence. After selection, the seeds were stored in laboratory at room temperature. Thirty treatments including

6 levels of NaCl solution (0, 100, 200, 300, 400 and 600 mM NaCl) and 5 levels of PEG 6000 solution (isotonic to 0, 50, 100, 200 and 400 mM NaCl) were tested to study the germination of both kinds of seeds. The isotonic potential was calculated by Van Hoff formula [24] in NaCl and by Michel equation in PEG 6000 [25].

Fifty seeds were put into one Petri dish of 10 cm in diameter and covered with two sheets of filter paper which had been soaked with 10 ml of test solution. The Petri dishes were sealed with Parafilm in order to avoid loss of water. There were four replicates in each treatment. The experiment was carried out in an auto controlled growth chamber (ZRX-2580, Hangzhou Qianjiang, China). The photoperiod was 12 h, the temperature was maintained at 15 and 25 °C during night and day respectively. Germination was scored when radicle emerged from the inner seed coat. Germination was recorded every day for 12 days and germinated seeds were taken off after counting.

The rate of germination was estimated by using a modified Timson's index of germination velocity [16]:

$$\text{Rate of germination} = \sum G / t \tag{1}$$

where G is percentage of seed germination at 1 day interval, and t is total germination period (the maximal value of rate of germination is 100 in this experiment).

After 12 days, un-germinated seeds in each treatment were transferred to distilled water for 5 days to determine the recovery of germination and total germination percentage. The recovery percentage was determined by the formula [6]:

$$\text{Recovery percentage} = (a - b)/(c - b) \times 100 \tag{2}$$

where a is the total number of seeds germinated after transfer to distilled water, b is the total number of seeds germinated in stress conditions, and c is the total number of seeds.

Total germination percentage was calculated by the formula:

$$\text{Total germination percentage} = a / c \times 100 \tag{3}$$

where a is the total number of seeds germinated after transfer to distilled water, and c is the total number of seeds.

Values of germination percentage, germination rate, recover percentage and total germination percentages were arcsine transformed before statistical analysis to ensure homogeneity of variance. The transformed values were analyzed using a three-way ANOVA. If significant differences were found, Bonferroni test was used to determine mean differences between treatments. All statistical analysis was done using SPSS 10.0 statistical software packages.

3 Results

A three-way ANOVA indicated a significant effect of seed dimorphism, salinity and drought and their interactions on germination (at the end of 12 days), rate of germination, recovery percentage and total germination after recovery of *S. salsa* seeds (Table 1).

Germination of brown seeds was substantially faster than that of the black seeds (Fig. 1). In all

Table 1 Three-way ANOVA of germination percentage, rate of germination, recovery percentage and total germination percentage for seed dimorphism (*SD*), salinity (*S*), drought (*D*) and their interactions

Sources of variation	SD	S	D	SD × S	SD × D	S × D	SD × S × D
df	1	5(3)	4	5(3)	4	20(12)	20(12)
Germination percentage	1,170.20***	605.55***	219.84***	87.94**	4.96**	5.84***	5.03***
Rate of germination	3,304.25***	760.54***	289.53***	65.13***	22.68***	5.75***	5.71***
Recovery percentage	504.74***	1.27^{ns}	25.72***	4.80*	7.359***	4.28***	3.51***
Total germination percentage	257.41***	46.75***	129.35***	42.44***	16.73***	5.13***	2.370**

Note: Values represent F-values. *, ** and *** indicate significant difference at $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively, ns indicate no-significant difference at $P > 0.05$. The values of df line in brackets were the df of Recovery percentage

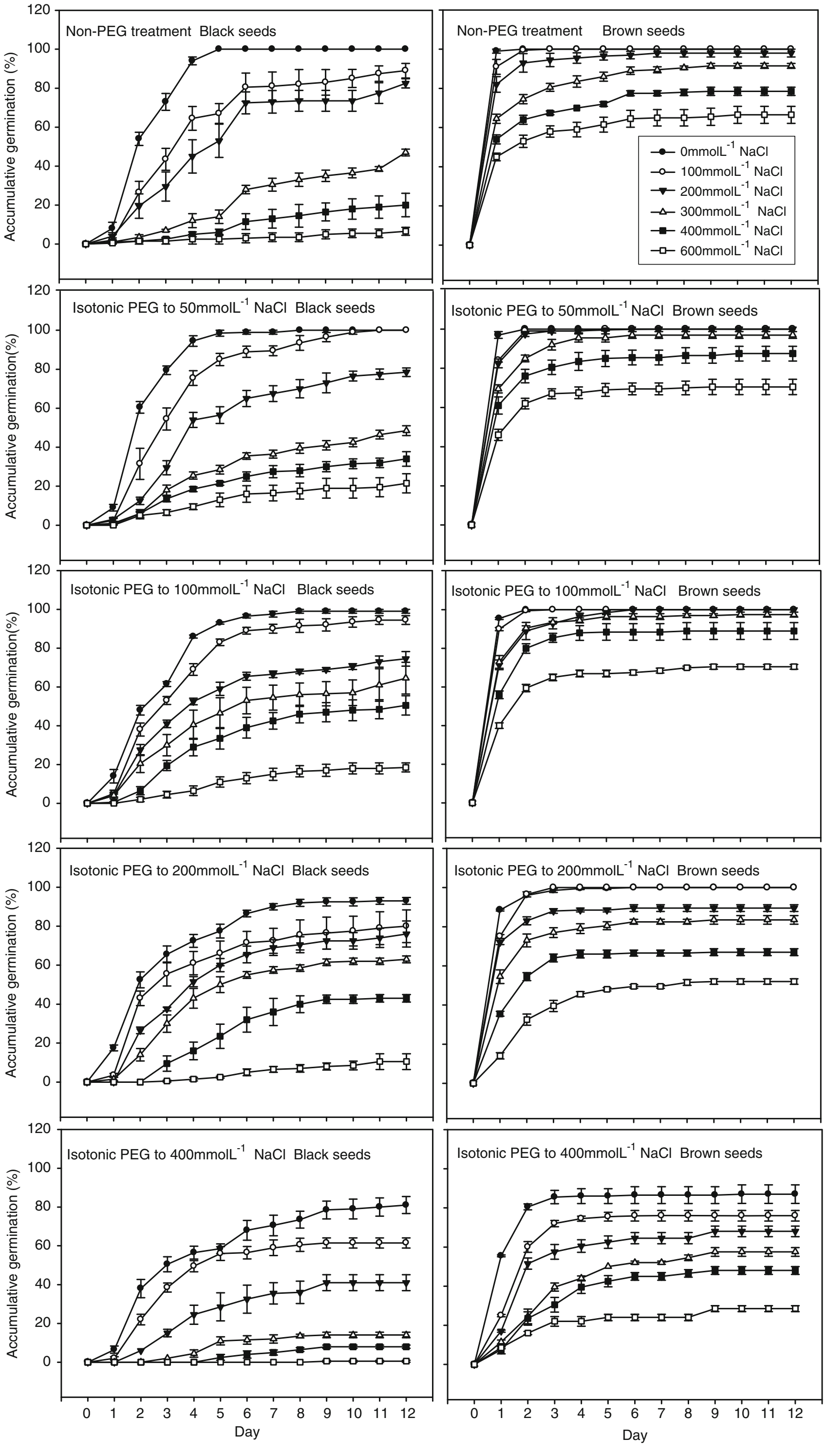

Fig. 1 Accumulative germination of dimorphic seeds of *Suaeda salsa* in 0, 100, 200, 400 and 600 mM NaCl solutions combined with isotonic PEG solution to 0, 50, 100, 200 and 400 mM NaCl for 12 days

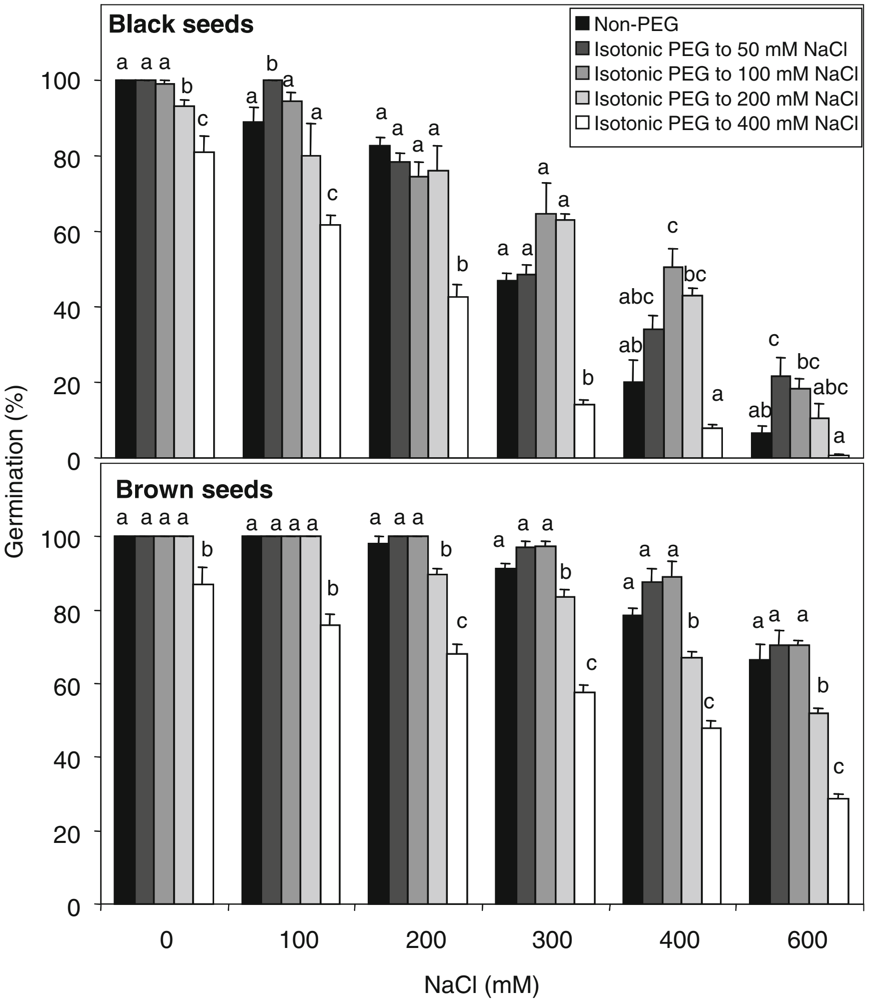

Fig. 2 Mean (±SE) germination percentage of dimorphic seeds of *Suaeda salsa* in 0, 100, 200, 300, 400 and 600 mM NaCl solutions combined with isotonic PEG solution to 0, 50, 100, 200, 300 and 400 mM NaCl for 12 days

treatments, brown seeds germinated rapidly during the initial test days and attained final germination percentage in 1–5 days, while black seeds germinated gradually and attained stable germination percentage in more than 5 days (Fig. 1).

Seed germination of both black and brown seeds decreased significantly with the increase of salinity ($P<0.001$) and PEG ($P<0.001$) and their interactive effect was also significant ($P<0.001$). Brown seeds germinated better than black seeds in the same intensity of stress, especially under high levels of stress (Fig. 2). The best germination of black seeds was obtained in distilled water and low salinities (below 100 mM NaCl) at non-PEG treatments (Fig. 2). Black seeds germinated rarely at 600 mM NaCl in all PEG solutions. In addition, at high salinity (≥400 mM NaCl), the presence of moderate PEG (isotonic to 50, 100 and 200 mM NaCl) increased germination in contrast to the same salinity treatment with non-PEG treatment in black seeds. In contrast, germination of brown seeds was not significantly affected by low or moderate PEG (isotonic to 0 and 200 mM NaCl) treatments (Fig. 2). High PEG stress inhibited brown seed germination significantly.

The rate of germination of both kinds of seeds decreased significantly with the increase in salinity ($P<0.001$) and PEG ($P<0.001$) concentration.

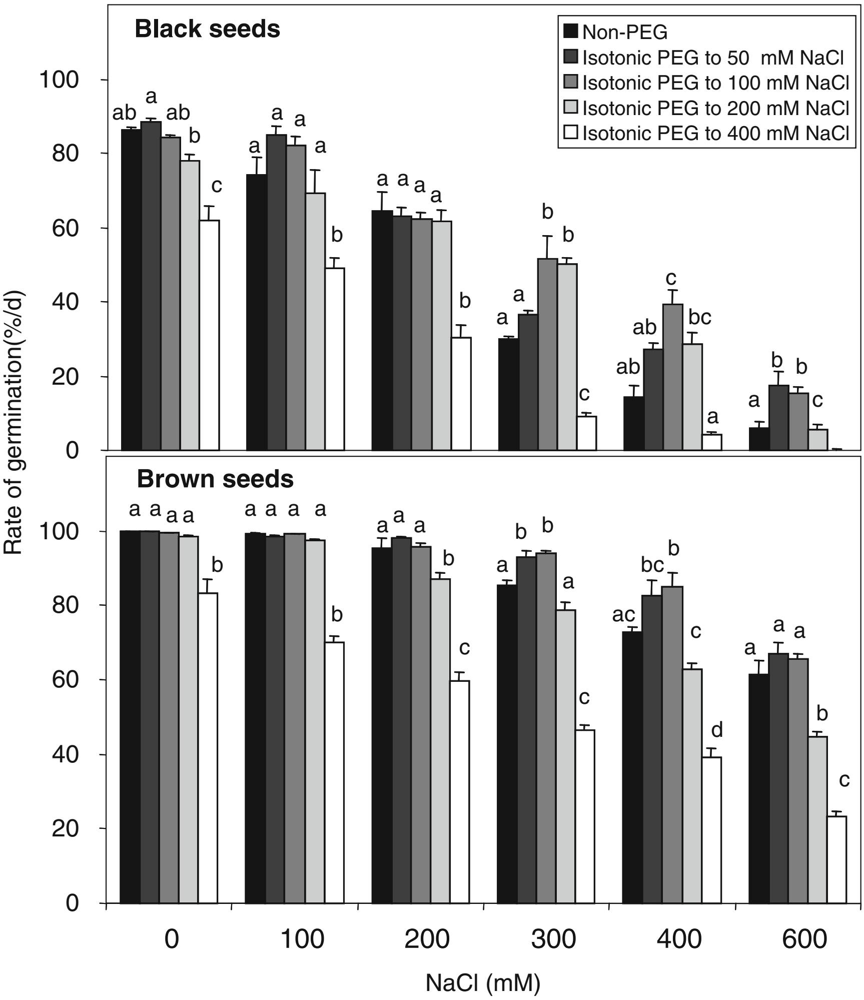

Fig. 3 Rate of germination in dimorphic seeds of *Suaeda salsa* in 0, 100, 200, 300, 400 and 600 mM NaCl solutions combined with isotonic PEG solution to 0, 50, 100, 200 and 400 mM NaCl for 12 days

Their interactive effect was also significant (P<0.001). Rate of germination was higher in brown seeds than black seeds under same stress treatment. The presence of moderate PEG (isotonic to 50, 100 or 200 mM NaCl) promoted the rate of germination in high salt (300–600 mM NaCl for black seeds and 300 and 400 mM NaCl in brown seeds) stress compared with non-PEG treatment (Fig. 3). High PEG (isotonic to 400 mM NaCl) significantly decreased the rate of germination in both black and brown seeds (Fig. 3).

When un-germinated seeds were transferred to distilled water for recovery for 5 days, the recovery percentage was not significantly affected by salinity in both black and brown seeds. PEG stress significantly affected recovery percentage of both black and brown seeds (P<0.001). Interaction between salt and PEG did not significantly affect recovery percentage in black seed, while in the case of brown seeds it was significant (P<0.001, Fig. 4).

The total germination percentage of black seed was not significantly (F=2.18, P=0.06) affected by salt stress. In case of brown seed this effect was significant (F=117.83, P<0.001). PEG effect (F=25.18, P<0.001 in black seeds and F=155.67, P<0.001 in brown seeds) and the interaction

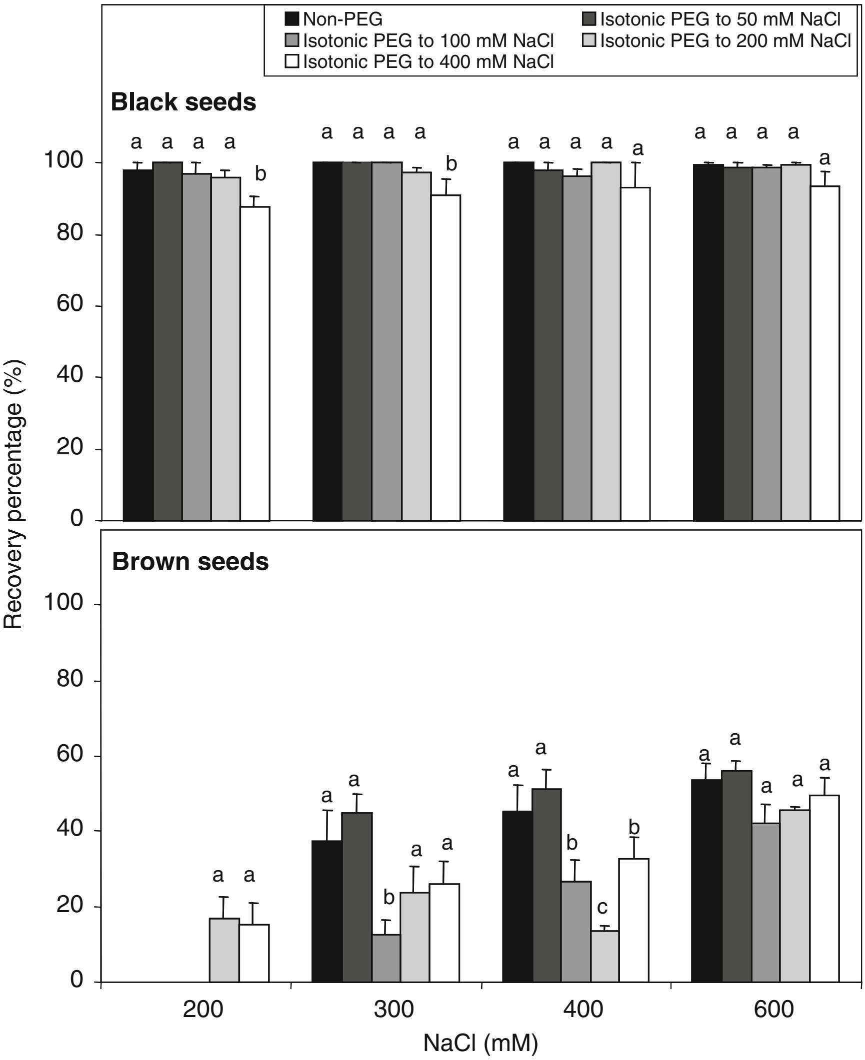

Fig. 4 Recovery percentage in dimorphic seeds of *Suaeda salsa* after 12 days in 0, 100, 200, 300, 400 and 600 mM NaCl solutions combined with isotonic PEG solution to 0, 50, 100, 200 and 400 mM NaCl, the ungerminated seeds were transferred to distilled water for 5 days

effect of PEG and salt (F=2.39, P=0.03 in black seeds and F=6.11, P<0.001 in brown seeds) on total germination percentage was significant in both black and brown seeds (Fig. 5).

4 Discussion

In agreement with previous studies [21, 22], brown seeds of *S. salsa* are more salt tolerant than black seeds, as they germinated better in high salinity conditions. Both black and brown seeds germinated very well in fresh water. This study additionally showed that brown seeds have higher germination not only in high salinity conditions but also in high drought stress and the combination of salt and drought stress conditions. However, the brown seeds showed lower recovery percentage and total germination ability than black seeds. Black seeds showed almost completely recovery when salt and PEG stresses were removed.

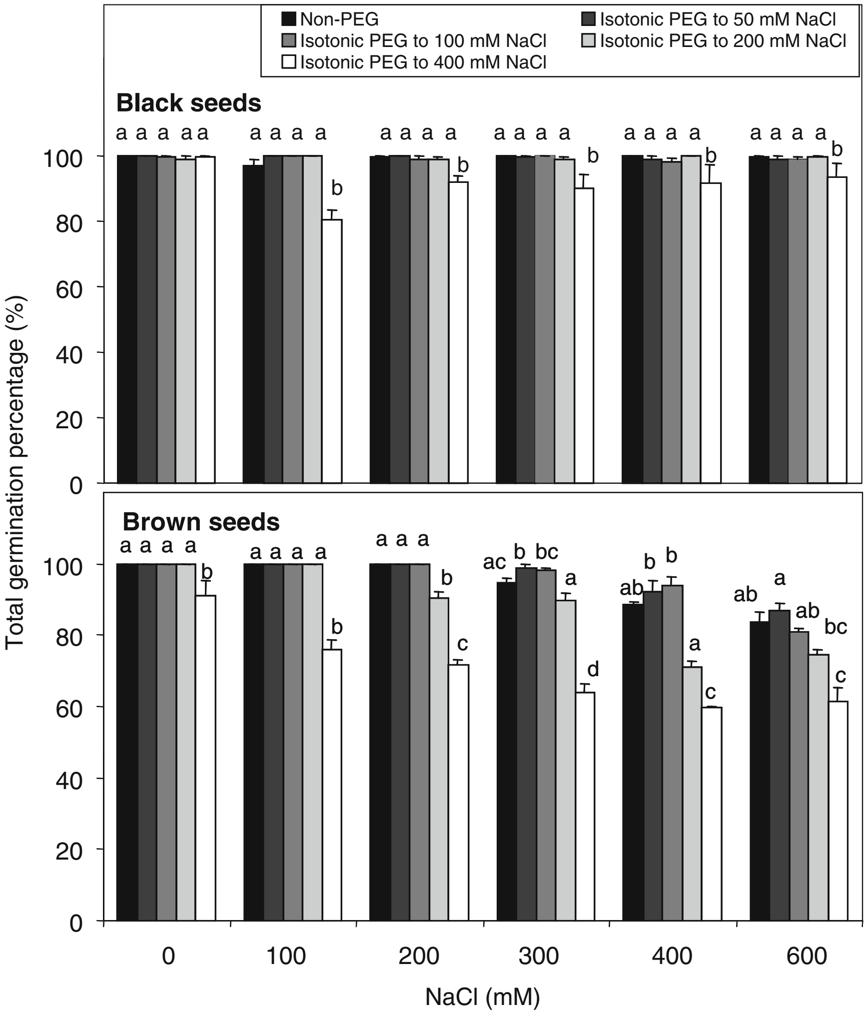

Fig. 5 Total germination percentage in dimorphic seeds of *Suaeda salsa* after 12 days in 0, 100, 200, 300, 400 and 600 mM NaCl solutions combined with isotonic PEG solution to 0, 50, 100, 200 and 400 mM NaCl, the un-germinated seeds were transferred to distilled water for 5 days

Seed dimorphism for dispersal characteristics is an evolutionary strategy to establish population under variable and harsh environmental conditions [9, 26]. Brown seeds had no dormancy and hence they had to undergo germination even when the growing condition would have been unfavorable for the seedlings. The black seeds on the other hand can avoid stress because of dormancy under stress. They can, therefore, contribute to forming seed band. The ability to produce dimorphic or polymorphic seeds enables halophytes to respond to salt-marsh and salt-desert environments by either varying dispersal distance of seeds from plants or the dormancy levels of seeds, which serves to extend the period of germination [7]. Past investigation on *Atriplex triangularis* showed similar results [16, 27]. The present study implies that brown seeds of *S. salsa* are more salt and drought tolerant and less dormant under salt and drought stress and could germinate better than black seeds in spring when soil salinity and drought is high, while during late spring and summer, this species may build up its population in low salinity through black seeds due to higher and complete recovery of germination once the stress was removed.

Germination process starts with water uptake by seeds and depends on several factors such as seed coat and salinity level of the medium [28]. Brown seeds germinated faster and better than black seeds under the same level of stress. They may be related to difference in water uptake due to different types of seed coats [22]. Similar results have been obtained in dimorphic seeds of *Atriplex* species [16–19, 29] and *Arthrocnemum indicum L.* and *Suaeda moquinii* [6, 20].

Increased salinity leads to a reduction and/or delay in germination of halophyte seeds [30]. Two processes mediate this reduction: osmotic effects and ionic effects. Our results showed that total germination percentage and recovery percentage of black seed was little affected by salt, which would imply that ionic effect was not more inhibitory than PEG in black seeds. Similar results were observed in several other halophytes [8]. Seed germination of halophyte under salinity is inhibited due to osmotic effects rather than specific ion effect [31]. Similar results were found in *Triglochin bulbosa* and *T. striata* [32], *Chrysothamnus nauseosus ssp. consimilis* and *Sarcobatus vermiculatus* [31], *Kalidium capsicum* [10], *Chenopodium glaucum L* [33], *Atriplex halimus* [5] and in *Haloxylon persicum* [23]. However, total germination percentage and recovery percentage of brown seeds were affected by salt and PEG stress, which would indicate that ion toxicity is also an inhibitory factor for germination of brown seeds. Similar results were founded in *Atriplex prostrata, A. patula* [19], *Haloxylon ammodendron*, *Suaeda physophora* [23], *Aristida adscensionis* and *Artemisia ordosica* [34].

Present study also showed that the seeds germination percentage and rate of germination were increased by addition of moderate PEG under high concentration of NaCl suggesting that moderate PEG may alleviate the detrimental effect of ion toxicity. These results differ from the recent results for another halophyte, *Atriplex halimus*, in which case NaCl alleviated PEG induced water stress [35]. Generally, interaction between ion toxicity and osmotic stress is very complex and needs further research. Further experimentation is needed to confirm the effect of PEG on seed germination under high salinity.

Seed germination of halophytic species is regulated by factors such as water, temperature, salinity and their interactions [36]. Inhibition of germination under hostile abiotic stress condition may have an important ecological significance, as it would enable the seedling to avoid stress. Once favorable conditions are created even transiently, such as after rainfall, seeds would germinate rapidly [8–10, 19, 37, 38]. Tolerance of seeds to salinity should be interpreted at two levels: (1) the ability to germinate at saline conditions and (2) the ability to germinate under non-saline condition after the exposure to high salinity is over [9]. Present study confirmed the hypothesis (1) brown seeds of *S. salsa* had higher germination than black seeds under saline conditions (2) black seeds had higher recovery percentage and total germination percentage than the brown seeds after exposure to high salinity and osmotic stress. Results indicate that the black seeds have a high longevity and thus can form a seed bank, which can germinate when the favorable environment occurs such as after rainfall.

5 Conclusions

The germination of the brown seeds was higher than the black seeds under high concentration of NaCl and PEG conditions. Brown seeds germinated more rapidly than black seeds under all conditions, however germination recovery and total germination percentage were higher in the black seeds than the brown seeds after NaCl and PEG stress was removed. The addition of moderate amount PEG (isotonic to 50, 100 or 200 mM NaCl solutions) in the medium with high salinity (above 300 or 400 mM NaCl) increased the germination of both two kinds of seeds, compared with no addition of PEG. Further studies are needed on some physiological and biochemical aspects of dimorphic seeds to get better understanding of the interactive effect of salt and drought stress on their germination.

Acknowledgements The authors would like to thank Drs. M. A. Khan and M. C. Saxena for going through the manuscript and making constructive commons. This study was supported by the National Natural Science Research Foundation of China (51179188) and the Project of the Knowledge Innovation Engineering of Chinese Academy of Sciences (KSCX2-YW-447).

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Kochia (*Kochia scoparia* (L.) Schrad) Unwanted or Wanted Plant for Forage Production in Harsh Environments

Mohammad Kafi, Bilquees Gul,
and Masoumeh Salehi

Abstract

Kochia (*Kochia scoparia)* have recently been considered as forage and fodder crop in marginal lands. Under severe drought and salinity kochia (35 dS m^{-1}) could produce up to 16 and 8 t DM ha^{-1} biomass in spring and summer cropping, respectively. Kochia produce 90 % biomass at 75 % water application in comparison to 100 % water application. Therefore, deficit irrigation is a useful management technique for Kochia even under saline conditions. Seeds of Kochia can germinate in a wide range of temperature, different levels of water potential, salinity, pH and depth of flooding and showed a high recovery from stress condition. Quick germination and growth of Kochia and its desirable drought, salinity and extreme temperature tolerance indicate that it can be considered as a valuable forage plant in case of shortage of conventional forage occurs, particularly in arid and semiarid regions. Cultivation of Kochia using saline waters for rehabilitation of saline areas, that have been left barren, can be regarded as an approach in sustainable and low-input agriculture. Biomass and seeds of Kochia can help in food production for people settled in these regions and their animals. Kochia in addition to be a forage crop can also be used bioremediation, oilseed and biofuel crop.

1 Introduction

Drought and salinity are the most important environmental factors inhibiting photosynthesis and decreasing growth and productivity of plants in many parts of the world. Therefore, extensive research into plant salt and drought tolerance has been carried out, to recognize or improve the tolerance of conventional crops as well as other capable plants [1]. Majority of the world's population relying on crops such as wheat, maize and rice to survive, evaluation and improvement of

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_11,

these crops salt tolerance are globally important. The result of many experiments shows that salt tolerance of above mentioned crops is limited to less than 10 dS m^{-1} [1].

There are as many as 6,000 species of terrestrial and tidal halophytes in the world [2]. In Iran, presently, a total of 365 species belonging to 151 genera and 44 families are known to grow in salty habitats, but they might be more than 400 species [3]. This group of plants tolerate salt concentrations that kill 99 % of glycophyte species [4].

Water is one of the essential resources in arid and semi-arid regions, where one-sixth of the world population lives [5]. In areas with water shortage, an attractive option is using seawater or brackish water for crop production, and this has worked well in inland and coastal sandy soils of some desert environments. Saline water aquifers and underground water sources exist in many arid lands of the world but these have been greatly underutilized. This brackish water could be a major resource in saline agriculture to produce food, feed, and fiber and oil seeds on non-productive, saline arid lands. In further support of saline agriculture, there would be no shortage of water since seawater in the oceans makes up 97 % of water on earth. Desert land is also plentiful, with around 43 % of the earth's total land surface being arid or semi-arid. A small part of this (about 15 %) is close to the sea and this would be convenient for growing crops using saline agriculture. There are hundreds of halophytes with characteristics to be used as cash crops. Saline agriculture, however, must fulfill two conditions to be cost-effective. First, it must produce useful crops at yields high enough to justify the expense of pumping salty water. Second, researchers must develop successful agronomic techniques for growing saline, water-irrigated crops in a sustainable way. These methods must also not contribute to further damage of natural environments. If applied successfully, this approach would lead to the domestication of wild, salt tolerant plants for use as food, forage, and oilseed crops. It was estimated that about 2,500–3,000 plant types occur naturally in saline habitats [6].

The most agriculturally useful halophytes are those that combine the attributes of efficient water use with high quality biomass production. Some halophytes used for millennia as forage species in arid and semi-arid areas. These species can support animal production provided they are grown in combination with less saline herbage such as legume species [7].

In the background of the progressive shortage of fresh water resources and soil salinization, a major aim is to evaluate the potential of local (xero-) halophytic species to be widely and economically used in arid and semi-arid regions. Major research topics are to identify and select plant species tolerant to drought and salt stress, to study their potential in the field of human or animal nutrition and to evaluate the possible use of non-conventional waters, such as seawater, brackish water and pre-treated wastewater. One possible concept of sustainable agriculture is based on "cash crop halophytes" irrigated with saline waters up to seawater salinity [8]. Scientists have conducted research on Kochia (*Kochia scoparia)* as a salt, drought and high temperature cash crop, that we will summarize them in the following sections.

2 Botany

Kochia (*Kochia scoparia)* is native to central and Eastern Europe and western Asia. It is well-adapted to arid conditions because of its deep root system. Penetration depths up to 5 m; lateral roots can extend to a horizontal distance of 7 m. The extensive taproot system and ball-like shoot mass that acts as tumbleweed are key morphological features that aid Kochia colonization or survival [9].

It is an annual herb, bushy to pyramid shaped, 0.15 to over 2 m tall; taproot up to 5 m long. Stems erect, green or red-tinged, much-branched, round, slender, soft-hairy or smooth; shoot breaks off at ground level forming a ball-like mass that acts as tumbleweed when mature and dry. Leaves are simple, alternate, sessile, narrow-linear to lanceolate, 1.5–6.0 cm long, tapering to a point at the tip, margins entire and fringed with hairs, pale green, upper surface usually smooth, lower surface usually covered with soft hairs; leaf blades with three or five prominent veins, leaves of the main stem larger than those of the branches, becoming progressively smaller along the branches toward the tips, often turning purplish-red in autumn. Flowers are inconspicuous, small, apetalous five-lobed calyx, sessile, green; solitary or clustered in groups of two to six in axils of upper leaves and dense bracted spikes. Sepals are spineless, with a short, wedge-shaped, scarious wing in fruit, sometimes surrounded by a cluster of long hairs; bracts linear lanceolate, attenuate, acute or acuminate, greenish. Flowers either perfect (three to five stamens) or pistillate (lacking stamens); ovary undivided, ovoid, single-seeded with the pericarp free from the seed.

Seeds nearly oval, ca. 1.5–2.0 mm long, flattened, grooved on each side, surface dull, brown with yellow markings to dark reddish-brown to black, covered by a thin papery envelope, and often enclosed by a fragile star-shaped hull (the attached flower parts) (Fig. 1). Kochia is diploid with a somatic chromosome number of $2n = 18$ [9].

3 Reproduction

Kochia is self-compatible and produces protogynous flowers where the stigmas emerge before anther development [13, 14]. The stigmas usually emerge 1 week before pollen is shed, are receptive to foreign pollen during that time, and deteriorate before anther dehiscence which prevents self-pollination in the same flower [14]. Pollen grains are spherical, and granular with 100–130 pores uniformly distributed over the grain surface [14].

It is estimated that 0.1 % of shed pollen would be distributed more than 150 m from the source [15]. Wind is an important pollination vector, but bees (Colletidae and Halictidae) also contribute to cross pollination in Kochia [16]. Kochia biotypes or ecotypes can show large variability in days to flowering, which may affect synchrony of pollination. In a field study in North Dakota. The reported time from emergence to flowering among 13 Kochia accessions collected from across the western USA varied from 57 to 100 d [17]. Two Kochia biotypes from North Dakota, which differed markedly in plant structure, also differed in time to flower initiation by as much as 24 d [14].

4 Ecology of Kochia

The ability of Kochia to establish quickly and grow vigorously under harsh environments allows it to become an important colonizer. It was non-existent in the forests, while it occurred in 45 % of the grain field and 17 % of the rangeland observed. A field study of Canadian prairies showed that Kochia was present in 45 % of all saline areas surveyed [18]. Kochia was one of the most common species occurring in dry land saline areas.

4.1 Soil Condition

Kochia germinated well over a wide pH range [19]. Germination was slightly reduced at pH extremes of 2 and 12 when compared to intermediate acidities. Kochia was thus shown to germinate in acidic to alkaline soils. Kochia seedlings had shorter radicles and hypocotyls at pH 2 than those at pHs between 3 and 10 [20]. Hypocotyls become shorter as the pH raised above 10. Germination percentage was approximately 50 % even in acidity of 4 and alkalinity of 9 solutions [21].

Much like any other plant, moisture is required by Kochia for germination and establishment. Germination of Kochia was not significantly reduced until the osmotic potential of the growth medium reached −8 bars. Germination declined as the potential decreased from −8 to −10 bars; even at −16 bars, Kochia still had 50 % germination, showing that soil moisture stress had no severe effect on germination [22].

Dry matter yield and root dry matter raised in a linear fashion as Nitrogen (N) application was increased from 0 to 250 kg ha^{-1} [23]. Phosphorous (P) fertilization also increased dry matter yield. Interactions were observed between N and P levels and the resulting dry matter yields. N at lower levels tended to have a greater yield

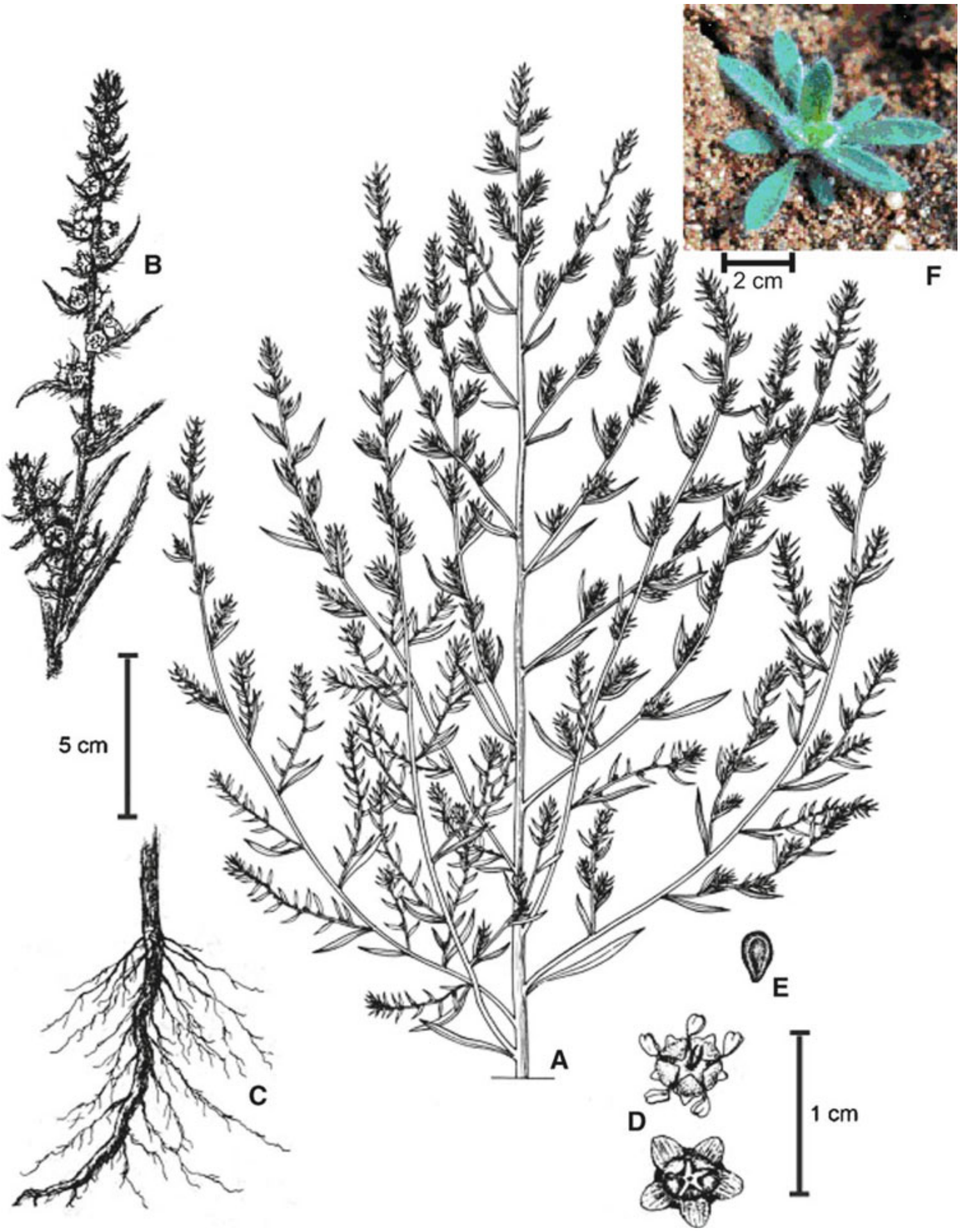


Fig. 1 *Kochia scoparia* (modified from [10, 11]: *A* mature plant; *B* upper branch; *C* root; *D* flowers; *E* naked/bare seed; *F* seedling [12])

increases. Whether N fertilization may hasten the plant maturity is still debatable. The effect of fertilizer on Kochia yield is previously reported in literature [24]. This experiment was conducted outdoors in pots buried in the ground. From the first 48 ppm of N added, a 3 fold increase in yield was obtained. Subsequent additions of N gave further yield increase. Plant color is the possible method for approximating the soil fertility.

Fertilization may become important with continuous Kochia cropping on the same site because an 8 t ha^{-1} yield with 12.5 % crude protein would remove about 160 kg N ha^{-1}[24]. In field trials, adding fertilizer gave substantial yield increases

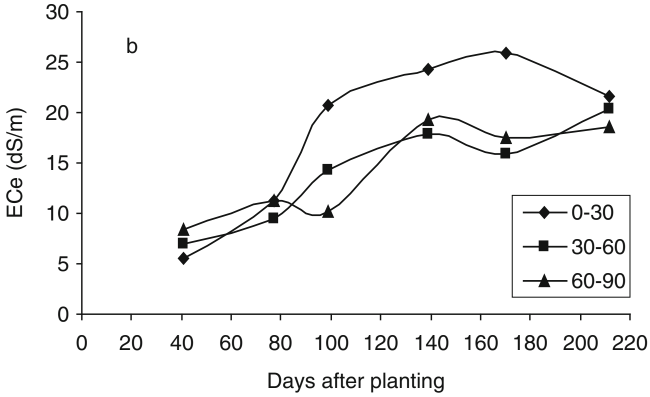


Fig. 2 Salinity variation (dS m^{-1}) of soil depth in Kochia farm as a function of days after planting at 28 dS m^{-1} and 100 % water application

judging by taller, darker green plants compared to the control.

The effects of various levels of phosphorus and nitrogen fertilizer was evaluated in irrigating condition with salt water on forage characteristics of Kochia by applying two levels of salinity of irrigating water (5.2 and 16.5 dS m^{-1}), and three nitrogen levels in the form of urea (0 (control), 100, 200 kg h^{-1}) and three phosphorus levels in super phosphorus form (0, 100, 200 kg h^{-1}) [25]. The results showed that nitrogen application leads to increase in height, lateral shoots, green area index and the leaf to stem ratio, fresh and dry biomass production compared with control. Phosphorous did not have any significant effect of forage parameters. The interactions of salt and nitrogen showed that nitrogen can partially decrease the negative effects of salt stress on Kochia and improve the forage characteristics and biomass production.

Evaluating the electrical conductivity of the saturated soil extract (ECe) in spring cropping showed that the soil salinity increased with saline water application [26]. The highest salt accumulation was observed at a depth of 0–30 cm of top soil at all levels of salinity. Soil salinity rose with saline water. For establishing Kochia, adequate leaching water must be applied for a proper stand, especially at 28 and 35 dS m^{-1}. Saline water up to 10 dS m^{-1} did not have a considerable effect on the Kochia seed germination [27]. But, after crossing this threshold the germination percentage and the rate decreased significantly and extreme reduction occurred at 20 dS m^{-1} salinity, but adequate rainfall leached the soil salinity from the top soil, thereby allowing Kochia a good opportunity to emerge fast in the existing conditions (Fig. 2).

4.2 Temperature

High growth of Kochia correlated closely with soil temperature with a base of 10 °C [28]. Low temperature is one of the most important environmental factors limiting the growth, product and geographical distribution of plants. A study carried out in three successive research phases to evaluate some agronomic, morphologic, biochemical and physiological traits of Kochia in different temperature conditions to assess the cold and freezing tolerance Kochia by using of pacloputrazol, hexaconazole and penconazole (0, 10 and 20 mg L^{-1}) and after that treated by freezing temperatures 0, −2, −4, −6 and −8 °C. Result showed that increase fungicide concentration in 10 and 20 mg L^{-1} than control decreased electrolyte leakage but electrolyte leakage build-up with decrease freezing temperature. Fungicide application increased −2 °C freezing tolerance in Kochia. Results showed that by reducing the temperature to −9 °C, electrolyte leakage remained constant and reducing the temperature below −12 °C caused a sharp increase in electrolyte leakage. Proline, soluble carbohydrates, total phenol concentration and electrolyte leakage decreased with increase in paclobutrazol concentration.

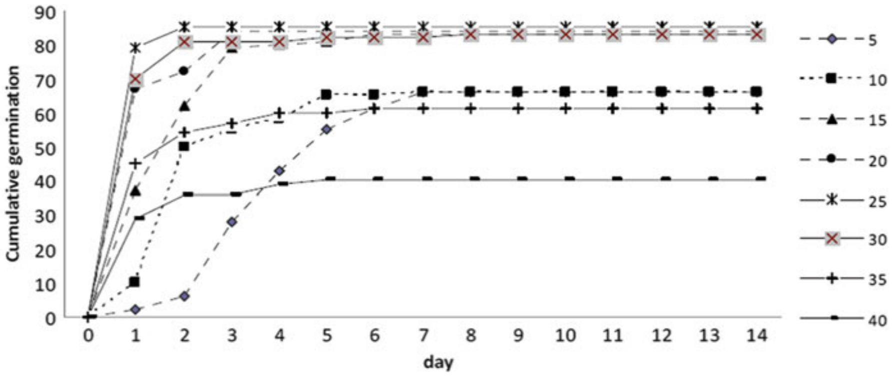


Fig. 3 Kochia cumulative germination at different temperature treatments during 14 days [21]

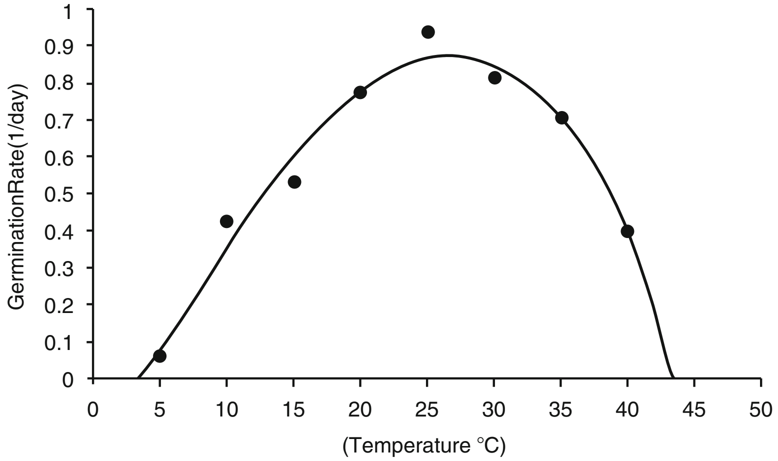


Fig. 4 Temperature and germination rate relationship in Kochia (to evaluate cardinal temperature) $R^2 = 90$ [21]

Germination characteristic of Kochia was evaluated at 5, 10, 15, 20, 25, 30, 35 and 40 °C under dark germinator showed that the highest germination percentage was obtained at 20–30 °C and the lowest obtained at 40 °C (Fig. 3) [29]. The longest and shortest period to 20 and 50 germination percentage was recorded to 5–10 °C and 20–30 °C respectively. Based on Five-Parameters Beta model, base, optimum and ceiling temperature for Kochia estimated 4 °C, 22.1 °C and 41.2 °C respectively (Fig. 4).

Kochia seeds were germinated in temperature regime of 25 °C night and 35 °C day yielded maximum germination [6]. Cooler temperature 5–15 °C significantly inhibited seed germination. Germination rate was highest at 25–35 °C and lowest at 5–15 °C, respectively. Previously reported that from 8 to 35 °C, average germination percentage was 85 %, but when temperature increased to 40 °C, germination percentage decreased to 31 % [30]. Although in 25 °C time taken to 50 % germination was achieved only at the first 24 h, when temperature increased or decreased from this level, germination rate decreased. Based on results, Kochia can adjust its germination in a wide range of temperature, from 3.5 (T_{base}) to 50 °C (T_{max}), with optimum germination temperature of 24 °C. This extended temperature range of Kochia germination and its ability of rapid germination reflect high potential of this plant to establish in most areas of Iran, as a new forage crop.

5 Water Requirement (Quantitatively and Qualitatively)

Kochia is responsive to water application but it can tolerate in the drought condition by reducing the transpiration surfaces. It is a halophyte, so that it can produce biomass in the presence of salinity. In an experiment arranged by Salehi [31], the effect of salinity on the shoot dry biomass was significant but interaction of drought and salinity effects were not significant in spring cropping [32].

The results of summer (first of June up to the end of September) and spring (first of April up to the end of September) cropping showed that increasing water application above the field capacity did not increase the salt tolerance level of Kochia [31]. It was found that the plant response to salinity depends largely on the soil water regimes [33]. Water and salt stress may have an additive effect in depressing the plant growth [34, 35]. The salinity tolerance level of Kochia could be improved by increasing water application. The highest and the lowest salt tolerance indices of Kochia were observed at 100 % and 50 % water application, respectively. Shortening the irrigation interval in saline conditions has the same benefit as shortening the irrigation interval in non-saline conditions [34]. It is predicted that the effects of salt stress may be ameliorated by more water [36]. However, in contrast it is reported that, the critical irrigation level decreased with increasing salinity, there by demonstrating that additional water does not compensate for salt stress [37]. The highest shoot biomass harvested at 1.5 dS m^{-1} treatment, in spring cropping (Table 1).

Table 1 Shoot dry biomass of Kochia irrigated with 6 levels of saline water and different levels of water application in 2008 (summer cropping), and 2009 (spring cropping), respectively

	Year	
	Summer cropping	Spring cropping
Salinity	Shoot dry biomass (g m^{-2})	
1.5	1342.1 a	3439.6 a
7.0	1393.9 a	2955.1 ab
14	1193.8 ab	2701.2 bc
21	1013.9 bc	2321.4 c
28	1017.4 bc	2199.6 c
35	883.1 c	1592.0 d
Irrigation		
50 %	1098.41 B	2572.4 A
75 %	1053.26 B	2714.2 A
100 %	1270.48 A	2573.6 A
125 %		2279.1 A

Shoot dry biomass followed by the same letter are not statistically different according to the least significant differences (*LSD*) between all pairs at the α-probability of 0.05. Irrigation levels compared separately [31]

In summer cropping, the highest shoot biomass was obtained at 7 dS m^{-1}. Under severe drought and salinity, Kochia still could produce 16 t DM ha^{-1} biomass spring cropping and 8 t DM ha^{-1} biomass in summer cropping, respectively (Table 1). Maximum biomass production of Kochia was 34 and 14 t DM ha^{-1} for spring and summer cropping at the mid bloom stage, respectively. Kochia produced 11 t DM ha^{-1} of dry matter in the Khorasan province of Iran [38]. Kochia production in Texas under dry condition and under irrigation was 11.3 t DM ha^{-1} and 26 t DM ha^{-1}, respectively [39, 40]. Kochia produced remarkable biomass in north of Iran.

In order to evaluate crop coefficient of Kochia in different salinity treatments; growing period of Kochia divided to four stages (Fig. 5). With increasing salinity crop coefficient reached to its maximum later and dropped earlier that indicate lower water requirement under salinity stress [31]. Salinity effect was evaluated on safflower water use and expressed that water consumption decreased with increasing salinity [41]. Reduction in crop coefficient may slow plant growth, lack of full coverage of canopy and lower evapotranspiration [42]. Salinity reduces growth, turgor pressure and so reduces water absorption [42].

Crop coefficient of Kochia in Birjand was 1.2 in its highest water consumption [27]. In fact plant height, leaf and soil albedo, canopy resistance and evaporation from soil can effect on determination of crop coefficient.

Optimal conditions for germination and recovery of germination from saline condition (0, 200, 400, 600, 800 and 1,000 mM NaCl) were

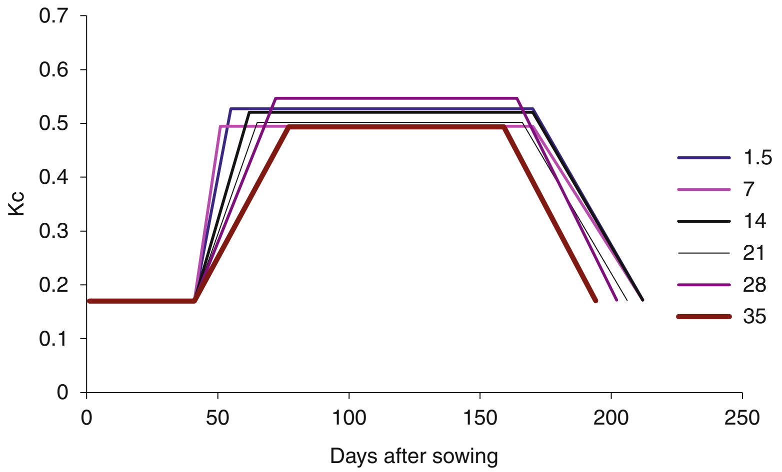
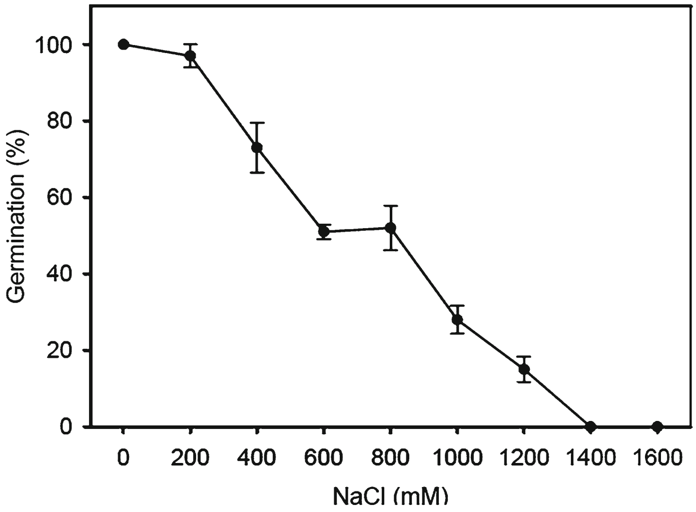


Fig. 5 Crop coefficient of Kochia at six levels of saline water in spring cropping [31]

Fig. 6 Seed germination (Mean ± S.E.) of *Kochia scoparia* under various concentrations of NaCl at 25–35 °C [43]



determined after being transferred to distilled water and reported that maximum germination occurred in distilled water, and an increase in NaCl concentration progressively inhibited seed germination [6]. Seeds were transferred from salt solutions to distilled water after 20 days and those from high salinities recovered quickly at warmer temperature regimes. Final recovery germination percentages in high salt treatments were high; indicating that exposure to high concentration of NaCl did not inhibit germination permanently.

The effects of salinity on germination, growth, ion accumulation and water relations of *Kochia scoparia,* was studied under greenhouse conditions and found that it is tolerant to salinity (600–800 mM NaCl) at germination; the seedling growth remained unaffected up to 600 mM NaCl and the plants survived with reduced growth up to a high salinity of 1,800 mM NaCl (Fig. 6) [43].

The germination characteristic of Kochia under different levels of salinity (0, 5, 10, 15, 20, 25, 30, 35 and 40 dS m^{-1}) using NaCl was evaluated and reported that the highest percentage of germination was in distilled water that didn't show any significant effect with 5 and 10 dS m^{-1} [21]. By increasing salinity, dry weight and length of seedling decreased. Potential of forage production of five different Kochia ecotypes in response to different levels of salinity

(5.2, 16.5 dS m^{-1}) in five Kochia ecotypes (Birjand, Urmia, Borojerd, Esfahan and Sabzevar) was investigated and showed that in the highest level of salinity, dry and fresh forage yield was comparable with low level of salinity and all Kochia ecotypes tolerates against these levels of salinities [44].

5.1 Disease

Kochia seedlings are susceptible to damping off. The causal organism of this disease was identified as Pythium de Baryanum. Attack of the disease occurred during and after seedling emergence. Discoloration of seedlings and collapse of the axis tissues were evident and the affected plants died. Leaf spot diseases attacked Kochia plants 3–6 in. high in nursery plots. The spot symptoms on leaves frequently became extensive enough to kill leaves. Stand destruction was a threat during cool rainy periods which are favorable to the spread of the disease [22] Kochia did not have diseases in Iran.

6 Cultivation Practices

6.1 Seeding Density and Depth

Emergence of Kochia averaged 74 % when seeds were left on the soil surface and it was reduced to 57 % when seeds were planted at a 3 mm depth. Maximum planting depth was 5 cm from which Kochia could successfully emerge. Since germination was unaffected by the absence of light, the decrease in emergence from depth was attributed to small seed size [22]. If Kochia is grown in stands of high density, primary axis growth is vigorous while lateral branch growth is suppressed resulting in tall, linear to lancelet shaped plants.

Kochia seed can germinate in a wide range of temperature, different levels of water potential, salinity, pH and depth of flooding and have a high recovery from stress condition. To obtain basic information from Kochia seed, result showed that the highest total germination and germination rate was observed in 20–25 °C. Hydropriming for 4 and 8 h cause decreasing in percentage, rate and germination index but increase in mean germination rate [29]. Increasing in flooding period caused decreasing in germination percentage compared to control. Electrolyte leakage increased with increasing in flooding [29].

Maximum forage yield was obtained from full irrigation with 13.22 t ha^{-1} dry matter and 31.81 t ha^{-1} fresh materials in Khorasan province [45]. In 40 % treatment a significant reduction in oil percentage (33 %) and seedling dry weight (65 %) were observed to complete irrigation.

The highest biological yield, leaf and stem dry weights and protein yield were obtained at 30 plant m^{-2} [46]. The best plant density, in terms of biomass production and leaf and stem dry weight, yield of protein was obtained at 30 plant m^{-2}, while for grain production a plant density of 20 plant m^{-2} could be recommended (Fig. 7).

Effect of salinity on seed yield was significant but the effect of water stress was not significant; however, salinity effect depends on the amount of water application. There were no significant differences in biomass production at 75, 100, and 125 % water requirement application but the effect of salinity was significant at 50 % water requirement application (Table 2). The highest seed yield was observed at 75 % water requirement application, 1.5 dS m^{-1} with 2.3 t ha^{-1} and the lowest seed yield was observed at 50 % water requirement application, 42 dS m^{-1} with 1.5 t ha^{-1}. In summer cropping kochia could produce 3.3 t ha^{-1} seed and at 35 dS m^{-1} produced 1.6 t ha^{-1} in the north of Iran. Kochia seed yield at full irrigation was 2.8 t ha^{-1} and reduced significantly at 80 % water requirement application in Kohorasan province [38]. It seems that the response of seed production to water requirement is dependent on the climate condition and sowing time.

7 Special Characteristics of Kochia

7.1 Drought Tolerance

Water potential measurements on Kochia plants showed a unique situation in which the potentials became and remained low even under irrigation [47].

Fig. 7 Kochia in a field trail [31]

Table 2 Effect of saline water and water application on seed production of Kochia in spring cropping

	Water application (%)			
Salinity (dS m^{-1})	50	75	100	125
	Seed yield (g m^{-2})			
1.5	231.00 a	229.09 a	251.14 a	279.27 a
7	272.24 ab	265.68 a	231.83 a	237.81 a
14	267.22 a	228.32 a	240.60 a	235.56 a
21	186.85 ab	181.94 a	210.55 a	229.01 a
28	194.05 ab	187.50 a	178.24 a	182.03 a
35	188.71 a	163.05 a	173.15 a	173.06 a
42	154.38 b	179.67 a	158.14 a	209.91 a

Seed yield followed by the same letter for salinity levels within each water application level are not statistically different according to the least significant differences (LSD) at α-probability of 0.05 [31]

Plants may show drought avoidance by one or more adaptation strategy. One adaptation is more vigorous and competitive root system which gives the plant access to more soil moisture by using a greater volume of soil. A second adaptation involves using a specialized, highly efficient photosynthetic pathway [22]. A series of experiments using different levels of saline water (1.5–42 dS m^{-1}) and different levels of applied water (25–125 % of the water requirement) in the farm and greenhouse was performed [31]. Results showed that Kochia like other halophytes is sensitive to drought and salinity at the earliest stages of growth. Salinity reduced linear phase of growth and decreased biomass production but salinity tolerance of Kochia was improved by increasing water application. Plants showed more tolerance against drought stress, when stress was induced in the whole growth season. In all experiments, ecotypes from the arid regions, revealed a better response to drought and salinity. Under severe drought and salinity, Kochia still could produce up to 16 and 8 t DM ha^{-1} biomass. Results of water depletion from different soil layers showed that Kochia uptakes more water from the 30–60 cm soil depth. The soil salinity (ECe) of this section was lower in comparison to the 0–30 cm soil depth. At 75 % application of water requirement, Kochia produced 90 % of biomass in comparison to 100 % water application. Therefore, deficit irrigation is a useful management technique for Kochia even under saline conditions.

7.2 Salt Tolerance

Kochia is very tolerant to salinity. It is so salt tolerant that only 50 % seed yield reduction occurred at 35 dS m^{-1} of irrigation water [26] and 50 % reduction of plant dry weight was calculated at 38.16 ± 3.53 dS m^{-1}. Using 7 dS m^{-1} of saline water and 50 % of water requirement application will cause only 13 % reduction in seed yield. The interaction effects of salinity and drought might not be additive or multiplicative and it might be even ameliorative. Plants under salinity stress will produce less transpiration area (leaves), so plant can manage drought more efficient. Drought might limit the water in the surface layer of the soil so that plants will send their roots to the deeper soil layers and the salt concentration at that layer might be lower than upper layers.

7.3 Rooting Habit

An investigation was undertaken at Hays, Kansas to study the root system of Kochia [48]. In first experiment, Kochia roots had penetrated to a depth of at least 2.4 m, but considerable lateral branching was also apparent. Kochia had a rooting profile of 6.7 m wide and more than 2 m in depth [49]. From such investigations, it appears that the rooting habit of Kochia is important in its drought resistance.

7.4 C4 Photosynthetic Pathway

Kochia is a C_4 plant that uses NADP-ME in the C_4 photosynthetic pathway [50], and displays a kochioid type of C_4 Krantz anatomy [51, 52]. A specific feature of such C_4 pathway is the requirement for sodium (Na) as a micronutrient [53]. Sodium may have a physiological role in enhancing in vivo activity of the C_4 enzyme phosphoenol pyruvate carboxylase [54]. This feature may partly explain the observed salinity tolerance in many C_4 species.

From the low water potentials observed, the suggestion was made that Kochia plants continued to exchange water vapor, oxygen, and CO_2 with the atmosphere for most of the day. The metabolism of the plant appeared to be modified to allow for continued growth at lower water potentials. For this reasons, plants such as Kochia are well suited to hot, bright regions [9].

7.5 Autoallelopathy

Several phytotoxic compounds have been found in Kochia: caffeic acid, chlorogenic acid, ferulic acid, myricetin, quercetin, saponins, alkaloids, oxalates, and nitrates [55–57]. Although these compounds are known inhibitors, they had no effect on Kochia germination because it germinates rapidly. Inhibition of growth was dramatic once the seedlings reached 40–60 h of age. Evidence to support auto-toxicity also came from field observation which showed that second year growth had a large density but much reduced growth.

Kochia can be toxic to livestock if consumed in large quantity, and death of cattle, sheep, and horses has been reported [58]. Toxic substances identified in Kochia include saponins, alkaloids, oxalates, and nitrates [55–57].

7.6 Insect Resistance

Kochia foliage contains compound(s) with insecticidal activity, and extracts from ground Kochia shoot biomass were found to have acaricidal activity (contact and systemic toxicity) against three species of mites (Tetranychus spp.; Acari: Tetranychidae) [59]. In an early study on Kochia, reported that, it was resistant to damage by grasshoppers [60]. In 1 year, yields from sweet clover were non-existent caused by grasshopper damage; Kochia remained unaffected.

7.7 Other Characteristics

Kochia may be detrimental to human health as a pollen allergen. In a study in Thailand, Kochia pollen was the second most important weed allergen, with 14 % of 100 patients with allergic rhinitis sensitized to it [61]. In Saudi Arabia, 51 % of indigenous patients and 28 % of North American expatriates living in the area (total of 1,159 patients) were sensitized to Kochia pollen, which ranked 2nd and 7th most important allergen resulting in sensitization in the respective groups [62]. Kochia is cultivated in Japan and China where the young shoots are used as a vegetable, and the seeds are used medicinally or ground into flour [9]. Kochia is cultivated in the countryside in China and Russia for making brooms [9]. The dried branches of this plant are harvested at the ripening stage for use as a broom for open-space cleaning, for example, cleaning public avenues [38].

8 Ions Accumulation of Kochia

Kochia leaf Na at vegetative stage was higher than flowering and ripening stages [31]. All Na which is transported to shoot remain there, because plant reabsorbs less amount of Na by phloem [32]. Na loading to shoot can be controlled by Na loading in xylem [63]. Higher amount of Na and K in shoot showed that both of these anions have role for regulating osmotic potential [64]. K content of leaf was twice the Na content even in the non-saline condition. K content of Kochia is 2.6–2.9 % of dry weight [24]. Salinity treatment 1.5–42 dS m^{-1} at initial growth changed Na/K ratio from 1.86 to 0.86 [32]. It is seems that plant ability for maintaining Na/K ratio in salinity tolerance of plant [65].

Leaf had the highest Cl accumulation [31]. Results showed that Cl content of stem was not affected up to 35 dS m^{-1} salinity. Leaf can tolerate 400 mM Cl in leaf; even very sensitive plant (lemon) can tolerate 250 mM Cl in leaf [63]. Salinity tolerance of Kochia to Cl is more than sulfate [66]. Selective absorption of anions showed that plant can exclude more Na and absorb more K; that showed the higher capacity of root system to absorb K [67]. Selective absorption of K increased by raising salinity up to 21 dS m^{-1} and after that decreased. By increasing Na in irrigation water selective transport of plant for K decreased and plant absorbed more Na. Because of the raising Na content of irrigation water; plant Na/K ration increased by raising salinity [31].

Table 3 Saline water effect on Na accumulation (Kg ha^{-1}) in the soil, and in plant at vegetative, flowering and ripening stages

Salinity (dS m^{-1})	Soil Na	Plant Na content		
		Vegetative	Flowering	Ripening
1.5	130.5	130.8	274.2	200.1
7.0	559.7	141.2	224.2	224.9
14	1095.7	108.7	215.5	333.0
21	1621.7	86.2	180.5	258.9
28	2478.7	69.4	205.8	231.7
35	2683.6	57.6	128.9	200.9
42	3214.6	78.0	135.8	238.5

Selective transportation of anions showed that root can control Na transportation and more K transported to leaf. Increasing salinity increased selective transportation and decreased Na transportation to leaf. Results showed that Na/K ratio at root is more than leaf and stem. In comparison of other halophytes like *Echinochloa frumentacea*, Kochia is a salt excluder [68]. Using saline water increased Na content of soil (Table 3). Kochia is a C_4 plant that uses NADP-ME in the C_4 photosynthetic pathway [50, 69], and displays a kochioid type of C_4 Krantz anatomy [51, 52]. A specific feature of such C_4 pathway is the requirement for sodium (Na) as a micronutrient [53]. Sodium may have a physiological role in enhancing *in vivo* activity of the C_4 enzyme phosphoenol pyruvate carboxylase [54]. This feature may partly explain the observed salinity tolerance in many C_4 species. With raising salinity despite the increasing Na accumulation in plant decreased because of decreasing shoot biomass. According to the result, it seems that plant can absorb all the Na if 3 dS m^{-1} saline water is used.

Kochia may need Na as a micronutrient [31]. Root system of this plant absorbs and transports Na to shoot selectively. Besides selective absorption, Na transport from root to shoot is selectively and all these factors help Kochia to manage Na/K ratio. Kochia can tolerate Cl accumulation in leaves (Table 4). These two strategies, selective absorb and transport, are used for maintenance of Na/K ratio in

Table 4 Saline water effect on Cl accumulation (Kg ha^{-1}) in the soil, and in plant at vegetative, flowering and ripening stages

Salinity (dS m^{-1})	Soil Cl	Plant Cl content Vegetative	Flowering	Ripening
1.5	49.4	308.4	504.7	735.8
7	212.5	333.2	414.8	771.1
14	418.1	274.4	441.8	1108.4
21	623.6	231.4	335.1	757.1
28	829.1	193.7	420.8	712.2
35	1034.6	149.0	289.3	664.9
42	1240.2	137.5	295.8	544.7

Table 5 Salinity effect on Na/K at vegetative, flowering and ripening stages and selective absorption (SA) of anions

Salinity dS m^{-1}	SA	Na/K plant Ripening	Flowering	Vegetative
1.5	7.85 abc	0.53 cd	0.68 bc	0.68 abc
7	9.71 a	0.67 cd	0.72 bc	0.63 bc
14	8.13 ab	0.96 ab	0.61 c	0.59 c
21	10.27 a	0.79 bc	0.80 abc	0.85 a
28	6.73 bcd	0.85 abc	0.80 abc	0.77 abc
35	4.69 d	1.02 a	0.91 ab	0.88 a
42	5.44 cd	0.93 ab	0.97 a	0.80 ab

Kochia (Table 5). Despite Kochia can maintain sodium at low level but it needs to spend a lot of energy and which in the end reduces the amount of plant biomass. The main advantage over other halophyte plants is in the feed value, because low amount of leaf Na raise feed value.

9 Water Use Efficiency and Water Productivity

One of the most important reasons for interest in Kochia is that it has low water use relations to the amount of dry matter produced when compared to other crops. Primary advantage of the C_4 photosynthetic pathway is the associated high water-use efficiency (WUE); C_4 species have higher ratios of photosynthesis to transpiration than C_3 species [54]. A study in New Mexico found that the WUE of Kochia was about three times that of alfalfa [39]. In a study in Iran, WUE in Kochia, subjected to irrigation water of varying salinity levels, ranged from 7.6 to 11.9 kg biomass mm^{-1} evapotranspiration and 2.4 to 2.9 kg seed mm^{-1}[27]. Kochia was about equal, in water use efficiency, to red root pigweed (*Amaranthus retroflexus*) and wild oats (*Avena fatua*) at 275 g of water used for each gram of forage produced [70].

Water productivity of Kochia decreased with raising salinity and water application. The highest water productivity was observed at 1.5 dS m^{-1} and 50 % water application treatment and the lowest was at 35 dS m^{-1} and 125 % water application. Salinity affects soil water potential and reduces soil available water or stomatal closure and evapo-transpiration rate reduction, leaf area and size reduction [71, 72]. Increasing salinity reduces root growth and water absorption [73]. Increasing salinity and water application decrease salinity effect on water productivity because abundant water is available for plant. Generally, deficient irrigation can be used in Kochia in the presence of salinity.

10 Possible Utilization of Kochia

10.1 Hay Production

Kochia has been used as a livestock feed during periods of forage shortages resulting from drought, in 1988 across the Canadian Prairies and USA Great Plains when the value of non-cultivated Kochia harvested as emergency forage in southern Saskatchewan was estimated at $7 million (Saskatchewan Research Council 1992). As a dry land forage crop in arid to semiarid regions, Kochia has several noteworthy characteristics including drought, salinity, and grasshopper (Orthoptera: Acrididae) tolerance, leafiness, high vegetative and seed yields, and high protein and carbohydrate content [60]. In the semiarid Canadian Prairies, forage production generally averages 4–7 t ha^{-1} annually; early spring and fall-seeded Kochia in southwestern Saskatchewan yielded between 5.4 and 10.9 t ha^{-1} on a severely saline soil [74]. Harvested during the vegetative stage, crude protein content ranges from 10 to 25 %, but decreases as the plant matures [75].

10.1.1 Forage Quality of Kochia

Digestibility of Kochia forage crude protein, digestible energy, and intake by sheep were lower than alfalfa [76]. Kochia forage has relatively high digestibility *in vitro* when harvested at the flowering stage compared with mature Kochia [24].

No difference was found in dry matter intake or dry matter digestibility when goats were fed diets of varying proportions (0–100 %) of fresh Kochia and ammoniated barley (*Hordeum vulgare* L.) straw [77]. Kochia hay can be fed at levels between 25 and 50 % of the diet without adverse effects on intake or digestibility by sheep [78]. Numerous feeding trials have generally concluded that Kochia fodder should not comprise the majority of the diet and pure Kochia stands should not be grazed by livestock [57]. In a feeding study in Saskatchewan, beef steers were fed rations with varying amounts of Kochia hay harvested from a saline flat in a field; the hay contained 2.6 % soluble oxalates and 0.5 % nitrates [79]. A later study by found that the maximum nitrate-N accumulation in Kochia forage was 0.5 g kg^{-1}, which was less than the recommended 1.1 g kg^{-1} (0.11 %) nitrate-N upper limit for livestock feed to avoid poisoning [80]. As the proportion of Kochia in the steers' diet exceeded 60 %, dry matter intake and N retention declined sharply [79]. Both urinary and fecal N excretion increased with increasing levels of Kochia in the diet, indicating possible liver and kidney damage.

Feeding trials with sheep indicated high digestible crude protein (83 %) and low total digestible nutrient value (57 %) for immature Kochia, and relatively low dry matter consumption per day; these values declined and crude fiber content increased with advanced growth stage [75]. The quality and quantity of forage production in intercropping of Kochia (*Kochia scoparia L.*) with Blue Panic Grass (*Panicum antidotale*) under irrigation with saline water was evaluated [81]. Mix of 50 % Blue Panic Grass and 50 % Kochia with an average of 1,408 g m^2 had the highest dry matter yield and then treatment 25 % Blue Panic Grass and 75 % Kochia and 75 % Blue Panic Grass and 25 % Kochia were 1,317 and 993 g m^{-2}, respectively. Due to lower growth rate of Blue Panic Grass (perennial) in the first year, a large proportion of dry matter per treatment was associated with Kochia and land equivalent ratio was less than one in all intercropping treatments. In first and second clippings, there was no significant difference between intercropping treatments in terms of crude protein, ash, NDF and ADF.

Previously reported that after being pastured on Kochia for 5 months, one cow had died and others were sick [82]. Photosensitization was evident in the sick animals as they had swollen eyelids, swollen necrotic muzzles, lacrimation, necrotic skins under white hair patches, and a necrosis of teat ends. The animals were generally lethargic and depressed. Some blindness was also noted in a few of the animals. Problems were alleviated once cattle were removed from the Kochia pasture. Although Kochia was considered a good feed, caution was recommended in its use.

Sheep grazing on Kochia pasture for 45–50 days became reluctant to graze and developed nasal swellings and nasal necrosis along with other complications [58]. In all cases, problem developed while animals were on mature Kochia. Kochia toxicity was thought to be related, in part, to high oxalate content in mature plants. Because of potential toxicity problems, a diet consisting of no more than 50 % Kochia is recommended [78].

Following various isolation experiments, and small animal feeding trials, the New Mexico researchers concluded that the toxic agent was an alkaloid. Some evidence was obtained recently that the alkaloid was spartine [83]. Previously isolated very small amounts of harmane and harmine alkaloids from Kochia [84]. Feeding trials with cattle showed that Kochia could be fed at amounts up to 40–50 % of the diet to cows without problems. Above 50 %, however, the animals' intake of feed fell off quit rapidly. The best stage of maturity to cut Kochia for hay was at late bud or early flower. This was the best compromise between yield, crud protein content, digestibility and reduced levels of nitrate and oxalate. Crimping the hay seems very important to hasten drying (e.g. use haybine type of equipment) [83].

Silage made from second growth Kochia at a height of 12 in. and from mature plants 5 ft. tall was evaluated [60]. The silage was considered satisfactory with and without the use of molasses. Intake of Kochia silage was dependent on the age of harvest. Plants harvested earlier had higher leaf: stem ratios and were much more preferred [75].

10.2 High Protein Seed Crop

Kochia produce high protein seed, which can be used in poultry feed. Fed turkey poults rations containing 15 or 30 % Kochia seed (25–33 % crude protein), with the saponins present in the seed either removed by washing with sodium hydroxide (NaOH) or inactivated by mixing the whole seed with phytosterols [85]. The control treatments, unwashed Kochia seed or seed without added phytosterols, resulted in 40 and 93 % mortality for the 15 and 30 % rations, respectively. If using Kochia in the ration, a diet containing 15 % Kochia seed treated with 1 % NaOH was recommended.

10.3 Phytoremediation

Kochia does not appear to be a suitable crop to mine salts from saline soils in an attempt to reduce salinity [86]. Research at Baildon, Saskatchewan showed that Kochia was useful in stabilizing of a particular saline site. Kochia was established on a localized saline seep in down slope position and alfalfa was planted in the upslope recharge area. After several years under normal forage management, marked soil improvement was detected in the seep. Previously noted that even though Kochia is not always a cure for saline soils, the yield potential and subsequent economic return from unproductive soils is of major interest [86]. Kochia is reported to have fairly high potassium (K), magnesium (Mg), calcium (Ca), and low chloride (Cl) contents [66, 87], tends to accumulate K and exclude sulfate relative to concentrations of these ions in the soil.

Kochia is also beneficial in phytoremediation, ranking 6th out of 10 plant species in bioaccumulation of cesium-137 from solution [88]. The species may also make easier remediation of hydrocarbon-contaminated soil, as Kochia and some native perennial grasses were the most abundant species at contaminated sites in southern Saskatchewan [89]. Furthermore, the rhizosphere of Kochia significantly enhances the microbial-mediated mineralization of herbicides such as atrazine and metolachlor, and insecticidal hexachlorocyclohexane isomers [90].

10.4 Edible Oil Crop

The oil content of Kochia seeds was between 8.4 % in the non-saline and 7.8 % under 42 dS m^{-1} salinity, and the effect of treatments on oil content was not significant. Drought stress up to 40 % of water application did not have significant effect on oil content [38]. Kochia could produce 192 kg ha^{-1} oil at 25 % of deficit irrigation and 1.5 dS m^{-1}; and 120 kg ha^{-1} at 42 dS m^{-1} and 50 % of deficit irrigation. Canola could not produce seed at 35 dS m^{-1} but Kochia produced 138 kg ha^{-1} oil in this level of salinity [91].

Analysis of Kochia's seed oil showed the presence of 14 fatty acids of which five were saturated and nine were unsaturated fatty acids (Table 6). Saturated and unsaturated fatty acid contained 12 and 84 % of seed oil content, respectively. Palmetic ($C_{16:0}$) was the dominant saturated fatty acid (8.4 %), and linoleic (50 %) and oleic (20 %) acids were the dominant unsaturated fatty acids. Kochia seeds also contained 4.7 % α-linolenic acid. Linoleic and α-linolenic acids are the two essential fatty acids that the human body needs and cannot manufacture [92]. The oil content of the halophytes of Pakistan was evaluated and reported that they did not have oleic and lenoleic acids in their oil components [93]. Kochia oil contains 4.6 %, 5- Hexadecanoic acid. Previously reported that this fatty acid can be used to control the disease carrying mosquito *Cluex quinquefaciatus* [94]. This unusual fatty acid is produced in the seed of *Kochia scoparia*. Kochia oil contains 28 % mono-unsaturated and 56 % poly-unsaturated fatty acids; therefore, Kochia seeds have the potential to be used as a source of edible oil.

Table 6 Saturated and unsaturated fatty acid fractions (%) in the oil of Kochia seeds

Fatty acid		Percent
Saturated		
Hexadecanoic acid methyl ester (palmetic)	$C_{16:0}$	8.39
Octadecanoic acid methyl ester (stearic)	$C_{18:0}$	2.74
Eicosanoic acid methyl ester (arachdic)	$C_{20:0}$	0.92
Docosanoic acid methyl ester (behenic)	$C_{22:0}$	0.06
Tetracosanoic acid methyl ester (lignoceric)	$C_{24:0}$	0.12
Total		12.23
Unsaturated		
5- Hexadecanoic acid methyl ester	$C_{16:1}$	4.59
9-Hexadecanoic acid methyl ester (palmitoleic)	$C_{16:1}$	0.14
9- Octadecanoic acid methyl ester (oleic)	$C_{18:1}$	19.69
5- Octadecanoic acid methyl ester	$C_{18:1}$	2.22
11- Eicosanoic acid methyl ester (gadoleic)	$C_{20:1}$	1.32
5, 9- Octadecanoic acid methyl ester	$C_{18:2}$	0.69
9, 12-Octadecanoic acid methyl ester (linoleic)	$C_{18:2}$	49.90
5, 9, 12- Octadecanoic acid methyl ester	$C_{18:3}$	0.63
9, 12, 15-Octadecanoic acid methyl ester (α-linolenic)	$C_{18:3}$	4.67
Total		83.85

Table 7 Lignin and other inhibitors in Kochia

Parameter	Units	Mean	St. dev.
Insoluble lignin	%	16.1	0.6
Soluble lignin	%	1.9	0.1
Hydroxymethylfurfural	$mg\ g^{-1}$	13.3	3.3
Furfural	$mg\ g^{-1}$	245.4	9.0
4-hydroxybenzoic acid	$ug\ g^{-1}$	35.2	1.0
Vanillic acid	$ug\ g^{-1}$	185.0	6.1
Syringic acid	$ug\ g^{-1}$	1017.8	27.5
4-hydroxybenzaldehyde	$ug\ g^{-1}$	89.6	3.4
Vanillic aldehyde	$ug\ g^{-1}$	73.2	13.7
Syringic aldehyde	$ug\ g^{-1}$	344.9	20.5

10.5 Potential Use of Kochia as Biofuel

Biomass-based ethanol (or bioethanol) is well-entrenched as a potential substitute for petroleum-based gasoline. One of the primary benefits of switching to this fuel is that biomass is renewable, and can potentially provide a sustainable fuel supply over the long term [95].

Many biofuels generate large benefits when compared to fossil fuels. Cellulosic materials are comprised of lignin, hemicelluloses, and cellulose and thus are sometimes called lignocellulosic materials. They have to be converted to five and six carbon sugars, before they can be fermented and converted into ethanol. Lignin which contains no sugars encloses the cellulose and hemicelluloses molecules, making them difficult to reach. Cellulose molecules consist of long chains of glucose molecules as do starch molecules, but have a different structural configuration. These structural characteristics plus the encapsulation by lignin makes cellulosic materials more difficult to hydrolyze than starchy materials. Also hemicelluloses is comprised of long chains of sugar molecules [96].

The feasibility of converting ligno-cellulosic vegetative biomass of plants into sugar, which is subsequently fermented to ethanol, opens new venues to tackle the problem of 'food or fuel' because the grain is spared for food in the process. Halophytes grow under conditions where both available water and soil are saline [97]. Therefore use of halophytes as biofuel crop is advantageous because they do not compete with conventional crops for high quality soil and water and hence do not encroach on the resources needed for food crops [98]. Kochia cellulose content was 40 % lower than Ethiopian mustard (Brassica carinata) residue, Kochia cellulose was 30 % lower than wheat straw and alfalfa, but only 15 % lower than corn stoffer. Hemicellulose content in kochia was fairly similar to that in alfalfa and corn, while kochia lignin was similar to lignin in other biomass feedstocks. Alfalfa biomass had the lowest hemicellulose content and oats the highest, with more than two fold difference between the two crops. Overall, the cell wall structure of kochia was most similar to corn stoffer.

During hydrolysis of lignocellulosic materials a wide range of compounds which are inhibitory to microorganisms are formed or released. Based on their origin the inhibitors are usually divided in three major groups: weak acids, furan derivatives, and phenolic compounds. These compounds limit efficient utilization of the hydrolysates for ethanol production by fermentation. If the inhibitors are identified and the mechanisms of inhibition elucidated, fermentation can be improved by developing specific detoxification methods, choosing an adapted microorganism, or optimizing the fermentation strategy [99]. Table 7 showed lignin and other inhibitors of Kochia. Vanillin, a major phenolic compound, has been suggested to be a stronger inhibitor of growth and bioethanol fermentation than other inhibitors because vanillin acts at low concentrations [100]. Furfural and hydroxymethylfurfural (HMF) are representative inhibitors among many inhibitive compounds derived from biomass degradation and saccharification for bioethanol fermentation. Most yeasts, including industrial strains, are susceptible to these inhibitory compounds, especially when multiple inhibitors are present [101]. *p*-Hydroxybenzoic aldehyde, a lignin-degradation product is more inhibitory than the sugar-derived products, such as furfural and 5-hydroxymethylfurfural [102].

Glucose was the main sugar of Kochia. Larger amounts of glucose are advantageous for ethanol production because glucose can (currently) be converted at higher yields to ethanol than most other sugars, especially compared to pentoses like xylose and arabinose. Xylose content of Kochia was the same as other alfalfa but arabinose was higher in Kochia.

This result suggests that Kochia can compete favorably with other conventional sources for biofuel production. It provides an option of selecting high biomass plant that contain suitable ligno-cellulosic material for conversion into ethanol and can be grown without encroaching upon arable land and fresh water.

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Importance of the Diversity within the Halophytes to Agriculture and Land Management in Arid and Semiarid Countries

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Abstract

Freshwater resources will become limited in near future and it is necessary to develop sustainable biological production systems, which can tolerate hyper-osmotic and hyper-ionic salinity. Plants growing in saline conditions primarily have to cope with osmotic stress followed by specific ion effects, their toxicities, ion disequilibrium and related ramifications such as oxidative burst. This is an exclusion criterion for the majority of our common crops. In order to survive under such conditions, suitable adjustments are necessary. Beside the control of the entrance on root level, the ability to secrete ions (excreter) or to dilute ions (succulents) helps to preserve a vital ion balance inside the tissues.

Sadly, traditional approaches of breeding crop plants with improved abiotic stress resistance have met limited success so far. Failures were due to two problem areas, lack of easy to detect traits and too many genes that had to be transferred at a time. These arguments underline the advantage of utilizing suited halophytes as crops on saline lands and to improve their individual crop potential. Because of their diversity, halophytes have been regarded as a rich source of potential germplasm. A variety of halophytic plant species already has been utilized as nonconventional cash-crops. Lieth H, Mochtchenko M (Cash crop halophytes: recent studies. Tasks for vegetation science, vol 38. Kluwer, Dordrecht, 2003) described the

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_12, © Springer Science+Business Media Dordrecht 2014

utilization of halophytic species for the improvement of sustainable agriculture as well as sources of income.

However, knowing that saline irrigation always comprises the risk of increasing salinity up to levels where no plants (even no halophytes) can exist anymore, it is important to achieve sustainable conditions. Therefore it is essential to study the interaction among soil salinity, individual species (to study heterogeneity within the halophytes and plant diversity), biotic interactions, and atmosphere at distinct conditions before application.

The heterogeneity within halophytes (biotic factor) is often ignored but biotic interactions can be in this context an ideal accessory to stabilize sustainable populations on saline lands. The aspect, that dicotyledonous halophytes, when grown in saline soils, generally accumulate more NaCl in shoot tissues than monocotyledonous halophytes (especially grasses) has several consequences on their suitability as crops and their culture conditions (procedure to apply salinity). The implementation of an intercropping system (halophyte culture) is such a way to use saline land and brackish water for producing an economically viable and environmentally sound agriculture. It was estimated that 15 % of undeveloped land in the world's coastal and inland salt deserts could be suitable for growing crops using saltwater agriculture. This amounts to 130 million hectares of new cropland that could be brought into human or animal food production chain - without cutting down forests or consuming more scarce freshwater for irrigation.

1 Introduction

There is overwhelming evidence that the ancestors of modern land plants evolved in aquatic environments, most probably in saline oceans where they existed and diversified over millions of years [1, 2]. However the plants growing on land have a distinct advantage over their counterparts in water in that about two-thirds of total annual photosynthetic CO_2 uptake takes place on land, and one-third in the rivers and oceans while land plants contain nearly 200 times as much carbon as aquatic plants [3]. Hence, low availability of carbon dioxide coupled with its high diffusion resistance in water may have forced these plants to move onto land and adjust their according to the prevailing conditions. Analysis of fossils suggests that by the Early Devonian, about 400 million years ago, plants were drought and probably salt resistant [4]. However, most of the plants lost the ability to resist high salt concentrations of the soil and cannot be grown on a salt affected land any more [5]. Such plants are known as non-salt resisting plants, non-halophytes or glycophytes. Only 2 % of the plants have still the ability to grow under salinity due to the presence of different mechanisms in them for salt resistance; such plants are known as salt resisting plants, salt tolerating plants or halophytes [6]. However all plants experiencing salinity stress face three major constraints: (a) water deficit arising from the low water potential, (b) ion toxicity on the basis of excessive uptake of Na^+ or Cl^- leading also to oxidative stress and (c) nutrient imbalance by depression in uptake of essential nutrients [7].

Freshwater resources will become limited in near future [8] and it is necessary to develop sustainable biological production systems, which can tolerate hyperosmotic salinity. A precondition is the identification and/or development of salinity-resistant crops. The arguments listed above demonstrate the advantage of utilizing suited halophytes as crops on saline lands and to improve their individual crop potential. However, knowing that saline irrigation always contains the risk of increasing salinity up to levels where no plants (even no halophytes) can exist anymore, it is important to achieve sustainable conditions. Therefore it is essential to study the interaction between soil salinity, individual species (to study heterogeneity in between halophytes and plant diversity), biotic interactions, and atmosphere at distinct conditions before application. The heterogeneity between halophytes (biotic factor) is often ignored but biotic interactions can be in this context an ideal accessory to stabilize sustainable populations on saline lands. It is necessary to understand the mechanism operating at each level in full detail so as to develop a complete understanding of salt resistance in plants and utilizing this knowledge to preserve crops from destruction.

2 Glycophytic Land Plants and Hyperosmotic Salinity

2.1 Primary Stress Factors

Plants growing in saline conditions primarily have to cope with osmotic stress followed by specific ion effects, their toxicities and related ramifications. In order to survive under such conditions, suitable adjustments are necessary (Fig. 1). The most terrestrial plants growing in saline soils must adjust osmotically to water potentials in the range of −3 MPa. They do this by accumulating a mixture of ions and organic solutes [9]. Plant adaptations to salinity are of three distinct types: osmotic stress tolerance, Na^+ or Cl^- exclusion, and the tolerance of tissue to accumulated Na^+ or Cl^- [10]. Even if terrestrial plants are able to exclude ions from a strong saline solution they must also adjust their water potential to be at least as low as that of the soil in which they are growing. On the other hand, the growth on well (fresh-) watered soils may have even facilitated the evolution of species with relatively low ion contents because of a reduced necessity for the uptake of ions (such as for osmotic reasons) and may have led to the loss or reduction of (a) exclusion or discrimination in favor of K^+ over Na^+ (or NO_3^- over Cl^-), (b) the ability to excrete or compartmentalize toxic ions such as Na^+ or Cl^- in vacuoles and (c) to a reduced regulation of the water balance in the plants.

As a consequence, the interaction of all three factors (see above a to c) can be harmful at saline habitats because the large difference in water potential is not only the driving force for the

Fig. 1 (**a**) Plant with drought symptoms on a dry habitat. (**b**) Plant with salt on its leaves and crusts around the base and on the soil

movement of water through the soil–plant–atmosphere continuum but also for any dissolved solutes that enter the transpiration stream is carried to the leaves where they accumulate in case they cannot be re-circulated or excreted. The exclusion of ions is under these circumstances one possible plant response to avoid ion toxicity but requires for the avoidance of internal water deficit the enhanced synthesis of organic solutes and a decrease in surface area to reduce transpiration [7]. Adverse effects include reduced growth and an upcoming water deficit leading to the closure of stomata and in consequence a decrease in cell expansion, CO_2 fixation and protein synthesis. In other words, the exclusion of ions leads at saline habitats to substantial overlaps with the effects of drought [10].

2.2 The Influence of Drought on Photosynthesis

In any case, plant water loss has to be minimized at low soil water potentials, since biomass production depends mainly on the ability to keep a high net photosynthesis by low water loss rates. In this field of moisture tension, biomass production of a plant has always to be seen in concurrence with the CO_2/H_2O-gas exchange, which can be estimated by the water use efficiency (WUE) of photosynthesis.

$$\mathrm{WUE}\left[\mu\mathrm{mol\,mmol}^{-1}\right] = \mathrm{J}_{\mathrm{CO2}}\left[\mu\mathrm{mol\,m}^{-2}\mathrm{s}^{-1}\right] / \mathrm{E}_{\mathrm{H_2O}}\left[\mathbf{mmol\,m}^{-2}\mathbf{s}^{-1}\right]$$

WUE = water use efficiency of photosynthesis
J_{CO2} = net assimilation of CO_2
E_{H2O} = evaporation of H_2O

A critical point for the plant is reached if the CO_2 fixation (apparent photosynthesis) falls below the CO_2 production (compensation point, Fig. 2). Therefore, one crucial aspect of the screening procedure (for drought or salinity resistance) is the study of growth reduction, water consumption, and net photosynthesis especially at the threshold of resistance [9].

Substrate salinization as well as drought decrease water availability and water uptake and thus lead to a reduction of turgor of the leaf cells,

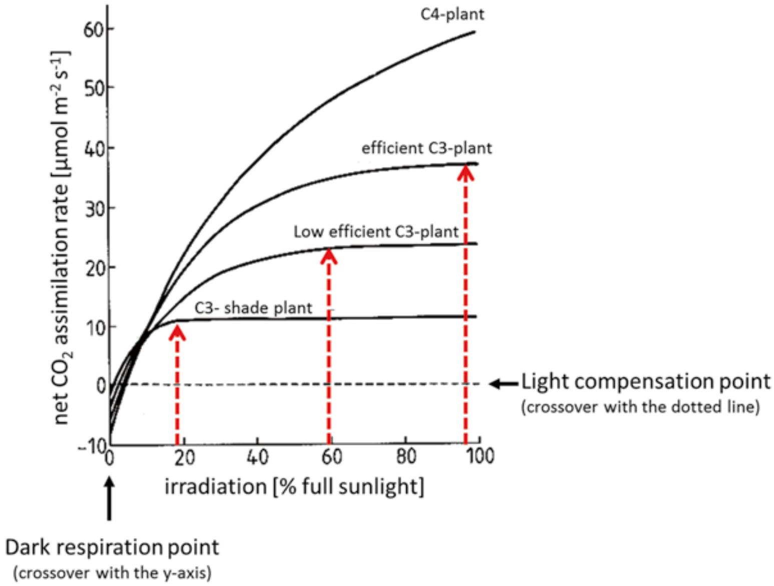

Fig. 2 Idealized light saturation curves of C3 and C4 plants. The light compensation point (crossover with the *dotted black line*), the photosynthetic efficiency (slope at light limiting conditions) and the light saturation point (*dotted red arrows*) are higher for C4 plants higher as for C3 plants. Latter one is for C4 plants often not reached at full sunlight. Light intensities left of light saturation point are light limited and right of it are CO_2 limited

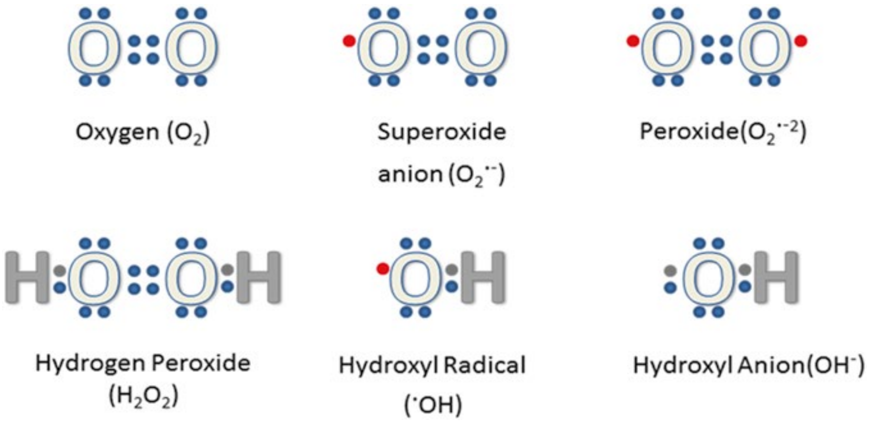

Fig. 3 List of reactive oxygen species (*ROS*) in the form of ions, free radicals, or peroxide

and finally to a reduction of water loss by stomatal closure which affects CO_2 intake. Photosynthetic CO_2 assimilation is the major consumer recycling the both coenzyme molecules (NADP+/NADPH and ADP/ATP) in the reaction sequence of the Calvin cycle. Otherwise, turnover of energy by the electron transport would be inhibited, which would impair electron release from activated chlorophyll and cause the so called secondary stresses [11]. Accordingly, in the literature the occurrence of various forms of ROS is described ([12, 13] Fig. 3). Cytotoxicity may be attributed to oxidative damage of membrane lipids [14, 15] as well as oxidation of proteins and nucleic acids [14, 16]. In the field, salt stress results in severe damage especially in situations when its inhibitory effects occur in presence of high light intensity. In such cases the PSII activity will result in high oxygen concentrations, especially if stomata are closed under stress. Concomitantly, chlorophyll will remain in its active state for a prolonged period of time, as electron transport rate is reduced by inhibited off flow of products. However, any reduction of electron transport rate, especially under high light conditions, will increase the risk of ROS production through transfer of electrons from activated chlorophyll to molecular oxygen to form O_2 radicals and the less reactive ROS H_2O_2 [16]. Concentration of these reactive compounds will build up in the light and eventually will reach concentrations toxic for cells active in photosynthesis. Even if this scenario describes only the action of a secondary stress it can lead to the dieback of plants and a defense will be essential for survival.

2.3 Nondestructive Buffer Capacity of the Plant Against Oxidative Stress

Under conditions that limit assimilation of CO_2, the potential rate of NADPH production exceeds the actual rate of consumption of reductive power. In order to be able to grow under stressful conditions, plants have to be equipped with mechanisms preventing excess reducing power. They lead to a decrease in quantum yield of photosystem II [17]. The principal adaptation mechanism in photosynthesis is the control of thermal dissipation of excess energy within the photosystem II antenna, thus matching physiological needs [18].

In C_3 plants, losses by non-photochemical energy quenching may exceed that caused by photorespiration. For experimental approaches investigating salinity effects, it is important to know that non-photochemical quenching of excitation energy is comprised of a fast and a slow component, qE and qI, respectively. Both reactions are reversible. qI is the quenching parameter puddle model that represents photo-inhibition,

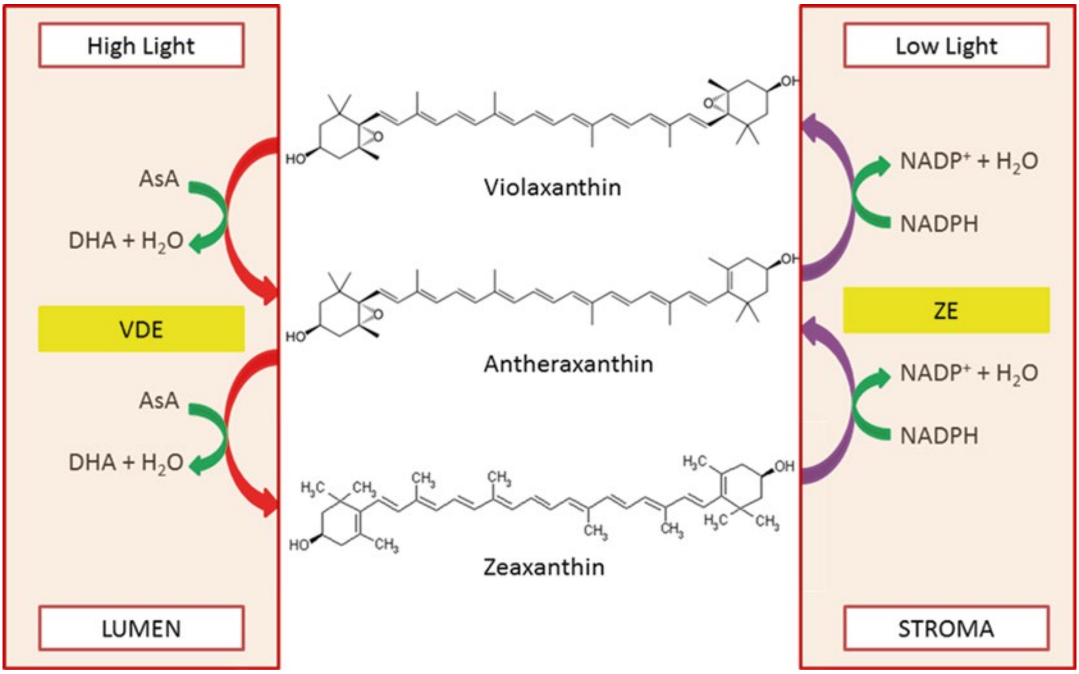

Fig. 4 The xanthophylls cycle. Violaxanthin de epoxidase (*VDE*) catalyses the de-epoxidation of violaxanthin to zeaxanthin in the presence of excess light, and Zeaxanthin epoxidase (*ZE*) catalyses the reverse reaction in *darkness* or *low light*. Zeaxanthin therefore accumulates under light intensities that exceed photosynthetic capacity

photo-damage or photoprotection [19]. The resulting decline in the number of active PSII units and the slow D1 repair both cause a decrease in electron transfer even when excess light is no longer there [20].

The trigger of qE is the ΔpH across the thylakoid membrane sensed by the PsbS subunit of the light-harvesting complex [21, 22] and function on the expense of NADPH. Full expression of qE is associated with the enzymatic de-epoxidation of violaxanthin to zeaxanthin (Fig. 4). This reaction is part of the xanthophylls cycle [23]. Based on current understanding, it can be expected that adverse effects of drought or salinity can be monitored by pigment shifts due to altered ratios of xanthophylls and by detection of qE and qI respectively. At high salinity or drought, several species use the masking of chlorophyll by anthocyanins, to prevent photooxidative damage. They can be identified, because leaf color will vary depending on their growth conditions like it can be observed with *Salicornia* and *Sesuvium* [11].

2.4 Enzymatic and Non-enzymatic Defense Against Oxidative Stress

Plants differ in their capacities to immediately detoxify ROS upon their occurrence and to build up a detoxification potential under stress such as salinity or drought. If the balance between production of ROS and quenching capacity of the respective tissues is upset, oxidative damage will be produced [15, 24]. In experimental approaches, it was demonstrated that enzyme activities of antioxidative pathways increase as a salt stress response [25] and that the maximal level of salt resistance correlated with maximal respective enzyme activities [26–29] suggesting the necessity and importance of a secondary stress response to the salinity reduced low water potential. Ascorbic acid is one of the major antioxidants in plants which detoxifies reactive oxygen species and maintains photosynthetic function. Through its ascorbate recycling function, dehydroascorbate reductase affects the level of foliar reactive oxygen species and photosynthetic activity during leaf development [30, 31]. In chloroplasts, H_2O_2 can be detoxified by an ascorbate-specific peroxidase [32] involved in the ascorbate–glutathione cycle, [12] while in the cytosol H_2O_2 detoxification is catalyzed in a catalase-dependent reaction. Other enzymes involved in detoxification of ROS are superoxide dismutase and several peroxidases [33].

3 Xerophytes and Halophytes

Plants that have adapted to survive in an environment that lacks average or sufficient amounts of water are called xerophytes (Fig. 5). Xerophytes may have adapted shapes and forms (morphology) or internal functions (physiology) that reduce their water loss or store water during long periods of dryness. It is easy to understand that plants excluding the uptake of ions in saline habitats also undergo physiological drought and show similar forms of adjustment as xerophytes. Nevertheless, most studies on water stress signaling have focused on salt stress primarily because plant responses to salt and drought are closely related and the mechanisms overlap. However, high levels of salt induce both hyper-osmotic and hyper-ionic stress leading to secondary stress effects like ion disequilibrium as mentioned above. This is the case for the majority of our common crops [34–36].

Fundamentally, plants cope by either escaping or resisting salt stress. Salt resistance is the reaction of an organism to salt stress. It includes both avoidance and tolerance. Exclusion meets by definition the requirements of avoidance. This means that plants are either dormant during the salt episode (escape), or (i) they avoid high salt concentrations in the plant by exclusion, (ii) they reduce the accumulation in sensitive organs or organelles, (iii) they adjust on cellular level by compartmentation and thus tolerate the saline environment [37].

Salt resistance involves physiological and biochemical adaptations for maintaining protoplasmic viability as cells accumulate electrolytes. Salt avoidance involves structural and physiological adaptations to minimize salt concentrations of the cells or physiological exclusion by root membranes. This led to the classification of halophytes as excluders *versus* includers [7]. Another classification recognizes excreters and succulents. Excreters have glandular cells capable of secreting excess salts from plant organs. Succulents use increase in water content within large vacuoles to minimize internal salt concentration and ion toxicity. By considering the diversity of halophytes and the current understanding

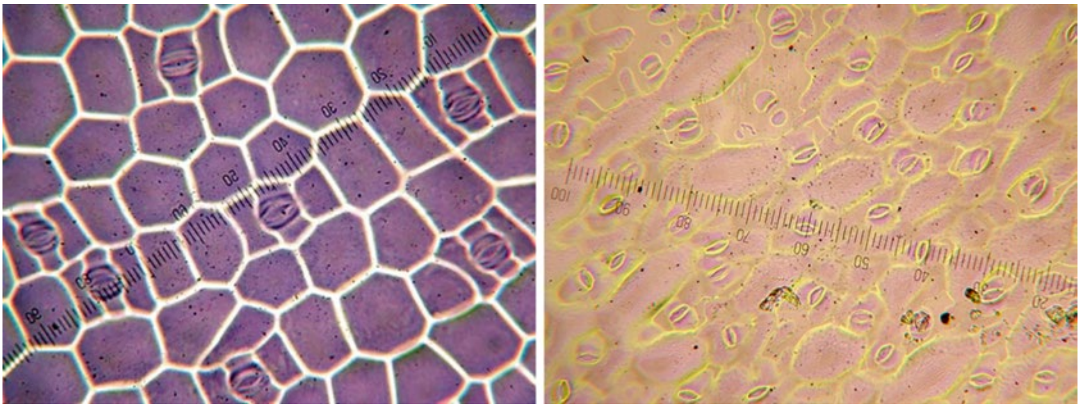

Fig. 5 Morphological adjustment. Surveys of the adaxial leaf surface of *Tradescantia zebrina* (drought sensitive) and *Sesuvium portulacastrum* (drought resistant). Tradescantia is hypostomatic and has few but large stomates. Sesuvium is amphistomatic and has many but small stomates. Latter one is ideal for short gas-exchange phases in times of high water potential in the air

of halophyte salt-resistance mechanisms we can deduce their relevance to efforts to improve crop plants and the status of halophyte agronomy.

4 Development of Specific Traits

The control of the accumulation of ions in distinct tissues or even cell compartments is needed as well in salt including as in salt excluding halophytes. Beside the control of the entrance on root level, the ability to secrete ions (excreter) or to dilute ions (succulents) helps to preserve a vital ion balance inside the tissues [38]. The resistance of plants to sodium chloride is often related to the concentration of sodium in the photosynthetically active tissue [9]. Several traits relating to salt resistance are associated with the absolute ion contents in plants, grown in the presence of salt and with the ratios in-between the monovalent cations (K^+/Na^+) or anions (NO_3^-/Cl^-) [39]. However, for plants growing on saline soils, the distribution of ions between plant tissues or cell compartments, the K^+ homeostasis in the cytoplasm, the maintenance of the $Na^+:K^+$ ratio by favoring the accumulation of potassium over sodium are also crucial for plant growth and development [40, 41].

The uptake of ions can be highly selective. A key property of all ion channels is their selective permeability; i.e., only certain species of ions may pass through a channel. Potassium channels are able to prefer K^+ transport to Na^+ transport, despite only a small difference in their ionic (i.e., Pauling) radii (0.133 nm vs.0.095 nm, respectively). In *Arabidopsis thaliana*, for example, this is accomplished by K^+-selective uptake channels and the sodium-detoxifying SOS system [42]. Genes encoding root K^+ uptake channels were identified in many plant species: AKT1 and AtKC1in Arabidopsis, SKT1 in potato, LKT1 in tomato, KDC1in carrot and ZMK1 in maize (see literature cited in [43]). However several channels, activated when the membrane potential is depolarized, are less selective and could be one means by which sodium enters cells [44–47].

Three classes of low-affinity K^+ channels, identified as K^+ inward rectifying channels (KIRC); K^+ outward rectifying channels (KORCs) and Voltage-independent cation channels (VIC) respectively K^+ outward rectifying channels (KORCs) could play a role in mediating the influx of Na^+ into plant cells. These channels, which open during the depolarization of the plasma membrane, could mediate the efflux of K^+ and the influx of Na^+ ions. Na^+ competes with K^+ uptake through Na^+–K^+ co-transporters and may also block the K^+ specific transporters of root cells under salinity [42, 48]. In particular, the regulation of the low-affinity K^+ channels is essential for plants to survive on saline habitats and therefore an important trait as well.

The cellular response to hyperosmotic salinity also includes the synthesis and accumulation of a class of osmoprotective compounds known as compatible solutes (Fig. 6). One of the essential functions of compatible substances is the substitution of ions to avoid protein precipitation and the counterbalance of the osmotic potential in the cytoplasm against the vacuole. In addition to the conventional role of these compatible solutes in cell osmotic adjustment or osmotic substitution of sodium [49], they are also suggested to act as low-molecular-weight chaperones, stabilizing the photosystem II complex, protecting the structure of enzymes and proteins, maintaining membrane integrity and scavenging ROS (see references in [50]). However, controversies exist as to whether hyper-accumulation of compatible solutes such as glycine betaine and proline is essential for improving salinity resistance, or whether it is just a symptom of salt stress in overlap with effective ROS scavenging. Their essentiality for salt resistance is therefore still not clear.

5 Utilization of Halophyte Crops for Transferring Resistant Traits in Glycophyte Crops *via* Breeding

As freshwater resources will become limited in near future [8], it is necessary to develop sustainable biological production systems, which can resist hyperosmotic salinity. A precondition is the identification and/or development of salinity

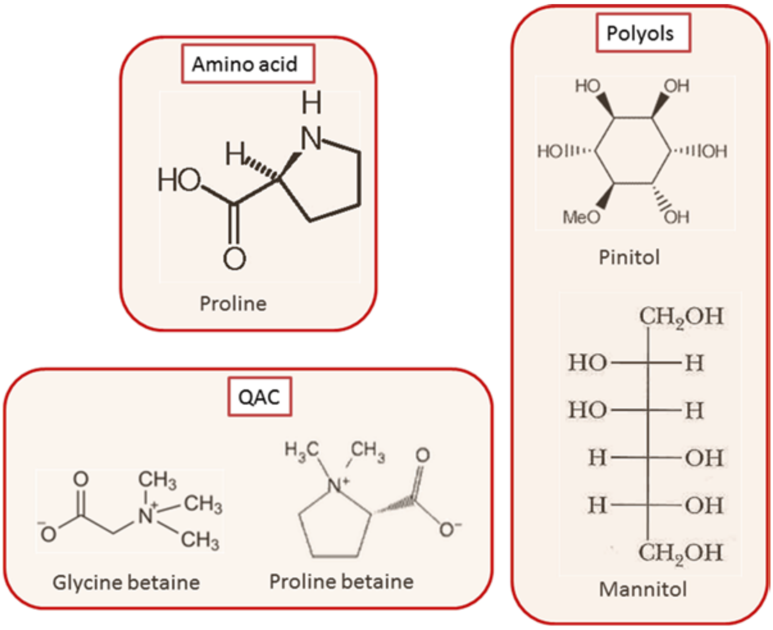

Fig. 6 Examples for compatible solutes

resistant crops. Almost all our modern crops are derived from glycophytes, plants apparently lacking the genetic basis for salt tolerance. Although the terms glycophytes and halophytes inseminate the impression that there are general qualitative differences in adaptation, in reality things are less complex. There is a fluent passage between these two groups and all plants rely on multiple adaptation mechanisms (see above) to cope with high salinity. But, the adjustment to salinity is a complex phenomenon that is characterized by ecological complexity, structural changes and physiological adjustment of gene expression, protein synthesis, stress signal transduction or regulation of catalytic activities of enzymes [48] and a number of factors, including climatic conditions and phenophases.

5.1 Breeding for Salt Resistance in Glycophytes

Knowing that a large number of halophytes are closely related to crop species, and that desired traits can only be introduced from closely related species [47] it is logical to conclude that gene transfer or genetic modification of plants can make them more salt resistant. Classical breeding for salt tolerance has been tried but with limited success. In tomato transgene have been inserted into its genome successfully, the main target was that tomato plant should be able to survive under salt stress while the taste must not be affected, however not much success in this regard has so far been achieved [51, 52]. NaCl resistance was observed in plants in which expression of a sodium transporter, HKT1, was reduced by antisense [53]. Grass has been made salt resistant by transforming it with rice vacuolar membrane Na^+/H^+ anti porter gene via the Agrobacterium-mediated transformation. The resultant plant species had a better resistance to hyperosmotic salinity [54, 55] showing at the same time a correlation between Na exclusion and Na tolerance. Recent strategy is to produce salt tolerant plants through genetic engineering and genes which are important for salt resistance are under investigation [56]. However, it has been questioned whether any cultivars bred for salt resistance have been commercially successful [57]. For a further progress a better understanding of how naturally adapted plants (halophytes) handle salts and how the mechanisms interact seems to be necessary.

5.2 The Potential of Halophyte Crops

Traditional approaches of breeding crop plants with improved abiotic stress resistance have so far met limited success because of several problems:

1. the focus has been on yield rather than on specific traits,
2. the difficulties in breeding for resistance traits due to the complexity of the multigenic trait. Selecting for salt resistance is genetically and physiologically complex because of the relatively infrequent use of simple physiological traits as measures of resistance and
3. desired traits can only be introduced from closely related species [47].

Halophytic crops have the potential to meet the requirements of all three problems:

to 1. Halophytes have been tested as vegetable (food), forage, fodder and oilseed crops in agronomic field trials and for chemical and ornamental uses. The most productive species yield 10–20 ton/ha of biomass on seawater irrigation, equivalent to conventional crops [57, 58]. Halophytes grown in an agronomic setting can be used to evaluate the overall feasibility of high-salinity agriculture, which depends on more than finding a source of tolerant germplasm. Halophytes may become a direct source of new crops.

to 2. Halophytes possess a wide range of adaptations and it is not necessary to breed for resistance traits. The mechanisms by which halophytes survive and maintain productivity on saline water can be used to define a minimal set of adaptations required in tolerant germplasm.

to 3. Halophytes show immense diversity in habitat and response to resist the abiotic stress conditions with uneven distribution across the taxa of flowering plants [59]. The largest number of halophyte species is found among the *Chenopodiaceae* (now called Amaranthaceae); over half of its 550 species are halophytic. The three families, *Poaceae* (grasses), *Fabaceae* (legumes), and *Asteraceae* (composites), also have large numbers of halophytes [57]. These four families solely contain a great number of closely related crop species as well.

Aronson listed ~1,550 species [60]; whereas a total of 2,600 species was recorded [61, 62] as salt-resistant based on their capacity to survive a salt concentration of more than 80 mM NaCl (equivalent to EC 7.8 dS m^{-1}). This knowledge can help to focus the efforts of plant breeders and molecular biologists working with conventional crop plants.

A further advantage of halophytes is that they are not a single taxonomic group, but are represented by a large diversity:

- Halophytes belong to the group of forbs, grasses, shrubs and trees,
- some can be found only in salt marshes and other grow in the desert,
- they are distributed form coastal areas to mountains and lowland deserts,
- they occupy important niches in many ecosystems often in diverse and generally harsh environments in a wide range of saline to alkaline habitats

A variety of halophytic plant species has been utilized as a source of nonconventional cash-crops [63]. Lieth et al. (2003) [64] described the utilization of halophytic species for the improvement of sustainable agriculture as well as sources of income. Using halophytes provides opportunities of introducing completely new options, e.g.:

1. The potential of plants to accumulate enormous salt quantities (salt includer, hyperaccumulating plants, [65]) could be of high significance particularly in the arid and semiarid regions where insufficient precipitations and inappropriate irrigation systems are unable to reduce the salt burden in the soil and suitable physicochemical methods are too expensive [66].
2. In the course of evolution from marine to freshwater habitat, halophytes are found to be most successful group of plants which have shown adaptations to a variety of abiotic stresses, resistance to heavy metal stress is one of these. Several examples of halophytic

plant species used for the purpose of phytoremediation of areas polluted with heavy metals are listed [58].

3. Marsh land and mangroves have provided ecological benefits in terms of shoreline stabilization, reduction in wave and wind energy against shorelines thus protecting inland structures, supporting coastal fisheries and support wildlife. Therefore, new planting, restoration, and re-vegetation of coastal halophytes has become important for the development of sustainable agriculture and to avoid the destructive natural calamities. Research in this field has demonstrated the potential of salt-resistant plants and halophytes on barren lands and wetlands along the coastal regions [67–69].

5.3 Heterogeneity in within the Halophytes

Because of their diversity, halophytes have been regarded as a rich source of potential new crops. However, it should not be ignored that halophytes are an extremely heterogeneous group. Between monocotyledons and dicotyledons there are great differences not only in development and anatomy but also in mechanisms to tolerate hyperosmotic salinity. For example, when grown in saline soils, dicotyledonous halophytes generally accumulate more NaCl in shoot tissues than monocotyledonous halophytes (especially grasses), which led early researchers to characterize the former as "includers" and the latter as "excluders" (see literature in [57]). This feature was related to the observation that succulence is observed more commonly in dicotyledons than monocotyledons, particularly the grasses [47].

This heterogeneity should be considered much more when breeding for salt resistance in crops. For example a transfer of knowledge from the dicotyledonous plant *Brassicaceae Thellungiella salsuginea* (an extremophile model for abiotic stress resistance studies and a close relative of Arabidopsis) to the most of the monocotyledonous crops makes not much sense [70]. Instead halophytic *Poaceae* are the best sources for cereals to optimize their gene pool. Step changes in resistance may arise from the introduction of *de novo* characteristics that are apparently completely absent from a particular gene pool. Increases in resistance of hyperosmotic salinity may be introgressed into commercial lines from tolerant halophytic *Poaceae* using marker-assisted breeding approaches [71], facilitated by recent successes with positional cloning [72].

The differentiation between includer and excluder may be one major reason why the enhancement of exclusion mechanisms still appears to be the principal strategy of researchers trying to improve the salt resistance of grains (see literature in [57]). However, such generalization can also lead to neglect some promising possibilities. Studies of *Leptochloa fusca* [73], *Puccinellia peisonis* [40], *Spartina alterniflora* and S. *townsendii* [40, 74], *Sporobolus viginicus* [75], *Plantago coronopus* [36], *Triglochin bulbosa* and *T. striata* [76, 77] show that grasses and other monocotyledonous halophytes which use Na^+ uptake into leaves for osmotic adjustment, as do dicot halophytes, should not be ignored. These halophytes could be used to breed for salt accumulating grains. However, because of their lower cell vacuolar volume and leaf water content, grasses do not need as much Na^+ uptake per unit of growth as typical dicotyledonous halophytes, so they still maintain low Na^+: K^+ ratios on exposure to salt [57].

6 Importance of the Diversity of Halophytic *gramineaes* to Agriculture and Land Management

6.1 Combating Desertification and Substitution of Fresh Water Utilization

Besides the use as food or fodder crops, *gramineae* are typically used for revegetation, greenification or as turf grasses. Among these measures, revegetation of the arid lands, using plant species that are more adapted to the harsh and stressful conditions of the deserts is probably the most effective practice because of its potential use in combating

Fig. 7 Photo of a salt resistant turf grasses

desertification. 43 % of the earth's total land surface is arid or semiarid. A mainly perennial vegetation cover is the best protection against desertification [78]. In desert regions perennial vegetation coverage can maintain adequate growth and persistence under variable levels of soil salinity or salinity-laden water over several years. Successful assessment of salinity resistance of perennial, halophytic plants, therefore, should be based on growth at non saline levels. Since the growth rates of the halophytic grasses, such as *Paspalum vaginatum* (seashore paspalum), were affected only under high levels of NaCl salinity and even stimulated under lower and medium levels of salinity, it can be concluded that these halophytic plant species are suitable candidates for growth and production under arid, desert regions and dry-land conditions to effectively combat desertification processes in these regions [78].

Critical water shortages are occurring not only in deserts but also in rapidly growing urban areas, resulting in restrictions on the use of potable water for irrigating turf grass landscape areas [79]. Turf grass landscape irrigation is typically considered a low priority use for fresh water, particularly when water shortages occur [80]. Instead of using fresh water for irrigation of turf, saline water sources can fill this gap. This can include reclaimed water (sewage effluent), brackish groundwater caused either by salt leaching or seawater intrusion, and other sources [79, 81]. Proper turf management techniques are critical in counteracting salinity and long-term solutions require the development and use of salt resistant turf grass genotypes. Most of the turf grasses present high salt sensitivity (such as *Poaannua* or *Eremochloa ophiuroides*) or moderate salt-sensitivity (such as *Lolium perenne*, *Agrostis stolonifera* or *Zoysia japonica*; [79]).

Turf grass salinity resistance is a complex phenomenon, influenced by a number of environmental, edaphic, and plant factors (Fig. 7). One strategy to enhance plants and turf grasses survival and recovery from salinity is to use cultivars with superior salinity resistance [57]. Several highly salt resistant turf grasses are already in use or under development such as *Puccinellia* spp. (alkali grass, EC values between 12 and 46 dS^{-1}), *Cynodon dactylon* (Bermuda grass, dead at EC values of 36 dS m^{-1}) or *Paspalum vaginatum* (seashore paspalum, survives EC values >30 dS^{-1}; [79]). There are also so called true halophytes in use such as *Distichlis spicata* (salt grass) or *Sporobolus virginicus* (marine couch). Both survive full strength seawater salinity (EC = 54 dS m^{-1} or 34,560 g L^{-1}) and are offering great potential for land stabilization in highly saline areas [82]. Again diversity and heterogeneity is of importance for the sustainable use of turf grasses at high salinity. It is noticeable that many of the highly salt tolerant turf grasses are crinohalophytes (*Distichlis spicata*, *Sporobolus virginicus*, *Cynodon dactylon*). They have salt glands or bladders, which excrete excess saline ions from shoots [79] that can be eliminated by cutting the grass periodically and disposing it off away from the site.

There are several similarities between the uses of *gramineaes* for revegetation, greenification and as turf grasses if freshwater is not available (see above). If freshwater is a limiting factor it is extraordinary promising to grow the grasses listed above and to attain a win-win situation by combatting desertification and create high net productivity at the same time. The number of halophytic grasses which are suitable as forage crops under these circumstances can be extended [83] and open complete new directions for economic utilization on these wastelands and ecological purposes such as CO_2 segregation. Khan and Weber mentioned [83] that grasses like *Aeluropus lagopoides* and *Urochondra setulosa* present in the vegetation of Pakistan could survive salinity up to 2 times seawater while a number of them survived salinity approaching seawater. The potential of using *gramineaes* for revegetation, greenification and as turf grasses is however not yet fully explored.

6.2 Intercropping Halophyte Culture

Halophytes have been tested as vegetable, forage, and oilseed crops in agronomic field trials (see above). The aspect, that dicotyledonous halophytes, when grown in saline soils, generally accumulate more NaCl in shoot tissues than monocotyledonous halophytes (especially grasses) has several consequences on their suitability as crops and their culture conditions (procedure to apply salinity). This aspect can be explained best by giving an example:

Halophyte forage and seed products can replace conventional ingredients in animal feeding systems. However, there are some restrictions on their use due to high salt content and anti-nutritional compounds present in some species [57]. The oilseed dicotyledonous halophyte, *Salicornia bigelovii*, accumulates a significant amounts of the supplied salts and yields 2 t/ha of seed containing 28 % oil and 31 % protein, similar to soybean yield and seed quality. The accumulation of salt in the plant tissues helps to control soil salts but reduces its value as a fodder crop. The presence of high contents of ash in such includer species needs to be taken into consideration when formulating diets containing halophytes and or salt-tolerant forages for small ruminants [84]. Sheep raised on a diet supplemented with salt-tolerant dicotyledonous *Chenopodiaceae* such as *Atriplex* (saltbush), *Suaeda linearis* (sea blite) and *Salicornia* (glasswort) gain at least as much weight and yield meat of the same quality as control sheep fed conventional grass hay, although they convert less of the feed to meat and must drink almost twice as much water [85]. In contrast, salt excluding *gramineae* do accumulate only small amounts of salt in foliage and could be used advantageously as alternative feed or food on saline land to replace completely common feedstuffs, thus to alleviate feeding cost [84]. Indeed, some halophytes, such as grain from the salt grass *Distichlis palmeri* (Palmer's grass), are used as food [85]. However the accumulation of relative small amounts of salts in their tissues is also favoring an increase of salinity in the soil during their culture and the risk of soil destruction.

This diversity of mechanisms (above shown by an example of an excluder and includer species) can be beneficial if the species are used in an integrated manner. This opens the possibility for an ecologically sustainable and economically feasible

Fig. 8 Example for a successful intercropping culture: *Panicum turgidum* and *Suaeda fruticosa* in a field near the Institute of Sustainable Halophyte Utilization (Karachi, Pakistan; Photo A. Khan)

agriculture of halophytes [86], especially when perennial species are selected (ontogenetic aspect). Perennial plants handle salinity better than annual plants because they do not often exhibit a salt resistant juvenile phase every year [87].

On the basis of these biological parameters first impressive plantings show the reliability of this system ([86], Fig. 8). A search within halophytic plant species to find suitable fodder replacement for calves has been successful in identifying a local salt excluding perennial grass, *Panicum turgidum*, with biomass yields of about 60,000 kg/ha/year (fresh weight) when grown in saline soil (EC 10–15 mS cm^{-1}) irrigated with brackish water (EC 10–12 mS cm^{-1}). *Panicum* was used as a complete replacement for maize in a cattle feeding trial and resulted in equivalent growth and meat production. It has been shown that the cultivation of *Panicum* together with the perennial salt accumulator *Suaeda fruticosa* in adjacent rows and with frequent irrigation was sustainable in terms of soil salt balance, with little change in soil salinity detected.

Implementation of this intercropping system is one way to use saline land and brackish water for producing an economically viable and environmentally sound agriculture. It was estimated that 15 % of undeveloped land in the world's coastal and inland salt deserts could be suitable for growing crops using saltwater agriculture. This amounts to 130 million hectares of new cropland that could be brought into human or animal food production, without cutting down forests or diverting more scarce freshwater for use in [85].

The intercropping (type of polyculture) with *Panicum* and *Suaeda* shown above also provides pest management, nutrient cycling, a greater variety of resource use, yield increases, production of diverse products, and a decrease in the risk of loss due to diseases [88]. It is suited to serve as an argument to transfer the monocultural practices of modern agricultural methods on saline agriculture. Monocultures have been the driving force behind a loss of genetic diversity and a need for expensive inputs i.e. fertilizers, pesticide, seed stock. These practices ultimately pollute the land, the water, and the food they are producing. A compromise between monoculture practices and polyculture could be the incorporation of multiple cropping systems by using rotations, borders, and cover crops. In general, however, the goals are usually the same: to secure food self-sufficiency, to preserve the natural resource base, and to ensure social equity and economic viability.

6.3 Reduction of the Dilemma Between Feed and Fuel by Halophytes

Since the amount of land and water resources that can be used for agricultural production is limited, there is now a widespread fear that the production of biofuels will have a severe impact on natural resources and food security. The diversity of halophytic *gramineae* can also be used to reduce this "dilemma between feed and biofuel" [89]. An unsustainable supply of fossil fuels necessitates the need to look for suitable alternatives [90]. The aim is to create aviation-grade biofuels without using any arable land, freshwater or standard food crops. Even NASA's green lab research facility is using halophytes to create food and fuel. Crops available for human consumption being used presently as biofuel feedstock may be replaced with halophytes, growing on saline lands and irrigated with brackish water. Some halophytes are being studied for use as "3rd generation" biofuel precursors. Halophytes such as *Salicornia bigelovii* can be grown in harsh environments and typically do not compete with food crops for resources, making them promising sources of biodiesel [85] or bio-alcohol.

Perennial salt resistant grasses like *Halopyrum mucronatum*, *Desmostachya bipinnata*, *Phragmites karka*, *Typha domingensis* and *Panicum turgidum* have also potential as bio-ethanol crops (Fig. 9, [91]). They show considerable high growth rates to produce ligno-cellulosic biomass of good quality (26–37 % cellulose, 24–38 % hemi-cellulose and <10 % lignin) suited for ethanol production. Third-generation biofuel production processes that can convert ligno-cellulosic biomass (from crop residues, grasses and trees grown on marginal land) to produce "cellulosic" ethanol are currently under development [89]. It is expected that third-generation biofuel production may contribute to mitigate eventual pressures on natural resources that can be used to produce food, but for the time being these technologies are not yet commercially viable [92]).

Abideen et al. [91] argue that the unexplored aspects of agronomy of these wild plants are leading again to the requirement of careful studies before large scale cultivation, especially with regards to land degradation and ecological consequences. Latter one might be faciliated by specific properties of *Phragmites*, *Typha* and *Panicum* allowing them to grow on extreme areas well, not suited for conventional crop (food) production but for saline irrigation. This can be seen again as an example of the importance of heterogeneity in halophytes for saline

Fig. 9 Photos of salt resistant grasses like *Panicum turgidum* (**a**) *Phragmites karka* (**b**), *Typha domingensis* (**c**) *Desmostachya bipinnata* (**d**) *and Halopyrum mucronatum* (**e**) have the potential as bio-ethanol crops

Fig. 9 (continued)

sustainable agriculture. These species unlike other cereals can grow well in saline paddy fields and are highly tolerant of excess water stress, from either submergence (in which part or all of the plant is under water) or waterlogging (in which excess water in soil limits gas diffusion). This habitat has similar advantages for saline irrigation as in coastal areas where the irrigation water is permanently renewed. A major advantage of this system is that a fluctuation of the salinity can be minimized in the soil and a precise balance of input and output of salt is less important as in conventional irrigation systems on farmland.

Fig. 9 (continued)

6.4 Ecological Sustainable Ditch Irrigation of Halophytes

The usefulness of heterogeneity or diversity in between extremophytes such as halophytes can be nicely demonstrated with another flooding resistant species, the C-4 marsh grass of the genus *Spartina*. It grows in the upper elevation of the salt marsh at coastal salinity, partially higher than that of seawater, as well as in fresh water. Salt marshes dominated by *Spartina* species are among the most productive ecosystems known, despite nitrogen limitation [40, 93, 94]. *Spartina alterniflora* was introduced first by Lieth in a sustainable halophyte production system for landscaping and fodder, using ditches of about 5 m width irrigated with ocean water of approx. 5 % salinity for 2 h every day ([62], Fig. 10). It is exceptional and impressive how many various ecological and economic benefits emerge with the ecological engineering of *Spartina* plants [95]:

Salt marshes dominated by *Spartina* species

- help to reduce atmospheric CO_2 enrichment [96],
- have a low vulnerability against sea level change and protect the estuaries against the effects of global changes, are 'therefore' an important component of new coastal management practices and useful in developing strategies for the stabilization of deteriorating marshes (in marsh restoration projects) [8, 97–99],
- can tolerate oil spills (its growth is even stimulated by crude oils) and are hosts of microbial degraders promoting oil spill cleanup in coastal wetlands [100–104].
- support biodiversity and the production of marsh fauna (e.g. fish, benthic invertebrates [105–110]),
- support bioremediation of recalcitrant complex carbohydrate biopolymers by marine bacteria [111].

Spartina itself

- is a potential biomass crop (e.g. grown for fodder [8, 112] in poor soil conditions),
- is highly effective in nutrient cycling (e.g. N-fixation, Fe-reduction, sulfate-reduction, sulfide-oxidation, Se-biotransformation to DMSeP, Si reservoir [113–117]),
- reduces toxic metal bioavailability (e.g. Cd, Pb, Cu, Cr, Hg and Zn), by sequestering a larger proportion of its metal burden in its belowground tissues which are likely to be permanently buried [118–121],
- is a bio-monitor for environmental toxicants from municipal and industrial wastes, agricultural

Fig. 10 Spartina alterniflora growing on full strength ocean water (ditch irrigation) in Dhubbayiah/Abu Dhabi (Photo: H. Lieth)

runoff, recreational boating, shipping and coastal development [122–124],
- is used as an indicator for estuarine sediment quality [122],
- can have, in the form of bio-mineral liquid extracts from *Spartina* culms, a number of health functions (e.g. cardiotonic, enhancer of life span); the total flavonoids of *Spartina* can be separated and used to resist blood coagulation and encephalon thrombus [125].

6.5 Complex Systems of Integrated Farming

Saltwater can be used in arid areas for economic purposes in even more complex systems as intercropping. A good example is the integrated farming with multi-species cultivations in Eritrea (Manzanar project): shrimps, fish, mangroves, seaweeds and live-stocks. Wastes from one species are used as nutrients for another species and thus effectively minimized to prevent pollution to the environment [126]. The long-term objective of this farming system is the transforming of the coastal region through sustainable and natural means [126].

In the Manzanar project in Eritrea, artificial mangrove swamps (planted using the fruit and propagules) are created by digging large areas to the depth of 1 ft below the average high tide level. Seawater is channeled from the sea into the mangrove swamps (Fig. 11). These species of trees are highly tolerant of salt and can remove salt from the water and retain it them in root, stem, and leaves. The propagules and leaves, while processed are suitable for human consumption [63] and can be fed directly to live-stocks such as goats and camels [126]. The mangrove trees also provide nourishment and shelter for large numbers of fish, shrimp and crab which feed indirectly from the decomposing leaves. Even the left-over roots help to stabilize the soil against erosion. It is entirely possible that water evaporation from vast-stretches of seawater farm will increase humidity and rainfalls in these areas, bringing in future desirable conditions for other economic activities. Next to the mangrove swamps, deeper ponds are dug which are fertilized with a mixture of camel and goat dung. The algae that grow in

Fig. 11 Photo from a Mangal near Karachi (Pakistan)

this environment supports the growth of an edible fish. The viscera and heads are used to feed crab, shrimp and carnivorous fish that are cultured in other ponds.

Zanella succinctly summarized the basic components of this seawater farming: a shrimp production facility, a mangrove forest, wetland systems [127]. The system can be extended if it feeds to the running approach. Each component must meet specific criteria in the eco-system of the integrated farm. The shrimp production facility must be made in concrete ponds to prevent the seeping and contamination of saltwater into the aquifer beneath. After the seawater is channeled into the shrimp and fish farm, the mangrove forest is flood-irrigated with the effluent from the shrimp and fish farms. Some water is filtered and returns to the sea, while the rest is used to irrigate the wetlands around the mangrove trees. However, in new approaches this irrigation water is also introduced into fields of *Salicornia*. At the peak of its operations, these farms employed almost 800 local people, shipped one metric ton of premium shrimp a week to Europe or the Middle East and cultivated 100 ha of the oil seed crop *Salicornia*, and was completing the planting of 100 ha of seawater forest [128]. Additionally it created a 60 ha wetland and was the home for over 200 species of birds and many other animals in the desert.

The waste water from the shrimp and fish farms offers, in comparison to pure sea water, advantages for the net productivity of the system. Shrimp and fish farming lead to an enrichment of phosphorus and nitrogen in the waste water. This is important because in the majority of cases, the low nitrogen and phosphorus contents limit the net productivity in sea water (although iron limitation has also been detected; [129]). Because nitrate is found in practice to be the most limiting nutrient in surface waters, this led to the conclusion that nitrate rather than phosphate is the main limiting nutrient and that it is the dynamics of the nitrogen cycle which are important for controlling phytoplankton productivity [130, 131]. This enriched seawater can be a valuable nutrient solution also for other halophytes. Strictly speaking is it conceivable that all application explained in the chapters above can be integrated in the complex system of integrated farming.

7 Conclusion

Research on sustainable utilization of halophytes is a very promising field. The diversity in halophytes offers promising options for utilization as shown in this review mainly with thematic priority on *gramineaes*. There is a need of new agronomic approaches as presented above and to revise currently accepted guidelines for water quality evaluation and recommendations for irrigation with saline waters. Only part of the knowledge about conventional agriculture can be used for this purpose. Meeting this challenge may lead to enormous strides towards mankind's well-being and environmental protection in future. However, halophyte agriculture ecosystems are very vulnerable; therefore all environmental issues such as the diversity in between halophytes biodiversity loss, soil and water depletion and salinization should be monitored carefully. The problems to be overcome for an environmentally safe and economically convenient use of saline lands and waters are still formidable and their solution requires a coordinated effort of a vast number of experts in various domains. However, the first steps are encouraging!

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Is Soil Heterogeneity the Major Factor Influencing Vegetation Zonation at Karachi Coast?

Salman Gulzar, Abdul Hameed, M. Zaheer Ahmed,
and M. Ajmal Khan

Abstract

This study attempts to understand whether changes in edaphic factors are key players in regulating ecophysiological parameters in coastal plants. Some ecophysiological parameters of selected populations along the coastal gradient (dune and salt marsh zones) were investigated. Significant variation in soil parameters such as ECe, moisture and organic matter were found between dune and marsh zones. However, populations mostly displayed plant-type specific variations in ecophysiological parameters i.e., dicot species had more negative xylem pressure potential and higher chlorophyll and transpiration rates than monocots. In addition, some species specific responses were also observed. Despite these differences all the species displayed almost similar water-use efficiency. Significance of results obtained in this study is discussed.

Keywords

Chlorophyll • Coastal vegetation • Dune • Halophyte • Marsh • Soil

1 Introduction

Coastal environments are highly productive yet exceptionally sensitive to climatic changes and are considered to be ecologically and economically valuable in terms of carbon cycling, productivity and stress evaluation [1]. Coastal populations face frequent environmental variations throughout the year which requires homeostasis by means of various physiological traits which may be either adaptive [2] or acclamatory in nature [3]. Moderate salinity in combination with dry soil conditions

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_13,

for extended periods could be challenging even for highly tolerant halophytes [4] for instance by hampering plant nutrition through decrease in mineral uptake [5].

In natural environmental conditions stress cannot be assessed by measurement of environmental variables alone but also needs to be matched with the actual perception of stress by the plants [6]. Physiological and biochemical responses are usually more easily assessed under controlled conditions in a greenhouse than under field conditions [7]. Such studies could also provide information on restoration and reclamation of moderately saline lands [8]. Abiotic stresses may lead to various physiological and biochemical responses in plants such as reduced leaf size to prevent water loss by transpiration, reduced rates of photosynthesis as well as high levels of endogenous macromolecules for osmotic adjustment [9, 10].

Patterns of vegetation along a gradient from coastal marshes to dunes could be related to changes in many abiotic factors such as soil physical and chemical characteristics [11–14]. Several researchers attempted to explain relationships between plant communities and soil characteristics of coastal dunes [14–16] and coastal salt marshes [17–19]. However, few studies included both types of environment [20–22]. This is particularly true for the coastal ecosystems of the subtropical areas. In addition, studies relating plant ecophysiological responses to soil characteristics are even scarcer. The present study attempted to understand the role of abiotic factors in determining vegetation zonation along a gradient from sand dune to coastal salt marsh. We tested the hypothesis that variation in soil salinity, moisture and organic matter will influence ecophysiological responses of coastal plant populations.

2 Materials and Methods

2.1 Study Site and Species

Study site was located near the Arabian Sea coast at Sandspit, Karachi (Fig. 1b). Four distinct habitat types dominated by different populations of halophytes were selected along an inundation gradient i.e., from the seaward high dune (*Halopyrum mucronatum*; Fig. 2a), the low dune (*Suaeda fruticosa*), upper marsh (*Sporobolus ioclados*) and the backwater low marsh (*Avicennia marina*) (Figs. 1a and 2b). Soil and plant analyses were carried out during summer (May 2009).

2.2 Soil Analyses

Soil samples were collected from the root zone in each habitat type from a depth of 6–18 in. at low tide. Soil pH and electrical conductivity (ECe) were measured with the help of pH and conductivity meters respectively (Radiometer, Copenhagen) in 1:5 (w/v) soil extracts in distilled water. Soil organic matter was determined by taking into account the loss in weight upon ignition of thoroughly mixed, ground and sieved (2 mm diameter) soil samples in a muffle furnace at 550 °C for 3 h. Soil moisture was calculated as the difference between fresh and dry soil samples.

2.3 Plant Analyses

Specific leaf mass or leaf mass area ratio (LMA) was calculated as the ratio of leaf dry matter to leaf area [23] for mature fully expanded leaves from the second or third node as an index of leaf toughness and thickness related to leaf area. Succulence and ash were determined through gravimetric methods. Leaf chlorophyll contents were quantified according to Lichtenthaler's method. While, leaf soluble sugars were quantified by using Anthrone method [24, 25].

Photosynthetic gas exchange data were taken with the help of LiCor-6400 portable photosynthesis system (LiCor Biosciences Inc. U.S.A.) with a 2 × 3 cm open sample chamber at ambient light, temperature and relative humidity. Light intensity was maintained at about 1,000 μmol m^{-2} s^{-1} by slightly tilting the leaf chamber against the incident sunlight, with 370 μmol m^{-2} s^{-1} CO_2 and a flow rate of 500 μmol s^{-1}. Leaf area measurements for gas exchange data were corrected by using projected leaf area directly exposed to the sun inside

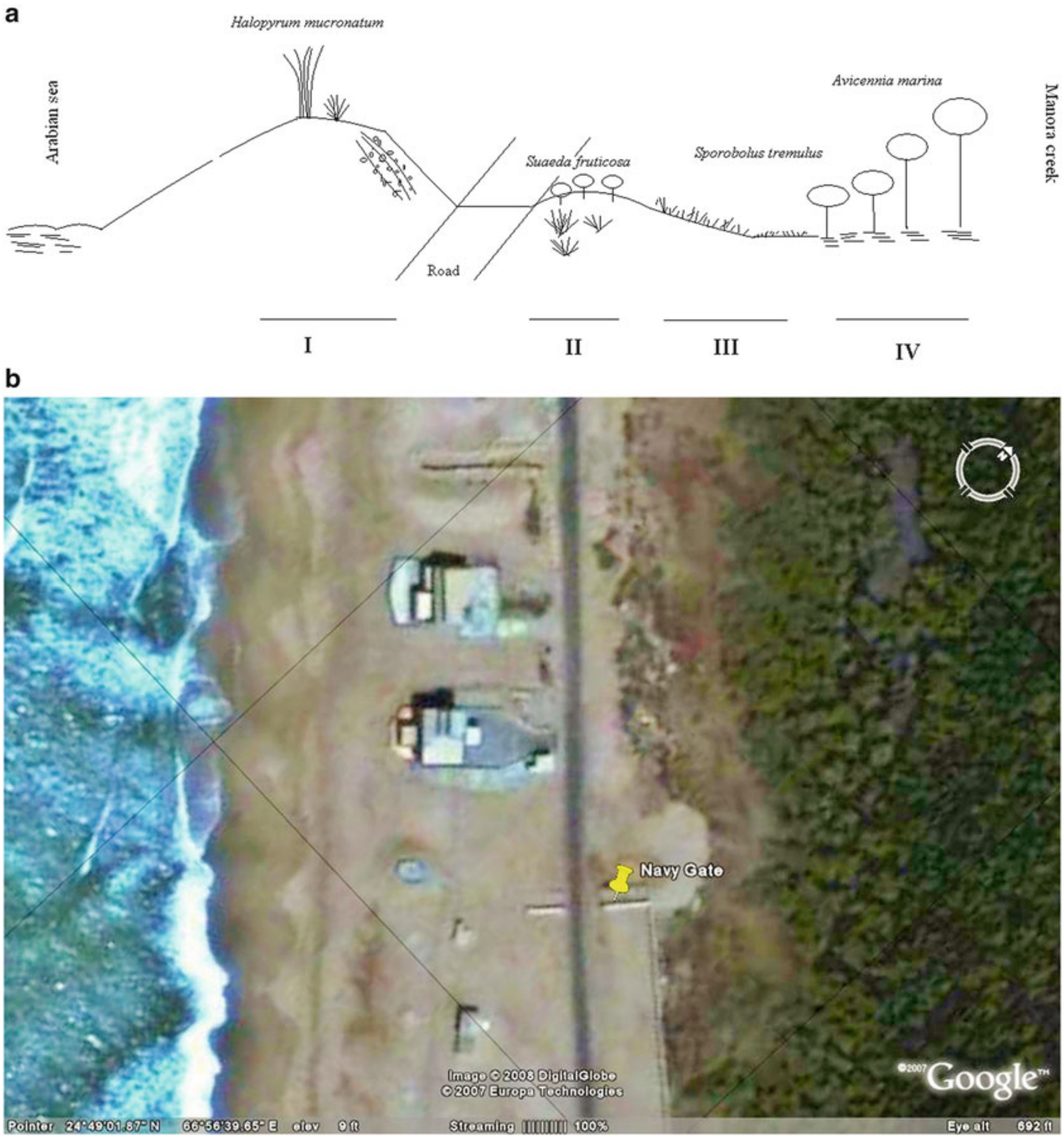

Fig. 1 Schematic diagram of the study site (**a**) with dominant species along the Arabian sea coast and (**b**) satellite image from Google earth

the sample chamber. Water use efficiency was calculated by dividing the rate of photosynthesis with transpiration. All gas exchange measurements were made between 11:00 am and 2:00 pm.

Xylem pressure potentials of excised shoots were measured at mid-day with the help of a plant water status console (Logan, Utah). Osmolality of the leaf sap was determined using a vapor pressure osmometer (VAPRO 5520, Wescor Inc, USA).

2.4 Statistical Analyses

Analyses of variance were used to determine whether significant differences exist in different parameters among four zones. Bonferroni test ($P < 0.05$) was used to determine significant differences among means. All statistical analyses were performed by using SPSS for windows version 11.

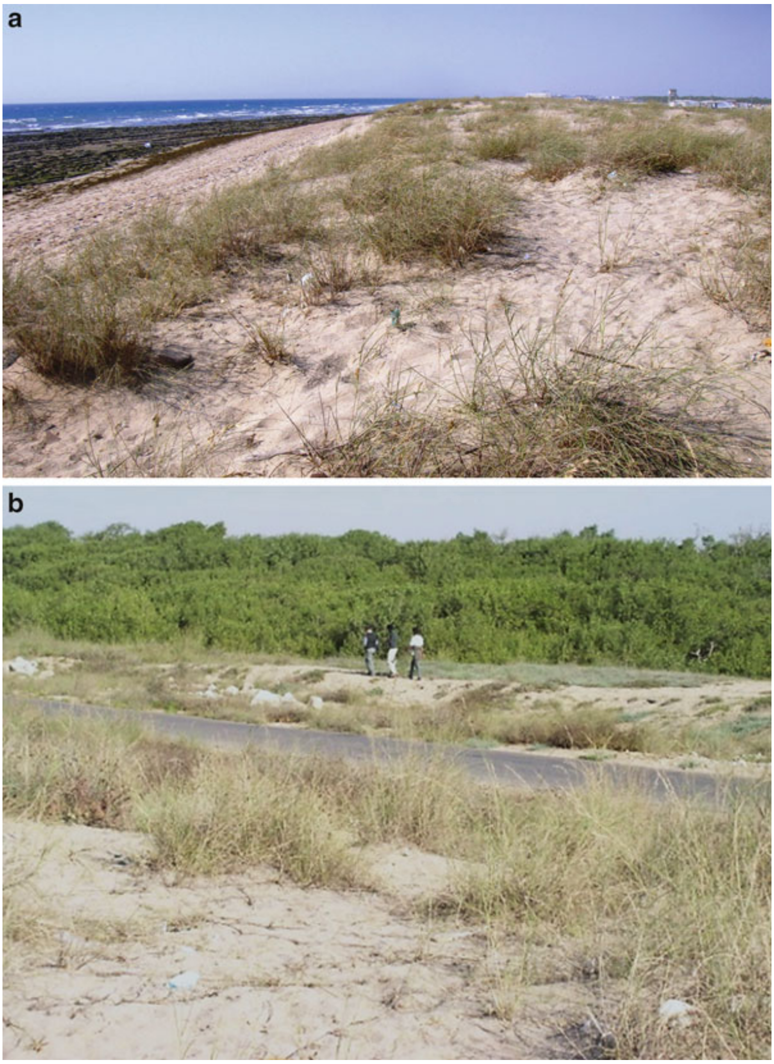

Fig. 2 Photographs of the study site showing the fore dune zone on the dominated by *Halopyrum mucronatum* (**a**) and the other three zones with *Suaeda fruticosa*, *Sporobolus tremulus* and *Avicennia marina* (**b**) respectively

3 Results

3.1 Soil Parameters

The soil electrical conductivity ($ECe_{1:5}$) values were significantly ($F=28.72$; $P<0.001$) higher in the salt marsh habitats in comparison to the dune habitats (Fig. 3). Soil moisture ($F=139.65$; $P<0.001$) and organic matter ($F=10.96$; $P<0.001$) were lowest in the dune zones compared to marsh zones (Fig. 3). Soil $pH_{1:5}$ values were ~8.5 in all the zones of the study site.

3.2 Eco-physiological Parameters

3.2.1 Leaf Mass Area (LMA), Succulence and Ash

LMA ($F=9.00$; $P<0.001$) was more or less similar in all species except for relatively lower values in

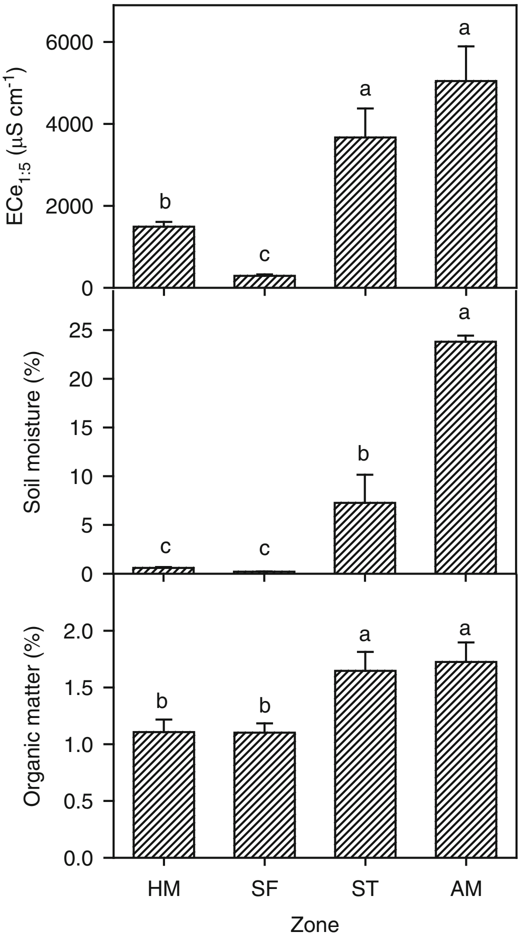

Fig. 3 Soil characteristics (ECe$_{1:5}$, soil moisture and organic matter content) of the four zones dominated by *Halopyrum mucronatum* (HM), *Suaeda fruticosa* (SF), *Sporobolus tremulus* (ST), and *Avicennia marina* (AM). Bars are means ± S.E. Similar letters represent non-significant differences among means, (Bonferroni, $P < 0.05$)

Sprorobolus tremulus (Fig. 4). Leaf succulence (F = 249.24; $P < 0.001$) and ash (F = 217.19; $P < 0.001$) were highest in *Suaeda fruticosa* compared to other test species (Fig. 4).

3.2.2 Xylem Pressure Potential and Leaf Osmolalities

Xylem pressure potential values were more negative in dicot species than monocots (Fig. 5; F = 11.43; $P < 0.01$). All the species displayed almost similar leaf osmolality except for lower values in *S. fruticosa* (Fig. 5; F = 4.36; $P < 0.05$).

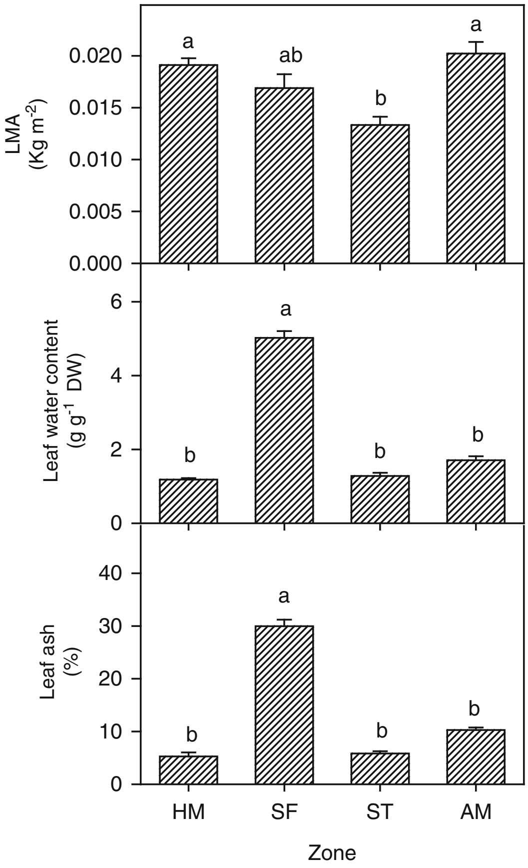

Fig. 4 Leaf mass area ratios (LMA), leaf water and ash content of *Halopyrum mucronatum* (HM), *Suaeda fruticosa* (SF), *Sporobolus tremulus* (ST), and *Avicennia marina* (AM). Bars are means ± S.E. Similar letters represent non-significant differences among means, (Bonferroni, $P < 0.05$)

3.2.3 Leaf Chlorophyll and Soluble Sugars

Total soluble sugar of test species varied in the order; *H. mucronatum* < *S. fruticosa* < *S. tremulus* < *A. marina* (Fig. 6) while leaf chlorophyll were higher in dicot species compared to monocots (Fig. 6).

3.2.4 Photosynthesis and Water Use Efficiency

Transpiration rates were higher in the dicots in comparison with monocot species (Fig. 7). Photosynthetic rate was highest in the C_3 species *Avicennia marina* compared to the other C_4

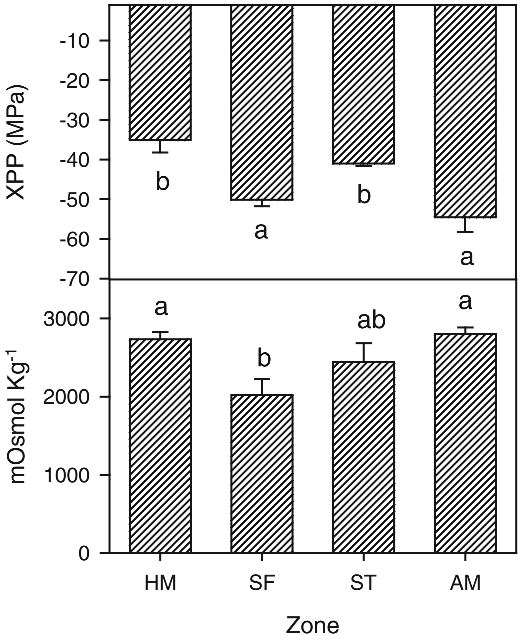

Fig. 5 Xylem pressure potential (XPP) and leaf sap osmolality (mOsmol Kg^{-1}) of *Halopyrum mucronatum* (HM), *Suaeda fruticosa* (SF), *Sporobolus tremulus* (ST), and *Avicennia marina* (AM). Bars are means ± S.E. Similar letters represent non-significant differences among means, (Bonferroni, $P < 0.05$)

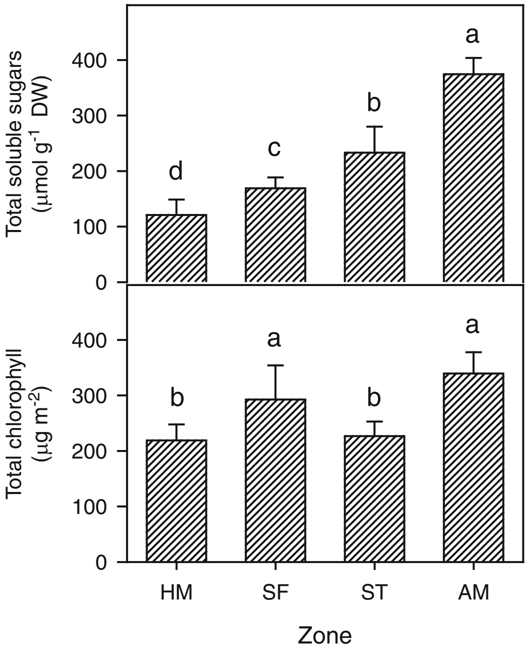

Fig. 6 Total soluble sugars and chlorophyll content of *Halopyrum mucronatum* (HM), *Suaeda fruticosa* (SF), *Sporobolus tremulus* (ST), and *Avicennia marina* (AM). Bars are means ± S.E. Similar letters represent non-significant differences among means, (Bonferroni, $P < 0.05$)

species (Fig. 7). However, all test species displayed almost similar water use efficiency (Fig. 7; $F = 1.97$; $P < \text{ns}$).

4 Discussion

Soil parameters such as ECe, moisture and organic matter varied along a gradient between the dune and marsh communities with high values in salt marsh than the dune environments. We investigated possible links between these soil properties and plant ecophysiology in determining plant zonation along the Karachi coast. Soil organic matter, field capacity, pH, $CaCO_3$ and NaCl were found to mediate vegetation distribution on the Mediterranean coast [22]. Such microsite variations may arise due to differences in soil compaction, vertical distance from sea level, top-soil movement by wind, physical disturbances by cattle grazing and trampling [26] and human interventions [27]. However, poor relationship between zonation pattern and soil characteristics have also been reported [28–30]. We also found plant-type specific variations rather than site related differences. For instance, dicot species *S. fruticosa* and *A. marina* showed more negative xylem pressure potential and higher leaf chlorophyll, and transpiration rates compared to monocot species; *H. mucronatum* and *S. tremulus*. Our findings indicate that the established rules may not directly explain vegetation zonation of unstudied habitats [31, 32].

Plant zonation in coastal environments has also been shown to depend on inter-specific differences in salinity tolerance [29, 33, 34] and water-logging [31, 33, 35]. In our study, marsh soils had substantially higher moisture than dune soils, due to tidal inundation. Occurrence of the deep rooted *S. fruticosa* on apparently less saline, low dunes along the edges of high marsh zones, despite its high salinity tolerance (~1,000 mM NaCl; [36]) indicates possible sensitivity to

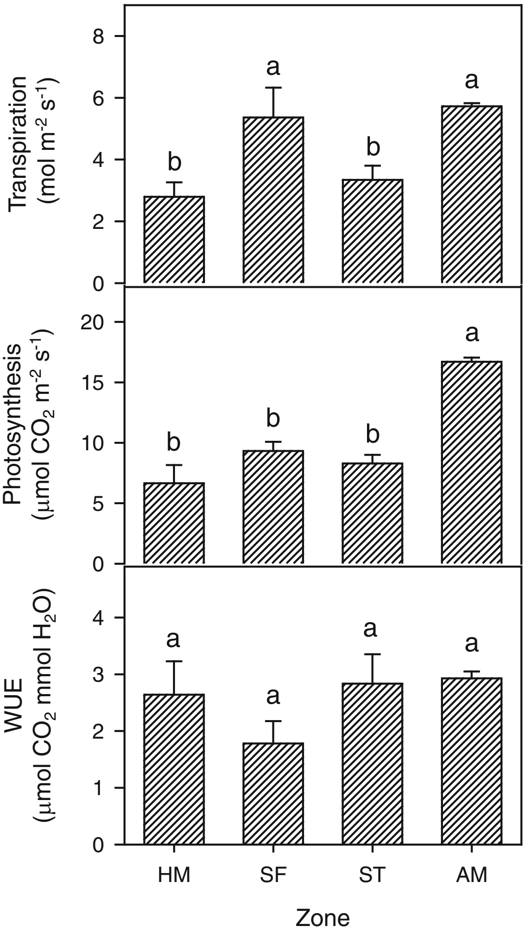

Fig. 7 Transpiration, photosynthetic rate and water use efficiency (WUE) of *Halopyrum mucronatum* (HM), *Suaeda fruticosa* (SF), *Sporobolus tremulus* (ST), and *Avicennia marina* (AM). Bars are means ± S.E. Similar letters represent non-significant differences among means, (Bonferroni, $P < 0.05$)

flooding among key factors affecting plant zonation. However, soil electrical conductivity measurements in this study do not reflect actual root zone salinity and moisture and need to be studied more comprehensively.

We also found some interesting species-specific responses. For example, *A. marina* displayed optimal photosynthetic rates typical of C_3 plants indicating ideal adaptive response to local conditions [37]. Whereas, the three C_4 species maintained lower photosynthetic rates and stomatal conductance, possibly due to poor soil nutrient status, low water availability and salinity [38]. Low dunes on the study site were dominated by *Suaeda fruticosa* which appeared to buffer the effects of environmental stresses by maintaining substantially higher succulence and leaf ash content [36]. Succulence helps plants to maintain physiological functions in times of water scarcity [39]. Relatively lower leaf osmolality in *S. fruticosa* could be due to salt dilution effect of succulence, an adaptive feature under saline conditions [40]. Lower xylem pressure and higher transpiration rates in *S. fruticosa* and *A. marina* indicate their ability to utilize soil moisture for growth under saline conditions. However, all the species studied displayed similar water use efficiency (WUE) for growing in their specific niche along the gradient. The occurrence of taller species with larger seeds at both extremes with low species diversity i.e., *H. mucronatum* on the high dunes and *A. marina* in the low marsh could be related to tolerance and/or species competitive abilities [41–43]. Higher soil organic matter in the marsh zones could be associated with higher leaf soluble carbohydrate due to nutrient enrichment in case of *A. marina*. However, higher sugars in *S. tremulus* could be due to lack of sugar metabolism and/or translocation under stressful conditions. Proline, an indicator of stress was about three times lower in most species except for *S. tremulus* (~12 ± 2 µmol g^{-1} DW) due to higher and variable salinity and moisture in the upper marsh zone [44].

5 Conclusions

Despite apparent variations in soil parameters such as ECe, moisture and organic matter, plant populations generally displayed plant-type specific variations in ecophysiological parameters. Species appear to employ various responses to achieve similar levels of water use efficiency regardless of their position along the gradient. It may also reflect a similar adaptive feature of subtropical halophytes to the macro-environmental conditions such as vapor pressure deficit rather than differences in local soil conditions. Coastal habitats constitute fragile transition zones between marine and terrestrial environments, which are under considerable threat particularly in overpopulated metropolitan cities such as Karachi. Such studies could prove useful in better ecological management of these threatened coastal ecosystems.

Acknowledgements SG would like to thank the Higher Education Commission of Pakistan for provision of funds for the NSRP research project No. 20-923.

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Research and Development with Seawater and Halophytic Plants for Sustainable Saline Agro Systems in the Arabian Gulf

Ronald A. Loughland, Ali Qasam, and Bruce Burwell

Abstract

The extensive natural coastal sabkha ecosystems along the Arabian Gulf's southern and western shoreline are detailed and their incorporation as part of saline agro-systems is outlined. This chapter is intended to showcase the inherent natural values of saline coastal sabkha, saline water resources and halophytic plants and provide sustainable alternatives for their utilization. It also discusses the alternative use of industrial brine water being discharged along the Arabian Gulf coast for saline agro-systems within sabkha landforms.

1 Introduction

This chapter outlines techniques for the utilization of saline water resources (i.e. seawater, ground water and industrial effluent), saline soils (known regionally as sabkha) and salt tolerant plants including mangrove, salt marsh, rangeland plants and micro algae for sustainable landscaping, production of livestock fodder, sources of natural pharmaceuticals and biofuels. Case studies from Abu Dhabi and Kuwait are provided to demonstrate the wide climatic applications of these different techniques along the Arabian Gulf and as a means of illustrating their wide climatic potential elsewhere.

Saline water effluent from industries adjacent the Gulf coast (i.e. desalinization, power production and cooling water discharges) and the industry's respective flue gas emissions such as CO_2 and NOX are discussed as a potential abundant source of brine and fertilizer for saline algae production in coastal sabkha ponds, therefore assisting in reducing heat and saline impacts on the marine environment, and detrimental air emissions.

The extensive natural coastal sabkha ecosystems along the Arabian Gulf's southern and western shoreline are detailed and their incorporation as part of saline agro-systems, particularly for the development of sustainable mangrove (*Avicennia marina*) ecosystems and as hyper saline ponds for the production of pharmaceuticals and biofuels

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_14, © Springer Science+Business Media Dordrecht 2014

using salt tolerant micro-algae (*Dunaleila & Pleurochrysis sp.*) are discussed.

Development of sustainable coastal landscaping utilizing saline irrigation and drainage, in combination with halophytic coastal and rangeland plants is illustrated from Kuwait.

A passive subsurface irrigation technology that allows the utilization of saline water within non-saline environments for landscaping and livestock fodder production is presented, with case studies from Abu Dhabi illustrating its potential.

This chapter is intended to showcase the inherent natural values of saline coastal sabkha, saline water resources and halophytic plants and provide sustainable alternatives for its utilization, particularly its potential for saline agro-systems providing non-marine sinks for industrial saline brine currently being discharged along the Arabian Gulf coast.

2 Background

The Arabian Gulf is a relatively shallow sea surrounded by large arid landmasses with little rainfall and therefore minimal terrestrial runoff [1]. The main exception being seasonal flows of the Shatt Al Arab (Euphrates and Tigris Rivers in Iraq) that drain higher elevations to the west of the Gulf. Seawater input through the Straits of Hormuz (from the Gulf of Oman) is also restricted [2] and sea surface evaporation is high in both summer and winter with the resulting denser saline waters sinking and driving local current patterns. This saline driven current phenomenon is particularly pronounced in the Abu Dhabi southern embayment between the Qatar Peninsular and the Straits of Hormuz [3].

The southern and western shoreline of the Arabian Gulf is generally flat with minor relief resulting in vast areas of shoreline that is either intertidal or supratidal, with both being inundated by tidal and or storm surges. One of the most unique features of the southern and western Arabian Gulf is the formation of extensive supratidal coastal saline sabkha. Sabkha is a regional term for evaporative coastal salt flats, and Abu Dhabi Emirate and the Eastern Province of Saudi Arabia have the most developed sabkha landforms [4]. The sabkha of Abu Dhabi were some of the first to be studied in detail [5, 6] and were known as the *Unique Trucial Coast Sabkha*. The development of the "*Evan's Line*" and some early borehole sites southwest of Abu Dhabi City which described the structure, development and sediment of coastal sabkha were instrumental in the early understanding of these unique coastal formations. The majority of the coastline of Abu Dhabi is active coastal sabkha, and is recognized as the largest in the world. It is around 300 km long and extends continuously for around 20 km or more inland. The hydrology of sabkha systems varies. At coastal sites, storms and gales may force seawater on the shallow and gently sloping southern Gulf shores, thus inundating extensive areas of coastal sabkha.

Winter rainfall is often also trapped on the sabkha surface until evaporated. The sabkha may remain flooded for many months; because the mineral precipitates principally gypsum or anhydrite seal the sabkha base, forming natural sabkha ponds that increase in salinity as water evaporates.

The Abu Dhabi Gulf coast also has numerous inshore and near shore islands, most of which are simply part of a former more extensive and continuous coastal sabkha ecosystem eroded by post-Quaternary storms and inundated by a higher sea level.

Because of their proximity to marine waters, their shallow soft substrate and saline groundwater, sabkha landforms were traditionally left undeveloped. Because sabkha saline crust inhibits plant establishment and growth, they were also considered to be of little value for grazing. As a result in most coastal areas large sabkha landforms still persist. It has only been in recent decades that sabkha landforms adjacent coastal communities became dumping sites for solid waste, or were filled with dune sand and used for makeshift developments, despite their inadequate and corrosive foundation.

Today sabkha are being developed at a much faster rate, and are being drained (dewatered), sheet pilled and filled with dune sand for expanding permanent developments around major towns and cities. Development of sabkha areas for commercial, residential and industrial purposes is likely to continue at a rapid pace because the price of coastal land continues to rise.

The Arabian Gulf's entire southern and western shoreline has become increasingly developed over the past few decades and now is extensively utilized for residential, commercial and industrial development [7, 8] having one of the highest proportion of desalination, power generation, hydrocarbon and petro-chemical coastal based industries in the world. Desalination of seawater is utilized to provide potable and industrial feed water and the resulting marine discharge is hot saline brine. Both heat and salt are natural marine ecosystem stressors in the Arabian Gulf with most species being at their biological threshold, and only a small sustained increase above ambient conditions for water temperature and salinity can be lethal. Seawater is also used for industrial cooling and large quantities of heated and slightly elevated saline cooling water is discharged back into the Gulf annually. The volume, and hence impacts of these combined discharges on the marine environment can be reduced through utilizing the same discharges as a source of saline brine for the cultivation of saline algae in nearby extensive coastal sabkha landforms.

The same coastal industries also have detrimental air quality impacts which affect coastal communities and reduction of some emissions such as CO_2 and NOX via their utilization as diffused fertilizers in adjacent saline algal cultivation ponds would be a win-win scenario, increasing the biomass production of algae and reducing harmful emissions to the air [9].

3 Saline Water Resources

The Arabian Gulf has high salinity levels ranging between 45 and 70 parts per thousand (ppt) compared to an average global ocean salinity of 36 ppt. This is due to long retention time of seawater in the Gulf and substantial surface evaporation as a result of the surrounding arid landmasses and high wind and air temperatures throughout most of the year. The evaporation results in humid coastal conditions, particularly in the southeastern areas of the Gulf, and influences coastal current patterns due to the sinking of denser saline water [3].

In some embayment's and back lagoon systems within the Gulf where flushing is minimal, salinity levels can be extreme with for example, the lagoons occurring behind the barrier islands along the Abu Dhabi coast (Fig. 1) and the Gulf of Salwa located between Saudi Arabia and Qatar.

Many coastal groundwater reservoirs are also saline, especially where there is no freshwater groundwater flow from inland, and particularly beneath evaporative sabkha landforms close to the coast.

Both seawater and saline groundwater is utilized by industry along the Arabian Gulf coast for desalination, energy production (steam generation) and for cooling water. Large areas of the Arabian Gulf's southern and western coastline has been developed for industry (Oil and gas extraction and refinement, Petro-Chemicals and shipping) and large cities requiring desalinated water and electricity have developed around these industrial centers [8].

The resulting industrial saltwater discharges are usually released directly into the Arabian Gulf and are warmer and more saline than the ambient conditions at the respective water intakes. The elevated heat and salinity can have detrimental impacts on local marine flora and fauna because most species in the Arabian Gulf are already living at their ecological upper threshold limits.

These same saline water discharges could be instead utilized within coastal saline agro-systems, eliminating their marine impact, and creating environmental, social and economic value for the surrounding communities.

4 Sabkha Landforms

Sabkha occur along the southern and western Arabian Gulf coastline occupying the sea – land interface, where infrequent supra-tidal inundation and evaporation of saline groundwater drawn upward by capillary action saturates, forming a well-defined salt crust.

The physical and chemical profile of sabkha is provided in detail with the surface being usually less than a meter in thickness, beneath the salt

Fig. 1 Landsat image illustrating the commencement of the Abu Dhabi barrier island complex along the Arabian Gulf coastline of the United Arab Emirates. The barrier islands reduce water flushing in the back lagoons resulting in increases in salinity of the lagoon waters along the mainland coast

crust is a layer of precipitate soft gypsum mush, and below is the saline groundwater [10]. Ecologically, sabkha has limited terrestrial habitat value, however windrows of detritus including seeds (that often germinate in adjacent sand hummocks) along their edges provide concentrated forage resources for wildlife and naturally folding sabkha salt crust formations (Teepees, Fig. 2) can also provide refuge habitat to small animals [11]. Despite its high salinity, sabkha are actually productive surfaces for micro-organisms. Coastal sabkha is also often coated in a stromatolitic algal mat with a reducing layer below. These mats are a mixture of cyanophytes, diatoms and bacteria. When the sabkha surface dries out the algal layers begin to crack and peel and the entire sabkha surface becomes a rough mosaic of drying layers. Permanent saline pools are a notable feature of coastal sabkha; these can often also have a subterranean connection to the sea and thus fluctuate tidally.

Some of the largest coastal sabkha occur along the west coast of Abu Dhabi Emirate into the Kingdom of Saudi Arabia (KSA), with the largest being Sabkha Matti straddling both the UAE/KSA border. In Abu Dhabi, Sabkha Matti continues for 100 km inland crossing into Saudi Arabia where it continues for a further 100 km. As a result Sabkha Matti covers many hundreds of square kilometers. Sabkha in Abu Dhabi Emirate has been profiled and mapped (Fig. 3) [10].

In the Eastern Province of the KSA, sabkha were classified using remote sensing. All sabkha within 100 km of the Arabian Gulf coast was mapped as part of this work (Figs. 4 and 5) with sabkha area representing around 2,775 km^2, or 4.5 % of the total land area examined. The largest sabkha covered an area of around 138 km^2 and many sabkha occurred close to existing large coastal industrial developments such as Jubail, Ras Tanura (Rahimah) and Dammam meaning that saline brine discharges from these industrial sites

Fig. 2 Coastal sabkha in Abu Dhabi illustrating Teepee salt crust formations. These formations are utilized by small animals (e.g. Cape Hare *Lepus carpensis*) for refuge

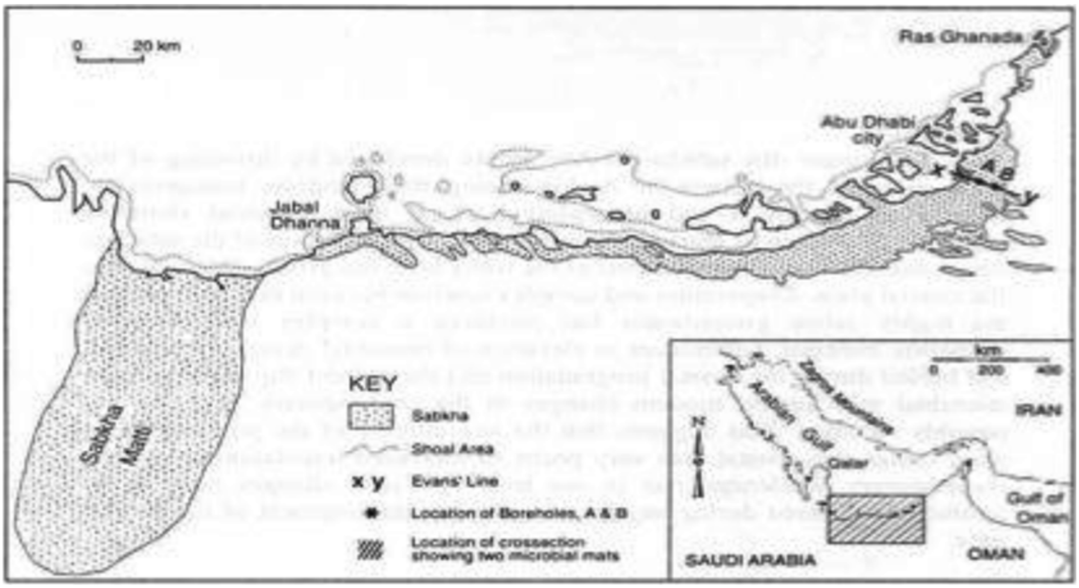

Fig. 3 The location of coastal sabkha along the Abu Dhabi Emirate Coast (illustrating the Evans Line and location of two exploratory boreholes) (Source: [10])

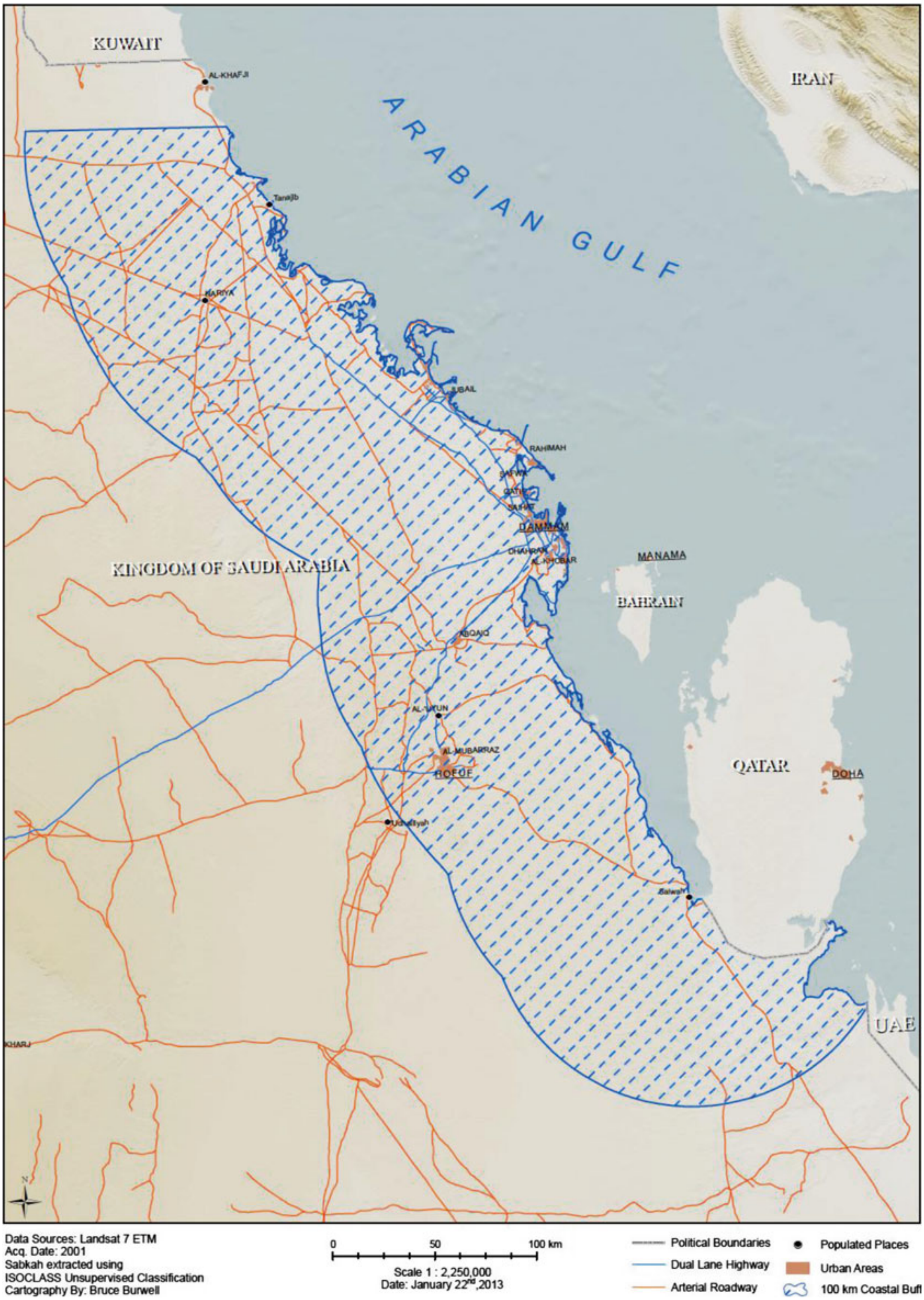

Fig. 4 Extent of coastal zone in the KSA (100 km) where sabkha landforms were mapped

Data Sources: Landsat 7 ETM
Acq. Date: 2001
Sabkah extracted using
ISOCLASS Unsupervised Classification
Cartography By: Bruce Burwell

Scale 1 : 2,000,000
Date: January 22nd, 2013

Fig. 5 Extent of coastal sabkha in the Eastern Province of KSA normally discharged to the marine environment, could be discharged instead inland within sabkha formations to create sustainable saline algae agro-systems.

Where present, coastal sabkha prevents coastal flooding and erosion, and is thus economically valuable. Coastal Sabkha along the Arabian Gulf coast also has both aesthetic value and cultural importance, as these were the same sabkha that were extensively studied and documented as part of the early petroleum geology undertaken in the region. Sadly, most of the original Evans Line has been lost due to development of the sabkha southwest of Abu Dhabi City.

5 Examples of Sustainable Saline Agro-systems

In Abu Dhabi Emirate coastal sabkha has been successfully converted to productive saline agro-systems using local mangrove (*Avicennia marina*) by the Public Works Department, Private Department of the President and other organizations such as the Emirates Heritage Club. In Abu Dhabi early mangrove planting was undertaken around Abu Dhabi City with varied success and in the late 1990s the Public Works Department surveyed existing mangrove habitats using theodolite, dumpy level and leveling staff to determine their optimal tidal range above mean sea level [12]. New mangrove plantation sites planned within sabkha areas were then excavated down to this optimal tidal level and with the provision of tidal channels to allow adequate flushing and drainage, sabkha landforms were converted to lower saline productive intertidal areas which were extensively planted with local mangrove (*A. marina*). The results were exceptional with large areas of sabkha around Abu Dhabi City, on near shore islands and at coastal sabkha sites in central and western Abu Dhabi Emirate being transformed to sustainable tidal irrigated saline agro-systems. Invertebrates, fish and bird species soon colonized these new plantations and today Abu Dhabi has some of the most productive mangrove habitats in the Gulf [13, 14].

Also in Abu Dhabi Emirate, coastal sabkha has been converted to grow saline tolerant micro algae within hyper saline agro-systems. This has been undertaken on a smaller scale than for mangroves, however has proven extremely productive in initial trials conducted on Futaisi Island adjacent Abu Dhabi City. Opposite to the concept of mangrove establishment through decreasing salinity within sabkha landforms through excavations and seawater flushing, conversion of sabkha for the development of algal systems requires increasing salinity within ponds developed on top of sabkha by mounding soil around the edge of sabkha to form shallow (<1 m) ponds. The algal ponds are flooded with seawater or saline groundwater and maintained at a depth of around 15 cm. Surface evaporation results in hyper salinity of the pond water and the resulting precipitates provide a natural seal for the base and walls of the ponds.

Once the pond water has reached high enough salinity levels (200 ppt), the pond is inoculated with saline tolerant algae such as *Dunaliella salina*, which has natural occurring strains occurring in the Arabian Gulf. The algae are able to persist and thrive in the hyper saline brine, however other organisms that normally control their growth in seawater cannot, which results in a monoculture of *Dunaliella salina*.

Dunaliella salina has been successfully grown in research scale saline agro-systems within sabkha landforms on Futaisi Island in Abu Dhabi (Fig. 6). More recent trials have also been conducted at Kiran in southern Kuwait. The objective was to test the efficiencies of producing a natural pharmaceutical known as Beta Carotene. Abu Dhabi trials indicated that *Dunaliella salina* algae cultivation in saline ponds is extremely productive, and rivals other global sites in its annual production potential. This is due to Abu Dhabi's abundant sabkha ecosystems, warm, sunny and dry climate, and high saline Gulf waters.

Other saline tolerant algae species (e.g. *Pleurochrysiscarterae*) can also be grown in saline ponds to produce biomass and oils used for developing biofuels. Algae produce around 36 times more oil per area than that sourced from vegetable crops such as canola, corn or sunflower. Algal oil has a similar caloric value to that of canola oil, being around 36,000 kJ/kg of oil.

Fig. 6 Sabkha ponds developed for the cultivation of *Dunaliella salina* on Futaisi Island in Abu Dhabi Emirate. The *red color* is the natural pharmaceutical Beta Carotene within the algae cells

Producing biofuel in coastal sabkha from saline based algae in saline agro-systems makes ecological, social and economic sense as unlike vegetable crops, no freshwater resources are required, and no arable land is utilized, hence not degrading the value of terrestrial environments and not diverting food crops to biofuel production. When brine discharges from coastal industry is discharged into coastal sabkha ponds, than the overall benefits are increased and the system is significantly more efficient. To increase the benefits even further, the industrial developments respective flue gas emissions such as CO_2 and NOX could also be utilized within the sabkha algae agro systems to increase algae productivity (source of fertilization) and decrease overall air emissions [9]. The industrial biodiesel (Diesel type 1) is possibly the most practical biofuel that can be developed from saline algae and the demand for "Green Biodiesel" is expanding rapidly [15].

Although the sabkha landforms utilized for mangroves and algae production require physical alteration, their marine ecological interface is still maintained and this is preferable than permanent sabkha conversion through reclamation for residential, commercial or industrial land use.

6 Examples of Sustainable Saline Irrigation Systems

There is a range of coastal plants both endemic and naturalized to the Arabian Peninsula that grow well under saline water (seawater) irrigation. Many succulent or chenopod plant species can cope with seawater salinity irrigation; it's the water logging and increases in salinity within the soils that is the issue. This is widely illustrated in the Region after rainfall, where plantations of salt tolerant trees planted on sabkha soils and irrigated with fresh

Fig. 7 Sustainable coastal vegetation developed on mounds adjacent the coast and irrigated with saline seawater at the Sabah Al Ahmad Sea City in Kuwait

(mostly STP) water e.g. *Conocarpus erectus or Ziziphusspina-christi* often show severe signs of salt stress and begin to wilt and drop leaves within days of rainfall. The issue is the salt rising in the overall soil profile, and the only remedy is to flush the roots continuously with irrigation water to leach out the salt. The same issue occurs when saline water is used for irrigating halophytes, the soil becomes saline water logged and after a short period becomes effectively similar to sabkha and cannot support vascular vegetation, regardless of how salt tolerant that vegetation may be.

The solution is to form mounding adjacent the coastline on which to plant the halophytes, and to irrigate with saline water using standard drippers spray heads ensuring the excess saline irrigation water runoff adequately drains back to the sea. This technique was used successfully on four islands developed from saline soils within a saline tidal creek in Kuwait. The islands were developed as part of the Sabah Al Ahmad Sea City development at Kiran adjacent the Arabian Gulf in southern Kuwait. The development flooded coastal sabkha to develop waterways on which to develop the City. The goal was to provide waterfront development without reclamation of the marine environment and the purpose of the islands was to control tidal flushing and water velocity within the creek to ensure good water quality. The islands were planted with a range of halophytic plants including mangrove (*A. marina*) at the intertidal interface and salt marsh, succulents and chenopod species on formed mounds developed along the supratidal zone. A range of chenopod shrubs and trees were established within the interior of the islands along drainage channels, which allow saline water drainage back into the creek. The supra-tidal mounds on the islands are irrigated exclusively with seawater from the tidal creek using traditional spray and drip irrigation (Fig. 7).

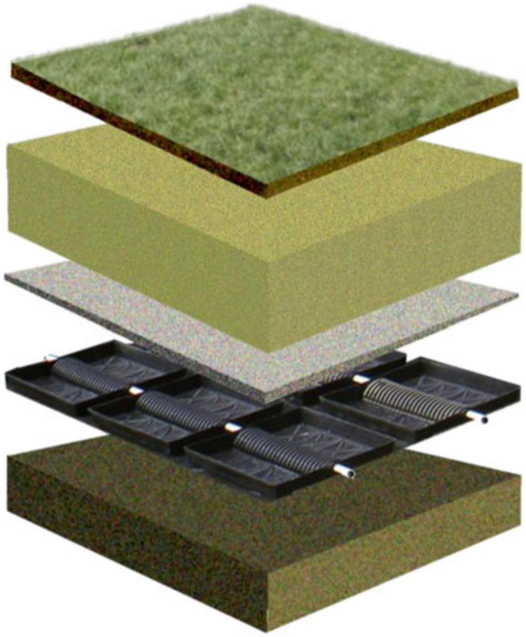

Fig. 8 The Environmental Passive Irrigation Chamber (EPIC) subsurface irrigation system allows saline water irrigation of halophytes without salt build up in the soil profile

Saline water irrigation of halophytic plants is also possible away from the coastline through the development of a subsurface irrigation system utilizing an Environmental Passive Irrigation Chamber (EPIC) that allows water distribution and prevents root and soil blockages. The chambers are positioned on top of a rubber liner forming a pan that prevents any saline water infiltration to terrestrial soils. The profile is around 30 cm deep and mimics' the capillary rise of water through natural sand profiles. The EPIC profile consists of a sand layer of 20 cm or more developed on top of a porous gravel bed of around 10 cm thickness; all positioned within an EPDM rubber lined profile, with a flat horizontal base and vertical sides providing a water holding pan (Fig. 8).

This subsurface irrigation system has been successfully utilized in Abu Dhabi on Al Sammaliah and Yas Islands. The profiles were established adjacent the shoreline on both islands and supplied with seawater from the Arabian Gulf. The saline water was circulated at the gravel base of the profile by a small solar pump, creating a saturated zone that is consistent in salinity with the ambient seawater (47 ppt). The saline water rises by capillary (wicking) through the sand profile to irrigate the halophytic plants established at the surface of the sand profile. The sand therefore provides a source of passive irrigation and also provides adequate drainage for the plants. Trials on the islands have indicated that a range of salt tolerant plants can be cultivated in the system, including succulent ground covers, some salt tolerant grasses and chenopod shrubs.

Initial concerns about salt build up in the profile was managed by periodically raising the drainage valve and flooding the profile therefore washing the excess salt in the profile out, returning the profile back to the ambient saline conditions of seawater. This was required in the early operation of the system before 100 % vegetation cover was achieved on the surface where there was increased surface evaporation from bare sand.

Long term results (5 years) have indicated that despite the consistent saline saturated base of the profile that the sand higher in the profile actually has less salt, and it seems likely that the sand is providing some form of salt exclusion as the water rises through the profile (Sipaila TJ, 2011, Environmental Passive Irrigation Chamber (EPIC) inventor, personal communication). The same principal is observed naturally in sabkha landforms, where a mound of windblown sand forms a hummock, or along a dune edge adjacent a sabkha where vegetation often germinates and develops to a certain height up the side of the dune (Fig. 9). The vegetation observed is salt tolerant, however the hummock or dune is irrigated from below by a source of saline irrigation water from the sabkha, that rises through the sand profile by capillary action (wicking) and is utilized by the plant. The hummock or dune also provides a porous substrate that facilitates adequate drainage and prevents water logging. The observations with decreased salinity further up the sand profile within the EPIC subsurface irrigation system may explain why even in hyper arid areas on saline sabkha, halophytic plants can germinate and grow abundantly on natural sand profiles.

Fig. 9 Hummocks of windblown sand, or sand dunes on or adjacent saline sabkha allow saline water to rise by capillary action and provide natural irrigation for halophytic vegetation. The sand also provides good drainage and a reduction in overall salinity. The vegetation range is limited by the capillary rise of the water through the sand, forming distinct banding of vegetation along the sabkha-dune interface

The agricultural application of EPIC saline irrigation for animal fodder production is promising. Saline irrigated halophytic crops are more palatable and nutritious to livestock and also use significantly less water resources to be produced. The plants produced on Al Sammaliah Island within the EPIC system consumed almost 80 % less water than conventional irrigated systems over the summer of 2007, and were so attractive to grazing animals (despite ample freshwater vegetation being available) that we had to fence the saline trial plots to stop hare, gazelle and camels from eating all the vegetation. The salt within the plants was obviously highly attractive to these animals. No salt build up in the overall profile, and the harvesting of the crop (cutting or allowing grazing) means that the system can go on producing fodder indefinably and coastal and inland areas where groundwater aquifers are saline, either naturally or from over utilization would be good sites for the establishment of saline water fodder agro-systems, helping local communities develop sustainable halophytic indigenous fodder crops and reducing the overall grazing pressure on natural rangelands.

7 Conclusion

Saline sabkha along the southern and western Arabian Gulf are unique coastal landforms and when combined with the abundant saline water resources that dominate in the Gulf coastal region, these landforms have huge potential for sustainable productivity utilizing indigenous halophytic plant species such as *Avicennia marina* and *Dunaliella salina*.

The long-term conservation of coastal sabkha will rely on its utilization within the overall development of the coastal zone, and lessons from the observations of natural sabkha ecosystems may provide the solutions. The utilization of coastal sabkha as a sustainable sink for industrial saline brine and incorporating various productive saline agro-systems using halophytes to absorb CO_2 and NOX emissions from these industries would mean that the productivity of the agro-system would increase, and the sabkha would be viewed not only as valuable environmental sink, but also productive systems with a substantial economic and social value.

Acknowledgements The Authors would like to thank the following individuals and organizations for their support of this work, and for their contributions to overall sustainable development along the Arabian Gulf coast: H.H sheikh Sultan bin Zayed Al Nahyan (Abu Dhabi), H.H sheikh Zayed bin Hamed Al Nahyan (Abu Dhabi), H.E Fawaz bin Khalid Al Marzouq (Kuwait), Jonas Sipaila (USA), Saudi Aramco (Saudi Arabia), EPIC – Green (Dubai).

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Salinity Tolerant Turfgrasses for Biosaline Urban Landscape Agriculture

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Abstract

Critical fresh water shortages are occurring in population centers worldwide. Overuse of fresh water resources, coupled with effects of global warming such as salt water intrusion and desertification, are resulting in salinization of water and soil resources. Rapid urban population growth has put enormous pressures on limited freshwater supplies, and many governments have responded by placing restrictions on the use of fresh water for irrigating turfgrass landscapes, instead requiring use of reclaimed, or other secondary saline water sources. Issues facing landscape managers using saline water sources are soil salinization, resulting in direct salt injury, and secondary problems of loss of soil structure ensuing from sodium and bicarbonate effects, resulting in loss of salt leaching potential and soil anaerobiosis. Long-term solutions to the salinity problem will require development of improved salinity tolerant turfgrasses. Progress has been made in understanding turfgrass salinity tolerance mechanisms, and in development of salinity tolerant turfgrass cultivars and alternate native species.

Abbreviations

CEC	cation exchange capacity
dS m^{-1}	decisiemens per meter
EC	electrical conductivity
ECe	electrical conductivity of saturated paste extract
ESP	exchangeable sodium percentage
Ksat	saturated hydraulic conductivity
LF	leaching fraction
mho cm^{-1}	mhos per centimeter
ppm	parts per million
PR	precipitation rate
SAR	sodium adsorption ratio
TDS	total dissolved solids

The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_15, © Springer Science+Business Media Dordrecht 2014

1 Water Issues: Nature and Extent of Problem

Critical fresh water shortages are now occurring worldwide, due predominately to increased demand resulting from population increase, competition from agriculture and other industries, and global climate change [1]. The United Nations estimates that 2.7 billion people will face severe water shortages by 2025 if consumption continues at current rates [2]. Closely coupled with fresh water shortage are the issues of soil and water salinity. World water shortages are necessitating use of lower quality, saline water sources for irrigation [3]. Aquifer over extraction and sea level rise are resulting in salt water intrusion and salinization of fresh water aquifers [4]. A total of nearly 900 million hectares of the world's soils are currently salt compromised [5]. Global warming and desertification are directly linked to salinization, as increasing droughts, temperatures, and evaporative demand accelerate soil salinization [6].

Critical water shortages are occurring in rapidly growing urban areas, resulting in restrictions on the use of fresh water for irrigating urban landscapes. Turfgrass landscape irrigation is typically considered a low priority use for fresh water, particularly when water shortages occur [7]. Policies have been implemented in the U.S.A., Australia, and elsewhere requiring use of saline water sources for turfgrass irrigation, when available [8–10]. Saline sources mandated for use on turfgrass may include reclaimed water (sewage effluent), brackish ground water, et al. Salinity issues on turfgrass are also becoming acute in coastal regions where most major urban population centers lie, due to salt water intrusion [11].

2 Importance and Value of Urban Landscapes

Urban turfgrass industries worldwide have grown rapidly in recent decades. Recent estimates place the land area planted to turfgrass in the United States at over 160,000 km^2, an area three times larger than that of any irrigated crop [12]. Turfgrass industries generated a total of $58 billion in the United States in 2002 [13]. This growth trend is also occurring in other developed, or rapidly developing countries, such as Australia, China, et al. [14, 15].

Urban turfgrass landscapes provide numerous functional, environmental, and economic benefits [16]. Green landscapes absorb air and water pollutants, filtering storm runoff and preventing erosion [17]. Evapotranspirational cooling and shading provide substantial temperature modification [18]. Turfgrass provides a venue for recreational and leisure activities [19]. Green landscapes improve psychological wellbeing and reduce urban crime [20]. Finally, green landscapes increase property values [21].

3 Salinity Issues in Urban Turfgrass Landscapes

Salinity related problems in turfgrass often occur gradually, causing decline in quality and functionality, and depending on a number of factors, may be expensive to manage. The major water and soil quality factors related to salinity issues are total salinity, sodium hazard, and bicarbonate hazard.

3.1 Irrigation Water Salinity Hazard

Irrigation water and soil contain various salts, the most common being sodium, potassium, calcium, and magnesium, typically associated with anions chloride, sulfate, and carbonate/bicarbonate [22]. Total salinity is expressed either as electrical conductivity (EC) or as total dissolved solids (TDS) in parts per million (ppm). Conversions between units of measurement can be made on the basis that EC: 1 mS cm^{-1} = 1 dS m^{-1} = 1 mmho cm^{-1} = 1,000 μmho cm^{-1} is approximately equal to TDS: 640 ppm, depending on the ratio of salts present in solution. Irrigation water salinity is generally classified as: low: <0.25 dS m^{-1}, medium: 0.25–0.75 dS m^{-1}, high: 0.75–2.25 dS m^{-1}, and very high: >2.25 dS m^{-1}, while soil is classified as saline when ECe (electrical conductivity of the saturated paste) >4 dS m^{-1} [23]. The best means of monitoring salinity is by measuring soil ECe, and turfgrass salt tolerances are generally expressed on the basis of ECe [24].

Salts quickly accumulate in the soil profile when irrigating with saline water, particularly when evaporative demand is high. For example, the application of only 2.5 cm of irrigation water having a low EC value of 2 dS m^{-1} will deposit over 3.0 kg of salt within a 100 m^2 area. To avoid salt injury, soil salinity must be maintained below the salinity tolerance level of the turfgrass. The leaching percentage required to maintain soil salinity below this level is termed the leaching fraction (LF):

$$\%\mathrm{LF} = \mathrm{EC}_{\text{irrigation water}} / \mathrm{EC}_{\text{drainage water}} \times 100 \quad (1)$$

where $\mathrm{EC}_{\text{drainage water}}$ is equivalent to the salinity of the root zone, and consequently the salinity tolerance of the turfgrass. The volume of irrigation water necessary to maintain $\mathrm{EC}_{\text{drainage water}}$ (soil salinity) at sustainable levels depends on the relative salinity tolerance of the turfgrass as well as irrigation water salinity; when irrigating with saline waters the volume may be quite large.

3.2 Sodium and Bicarbonate Hazard

Turfgrass salinity problems are often compounded by the effects of sodium (Na^+) on the dispersion of soil colloids, resulting in loss of soil structure. Loss of structure results in compaction-prone soils (of great concern in high traffic turfgrass areas), with resultant anaerobiosis and loss of rooting. Anaerobiosis decreases root ion selectivity, thereby increasing transport of saline ions to shoots, resulting in reduced plant growth and survival [25]. Further, leaching potential is lost, accelerating salinity buildup within the root zone. Maintenance of good saturated hydraulic conductivity (Ksat) is important; an acceptable Ksat for medium textured soils is 1.2 cm h^{-1} or higher. Ksat must be maintained above the precipitation rate (PR), otherwise irrigation cycling will be necessary.

Soil colloid dispersion is affected by the ratio of Na^+ to divalent cations calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations (meq L^{-1}) in the irrigation water, a ratio known as the sodium adsorption ratio (SAR), where:

$$\mathrm{SAR} = \left[\mathrm{Na}^{+}\right] / \left\{\left[\left[\mathrm{Ca}^{2+}\right] + \left[\mathrm{Mg}^{2+}\right]\right] / 2\right\}^{1/2} \quad (2)$$

Sodium hazard of irrigation water is classified as follows, low: 0–10, medium: 10–18, high: 18–24, and very high: >24 SAR [23]. Clays are more susceptible to deflocculation than silt, and 2:1 clays are particularly susceptible. For example, medium SAR's are generally a problem on fine-textured soils only, and particularly on soils rich in illite or montmorillonite. High SARs are a problem on all soils except sand, and very high SARs should not be used on any soil without gypsum or similar amendments.

Gypsum neutralizes the dispersive effects of Na^+ via the reaction:

$$2\mathrm{Na}^{+} - \mathrm{X} + \mathrm{CaSO}_4 \rightarrow \mathrm{Ca} - \mathrm{X}_2 + \mathrm{Na}_2\mathrm{SO}_4 \quad (3)$$

where X is a soil colloid. Gypsum should be incorporated into the soil profile whenever possible, as it has a low solubility (solubility product 9×10^{-6}). The amount required to displace exchangeable Na^+ on the soil colloids depends on the soil cation exchange capacity (CEC), and on the percentage of cation exchange sites (percentage of CEC) taken up by Na^+, expressed as the exchangeable sodium percentage (ESP). Ideally, the ESP should be maintained below 15 %. Lowering ESP is a gradual process, with light, frequent gypsum applications being more effective than single, heavy ones. Typical rates vary from 12 to 24 kg per 100 m^2 per month. Gypsum can also be applied at low, maintenance-level rates through the irrigation system with specialized metering equipment.

Bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) affect Na^+ hazard indirectly, by precipitating Ca^{2+} and Mg^{2+}, via the reaction:

$$\begin{aligned} &\mathrm{CO}_3^{2-}\left(\text{or } \mathrm{HCO}_3^{-}\right) + \mathrm{Ca}^{2+}\left(\text{or } \mathrm{Mg}^{2+}\right) \rightarrow \\ &\quad \mathrm{CaCO}_3^{-}\left(\text{or } \mathrm{MgCO}_3^{-}\right) \end{aligned} \quad (4)$$

The bicarbonate hazard (concentration of bicarbonate in the irrigation water) is generally defined as: low: 0–120 ppm, moderate: 120–180 ppm, severe: 180–600 ppm, or very severe: > 600 ppm. When bicarbonates are a problem, acidifying amendments are typically used, such as sulfur or sulfuric acid. Acid reacts directly with bicarbonate to form carbon dioxide. In addition, sulfuric acid will react with soil calcium carbonate to form gypsum, thereby reducing Na^+ hazard, via the reaction:

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2O + CO_2 \quad (5)$$

Sulfur products should only be applied to soils when free calcium carbonate is present, which is typical in many arid-land calcareous soils. Powdered sulfur can be added to the soil, or onto turf, but application rates must be minimal to avoid turf burn <2.4 kg per 100 m^2, and when temperatures are above 21 °C to allow oxidation of the sulfur by soil bacteria to form sulfuric acid. Alternately, sulfuric acid can be injected directly into the irrigation system to neutralize bicarbonates. Injection must be at a low rate, sufficient to neutralize only 70–80 % of bicarbonates, otherwise, irrigation water pH will drop precipitously. Sulfuric acid injection is also utilized as a long-term maintenance technique, maintaining soil ESP and Na^+ hazard below harmful levels.

4 Selection for Salinity Tolerance in Turfgrasses

4.1 Salinity Tolerance in Turfgrasses

Good agronomic management practices are essential when using saline water for irrigation. However, as the world fresh water crisis escalates, waters of higher salinity are increasingly being used for irrigation, requiring development and use of salinity tolerant turfgrass genotypes. Salinity tolerance is a complex phenomenon, influenced by a number of environmental, edaphic, and plant factors [26]. For a given genotype, salinity response differs with developmental stage [e.g. seedling, juvenile, mature] [27]. Climatically, temperature and relative humidity can influence salinity response [28]. For example, plants are more sensitive to salinity under hot, dry conditions than under cool, humid ones, probably due to increased evapotranspirational demand, favoring increased salt uptake [29]. Edaphic factors also influence plant salinity response [30, 31]. Anaerobic soil conditions cause decreased root ion selectivity, thereby increasing transport of saline ions to shoots [25]. High soil Ca^{2+} ion concentrations reduce adverse salinity impact by playing an essential role in preserving functional integrity of cell membranes and in regulating ion exchange behavior [32]. Fluctuations in soil water content have a direct effect on root zone salinity. Soil salinity varies with time, increasing as the soil dries between irrigations [28]. Soil salinity also varies with depth in irrigated soil, often increasing two or more orders of magnitude from surface to bottom of root zone [23]. To minimize the effects of variable edaphic and climatic conditions on plant responses to salinity, researchers have utilized solution or hydroponic culture under controlled environmental conditions (growth chambers, greenhouses) in plant salinity research.

Due to the interacting factors discussed above, 'absolute' salinity tolerance level of a particular plant genotype or cultivar cannot be determined [28, 30]. For example, root zone salinity level resulting in 50 % reduction of shoot dry weight of 'Tifway' bermudagrass (*Cynodon dactylon* × *C. transvaalensis* [Burtt-Davey]), has been reported as 33 dS m^{-1} [33], 27 dS m^{-1} [34], 18.6 dS m^{-1} [35], and 12 dS m^{-1} [36]. Furthermore, comparison of results of different studies is complicated by the use of different criteria to measure salinity tolerance. For example, shoot weight [37], shoot weight reduction relative to nonsalinized plants [27], root weight or length [38], shoot/leaf length [39], shoot visual injury [40], plant survival [41], and seed germination [42] have all been used as measures of salinity tolerance in turfgrasses. Units used in measuring salinity often vary from study to study, whether on an ion weight basis (parts per million), ion molar basis (milliequivalents per liter), or on a conductivity basis (dS m^{-1}). Salts of different ionic compositions are used as salinity treatments, making exact comparisons of salinity treatments

Table 1 Relative salinity tolerance of turfgrass species

C$_3$ (cool season) Turfgrasses	Salinity Tolerance (ECe)[a]	C$_4$ (warm season) Turfgrasses
	+40 dS m^{-1}	*Sporobolus virginicus*
		Distichlis spicata spp. stricta
	28 dS m^{-1}	*Paspalum vaginatum*
		Zoysia matrella 'Diamond'[b]
		Zoysia pacifica
Puccinellia spp. 'Fults'	18 dS m^{-1}	*Stenotaphrum secundatum* 'Seville'
	15 dS m^{-1}	*Cynodon* spp. 'FloraTex'
	12 dS m^{-1}	*Zoysia japonica* 'El Toro'
Agrostis stolonifera 'Mariner'	9 dS m^{-1}	
Festuca arundinaceae 'Alta'	7 dS m^{-1}	
Festuca rubra 'Dawson'	6 dS m^{-1}	
Lolium perenne 'Paragon'	5 dS m^{-1}	*Buchloë dactyloides*
		Bouteloua spp.
Poa pratensis 'North Star'	3 dS m^{-1}	*Axonopus* spp.
		Eremochloa ophiuroides
P. trivialis		
Festuca longifolia		
F. elatior		
F. ovina		
Poa annua	2 dS m^{-1}	*Paspalum notatum*
Agrostis tenuis		
A. canina		

[a] Salinity level (dS m^{-1}) of soil saturated paste extract resulting in 50 % growth reduction, representing approximate midrange tolerance per species

[b] Indented names in single quotes represent the most salt tolerant cultivar currently known within the turf species listed directly above it

between studies impossible. Finally, time of exposure to salinity treatments varies among studies, though plant tolerance to abiotic stress is the product of stress level and duration [43].

Even with these limitations, relative salinity tolerances can be estimated between studies having at least one genotype in common. Table 1 is a synopsis of turfgrass salt tolerance research literature. Results are presented in standardized units, i.e. ECe values (dS m^{-1}) resulting in 50 % shoot yield reduction.

The definition of "halophyte" varies, but is currently interpreted to be plants which are able to complete their life cycle when continuously exposed to root zone salinities above 200 dS m^{-1} [44]. The term "euhalophyte" has been reserved for species which can tolerate salinity levels of 50–55 dS m^{-1} [45], equivalent to seawater [46]. From Table 1, it can be seen that several common turfgrass species may be considered halophytic, including *Paspalum vaginatum* Sw., *Zoysia matrella* [L.] Merr., and *Zoysia pacifica* [Gaud.] Hotta & Kuroti. These three species are reported to have similar salinity tolerance, though the range in tolerance among genotypes within each species is substantial, ranging from 25 to 40 dS m^{-1} [47–49]. Salinity tolerant *Zoysia matrella* cultivars have been developed having high salt gland saline ion excretion rates [47, 50, 51]. There are currently no developed cultivars of *Zoysia pacifica* available, though natural selections are being utilized for turf.

Two euhalophyte species of the Chloridoideae subfamily which have turf type morphologies, *Distichlis spicata* [L.] Greene ssp. stricta [Torr.] Thorne and *Sporobolus virginicus* [L.] Kunth, are being developed into alternative use turfgrasses for low maintenance conditions. *Distichlis spicata* ssp. *stricta*, native to North American deserts, is typically found in desert areas, salt flats (playas) and drainage areas [52]. *Sporobolus virginicus*, a cosmopolitan species indigenous to tropical and subtropical coastal regions worldwide, is typically found along coastlines and coastal estuaries [53]. A substantial range in salinity tolerance has been found among *Distichlis spicata* ssp. *stricta* turf type genotypes, from euhalophytes which maintain good growth under seawater (50 dS m^{-1}) root zone salinity levels, to halophytes which tolerate no more than 30 dS m^{-1} [54–56]. A number of studies have reported *Sporobolus virginicus* tolerant to 50+ dS m^{-1} root zone salinity; it is not know whether less salinity tolerant halophytic genotypes exist. Several improved turf type genotypes have been selected, and are being used to a limited extent under highly saline conditions [57, 58].

4.2 Mechanisms of Salinity Tolerance in Turfgrasses

Historically, salinity tolerance has been associated with the level of osmotic adjustment, deemed necessary to avoid "physiological drought" [59]. However, more recent studies of non-succulent plants, including grasses (Poaceae), have shown that shoot saline ion exclusion, coupled with minimal yet adequate osmotic adjustment, is central to salinity tolerance [60, 61]. Saline ion (Cl^- and Na^+) exclusion has been correlated with salinity tolerance among divergent plant genera [62, 63]. In grass species of the Chloridoideae subfamily, which include a number of C_4 turfgrasses, salinity tolerance was correlated with shoot saline ion exclusion and minimal osmotic adjustment. All species in the study maintained complete shoot osmotic adjustment under saline stress. However, salt-sensitive species accumulated saline ions to toxic levels, resulting in shoot osmolalities well above those required for osmotic adjustment [64]. In turfgrasses, shoot saline ion exclusion has also been correlated to salinity tolerance among genotypes *within* species of *Cynodon* [65], *Poa* [66], and *Zoysia* [47].

A number of salinity-adapted species have salt glands or bladders, which eliminate excess saline ions from shoots by excretion [67, 68]. Within the Poaceae, bicellular leaf epidermal salt glands have been reported to occur in over 30 species within the tribes Chlorideae, Eragrosteae, Aeluropodeae, and Pappophoreae [64, 68–70], all members of the subfamily Chloridoideae [71]. Salt glands of the Poaceae are bicellular, in appearance similar to leaf trichomes [68]. The basal cell, imbedded into the leaf epidermis, has ultrastructural characteristics, including a series of parallel membranes associated with mitochondria and microtubules, consistent with the ion pumping/excretion process [72]. Glands are characterized by cutinized cell walls, varying in length from 15 to 70 mm, longitudinally arranged in parallel rows, adjacent to rows of stomata [64].

Table 2 Salinity tolerance and Cl^- excretion rates of eight Chloridoid turfgrasses

Grass species	Salinity tolerance[a]	Cl^- excretion[b]
Sporobolus virginicus	725	4,336
Distichlis spicata spp. stricta	670	1,267
Sporobolus airoides	580	564
Zoysia matrella	512	423
Cynodon dactylon	337	191
Zoysia japonica	225	198
Sporobolus cryptandrus	182	85
Buchloë dactyloides	150	39
Bouteloua curtipendula	144	28

[a] Salinity level (mM NaCl) of root zone media resulting in 50 % growth reduction

[b] Excretion rate in μmol Cl^- g leaf weight^{-1} week^{-1}

Salt gland Na^+ and Cl^- excretion rates are negatively correlated with shoot Na^+ and Cl^- concentrations, and positively correlated with salinity tolerance among diverse Chloridoid species (Table 2) [34, 64, 74, 75]. In these studies, halophytic *Sporobolus virginicus* had Cl^- excretion rates approximately 150 times higher than salt-sensitive *Bouteloua* spp. The amount of Cl^- excretion per week by *Sporobolus virginicus* was 20 times that of internal shoot levels of plants grown at 200 mM salinity, illustrating the large quantities of saline ions excreted by this species. Strong correlations were maintained between salt gland excretion rates, shoot saline ion exclusion, and salinity tolerance among genotypes *within* species, specifically among 57 *Zoysia* spp. genotypes, 8 *Distichlis spicata* ssp. *stricta* genotypes, and 30 *Cynodon* spp. genotypes (Fig. 1) [47, 54, 65]. Salt gland excretion rates and salinity tolerance were found to be correlated with the number of glands present per unit leaf surface area, i.e. gland density, among 57 *Zoysia* spp. genotypes. Salt gland density was found to be highly heritable, an innate characteristic not influenced by salinity level, but solely by genotype [74]. Therefore, leaf salt gland density represents a morphological trait which can be used as a selection tool in breeding for salt tolerance in Chloridoideae genera.

As cellular enzymes of both glycophytes and halophytes have similar sensitivities to salinity, being inhibited at concentrations above 100–200 mM, salinity tolerant plants growing under saline conditions must restrict saline ion levels in the cytoplasm [76]. Salinity tolerant grasses utilize predominately inorganic ions for cellular osmotic

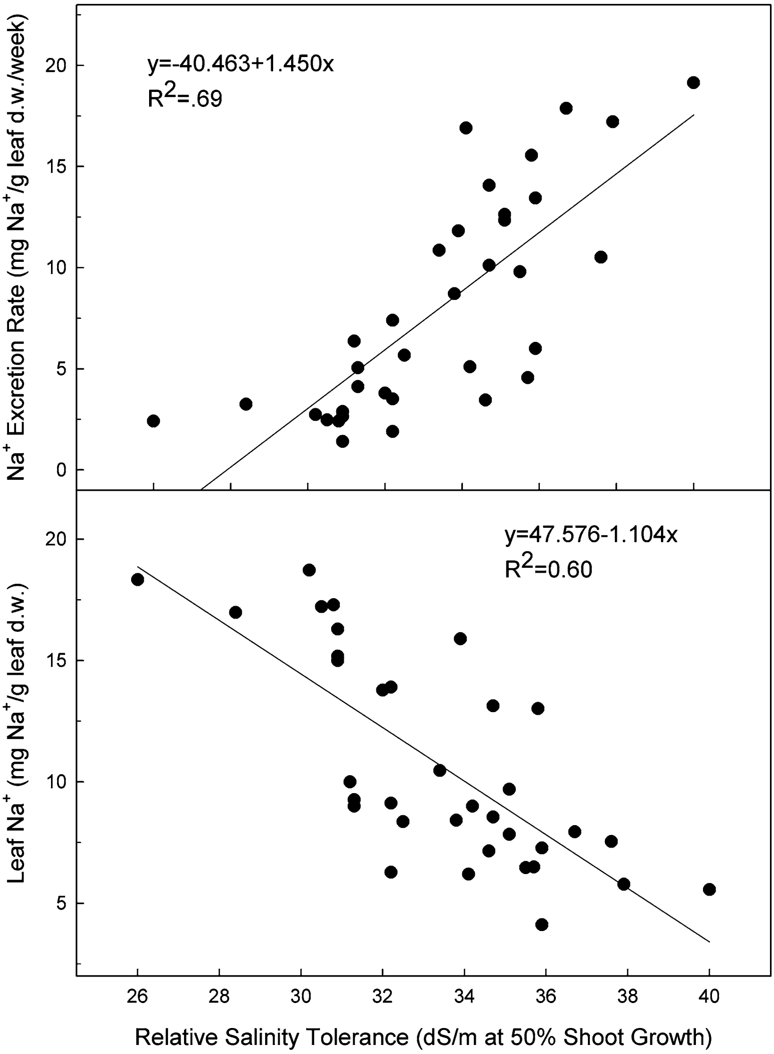

Fig. 1 Leaf salt gland Na$^+$ excretion rate, and leaf sap Na$^+$ concentration vs. relative salinity tolerance of 35 *Cynodon* spp. cultivars [64]

adjustment under saline growing conditions, as accumulation of organic solutes on a whole cell basis is metabolically expensive, and therefore limited [76, 77]. Salinity tolerant plants that successfully accumulate saline ions for osmotic adjustment above concentrations of 100–200 mM do so by compartmentalizing them within the vacuole, which typically makes up 90 % of a mature plant cell's volume [78]. Salinity tolerance in *Festuca arundinaceae* Schreb., a moderately salinity sensitive C$_3$ turfgrass, was enhanced by transformation with overexpressed AtNHX1, a vacuolar Na$^+$/H$^+$ antiporter gene from *Arabidopsis thaliana* [79]. Cytoplasmic osmotic adjustment is concurrently maintained by accumulation of organic solutes compatible with enzyme function, termed "compatible solutes" [80]. Under highly saline conditions, relatively few organic solutes, including glycinebetaine, proline, and certain polyols and cyclitols, can be accumulated in sufficient concentrations for effective cytoplasmic osmotic adjustment without inhibiting enzymes [81]. Of these, glycinebetaine, and in some cases proline, typically accumulate in grasses [82].

Among candidate compatible solutes, only glycinebetaine has been associated with salinity tolerance in turfgrasses, though proline may play a minor role in *Puccinellia distans* [Jacq.] Parl. [83]. Glycinebetaine, but not trigonelline or proline, has been correlated to salinity tolerance among C_4 turfgrasses, including *Bouteloua* spp. Lag., *Buchloë dactyloides* [Nutt.] Englem., *Cynodon* spp.[L.] Rich., *Distichlis spicata* ssp. *stricta*, *Eremochloa ophiuroides* [Munro] Hack., *Paspalum vaginatum*, *Sporobolus virginicus*, *Stenotaphrum secondatum* [Walt.] Kuntz, and *Zoysia* spp. Willd. [34, 64, 75, 84]. In contrast, proline levels were low, and negatively correlated to salinity tolerance in these studies. As glycinebetaine exists in the cytoplasm [85], which occupies approximately 10 % of total cell volume [80], its contribution to cytoplasmic osmotic adjust can be estimated. Glycinebetaine levels were highly correlated to salinity tolerance, and made substantial contributions to cytoplasmic osmotic adjustment in salinity tolerant turfgrasses (*Sporobolus virginicus*, *Distichlis spicata* ssp. *stricta*, *Cynodon* spp., *Paspalum vaginatum*, *Stenotaphrum secondatum*, and *Zoysia* spp.), but not in saline-sensitive ones (*Bouteloua* spp., *Buchloë dactyloides*, and *Eremochloa ophiuroides*) [34, 64].

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Ecology, Distribution and Ecophysiology of *Salicornia Europaea* L.

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Abstract

Salicornia, belonging to the family *Chenopodiaceae*, can tolerate total immersion in salt water absorbing the salt dissolved in the water without any harm. It is an ideal, high quality edible-oil yielding plant and its high economic value is attributed to the content of poly-unsaturated oil. In order to solve a number of global problems, this salt-tolerant crops should better be grown on millions of hectares of unproductive, arid land, and in all salty, marshy coastal area of the earth, while conserving freshwater and providing food, fodder, oil and valuable byproducts. For this reasons, knowledge of the ecology and ecophysiology of *Salicornia europea* can help to evaluate its salt tolerance and potential as crop, but also to give insight into the optimal agronomic conditions for cultivation. In this regard, we evaluated the effects of salinity on *S. europaea* growth to obtain insight in its performance. Our results showed that *S. europaea* grows rapidly at moderate salt concentrations (150 and 300 mM NaCl) and can survive at extreme salinities, including seawater concentrations. The results evidenced also that salinity triggered inorganic ions (Na^+) accumulation. In conclusion, germination responses to salinity of *S. europaea* seem likely to influence their colonisation capacities down the tidal gradient and hence may be important in the maintenance of taxa zonation in salt marshes. In addition seedling growth data and biochemical analysis suggest that this taxa may be successfully used to reclaim highly salinized areas in semi-arid and arid regions of the world.

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_16,

1 Introduction

Salicornia, belonging to the family *Chenopodiaceae*, deserves full interest for agricultural production in saline coastal areas, providing food, fodder and oil or biofuel without using fresh irrigation water.

It is an ideal, high quality edible-oil yielding plant [1]. High economic value is attributed to the somewhat 30 % of edible oil in its seeds (more than in soybean seeds). Growing interest in Salicornia-biofuel could also motivate people to start projects aiming at developing inhospitable, marshy coastal regions into productive lands. The oil of *Salicornia* is poly-unsaturated and has a pleasant flavor. Some ingredients of the oil are also used for the production of cosmetic and pharmaceutical substances. *Salicornia* can even tolerate total immersion in salt water or irrigation with seawater. Thriving on saline water, this species absorb the salt dissolved in the water without any harm [2].

In order to solve a number of global problems, this salt-tolerant crops should be better grown on millions of hectares of unproductive arid land, in all saline lands and in marshy coastal terrains worldwide to provide food, fodder, oil and some valuable byproducts of the oil extraction from its seeds in adverse condition. In addition a dense *Salicornia* cover of saline land is seen as a good carbon-sink area, delivering more carbon credits, for making the environment better.

Salicornia grows in periodically wet saline coastal and inland habitats such as salt marshes, salt lake shores, mud flats and salt pans. The genus currently comprises ca. 25–30 species. This is a rough estimate because no general agreement exists on the number of accepted species [3]. *Salicornia* is widely distributed in boreal, temperate and subtropical regions of the northern hemisphere and in South Africa. It is considered as absent from South America and Australia. The habitats of Salicornia are characterized by diurnal and/or seasonal dynamics where the duration of submergence, the tidal scour, water logging and especially salinity vary locally as well as within or between seasons [4]. These fluctuations that require high physiological plasticity in plants, cause strong phenotypic variations. Since most conventional crops are relatively sensitive to soil salinity and can only be cultivated under 'moderately' saline conditions (up to circa 20 % seawater salinity), the domestication of halophytes is an approach that should be considered. Thus, the capability of *Salicornia* to adapt to salt affected soils permits to turn land unsuitable for agriculture into productive agricultural areas [5].

For this reasons, knowledge of the ecology and ecophysiology of *Salicornia europaea* can help to evaluate/assess the salt tolerance and potential as a crop, but also to give insight into the optimal agronomic conditions for cultivation. In this regard, the aim of this study is to evaluate the effects of salinity on *Salicornia europaea* growth to obtain insight in its performance.

2 Materials and Methods

The mature plants and seeds for experimental study have been collected in Poland in two inland stands of *Salicornia europaea* (Fig. 1). Synonyms of names of this species are *S. herbacea* L. and *S. patula* [7, 8]. Presence of this species in the humid climate of Central Europe is connected with salty springs accompanying Zechstein salt deposits uplifted in the form of salt domes. One of the stands was located in the area affected with natural brine in the health resort in the town of Ciechocinek and second in the area affected by

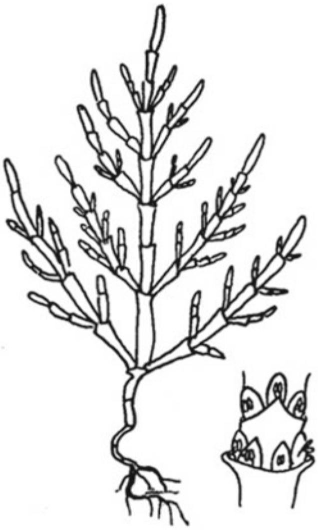

Fig. 1 Inland *Salicornia europaea* [6]

Fig. 2 Locality of the study populations

industry on salty meadow in the vicinity of soda factory in the town of Inowrocław-Mątwy (Fig. 2). Today these are the only inland stands of *Salicornia* in Poland [9]. Soils were classified as mineral with organic matter content up to 10 % and mineral-organic with content between 10 and 20 % according to Systematics of Polish Soils [10]. The soil salinity in the upper part of soil (0–25 cm) was high, and EC_e reached ca. 63 dSm^{-1} in the industry area and 39 dSm^{-1} in the natural saline stand (Table 1). The soil reaction was neutral to slightly alkaline. The most dominant ions were Cl^- and Na^+ and in the industry area Ca^{2+}. Seeds were collected in October 2011 and mature plants in September 2012.

Four 25-seed replicates of *Salicornia europaea* were placed on filter paper, in 9 cm Petri dishes, and submerged in 5 ml solutions of 0, 150, 300 and 600 mM NaCl. Salinity concentrations were chosen to cover variations though the tidal frame in salt marshes. Dishes were placed in a growth chamber and subjected to a regime of 16 h of light (25 °C, 400–700 nm, 35 μmol photons m^{-2} s^{-1}) and 8 h of dark for 15 days. This temperature regime was chosen to replicate the temperatures when these species germinate. The dishes were inspected daily and germinated seeds were counted. Seed germination was accepted when the radical appeared. The water level was adjusted daily with distilled water to avoid changes in salinity due to evaporation [11].

The mean time to germinate was calculated as follow:

$$\mathrm{MTG} = \sum(\mathrm{n} \times \mathrm{d}) / \mathrm{N}$$

where n is the number of seeds germinated between scoring intervals; d the incubation period in days at that time point, and N the total number of seeds germinated in the treatment [12].

Four 15-germinated seed replicates of *Salicornia europaea*, were grown for 40 days in plastic pots (10 cm diameter × 7 cm height). Each pot was filled with 350 g of perlite and watered with distilled water (0 NaCl), or 150, 300, 600, mM NaCl. All pots were exposed to a standard watering regime, replenishing water content whenever 30 % of maximum available water was depleted by evapo-transpiration. Root and shoot fresh length were evaluated.

Table 1 Soil properties in the root zone (0–25 cm) of *Salicornia europaea* stands in Central Poland

	Org.mat. (%)	N_{tot} (mg/l)	HCO_3^-	Cl^-	SO_4^{2-} (dS/m)	K^+	Ca^{2+} (%)	Mg^{2+}	Na^+	TDS	Ca^{2+}/Na^+	SO_4^{2-}/Cl^-	EC_e	pH	Moisture
Mątwy	13.4	0,539	742	23,770	573	70	9,079	102	8,283	42,619	1.10	0.024	63.1	7.3	150
Ciechocinek	6.88	0,203	714	22,473	2,216	256	1,117	275	14,579	41,630	0.08	0.099	38.5	7.6	73

Abbreviations: *org.mat.* organic matter content, N_{tot} total content of nitrogen, *TDS* total dissolved salts, EC_e electrical conductivity of saturated extract
Concentrations of anions and cations expressed in saturated extract

For determination of protein content, 500 mg fresh seedling was homogenized in a chilled (4 °C) mortar using a 50 mM Tris–HCl buffer (pH 7.0) containing 10 mM EDTA, 20 mM glycerol and 2 % (m/v) polyvinylpyrrolidone. After centrifugation at 13,000 g for 20 min at 4 °C, the supernatant was filtered and then kept at 4 °C. Total protein content was measured by the spectrophotometric method using bovine serum albumin (BSA) as standard.

0.5 g of fresh plant material were boiled in 10 ml of water for 2 h at 100 °C using a heat bath. This hot water extract was cooled and filtered using Whatman # 42 filter paper, and then used directly for ion analysis. K^+ and Na^+ contents were determined by flame photometer. Inorganic P content was detected by spectrophotometer (Shimadzu UV-160). Ca^{2+} and Mg^{2+} concentrations were assayed by atomic absorption spectrometry. Chloride ion content was measured with a Beckman specific ion electrode. Chlorophylls (Chl a and Chl b) and carotenoids were extracted by 80 % acetone and quantified spectrophotometrically [13]. Anthocyanins were extracted in methanol-HCl (1 % HCl, v/v), the samples were left at 4 °C in the refrigerator for 1 day. Later on, the extract were filtered and the total anthocyanin content was measured by an UV visible spectrophotometer as the difference between the absorbance at 530 and 657 nm wavelength and placed in the A530-A657 formula to eliminate the chlorophyll content in the extract, defined quantitatively as OD 530 g^{-1} fresh weight [14].

3 Results and Discussion

This study shows that *Salicornia* colonising contrasted habitats has different germination patterns in response to salinity. However, also we recorded some features common to other halophytes: short germination periods and reduction in final germination percentage by increasing salinity. After 15 days, germination percentage didn't show any differences among control, 150 and 300 mM NaCl treated plants. Only at 600 mM NaCl the germination strongly decreased (45 %) due to a reduction of seed hydration [15] caused by a higher osmotic potential of the solution under salinity. The very high final germination (85 %) in distilled water (control) suggests that the studied taxa do not necessarily have a physiological requirement for salt to germinate, confirming previous results obtained for *Halocnemum strobilaceum* [16], *Phragmites australis* [11] and *Salicornia ramosissima* [17].

Germination period (time between first and final germination) was shorter for 150 and 300 mM NaCl ranging between 7 and 15 days due to an increase in the number of days to first germination with highest level of salinity, while the number of days to final germination was constant (Table 2). A short mean time to germination and high final germination percentage are considered important indices related to plant performances. Our results showed that the mean time to germination was higher in absence of salinity and in presence of 600 mM NaCl, and lower in presence of 150 and 300 mM of NaCl, suggesting that 150 and in particular 300 mM of NaCl are the best conditions for this species to germinate as evidenced by higher final germination proportion but shorter mean time to germination (Table 2).

This germination strategy has been recorded previously in other halophytes [17] and it is common in desert annuals [18]. After 40 days of treatments the measured growth parameters indicated that root and shoot length, and the fresh masses, especially those of shoots, were lower in the control and in the 600 mM NaCl treated

Table 2 Final germination (%), days to first germination, days to final germination and mean time-to-germinate (MTG) of *S. europaea* in growth chamber for 15 days

NaCl treatments (mM)	Final percentage (%)	First germination (days)	Final germination (days)	MTG (days)
0	85^a	5 ± 1	12 ± 1	7.44
150	85^a	4 ± 1	10 ± 1	6.44
300	85^a	6 ± 0.5	10 ± 1	6.66
600	50^b	7 ± 0.3	15 ± 1.5	7.11

Values are mean ± S.E. (n = 4). Different letters in the same column indicate significant differences ($p < 0.05$)

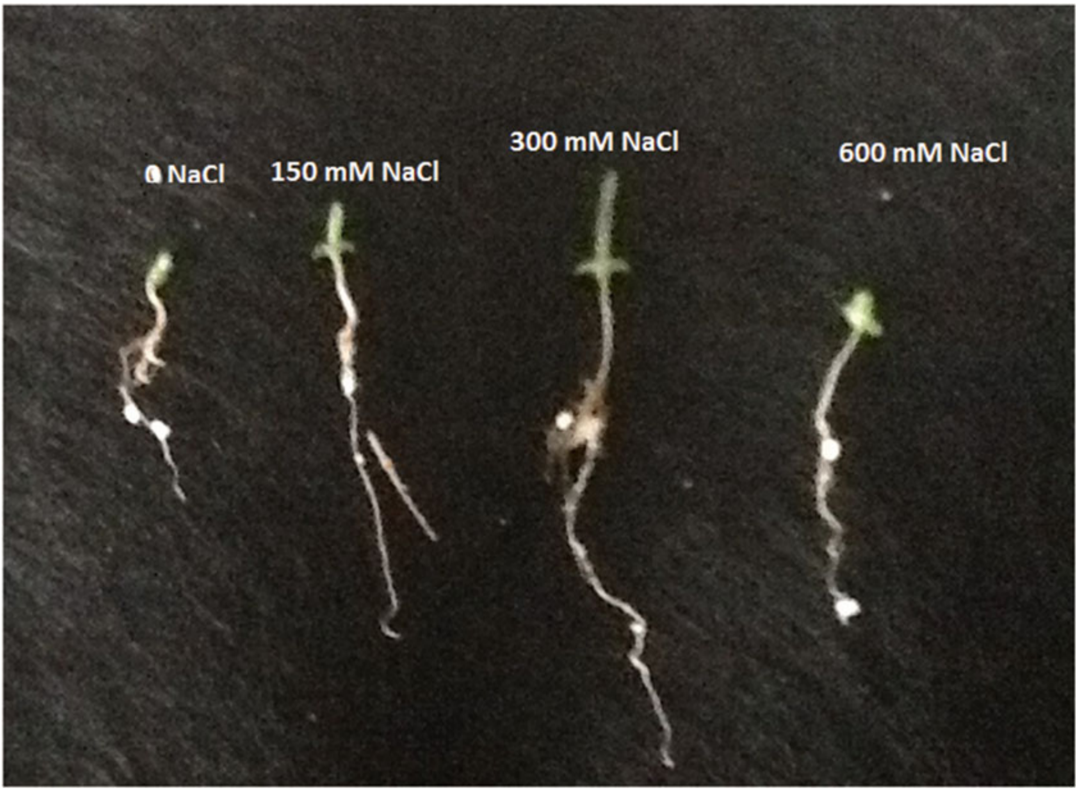

Fig. 3 Seedlings of *Salicornia europaea* 40 days old grown in Perlite with different NaCl concentrations

plants compared to those of seedlings treated with 150 and 300 mM NaCl (Table 2). These results evidenced that nevertheless *S. europaea* is able to germinate in presence of fresh water, it is not able to maintain the optimal performance during the growth. In addition these data evidenced also that even if in presence of 600 mM NaCl the final germination percentage was lower than control, the seedlings showed a subsequent better growth in comparison to control (Fig. 3). This means that the seedlings are still able to grow and remains alive in presence of 600 mM NaCl, a salt concentration higher than that of sea water. Similar results were previously reported for other halophytic species [19–21] (Table 3).

Regarding ion contents, a significant reduction in K^+ and Pi amounts under NaCl salinity concomitant with a significant Na^+ accumulation in shoot of *S. europaea* seedlings was observed (Table 4). Conversely, Ca^{2+} decreased at the highest NaCl treatment while Mg^{2+} content remained unchanged. Cl^- ions followed the same accumulation trend of Na^+ (Table 4). Generally, to maintain an osmotic gradient for the uptake of water from medium, many halophytic plants accumulate inorganic ions to a concentration equal to or greater than that of the surrounding root solution [22]. It would appear that the growth response at moderate salinities of *S. europaea* may be largely the consequence of an increased uptake of solutes that are required to induce cell expansion, since this maintains the pressure potential in plant tissues.

Table 3 Root and shoot length (cm) of *S. europaea* seedlings 40 days old

NaCl treatments (mM)	Root length	Shoot length
0	$1.2^a \pm 0.3$	$0.5^a \pm 0.2$
150	$2.9^c \pm 0.8$	$1.5^c \pm 0.9$
300	$2.5^c \pm 0.9$	$1.9^c \pm 0.8$
600	$1.5^b \pm 0.5$	$0.8^{ab} \pm 0.2$

Values are mean ± S.E. (n = 4). Different letters in the same column indicate significant differences ($p < 0.05$)

Table 4 Contents of Chlorophyll a (Chl a), Chlorophyll b (Chl b), carotenoids (Carot), Anthocyanins (Anthoc) and total proteins (Prot) in shoots of *S. europaea* 40 days old under different NaCl stress

NaCl treatments (mM)	Chl a	Chl b	Carot	Anthoc	Total phenols (mgTAET/l)	Prot (mg/g d.w.)
0	$0.81^{a}\pm0.1$	$0.48^{a}\pm0.8$	$0.43^{a}\pm0.9$	0.07	237.9	$0.52^{a}\pm0.8$
150	$0.52^{b}\pm0.8$	$0.31^{b}\pm0.5$	$0.28^{b}\pm0.6$	0.65	445.9	$0.54^{a}\pm0.7$
300	$0.50^{b}\pm0.6$	$0.21^{c}\pm0.4$	$0.22^{b}\pm0.5$	0.75	437.9	$0.35^{b}\pm0.6$
600	$0.31^{c}\pm0.3$	$0.19^{c}\pm0.7$	$0.21^{b}\pm0.4$	0.97	675.3	$0.33^{b}\pm0.5$

Values represent means ± S.E. (n = 4). Different letters in the same column indicate significant differences ($p < 0.05$)

Table 5 The effect of NaCl on the concentration of ions in shoots of *S. europaea*

NaCl treatments (mM)	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	Pi	Cl^{-}
0	$15^{a}\pm0.7$	$18.1^{a}\pm1.7$	3.2	1.6	5.8	12.5
150	$61^{b}\pm25$	$13.0^{b}\pm2.5$	3.3	1.58	3.6	21.0
300	$85^{b}\pm25$	$10.5^{b}\pm2.7$	3.1	1.64	3.4	22.2
600	$164^{c}\pm21$	8.0	1.8	1.61	2.9	28.5

Values represent means ± S.E. (n = 4). Different letters in the same column indicate significant differences ($p < 0.05$)

At high salinities, growth reduction might either be caused by a reduced ability to adjust osmotically as a result of saturation of the solute uptake system, or by nutrient deficiencies in particular by low amount of Ca^{2+} that is a crucial regulator of growth and is involved in nearly all aspects of plant development [23–27]. It is well known that chlorophyll loss is associated to environmental stress and the variation in total chlorophyll/carotenoids ratio is considered a stress index in plants [28]. In order to clarify the protective mechanisms of this plant against salt stress, the changes in pigment (chlorophyll, carotenoids and anthocyanin) and total phenol contents of the seedlings subjected to salt stress were determined and our results demonstrated that salinity affected all of them (Table 5). Chl a and Chl b and carotenoids, decreased remarkably under NaCl stress, in particular in presence of the highest salinity concentration, conversely, anthocyanins and total phenols increased. The observed increase in total phenols and the decrease in chlorophylls is a symptom of oxidative stress condition [29], and it may also be caused by the lower Ca^{2+} content [30]. This is one of the reasons of the lack in growth and development of *Salicornia europaea* at 600 mM NaCl. In addition our results suggested that the anthocyanin increase, especially in leaf tissues under high salinity, may allow to the *S. europaea* to develop resistance to high NaCl content, confirming previous findings [31–33].

In summary, our results showed that *S. europaea* exhibits growth and other properties entirely consistent with those of other halophytes. It grows rapidly at moderate salt concentrations (150 and 300 mM NaCl) and can survive at extreme salinities, similar to seawater concentrations. The present study also shows that in this plant salinity triggered inorganic ions (Na^{+}) accumulation.

In conclusion, germination responses to salinity of *Salicornia europaea* seem likely to influence their colonisation capacities down the tidal gradient and hence may be important in the maintenance of taxa zonation in salt marshes. In addition seedling growth data and biochemical analysis suggest that this taxa may be successfully used to reclaim highly salinized areas in semi-arid and arid regions of the world.

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Germination Pre-treatments in *Haloxylon persicum* (Amaranthaceae), an Economically Important Tree of Desert Ecosystems in Western Asia

Kazem Nosrati, Salman Zare, and Todd P. Egan

Abstract

Seed dormancy is an obstacle to revegetation and reclamation efforts, particularly in arid and semiarid environments. Therefore, the objective of this study was to determine the most effective germination pretreatment for *Haloxylon persicum*, a tall desert shrub or small tree. The experiment employed a completely randomized block design. Dormancy breaking treatments included scarification with 98 % sulfuric acid for 10, 20, 30, and 60 min; debracting seeds; debracting + piercing seeds; stratification for 1, 2, 3 and 4 weeks; and leaching seeds in flowing water for 1, 2, 3, and 4 days. Results demonstrated that scarification with 98 % sulfuric acid for 10 min was the most effective treatment which increased germination from 23.3 % (control) to >82.6 %.

Keywords

Haloxylon persicum • Revegetation • Seed dormancy breaking • Sulfuric acid

1 Introduction

Two broad approaches to revegetation in arid and semiarid environments are seeding and transplanting. Seeding is a common revegetation practice in natural resources management because it has a low initial expense. Unfortunately, seeding is less reliable when climatic conditions, particularly rainfall, are variable [1].

Revegetation of deserts increases water quantity and quality, thus triggering or enhancing socio-economic opportunities at the national and international level. Native species are often required because they are either adapted to the conditions

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_17, © Springer Science+Business Media Dordrecht 2014

that will exist at the site after revegetation, or because they are disturbance adapted and perform well during the first few years [2].

A key species in desert revegetation efforts is *Haloxylon persicum* Bunge ex Boss. et Buhse. Like many members of the Amaranthaceae, *H. persicum* is a stem-succulent xerophytic shrub that grows only in non-saline sandy desert soils [3]. *Haloxylon persicum* has traditionally been used as livestock feed and for firewood; therefore it is crucial to protect this species in desert lands [4]. As with other species used for revegetation, establishment of *H. persicum* is constrained by poor germination and seedling emergence. Therefore, an understanding of the requirements to break dormancy and initiate germination of a potential revegetation species is necessary to maximize production from the often limited native seed supply in many restoration efforts [5].

Influences of pretreatment on seed germination enhancement and breaking seed dormancy for desert and other species have been reported and studied by many authors [6–12].

Preliminary studies demonstrated high seed dormancy for *H. persicum*. Therefore, the objective of the present study is to determine the most effective treatment at breaking dormancy. It is our goal to find a method that is both cost and time efficient as an initial step in desert revegatation and reclamation. We hypothesize that pretreatments can break seed dormancy and increase *H. persicum* germination compared to untreated seeds.

2 Materials and Methods

Seeds of *Haloxylon persicum* were collected from 15 to 16 September 2009 from the salty soil on the shallow sandy dunes at Naein, Isfahan Province (33° 44′N, 50°, 48′E). Long term (1975–2003) annual average maximum and minimum temperatures are 23.4 and 9 °C, respectively. Long term mean precipitation has been 121.1 mm per year (www.irimet.net). Preliminary studies demonstrated that *H. persicum* flowers in the early spring, and seeds reach maturity by the autumn to be dispersed from November to December. However, the seeds are dormant upon dispersal, so this experiment studied different dormancy pretreatments. To prevent fungal infection, seeds were surface sterilized with 5 % sodium hypochlorite for 2 min, and then rinsed in distilled water before pretreatments.

2.1 Scarification Pretreatments and Germination Conditions

Pretreatments included scarification with 98 % sulfuric acid for 10, 20, 30, and 60 min. Seeds were also debracted and placed under optimal germination conditions in a dark germinator at 25 °C. A similar but more mechanically abrasive pretreatment was debracting the seeds as well as piercing the seed coats using a scalpel. Another pretreatment included imbibing seeds in water for 4 h, and then stratifying them for 1, 2, 3 and 4 weeks at 6 °C in a dry Petri dish before placing them under optimal germination conditions. As a final group of pretreatments, seeds were leached in flowing water for 1, 2, 3, and 4 days. There were a total of 15 different treatment groups. The control group consisted of non-treated seeds. For each group there were three replicates of 25 seeds.

Seeds were placed on Whatman No. 1 filter paper within 10 cm plastic Petri dishes with a tight fitting lid and containing 10 mL distilled water. Petri dishes were placed in plastic bags to reduce moisture loss, and then randomly placed in a dark germinator (model 2848; Cleland International, Inc.) at 25 °C.

2.2 Germination Determination

Germination was recorded every other day for 20 days. Seeds were counted as germinated when the emerging radicle was at least 2 mm in length [13]. Characteristics of final germination, cumulative germination, and first and final germination day were calculated. In addition, germination rate was estimated using a modified Timson's index of germination velocity ($\sum G/t$) where G equals the percentage of seed germination at 2 day intervals, and t is the total germination period [14]. The maximum value possible using this index with our data was 62.5 (i.e., 1250/20).

2.3 Statistical Analysis

Statistical analyses were based on randomized block design. Germination data were arcsine transformed before statistical analysis to ensure homogeneity of variance. Data were subjected to a one-way ANOVA using the MSTAT-C program [15]. Treatment means were compared via the Duncan's multivariate test at a 5 % level.

3 Results

One-way ANOVA results showed that all treatments had a significant effect on final percent germination and germination rate ($P \leq 0.01$; Table 1).

Final percent germination and germination rate results showed that all treatments significantly increased percent germination and the germination rate of *H. persicum* (Table 2) compared to the control. All treatment groups except 1 week of stratification, 1 day of leaching, and the control decreased the number of days it took for the seeds to first germinate (Table 2). None of the treatments significantly affected the number of days till final germination (Table 2).

3.1 Effect of Sulfuric Acid Treatments

Sulfuric acid significantly increased percent seed germination and germination rate of *H. persicum*. All four sulfuric acid time treatments (10, 20, 30, and 60 min) increased final germination percent and germination rate compared to the control.

Table 1 Effects of seed dormancy breaking treatments on germination characteristics of *H. persicum*

Sources	Degrees of freedom	Final germination day	First germination day	Germination rate index	Final germination day
Replication	2	7.27	0.47	0.20	39.82
Treatments	14	6.01[a]	8.62[a]	26.47[a]	756.36[a]
Error	28	1.79	0.37	5.67	80.97
CV	–	8.96	18.28	15.54	15.54

[a] Are significantly different at 1 %

Table 2 The effects of different seed dormancy breaking treatments on germination characteristics in *H. persicum*

		Germination characteristics			
Treatments		Final % germination	Germination rate index	First germination day	Final germination day
H_2SO_4 (min)	10	82.7 a	51.7 a	2.0 d	14.0 bcd
	20	65.3 bc	40.8 bc	2.0 d	15.3 abc
	30	57.3 cde	35.8 cde	3.6 bc	16.0 ab
	60	41.3 e	25.8 e	2.0 d	13.3 cd
Stratification (week)	1	45.3 de	28.3 de	6.0 a	15.3 abc
	2	74.7 ab	46.7ab	2.6 cd	17.3 a
	3	61.3 bcd	38.3 bcd	2.0 d	12.6 d
	4	48.0 de	30.0 de	4.0 b	15.0 abcd
Leaching (day)	1	45.3 de	28.3 de	6.0 a	15.3 abc
	2	74.7 ab	46.7 ab	3.3 bc	17.3 a
	3	61.3 bcd	38.3 bcd	2.0 d	12.6 d
	4	48.0 de	30.0 de	4.0 b	15.0 abcd
Debracted		70.7 abc	44.2 abc	2.0 d	15.3 abc
Debracted & Pierced		69.3 abc	43.3 abc	1.6 d	15.3 abc
Control		23.3 f	14.6 f	6.6 a	14.0 bcd

Different letters indicate that germination characteristics are significantly different at 1 % level based on Duncan's multivariate test

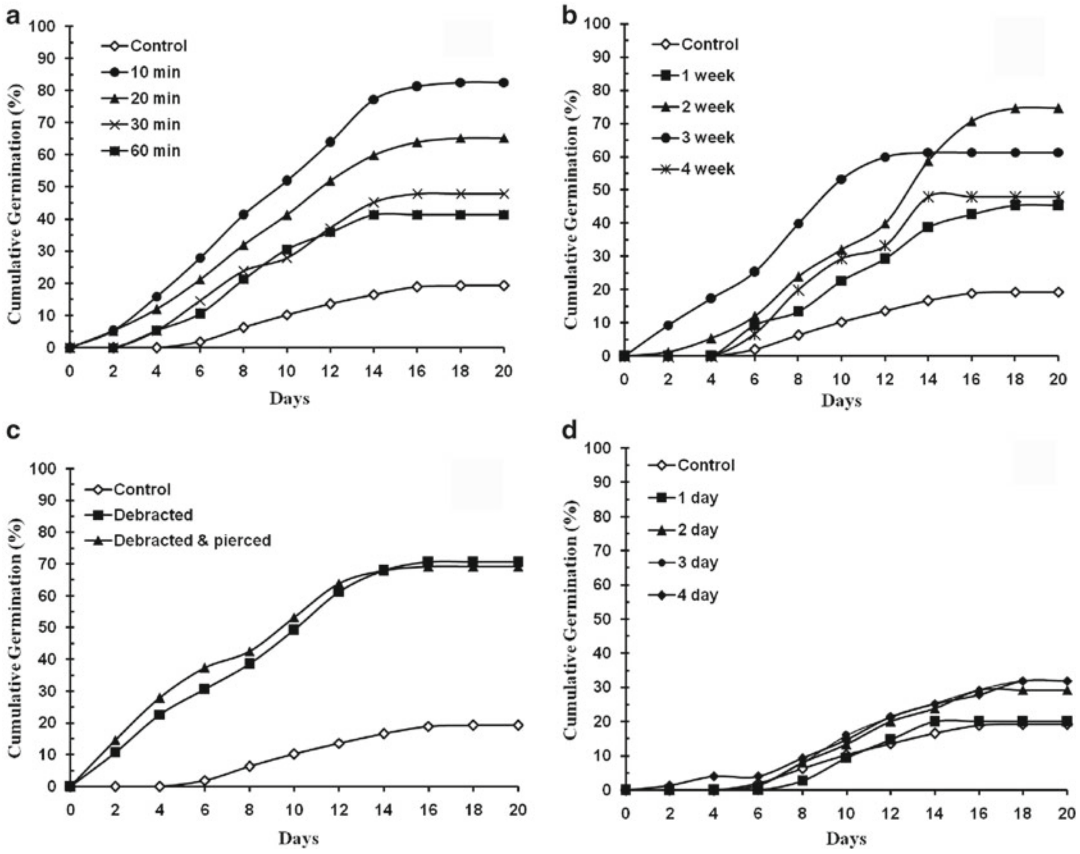

Fig. 1 Cumulative percent germination vs. number of days for *H. persicum* seeds (**a**) after being exposed to 98 % sulfuric acid treatments for up to 60 min, (**b**) after being exposed to stratification treatments for up to 4 weeks, (**c**) that have been debracted or debracted and pierced with a scalpel, and (**d**) that have been leached for up to 4 days in flowing water

However, the 10 min treatment had the greatest increase in cumulative percent germination from 23.33 % (control) to 82.67 % (Fig. 1a), and germination rate index from 14.5 to 51.6 (Table 2). Sulfuric acid treatments decreased the number of days until seeds germinated (Table 2), but had no effect on the final day of germination (Table 2).

3.2 Effect of Stratification Treatments

Seed stratification significantly increased final percent germination and germination rate (Fig. 1b). Even though all stratification treatments increased final percent germination and germination rate, seeds that were stratified for moderate time period (2 and 3 weeks) demonstrated a greater increase in germination compared to the shortest (1 week) and longest (4 weeks) stratification treatments. With the exception of week one, stratification decreased the number of days until seeds germinated (Table 2). Only 3 weeks of stratification had a significant effect on the final day of germination (Table 2).

3.3 Effect of Debracting Treatments

Final percent germination (Table 2) and germination rate (Table 2) increased significantly due to debracting. Seeds that were debracted and had their seed coats pierced also had a higher final percent germination and an increased germination rate compared to the control (Table 2). These treatments decreased the number of days until germination, but the final day of germination was not affected (Table 2). There were no significant differences between debracted or debracted and pierced treatment groups for any of the parameters measured (Fig. 1c).

3.4 Effect of Leaching Treatments

All leaching treatments resulted in a significant increase in final percent germination (Table 2) and germination rate (Table 2) compared to the control. However, 1 day of leaching had no effect on decreasing the number of days until seeds first germinated (Table 2). Two and 4 days of leaching caused an intermediate decrease in germination time, and 3 days of leaching had the greatest decrease in time to first seed germination (Table 2). Only the 2 day treatment significantly decreased the final day of germination compared to the control (Table 2), and as an overall trend 2 days of leaching had the greatest effect on seed germination (Table 2 and Fig. 1d).

4 Discussion

Acid scarification is known to be highly effective at improving germination of other species with hard seed coats [16], and the results of this experiment corroborated these findings.

The 98 % sulfuric acid treatment was fully effective in breaking dormancy of *H. persicum* at 10 min. as reported in some studies [12, 17, 18]. For species like *H. persicum* with hard seed coats, the resistance of the seed integument to the penetration of water may be alleviated by a sulfuric acid treatment, manual or mechanical scarification, or by scalding with hot water. These treatments reduce the resistance and impermeability of the integument [19].

Stratification for 2 weeks, leaching for 2 days, debracting, and debracting + piercing the seed coats increased the Timson's Index and first day of germination, although not to the same degree as the acid treatment. Our findings concurs with other reports [9, 20] in which the most effective treatment in breaking the hard seed dormancy of legume seeds was mechanical disruption.

This experiment demonstrated that mechanical scarification broke seed dormancy. It is therefore believed that *H. persicum* is exogenously dormant. Seeds with exogenous dormancy are not permeable to water and gas because of a hard seed coat, so imbibition cannot occur which decreases or prevents germination. When imbibition cannot occur, turgor pressure and radicle growth is not enough to rupture the seed coat and therefore break seed dormancy [21]. Exogenous dormancy can also result from inhibitory chemicals in the seed coat [22].

The 98 % sulfuric acid treatment for 10 min. demonstrated to be a very practical way to break dormancy in *H. persicum*. The hypothesis that seed dormancy of *H. persicum* can be broken through different pretreatment methods was supported. Moreover, we feel our goal in finding a cost and time efficient method in breaking seed dormancy in *H. persicum* has been met because treating seeds with sulphuric acid is simple and cost effective for land managers.

Acknowledgments This project was funded by a grant from the research council of Shahid Beheshti University, Tehran, Iran. The authors thank Dr. J. Forrest Meekins for assisting us with manuscript preparation and Dr. Daniel Kjar for computer assistance.

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Halophytes in the East Mediterranean – Their Medicinal and Other Economical Values

Münir Öztürk, Volkan Altay, Salih Gucel, and Aykut Guvensen

Abstract

The East Mediterranean includes Turkey, Syria, Lebanon, Palestine, Jordan and Israel. It is a typical transition zone between the Saharo-Arabian desert biome and temperate climates. A total of 304 halophytic taxa from 50 families belonging to 172 genera are distributed in the region. The families with the highest number of taxa are; Chenopodiaceae (51 taxa-16.78 %), Poaceae (44 taxa-14.47 %), Asteraceae (23 taxa-7.57 %), Fabaceae (22 taxa-7.24 %), Cyperaceae (17 taxa-5.59 %) and Plumbaginaceae (13 taxa-4.28 %) respectively. They constitute 55.93 % of the halophytes distributed in the East Mediterranean. The genera with the highest number of species are; *Limonium* (13), *Juncus* (11), *Atriplex, Salsola* (8 each), *Suaeda* (7), *Tamarix, Plantago, Silene* (6 each) and *Euphorbia, Centaurium, Bromus* (5 each). Out of 304 taxa 9 are endemics, 24 are rare plants, 16 taxa are vulnerable, 9 taxa endangered, 6 taxa critical and two taxa have lower risk. These taxa can be grouped as; Xerophytes (79), Psammohalophytes (73), Hygrohalophytes (68), Halophytes (56), Xerohalophytes (22) and ruderals (6). Out of the halophyte taxa listed 124 taxa (40.79 %) are of economic importance. The most widely used parts of the plants are leaves (28.24 %) and roots (21.18 %). The most common preparation of the traditional folk medicine is decoction (42.55 %), followed by infusion (11.70 %), poultice (10.64 %) and powder (8.51 %).

The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_18,

In addition to these some plants are consumed fresh for the treatment of some ailments, their percentage lies around 10.64, but consumption as cooked meal is 8.51 %. A majority of these plants are used for the treatment of urinary system disorders (21.74 %). Many halophytic species are used as either forage or fodder, even as ornamentals, but some are poisonous. These taxa play an important role in the control of soil erosion. They are also used to clean contaminated soils and water. Similarly *Cynodon dactylon*, *Ruppia maritima* and *Inula crithmoides* can be used to produce biomass through biosaline agriculture.

1 Introduction

The area of saline lands on our planet is said to lie around 1.5 billion hectares [1]. These lands abound in plant cover commonly known as halophytes numbering approximately 6,000–10,000 species [2, 3]. Out of these the number of euhalophytes is said to lie around 4,000 species in the world [1, 4].

It has been fully enlightened that the halophytic plants play an important role in the maintenance of ecological balance as well as preservation of habitats for both aquatic and terrestrial animals. Their economic potential emerged very slowly which has attracted the attention of many researchers to understand their role in the development of human resources [1, 5]. During the last few decades as the area of degraded lands increased studies on these plants in different parts of the world gained great momentum. Halophytes are plants which grow all over the world, in different climatic regions on areas with high soil salinity (salt marshes, terrestrial saline soils, saline deserts, arid lands and tidal areas and sand dunes) [5]. They can complete their life cycle at places with salt concentrations of at least 200 mM NaCl [6, 7] or on areas with salt concentrations greater than 0.5 % [8]. These plants have the ability to flourish on such habitats through a variety of physiological, anatomical and morphological adaptations to environmental factors [9].

In this context the East Mediterranean region was selected for this study and attempt made to compile the halophytic plant diversity in this region [5, 10–21]. This region is a part of the Mediterranean basin which has nearly 700 halophytic taxa [2, 22, 23]. It is also included in the famous fertile crescent, wherefrom many plants and animals originated. Aim here is to present an overview of the widely distributed halophytic plant taxa in the East Mediterranean together with their ecological features, chorotypes, position of endemic and rare taxa In addition, halophytic plant species with medicinal and economic potential are evaluated.

2 Study Area

Geographically Mediterranean region is located between the continents of Europe, Africa and Asia. It is considered as one of the 18 world centers of biodiversity (world hotspots) [24, 25]. The region represents 1.6 % of the worlds arid areas, but more than 25,000 vascular plant species (approximately 10 % of the world) are distributed in this region [26, 27]. More than half of these plant taxa are endemics, which when compared with total European endemics constitutes 80 % [28].

The reasons for the richness of plant diversity and endemism in the region is attributed to four major factors biogeography, paleogeological-climatic history, ecogeographical heterogeneity and human influence [29–31]. Thus, factors driving plant diversity patterns in these regions are of both theoretical and practical nature [32].

The basin extends over an area of nearly 2.3×10^6 km^2 which is equivalent to half the total area of the Mediterranean climate zone in the world [33]. It shows unique ecological and topographical diversity, with a striking alternation of complex stream eroded mountains, hills, alluvial plains, a very long coastline and hundreds of islands [34–37]. The basin can be divided into east and west regions. A great percentage of the

Fig. 1 Map showing the East Mediterranean part of the Mediterranean Region

eastern Mediterranean includes Turkey, Syria, Lebanon, Palestine, Jordan and Israel (Fig. 1), which is a typical transition zone between the Saharo-Arabian desert biome and temperate climates [26, 38, 39]. The area shows a rich plant diversity with nearly 15,000 plant taxa belonging to 100 genera and 500 families [40], holding a unique position as a meeting area of the Mediterranean, Irano-Turanian, Saharo-Sindian and Sudano-Decanian phytogeographical divisions together with a large number of biregional and pluriregional plant taxa [12, 41, 42]. The floristic richness in this region has attracted the attention of many researchers; in Turkey [43–45], in Cyprus [18, 46–48], in Syria [46, 49, 50], in Lebanon [46] and in Palestine [46, 51].

3 Halophyte Diversity

The halophytic plant taxa distributed in the East Mediterranean are listed alphabetically according to their families and within these different taxa are listed (Table 1). For each taxon information on the distribution area, life form, and ecological chorotypes are included according to previous reports [5, 12–14, 18–20, 52–54]. The categories and criteria of rare and endangered species are presented according previous literature [14, 23, 55–59]. The information on the economic potential of halophytes has been compiled from the literature published [5, 13, 60–62].

A total of 304 taxa from 50 families and belonging to 172 genera are listed in Table 1. The families with the highest number of taxa are; Chenopodiaceae (51 taxa-16.78 %), Poaceae (44 taxa-14.47 %), Asteraceae (23 taxa-7.57 %), Fabaceae (22 taxa-7.24 %), Cyperaceae (17 taxa-5.59 %) and Plumbaginaceae (13 taxa-4.28 %) respectively. These six families constitute 55.93 % of the halophytes distributed in the East Mediterranean.

The genera with the highest number of species are; *Limonium* (13), *Juncus* (11), *Atriplex, Salsola* (8 each), *Suaeda* (7), *Tamarix, Plantago, Silene* (6 each) and *Euphorbia, Centaurium, Bromus* (5 each). Therophytes (43.75 %) and Cryptophytes (19.41 %) form the largest groups on the basis of Raunkier's life form spectrum (Fig. 2). An evaluation of different taxa from the phytogeographical point of view revealed that highest percentage of elements belonged to the Mediterranean (24.02 %) followed by Irano-Turanian (7.57 %). Other phytogeographical elements included here are Saharo-Arabian (4.61 %) and Euro-Siberian (4.28 %). The phytogeographical identity of 165 taxa is not clear, these are listed as unknown (Fig. 3).

Out of 304 taxa 9 are endemics and 24 are rare plants. The information available on the threatened categories of the plant taxa in the region has shown that 16 taxa are vulnerable, 9 taxa endangered, 6 taxa critical and two taxa have lower risk (Table 2) [19, 20, 55, 56]. Halophytes of the region can be grouped as; Xerophytes (79), Psammohalophytes (73), Hygrohalophytes (68), Halophytes (56), Xerohalophytes (22) and ruderals (6) on the basis of their ecological

Table 1 Halophyte taxa from the East Mediterranean and their ecological features

	Family/Taxa	Country	Life forms	Ecological types	Choro-types
	AIZOACEAE				
1	**Aizoon hispanicum*	C, P, S	T	X	SA
2	**Mesembryanthemum crystallinum*	C, P	T	X	IN
3	**Mesembryanthemum forsskahlei*	P, S	T	X	S
4	**Mesembryanthemum nodiflorum*	C, P, S	T	X	IN
	AGAVACEAE				
5	**Agave sisalana*	C	C	X	CA
	AMARYLLIDACEAE				
6	**Pancratium maritimum*	C, L, P, S, T	C	PH	M
	APIACEAE				
7	*Apium nodiflorum*	L, P, T	H	HG	IN
8	*Bupleurum euboeum*	T	T	HA	EM
9	*Cachrys scabra*	C	CH	PH	IN
10	*Crithmum maritimum*	C, L, P, T	CH	X	IN
11	*Eryngium campestre var. virens*	T	H	X	IN
12	**Eryngium maritimum*	C, L, P, S, T	H	PH	IN
13	*Ferulago syriaca*	C, L, P, S, T	H	X	EM
14	*Pseudorlaya pumila*	C, S, T	T	X	M
	APOCYNACEAE				
15	*Trachomitum venetum ssp. sarmatiense*	C, T	C	PH	EM
	ASTERACEAE				
16	*Achillea cretica*	C, T	CH	X	EM
17	**Achillea fragrantissima*	L, P, S	CH	X	IN
18	*Achillea maritima ssp. maritima*	C, T	CH	PH	M
19	*Aetheorhiza bulbosa ssp. microcephala*	C, T	C	X	EM
20	*Ambrosia maritima*	C, L, T	CH	X	M
21	*Bellis annua*	L, P, T	T	HG	M
22	*Carlina lanata*	L, P, S, T	T	X	M
23	**Centaurea postii*	S	H	HA	M
24	*Chlamydophora tridentata*	C	T	HG	M
25	*Cousinia birandiana*	T	H	HG	IR
26	*Crepis foetida ssp. commutata*	C, S, T	T	X	IN
27	*Crepis foetida ssp. rhoeadifolia*	C, L, S, T	T	PH	IN
28	*Crepis sancta*	T	T	XH	IN
29	*Filago eriocephala*	L, P, T	T	R	EM
30	*Hedypnois cretica*	T	T	PH	M
31	*Helichrysum conglobatum*	C	CH	X	IN
32	**Inula crithmoides*	C, L, P, S, T	CH	HG	IN
33	*Inula graveolens*	L, P, T	T	PH	M
34	**Inula viscosa*	L, P, T	CH	X	M
35	*Launea resedifolia*	C	H	X	IN
36	*Reichardia picroides*	C, L, P, S, T	H	X	M
37	*Taraxacum aphrogenes*	C	H	X	EN
38	**Xanthium strumarium*	S, T	T	R	IN
	BORAGINACEAE				
39	*Anchusa aggregata*	C, L, P, S, T	T	PH	M
40	*Cynoglossum creticum*	C, L, P, S, T	H	PH	IN
41	*Echium angustifolium*	C, L, P, T	CH	PH	EM
42	*Heliotropium europaeum*	L, P, S, T	T	R	IN

(continued)

Table 1 (continued)

	Family/Taxa	Country	Life forms	Ecological types	Choro-types
	BRASSICACEAE				
43	*Alyssum pateri ssp. pateri*	**T**	**H**	**X**	**EN, IR**
44	*Alyssum linifolium var. linifolium*	**T**	**T**	**X**	**IN**
45	**Cakile maritima*	**C, S, T**	**T**	**PH**	**IN**
46	*Clypeola jonthlaspi*	**S, T**	**T**	**X**	**IN**
47	*Enarthrocarpus arcuatus*	**C, S, T**	**T**	**X**	**EM**
48	**Malcolmia grandiflora*	**S**	**T**	**HA**	**IN**
49	*Malcolmia nana var. glabra*	**C**	**T**	**PH**	**EN**
50	*Maresia nana*	**T**	**T**	**PH**	**IN**
51	**Matthiola tricuspidata*	**C, L, P, S, T**	**T**	**PH**	**M**
52	*Raphanus raphanistrum*	**L, P, T**	**T**	**X**	**IN**
53	*Sinapis arvensis*	**L, P, T**	**T**	**XH**	**IN**
	CAPPARACEAE				
54	**Capparis spinosa*	**S, T**	**P**	**HA**	**IN**
	CARYOPHYLLACEAE				
55	**Gypsophila anatolica*	**S**	**H**	**PH**	**IR**
56	*Minuartia hybrida ssp. hybrida*	**T**	**T**	**X**	**IN**
57	*Silene aegyptica ssp. ruderalis*	**T**	**T**	**X**	**IN**
58	*Silene colorata var. decumbens*	**C, L, P**	**T**	**X**	**IN**
59	*Silene discolor*	**C, T**	**T**	**PH**	**IN**
60	*Silene kotschyi var. maritima*	**C, S, T**	**T**	**PH**	**IN**
61	*Silene nocturna*	**L, P, T**	**T**	**PH**	**M**
62	*Silene supina ssp. pruinosa*	**T**	**H**	**X**	**IN**
63	*Spergularia bocconii*	**C, T**	**T**	**X**	**M**
64	*Spergularia marina*	**C, P, S, T**	**T**	**XH**	**IN**
	CERATOPHYLLACEAE				
65	*Ceratophyllum demersum*	**P**	**T**	**HG**	**ES**
	CHENOPODIACEAE				
66	**Aellenia autrani*	**S**	**T**	**HA**	**IR**
67	**Aellenia glauca ssp. lancifolia*	**S**	**CH**	**HA**	**IR**
68	**Anabasis articulata*	**P, S**	**CH**	**X**	**SA**
69	**Anabasis haussknechtii*	**S**	**H**	**X**	**IR**
70	**Arthrocnemum fruticosum*	**S, T**	**CH**	**HG**	**M**
71	**Atriplex halimus*	**C, L, P, S, T**	**CH**	**XH**	**IN**
72	**Atriplex hastata*	**L, P, S, T**	**T**	**HA**	**IN**
73	**Atriplex leucoclada*	**P, S**	**CH**	**HA**	**SA**
74	**Atriplex littoralis*	**L, S**	**T**	**HA**	**IN**
75	**Atriplex patula*	**C**	**T**	**X**	**IN**
76	**Atriplex prostrata*	**C**	**T**	**X**	**IN**
77	**Atriplex rosea*	**L, P, S, T**	**T**	**R**	**IN**
78	**Atriplex stylosa*	**S**	**CH**	**HA**	**SA**
79	*Bassia hirsuta*	**C**	**T**	**X**	**IN**
80	**Bassia hyssopifolia*	**S**	**T**	**X**	**IN**
81	**Bassia muricata*	**S**	**T**	**X**	**IN**
82	**Beta vulgaris ssp. maritima*	**C, S**	**T**	**X**	**IN**
83	**Chenolea arabica*	**S**	**CH**	**X**	**SA**
84	**Chenopodium album ssp. album*	**P, S, T**	**T**	**PH**	**IN**
85	**Chenopodium murale*	**L, S, T**	**T**	**XH**	**IN**
86	**Chenopodium rubrum*	**S**	**T**	**XH**	**IN**

(continued)

Table 1 (continued)

	Family/Taxa	Country	Life forms	Ecological types	Choro-types
87	**Girgensohnia oppositifolia*	**S**	**T**	**HA**	**IR**
88	**Halimione portulacoides*	**C, S, T**	**CH**	**HA**	**IN**
89	**Halocnemum strobilaceum*	**C, P, S, T**	**CH**	**HA**	**IN**
90	**Halopeplis amplexicaulis*	**C, S, T**	**T**	**HA**	**IN**
91	**Halopeplis perfoliata*	**S**	**CH**	**HA**	**IN**
92	**Haloxylon articulatum*	**P, S**	**P**	**X**	**IR**
93	*Petrosimonia brachiata*	**T**	**T**	**HA**	**IN**
94	**Salicornia europaea*	**C, S, T**	**T**	**HA**	**IN**
95	**Salsola crassa*	**S**	**T**	**HA**	**IR**
96	*Salsola inermis*	**C, P, S**	**T**	**XH**	**IR**
97	**Salsola jordanicola*	**S**	**T**	**HA**	**SA**
98	**Salsola kali*	**C, L, P, S, T**	**T**	**PH**	**IN**
99	*Salsola soda*	**C, P, T**	**T**	**PH**	**IN**
100	*Salsola ruthenica*	**T**	**T**	**PH**	**IN**
101	**Salsola tetrandra*	**S**	**CH**	**X**	**SA**
102	**Salsola volkensii*	**S**	**T**	**HA**	**M**
103	**Sarcocornia perennis*	**C**	**CH**	**HA**	**IN**
104	**Schanginia baccata*	**S**	**T**	**HG**	**SA**
105	**Seidlitzia rosmarinus*	**S**	**CH**	**HA**	**SA**
106	**Suaeda aegyptiaca*	**C**	**T**	**HA**	**IN**
107	**Suaeda asphaltica*	**S**	**CH**	**X**	**SA**
108	**Suaeda carnosissima*	**S**	**T**	**HA**	**IR**
109	**Suaeda fruticosa*	**L, P, S**	**C**	**HA**	**S**
110	*Suaeda maritima*	**C**	**T**	**HA**	**IN**
111	**Suaeda vera*	**C, S**	**CH**	**HA**	**IN**
112	**Suaeda vermiculata*	**S**	**CH**	**HA**	**SA**
	CISTACEAE				
113	*Helianthemum ledifolium var. microcarpum*	**L, P, T**	**T**	**HG**	**IN**
114	**Helianthemum lippii*	**S**	**CH**	**X**	**SA**
	CONVOLVULACEAE				
115	**Convolvulus lineatus*	**C, L, P, S**	**CH**	**X**	**IN**
116	**Cressa cretica*	**C, P, S, T**	**H**	**XH**	**IN**
	CUSCUTACEAE				
117	*Cuscuta campestris*	**T**	**T**	**X**	**IN**
	CYPERACEAE				
118	*Bolboschoenus maritimus var. maritimus*	**C, T**	**C**	**HG**	**IN**
119	*Carex distans*	**C, L, P, S, T**	**C**	**HG**	**ES**
120	*Carex divisa*	**C, L, P, T**	**C**	**HG**	**ES**
121	*Carex extensa*	**C, T**	**H**	**HG**	**ES**
122	*Carex flacca ssp. serrulata*	**C, S, T**	**C**	**HG**	**M**
123	*Cladium mariscus*	**C, P, T**	**C**	**HG**	**IN**
124	*Cyperus capitatus*	**C, T**	**C**	**HG**	**IN**
125	*Cyperus longus*	**L, P, S, T**	**C**	**HG**	**IN**
126	*Eleocharis mitracapa*	**T**	**C**	**HG**	**IN**
127	*Eleocharis palustris*	**C, L, P, S, T**	**C**	**HG**	**IN**
128	*Isolepis cornua*	**C, S, T**	**T**	**HG**	**IN**
129	*Schoenoplectus litoralis*	**C, T**	**C**	**HG**	**IN**

(continued)

Table 1 (continued)

	Family/Taxa	Country	Life forms	Ecological types	Choro-types
130	*Schoenoplectus lacustris ssp. tabernaemontani*	**C, T**	**C**	**HG**	**IN**
131	*Schoenus nigricans*	**C, L, P, T**	**H**	**HG**	**IN**
132	**Scirpus holoschoenus*	**C, S, T**	**C**	**HG**	**IN**
133	**Scirpus littoralis*	**L, P, S**	**C**	**HG**	**IN**
134	**Scirpus maritimus*	**L, P, S**	**C**	**HG**	**IN**
	EUPHORBIACEAE				
135	*Euphorbia falcata ssp. falcata*	**L, P, T**	**T**	**XH**	**IN**
136	**Euphorbia paralias*	**C, L, P, S, T**	**H**	**PH**	**M**
137	**Euphorbia peplis*	**C, L, P**	**T**	**PH**	**M**
138	*Euphorbia pubescens*	**L, P, T**	**H**	**HG**	**IN**
139	*Euphorbia terracina*	**C, L, P, T**	**CH**	**PH**	**M**
	FABACEAE				
140	**Acacia cyanophylla*	**S, T**	**P**	**HA**	**A**
141	**Acacia saligna*	**C, L**	**P**	**HG**	**A**
142	*Alhagi mannifera*	**C, T**	**CH**	**X**	**IN**
143	*Alhagi pseudalhagi*	**T**	**CH**	**XH**	**IR**
144	*Argyrolobium uniflorum*	**C, L, P, T**	**CH**	**X**	**SA**
145	*Astragalus hamosus*	**L, P, S, T**	**T**	**R**	**IN**
146	**Astragalus squarrosus*	**S**	**CH**	**X**	**IR**
147	*Coronilla repanda ssp. repanda*	**C, P**	**T**	**PH**	**IN**
148	**Glycyrrhiza glabra var. glandulifera*	**P, S, T**	**H**	**PH**	**IN**
149	**Lotus corniculatus var. tenuifolius*	**S, T**	**H**	**HA**	**IN**
150	*Lotus halophilus*	**C, S, T**	**T**	**PH**	**IN**
151	*Medicago littoralis var. littoralis*	**C, S, T**	**T**	**X**	**IN**
152	*Medicago marina*	**C, T**	**H**	**PH**	**IN**
153	*Melilotus indica*	**T**	**T**	**HA**	**IN**
154	*Ononis diffusa*	**C**	**T**	**PH**	**IN**
155	**Prosopis farcta*	**C, S, T**	**P**	**PH**	**IR**
156	*Trifolium campestre*	**L, P, T**	**T**	**X**	**IN**
157	*Trifolium scabrum*	**L, S, T**	**T**	**X**	**IN**
158	*Trifolium tomentosum*	**C, L, P, T**	**T**	**HG**	**IN**
159	*Vicia sativa ssp. sativa*	**L, P, T**	**T**	**X**	**CO**
	FRANKENIACEAE				
160	**Frankenia hirsuta*	**C, P, S**	**CH**	**PH**	**IN**
161	**Frankenia pulverulenta*	**C, P, S, T**	**T**	**PH**	**IN**
	GENTIANACEAE				
162	*Blackstonia perfoliata ssp. perfoliata*	**C, S, T**	**T**	**HG**	**IN**
163	**Centaurium erythraea ssp. erythraea*	**T**	**T**	**HG**	**ES**
164	**Centaurium erythraea ssp. rhodense*	**C, L, T**	**T**	**HG**	**M**
165	*Centaurium maritimum*	**C, L, T**	**T**	**X**	**M**
166	**Centaurium pulchellum*	**T**	**T**	**HG**	**IN**
167	*Centaurium tenuiflorum ssp. tenuiflorum*	**C, T**	**T**	**HG**	**IN**
	GERANIACEAE				
168	*Erodium crassifolium*	**C**	**CH**	**X**	**IN**
169	*Geranium dissectum*	**L, P, T**	**T**	**X**	**IN**
	ILLECEBRACEAE				
170	*Paronychia argentea*	**C, L, S, T**	**H**	**PH**	**M**

(continued)

Table 1 (continued)

	Family/Taxa	Country	Life forms	Ecological types	Choro-types
	IRIDACEAE				
171	*Iris orientalis*	**T**	**C**	**HG**	**EM**
	JUNCACEAE				
172	**Juncus acutus*	**C, L, P, S, T**	**C**	**HG**	**IN**
173	**Juncus arabicus*	**S**	**C**	**HG**	**IN**
174	**Juncus articulatus*	**T**	**C**	**HG**	**ES**
175	**Juncus fontanesii ssp. pyramidatus*	**L, P, T**	**C**	**HG**	**EM**
176	**Juncus gerardi ssp. gerardi*	**T**	**C**	**HG**	**IN**
177	**Juncus gerardi ssp. libanoticus*	**L, S, T**	**C**	**HG**	**IR**
178	**Juncus heldreichianus ssp. heldreichianus*	**C, T**	**C**	**HG**	**EM**
179	**Juncus littoralis*	**C, T**	**C**	**HG**	**M**
180	**Juncus maritimus*	**C, P, S, T**	**C**	**HG**	**IN**
181	**Juncus rigidus*	**C, T**	**C**	**HG**	**IN**
182	**Juncus subulatus*	**C, P, S, T**	**C**	**HG**	**M**
	JUNCAGINACEAE				
183	*Triglochin bulbosa ssp. barrelieri*	**C, T**	**C**	**HG**	**M**
	LAMIACEAE				
184	*Salvia syriaca ssp. nusairiensis*	**S, T**	**H**	**XH**	**EM**
185	**Salvia viridis*	**C, L, P, S, T**	**T**	**X**	**M**
186	**Teucrium polium*	**S, T**	**H**	**PH**	**IN**
187	*Teucrium scordium*	**L, P, T**	**C**	**PH**	**ES**
	LILIACEAE				
188	*Allium cupani ssp. hirtovaginatum*	**T**	**C**	**HG**	**M**
189	*Allium curtum*	**C, L, P, S, T**	**C**	**PH**	**EM**
190	**Allium trifoliatum*	**C, L, P, T**	**C**	**XH**	**M**
191	*Asparagus stipularis*	**C, L, P**	**C**	**X**	**IN**
192	*Asphodelus tenuifolius*	**C, P**	**T**	**X**	**IN**
193	*Gagea gageoides*	**L, S, T**	**C**	**HG**	**IR**
194	*Merendera sobolifera*	**P, S, T**	**C**	**HG**	**IR**
195	**Urginea maritima*	**P, S, T**	**C**	**PH**	**M**
	LINACEAE				
196	*Linum bienne*	**S, T**	**H**	**HG**	**M**
197	*Linum maritimum*	**C, P**	**H**	**HG**	**IN**
	LYTHRACEAE				
198	**Lythrum salicaria*	**T**	**H**	**HG**	**ES**
	NEURADACEAE				
199	*Neurada procumbens*	**C, L, P**	**T**	**X**	**IN**
	ORCHIDACEAE				
200	*Orchis palustris*	**P, T**	**C**	**HG**	**IN**
	OROBANCHACEAE				
201	**Cistanche phelypaea*	**C**	**H**	**HA**	**IN**
202	**Orobanche minor*	**P, T**	**T**	**X**	**IN**
	PAPAVERACEAE				
203	**Glaucium flavum*	**C, L, P, S, T**	**H**	**X**	**IN**
204	*Glaucium leiocarpum*	**P, S, T**	**H**	**HG**	**IN**
205	*Hypecoum procumbens*	**C, L, P, S, T**	**T**	**X**	**M**

(continued)

Table 1 (continued)

	Family/Taxa	Country	Life forms	Ecological types	Choro-types
	PLANTAGINACEAE				
206	**Plantago coronopus ssp. commutata*	**C, S, T**	**T**	**PH**	**EM**
207	**Plantago coronopus ssp. coronopus*	**T**	**T**	**HG**	**ES**
208	*Plantago lagopus*	**C, L, P, S, T**	**H**	**HG**	**M**
209	*Plantago lanceolata*	**T**	**H**	**HG**	**IN**
210	**Plantago maritima*	**C, P, S, T**	**T**	**PH**	**IN**
211	*Plantago scabra*	**T**	**T**	**X**	**IN**
	PLUMBAGINACEAE				
212	*Limonium albidum ssp. cyprium*	**C**	**H**	**X**	**EN**
213	**Limonium angustifolium*	**S, T**	**H**	**HA**	**M**
214	*Limonium echioides*	**C, T**	**T**	**HA**	**M**
215	*Limonium effusum*	**T**	**H**	**HA**	**EN, EM**
216	*Limonium globuliferum*	**S**	**H**	**HA**	**IR**
217	*Limonium gmelinii*	**T**	**H**	**HA**	**ES**
218	*Limonium graecum var. graecum*	**C, L, T**	**H**	**HA**	**EM**
219	*Limonium meyeri*	**C**	**T**	**HA**	**IR**
220	*Limonium mucronulatum*	**C**	**H**	**HA**	**EN**
221	**Limonium palmyrense*	**S**	**H**	**HA**	**M**
222	**Limonium sieberi*	**L, P, S, T**	**H**	**HA**	**EM**
223	**Limonium sinuatum*	**C, L, P, S, T**	**H**	**HA**	**M**
224	**Limonium virgatum*	**C, S, T**	**H**	**HA**	**M**
	POACEAE				
225	**Aeluropus lagopoides*	**C, S, T**	**C**	**PH**	**IN**
226	**Aeluropus littoralis*	**C, P, S, T**	**C**	**PH**	**IN**
227	**Agropyron junceum*	**L, P, S**	**H**	**PH**	**M**
228	*Aira elegantissima var. elegantissima*	**S, T**	**T**	**PH**	**M**
229	**Ammophila arenaria ssp. arundinacea*	**C, P, S, T**	**C**	**PH**	**M**
230	**Arundo donax*	**C, L, P, S, T**	**C**	**HG**	**IN**
231	*Brachypodium distachyon*	**C, L, P, S**	**T**	**X**	**IN**
232	*Bromus japonicus ssp. japonicus*	**T**	**T**	**X**	**IN**
233	*Bromus madritensis*	**C, T**	**T**	**X**	**IN**
234	*Bromus rubens*	**L, P, T**	**T**	**PH**	**IN**
235	*Bromus scoparius*	**L, P, S, T**	**T**	**X**	**IN**
236	*Bromus tectorum*	**L, P, T**	**T**	**PH**	**IN**
237	*Catabrosa aquatica*	**T**	**C**	**HG**	**IN**
238	*Catapodium marinum*	**C, T**	**T**	**PH**	**M**
239	**Cynodon dactylon var. dactylon*	**L, P, S, T**	**C**	**PH**	**IN**
240	**Cynodon dactylon var. villosus*	**T**	**C**	**PH**	**IN**
241	*Elymus elongatus ssp. elongatus*	**T**	**C**	**PH**	**IN**
242	*Elymus farctus ssp. farctus var. farctus*	**C, T**	**C**	**PH**	**M**
243	*Elymus hispidus ssp. hispidus*	**T**	**C**	**XH**	**IN**
244	**Hyparrhenia hirta*	**S**	**H**	**X**	**IN**
245	*Hordeum marinum var. marinum*	**C, L, P, T**	**T**	**PH**	**IN**
246	*Hordeum murinum ssp. glaucum*	**T**	**T**	**X**	**IN**
247	*Hordeum murinum ssp. murinum*	**T**	**T**	**PH**	**IN**
248	**Imperata cylindrica var. cylindirica*	**C, L, P, T**	**C**	**PH**	**IN**
249	*Lagurus ovatus*	**C, L, P, T**	**T**	**PH**	**M**
250	*Lolium rigidum var. rigidum*	**L, P, T**	**T**	**XH**	**IN**

(continued)

Table 1 (continued)

	Family/Taxa	Country	Life forms	Ecological types	Choro-types
251	*Lolium subulatum*	**C, S, T**	**T**	**XH**	**EM**
252	*Parapholis incurva*	**C, T**	**T**	**HG**	**IN**
253	*Parapholis marginata*	**C, S, T**	**T**	**HG**	**EM**
254	*Phalaris arundinacea*	**L, T**	**C**	**XH**	**IN**
255	**Phragmites australis*	**C, P, S, T**	**C**	**HG**	**ES**
256	*Poa annua*	**L, P, T**	**T**	**PH**	**CO**
257	*Poa bulbosa*	**L, P, T**	**C**	**X**	**IN**
258	*Poa trivialis*	**L, P, S, T**	**H**	**XH**	**IN**
259	*Polypogon maritimus ssp. maritimus*	**C, L, P, T**	**T**	**PH**	**ES**
260	**Polypogon monspeliensis*	**L, S, T**	**T**	**XH**	**IN**
261	**Puccinella distans ssp. distans*	**S, T**	**H**	**XH**	**IN**
262	*Rostraria cristata var. cristata*	**T**	**T**	**PH**	**IN**
263	*Sphenopus divaricatus*	**S**	**T**	**PH**	**IN**
264	**Sporobulus virginicus*	**C, L, P, S, T**	**C**	**PH**	**IN**
265	*Stipa bromoides*	**L, P, T**	**C**	**X**	**M**
266	*Trachynia distachya*	**C, T**	**T**	**PH**	**M**
267	*Triplachne nitens*	**C, P, T**	**T**	**PH**	**M**
268	*Vulpia brevis*	**C, P, S**	**T**	**PH**	**IN**
	POLYGONACEAE				
269	*Polygonum aviculare*	**L, P, T**	**T**	**PH**	**CO**
270	*Polygonum equisetiforme*	**L, P, T**	**H**	**X**	**IN**
271	**Polygonum maritimum*	**C, L, P, S, T**	**H**	**PH**	**IN**
	PRIMULACEAE				
272	*Anagallis arvensis var. arvensis*	**L, P, S, T**	**T**	**PH**	**IN**
	RANUNCULACEAE				
273	*Consolida glandulosa*	**T**	**T**	**X**	**EN, IR**
274	*Ranunculus neapolitanus*	**C, L, T**	**H**	**HG**	**IN**
	ROSACEAE				
275	*Rubus sanctus*	**L, P, T**	**CH**	**X**	**IN**
	RUPPIACEAE				
276	**Ruppia maritima*	**S, T**	**H**	**HG**	**TA**
	SCROPHULARIACEAE				
277	*Bellardia trixago*	**C, L, P, S, T**	**T**	**X**	**IN**
278	*Verbascum sinuatum var. adenosepalum*	**T**	**H**	**PH**	**EM**
	SOLANACEAE				
279	**Solanum elaeagnifolium*	**S**	**CH**	**R**	**NA**
	TAMARICACEAE				
280	**Reumuria alternifolia*	**S**	**CH**	**XH**	**IR**
281	**Tamarix hampeana*	**L, P, T**	**P**	**HA**	**IN**
282	**Tamarix macrocarpa*	**P, S**	**P**	**HA**	**IN**
283	**Tamarix mannifera*	**P, S**	**P**	**HA**	**IN**
284	**Tamarix smyrnensis*	**C, P, S, T**	**P**	**HA**	**IN**
285	**Tamarix tetragyna*	**C, P, S**	**P**	**HA**	**EM**
286	**Tamarix tetrandra*	**C, L, S, T**	**P**	**HA**	**IN**
	THYMELAEACEAE				
287	**Stellera lessertii*	**S**	**P**	**X**	**IN**
288	*Thymelaea hirsuta*	**L, P, T**	**CH**	**X**	**M**

(continued)

Table 1 (continued)

	Family/Taxa	Country	Life forms	Ecological types	Choro-types
	TYPHACEAE				
289	**Typha latifolia*	**P, S**	**C**	**HG**	**IN**
290	*Typha minima var. gracilis*	**T**	**C**	**HG**	**ES**
	VALERIANACEAE				
291	*Valerianella vesicaria*	**C, L, P, S, T**	**T**	**XH**	**IN**
	VERBENACEAE				
292	**Phyla nodiflora*	**C, S, T**	**CH**	**PH**	**IN**
	ZANNICHELLIACEAE				
293	*Zannichellia palustris*	**C, L, P, T**	**T**	**HG**	**IN**
	ZYGOPHYLLACEAE				
294	**Nitraria retusa*	**S**	**CH**	**HA**	**SA**
295	*Zygophyllum album*	**C, P, T**	**CH**	**XH**	**IN**
296	**Zygophyllum fabago*	**L, P, S, T**	**H**	**X**	**IR**

*Medicinal and economically important plants
Country: *C* Cyprus, *L* Lebanon, *P* Palaestina, *S* Syria, *T* Turkey
Life forms: *C* Cryptophytes, *CH* Chamaephytes, *H* Hemicryptophytes, *P* Phanerophytes, *T* Therophytes
Chorotypes: *A* Australian, *CA* Central America, *CO* Cosmopolitan, *EM* East Mediterranean, *EN* Endemic, *ES* Euro-Siberian, *IN* Imperfectly Known, *IR* Irano-Turanian, *M* Mediterranean, *NA* North America, *S* Sudanian, *SA* Saharo-Arabian, *TA* Tropical America

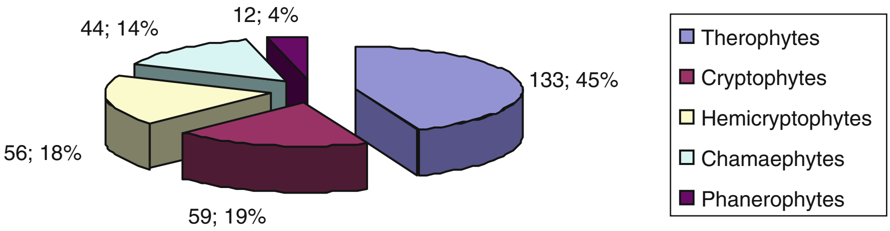

Fig. 2 Distribution and number of halophytes on the basis of their life forms (*C* Cryptophytes, *CH* Chamaephytes, *H* Hemicryptophytes, *P* Phanerophytes, *T* Therophytes)

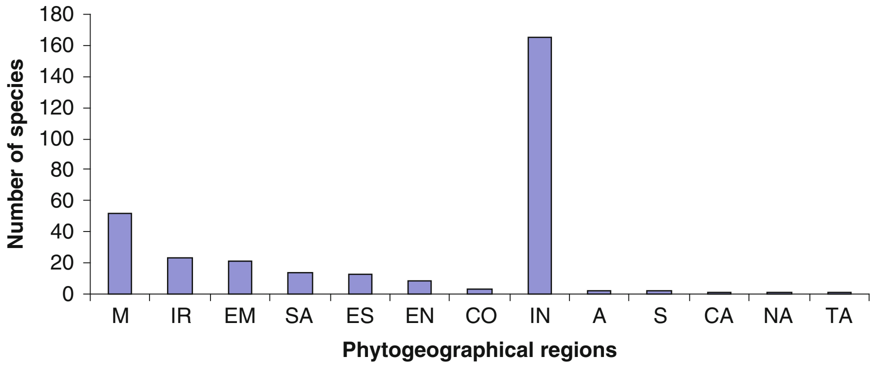

Fig. 3 Chorotypes of halophytic plant taxa (*A* Australian, *CA* Central America, *CO* Cosmopolitan, *EM* East Mediterranean, *EN* Endemic, *ES* Euro-Siberian, *IN* Imperfectly Known, *IR* Irano-Turanian, *M* Mediterranean, *NA* North American, *S* Sudanian, *SA* Saharo-Arabian, *TA* Tropical America)

Table 2 Conservation status of the halophyte taxa in the East Mediterranean

No	Latin name	Threatened category
1	[b]*Aizoon hispanicum*	**EN**
2	[b]*Alhagi mannifera*	**VU**
3	[a]*Alyssum pateri ssp. pateri*	**LR (lc)**
4	[b]*Ambrosia maritima*	**EN**
5	[b]*Argyrolobium uniflorum*	**EN**
6	[b]*Asphodelus tenuifolius*	**VU**
7	[b]*Cachrys scabra*	**EN**
8	[b]*Chlamydophora tridentata*	**VU**
9	[b]*Cistanche phelypaea*	**CR**
10	[a]*Consolida glandulosa*	**LR (lc)**
11	[b]*Coronilla repanda ssp. repanda*	**VU**
12	[b]*Erodium crassifolium*	**VU**
13	[b]*Halopeplis amplexicaulis*	**EN**
14	[a]*Limonium albidum ssp. cyprium*	**CR**
15	[a]*Limonium effusum*	**VU**
16	[b]*Limonium graecum var. graecum*	**VU**
17	[a]*Limonium mucronulatum*	**CR**
18	[b]*Limonium sieberi*	**VU**
19	[b]*Linum maritimum*	**VU**
20	[a]*Malcolmia nana var. glabra*	**CR**
21	[b]*Mesembryanthemum crystallinum*	**VU**
22	[b]*Mesembryanthemum nodiflorum*	**VU**
23	[b]*Neurada procumbens*	**EN**
24	[b]*Ononis diffusa*	**EN**
25	[b]*Pancratium maritimum*	**EN**
26	[a]*Salicornia palasiana ssp. palasiana*	**VU**
27	[a]*Salicornia palasiana ssp. lahonderei*	**CR**
28	[b]*Salsola inermis*	**VU**
29	[b]*Suaeda aegyptiaca*	**EN**
30	[b]*Tamarix tetragyna*	**VU**
31	[a]*Taraxacum aphrogenes*	**VU**
32	[b]*Vulpia brevis*	**CR**
33	[b]*Zygophyllum album*	**VU**

[a] Endemic plants
[b] Rare plants

features (Fig. 4). Out of the halophytes listed 124 taxa (40.79 %) are of economic importance and these are marked in Table 1 with the (*) sign.

4 Economically Important Halophytes

The halophytes possess a significant economic potential and they have been used as fodder, food, fiber, fuel, medicine, for bread making, and for the production of ethereal oils and chewing gum [2, 8, 13, 61, 63–70]. They grow mainly on saline habitats, alongside the coastal zones, delta swamps and in arid deserts. The cultivation of halophytes for commercial production purposes has increased after 1960s [5]. Information on economic uses and ecological characteristics such as; life form, plant type and salinity tolerance, together with the details on the geographical distribution of some halophytes was previously reported [4, 64]. A catalog of halophytic plants of Syria including the distribution, description, salt tolerance, habitats and uses was previously published [5]. The halophytic taxa with medicinal and aromatic values are listed in alphabetical order with their botanical name, part used, ailment treated and preparations used (Table 3).

The most widely used parts of the plants are leaves (28.24 %) and roots (21.18 %). Other utilized plant parts are mentioned in the Table 3. The most common preparation of the traditional folk medicine is Decoction (42.55 %), followed by infusion (11.70 %), poultice (10.64 %) and powder (8.51 %). In addition to these some plants are consumed fresh for the treatment of some ailments their percentage lies around 10.64, but consumption as cooked meal is 8.51 %. A majority

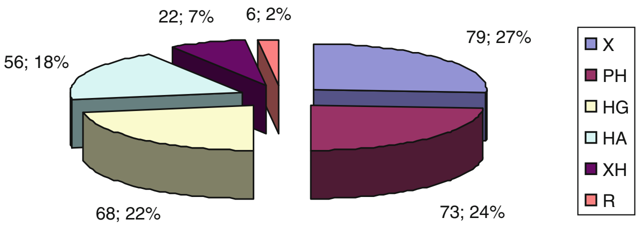

Fig. 4 Ecological types of the halophytes distributed in the East Mediterranean (*HA* Halophyte, *HG* Hygrohalophytes, *PH* Psammohalophytes, *X* Xerophyte, *XH* Xerohalophytes, *R* Ruderal)

Table 3 Medicinal and aromatic halophytes distributed in the East Mediterranean

Botanical name	Part used	Preparation	Treatment	Source
Achillea fragrantissima	Flower	Infusion	Cough	[71]
			Stomach ache	
			Anthelmintic	
Agave sisalana	Root	Decoction	For veterinary purposes	[72]
Agropyron junceum	Seed	Powder	Bread-making	[5]
Aizon hispanicum	Stem, leaves	Raw/cooked	Food purposes	[73]
Alhagi maurorum	Whole plant	Decoction	Diaphrotic	[74]
			Diuretic	
			Expectorant	
			Antibacterial	
			Cholagogue	
			Anti-inflammatory	
	Leaves	Oil	Rheumatism	
	Fruit		Laxative	[75, 76]
Allium trifoliatum	Leaves	Raw	Food purposes	[77]
Anabasis species	Herb	Powder	Wounds	[5]
			Skin diseases	
Arundo donax	Root	Infusion	Diaphrotic	[16]
			Diuretic	
			Emollient	
	Rhizome		Menstrual stimulates	[78]
			Dropsy	
			Cancer	
Atriplex halimus	Leaves	Raw/cooked	Food purposes	[5]
Atriplex leuclada	Seeds	Decoction	Laxative	[79]
Bassia species	Herb	Decoction	Antifungal	[80]
	Leaves		Cardiotonic	[81]
	Fruit		Diuretic	
	Seeds		Skin infection	[82]
Beta vulgaris ssp. maritimus	Leaves	Cooked	Food purposes	[83]
	Seed	Decoction	Tumor	[84]
	Juice	Decoction	Ulcer	
			Hemorrhoid	
	Root, leaves		Pain	
Cakile maritima	Leaves	Raw/cooked	Food purposes	[85]
Capparis spinosa	Flower buds	Decoction	Rheumatism	[86, 87]
			Diuretic	
			Laxative	
			Expectorant	
			Analgesic	
			Tonic	
			Spleen enlargement	
Centaurea postii	Root	Decoction	Tonic	[88]
	Leaves		Diuretic	
			Stomach ache	
			Digestive system	
			Antipyretic (in children)	

(continued)

Table 3 (continued)

Botanical name	Part used	Preparation	Treatment	Source
Centaurium erythraea	Flowers	Decoction	Appetizing	[77]
Centaurium pulchellum	Flowers	Decoction	Appetizing	[77]
Chenopodium album	Leaves		Anthelmintic	[80, 89]
			Antiphlogistic	[90]
			Rheumatism	
			Laxative	
		Poultice	Bug bites	[81]
			Sunstroke	
		Decoction	Carious teeth	[81]
Chenopodium rubrum	Seed	Powder	Bread and Pastries	[85]
Cistanche phelypaea	Stem	Decoction	Diarrhea	[91]
Convolvulus lineatus	Root	Decoction	Diuretic	[5]
			Laxative	
	Flowers	Decoction	Wound	
			Antipyretic	
Cressa cretica	Herb	Decoction	Diabetes	[5]
Cynodon dactylon	Root	Decoction	Diuretic	[78]
			Dropsy	
			Secondary syphilis	
		Infusion	To stop bleeding	[92, 93]
			Skin diseases	
	Juice		Hysteria	[92]
			Epilepsy	
			Chronic diarrhea	
			Dysentery	
			Tumor	
			Cough	
			Headache	
			Hypertension	
Eryngium maritimum	Root	Decoction	Diuretic	[74, 79]
			Laxative	[93]
			Expectorant	
			Urinary infections	
			Kidney stone	
			Prostate	
Euphorbia paralias	Whole plant	Decoction	Bronchitic	[80]
			Asthma	
			Laryngeal spasm	
			Intestinal amoebic dysentery	
			Dysentery	[81]
			Enteritis	
			Skin diseases	
	Latex	Poultice	Warts	[94]
Euphorbia peplis	Latex	Poultice	Warts	[77]
Frankenia species	Root	Decoction	Genito-urinary tracts	[94]
Glaucium flavum	Flower	Powder	Wound	[95]

(continued)

Table 3 (continued)

Botanical name	Part used	Preparation	Treatment	Source
Glycyrrhiza glabra			Cough	[88]
			Sore throats	
			Gastric inflammation	
			Antispasmodic	
			Demulcent	
			Diuretic	
			Expectorant	
			Laxative	
			Tonic	
			Addison's disease	[5]
			Asthma	
			Bronchitis	
			Gastric ulcers	
			Diabetes	
Gypsophila anatolica	Root	Infusion	Expectorant	[5]
			Diuretic	
			Dysentry	
			Diarrhea	
			Stomach ulcers	
			Analgesic	
			Antipyretic	
			Antiinflammatory	
Haloxylon articulatum	Herb	Poultice	Skin diseases	[5]
			Animal psora (sedef)	
Helianthemum lippii	Leaves	Decoction	Kidney ailments	[5]
			Sore throat	
			Scrofula	
			Skin diseases	
			Eye infections	
Imperata cylindrica	Root, young shoot	Infusion	Diuretic	[91]
			To stop bleeding	
Inula critmoides	Leaves	Raw/cooked	Food purposes (in Lebanon)	[96]
	Root		Tonic	[5]
Inula viscosa	Herb	Decoction	Anthelmintic	[97–99]
			Herbal fungicide	
			Wound	
			Ulcer	
			To stop bleeding	
			Pain	
			Respiratory tract infections	
			Hemorrhoids	
			Fractured bones	
			Diabetes	
			Backache	
			Gum disorder	
			Skin fungi	
Juncus species	Stem	Decoction	Diuretic	[80, 82]

(continued)

Table 3 (continued)

Botanical name	Part used	Preparation	Treatment	Source
			Sedative	
			Pectoral	
			Febrifuge	
			Antiphlogistic	
			Sore throat	[82]
			Jaundice	
			Oedema	
			Acute urinary tract infection	
Lotus corniculatus	Herb	Decoction	Sedative	[77]
Lythrum salicaria	Leaves	Poultice	Constipation	[77]
			Hemorrhoids	
			Eczema	
			To stop bleeding	
Matthiola tricuspidata	Seed	Decoction	Aphrodisiac	[78]
			Diuretic	
			Expectorant	
			Stomach ulcer	
			Tonic	
			Snake bites	
	Seed	Oil	Cholesterol-lowering	
Mesembryanthemum species	Leaves	Juice	Respiratory system	[100]
			Urinary system	
			Ascites	[78]
			Dysentery	
			Liver diseases	
			Kidney diseases	
	Root, leaves	Raw	Stimulant	[5]
Nitraria retusa	Leaves	Decoction	Urinary tract infections	[101]
Orobanche minor	Stem	Decoction	Kidney stones and sand	[95]
Pancratium maritimum	Bulbs	Cooked	Food purposes	[102]
		Powder	Emetic	[77]
			Antifeedant	[5]
			Purgative	
Peganum harmala	Seeds	Decoction	Diuretic	[93, 103]
			Emetic	
			Stimulant	
			Anthelmintic	
			Itches	
	Root		Parkinson’s diseases	
			Rheumatism	
			Nervous system	
			Kill body lice	[78, 102]
Phragmites australis	Rhizome	Decoction	Diuretic	[77]
			Antipyretic	
			Blood purifier	
			Urinary tract diseases	
Phyla nodiflora	Leaves	Decoction	Anodyne	[104]
			Diuretic	
			Emmenagogue	

(continued)

Table 3 (continued)

Botanical name	Part used	Preparation	Treatment	Source
	Root	Juice	Fever	[90]
			Cold	
			Gastric problems	
Plantago species	Seed	Oil	Reducing blood cholesterol	[78]
	Leaves	Raw	Food purposes	[79]
			Ague	
			Sore eyes	
		Infusion	Wound	[77]
			Emollient	
			Constipation	
			Expectorant	
			Diuretic	
		Powder	The treatment of boils	[77]
	Seed	Decoction	Laxative	[74]
			Diarrhea	
			Hemorrhoids	
Polygonum maritimum	Whole plant		Anthelminitic	[81]
			Cardiotonic	[79]
	Juice		To stop nose-bleeds	
			Sores	
Polypogon monspeliensis	Ash	Infusion	Heart palpitations	[105]
Prosopis farcta	Leaves, seed	Decoction	Antidysenteric	[51]
			Rhematism	
			Demulcent	[92]
			Pectonal	
			Scorpion stings	
Reaumeria alternifolia	Herb	Poultice	Itching	[106]
Salicornia europaea	Herb	Decoction	Diuretic	[77]
			Tonic	
	Stem	Raw	Food purposes	
Salsola kali	Herb	Juice	Diuretic	[79]
			Cathartic	[107]
			Emmenagogue	
			Stimulant	
			Dropsy	
Salvia viridis	Flower, Leaves	Infusion	Stomachic	[77]
			Constipation	
			Sedative	
Schanginia baccata	Leaves	Raw/cooked	Food purposes	[5]
Scirpus species	Rhizome	Decoction	Diuretic	[78]
			Amenorrhoea	[82]
			Dymenorrhea	
			Abdominal pain	
			Indigestion	
			Galactogogue	[5]
Solanum elaeagnifolium	Fruits	Crushed	Make cheese (in America)	[108]
Stellera lessertii	Root, leaves	Decoction	Sprains	[5]
			Cancer	

(continued)

Table 3 (continued)

Botanical name	Part used	Preparation	Treatment	Source
Suaeda fruticosa	Leaves	Raw/cooked	Food purposes	[102, 109]
		Poultice	Ophthalmia	[78]
		Infusion	Emetic	
	Root	Decoction	Cold symptoms	[94]
			Cholesterol-lowering	[110]
Tamarix tetrandra	Leaves	Decoction	Appetizing	[77]
			Constipation	
			Diuretic	
Teucrium polium	Herbs	Infusion	Appetizing	[77]
			Pain	
			Tonic	
			Stomach diseases	
			Diabetes	
Typha latifolia	Root	Powder	Bread and pastry	[111]
			Tumors	[112]
			Diuretic	
			Tonic	
			Galactogogue	
		Poultice	Sores	[105]
	Stem	Decoction	Whooping cough	[105]
Urginea maritima	Bulbs	Powder	Diuretic	[77]
			Heart strengthener	
Xanthium strumarium	Leaves	Infusion	Malaria	[78]
			Rheumatism	[105]
			Kidney diseases	
			Tubercularis	
	Fruit	Decoction	Antibacterial	[74]
			Antispasmodic	
			Antitussive	
			Stomachic	
			Allergic rhinitis	
			Rheumatism	
			Constipation	
			Diarrhea	
			Leprosy	
	Root	Decoction	Scrofulous tumour	[100]
	Seed	Poultice	Wound	[105]
Zygophyllum fabago	Flower buds	Decoction	Rheumatism	[85, 113]
			Antelmintic	[77]
			Shortness of breath	
		Poultice	Cancer	[114]
			Injuries	

of these plants are used for the treatment of urinary system disorders (21.74 %) (Table 4).

There are many halophytic species which can be used as either forage or fodder. *Leptochloa fusca, Lasarius scindicus, Panicum turgidum, Dactyloctenium sindicum, Cynodon dactylon, Paspalum vaginatum, Sporobolus marginatus, S. ioclados, Chloris gayana, C. virgata, Echinochloa turnerana, Echinochloa colonum* and *Puccinellia distans* are some of the common

Table 4 Therapeutic uses of the medicinal halophytes

Name of the disease	Percent (%)
Urinary system disorders	21.74
Internal diseases	10.14
Skin disorders	9.06
Respiratory diseases	6.52
Pains	5.80
Cold	5.07
Increase sexual power	4.35
Rheumatism	2.90
Cardiac diseases	2.54
Digestive system diseases	2.54
Gynecological diseases (For women)	2.54
Anthelmintic	2.17
Mouth, Teeth and throat diseases	2.17
To stop bleeding	1.81
Diabetes	1.45
Tumor	1.45
Dropsy	1.45
Antibacterial and antifungal	1.45
Eye diseases	1.09
Cancer	1.09
Cholesterol-lowering	1.09
Emetic	1.09
Antidote against the bites of venomous	1.09
Nervous system	0.72
Bone and joint diseases	0.72
Jaundice	0.72
For veterinary purposes	0.72
Parkinson's diseases	0.36
Scrofula	0.36
Hypertension	0.36

grass species found on saline-alkaline habitats. Many species of the genera *Alhagi, Salicornia, Chenopodium, Atriplex, Salsola, Suaeda* and *Kochia* are common fodder shrubs (60). The species of *Atriplex* and *Tamarix* can be used as fodder for livestock and wildlife [115]. *Atriplex* as well as *Suaeda fruticosa* are deliciously consumed by the livestock and generally overgrazed in their natural habitats. *Halocnemum strobilaceum* is also used as fodder because of its rich raw protein content [13]. The *Atriplex* and *Spartina* species in Africa, Europe and the Americas; the *Distichlis spicata* in Mexico, and *Prosopis tamarugo* in Chile are used as animal feed [116]. The halophytes used as fodder and plants with high fodder potential and preferred by the animals are presented in Table 5.

From the very early days people have got exposed to the adverse effects of poisonous plants. A portion of some of these toxic plants or the entire plant may be toxic [122]. In this context, hand in hand with the halophytes possessing good medicinal value and high economic potential, some are poisonous. The plants recorded as poisonous in the East Mediterranean are *Urginea maritima, Xanthium strumarium, Pancratium maritimum,* and the species of *Glaucium*, *Euphorbia, Inula,* and *Orobanche* [77, 123], *Teucrium polium, Peganum harmala, Solanum elaeagrifolium* [122]; the species of *Anabasis* [124], *Bassia* [125], *Medicago marina* and *M. littoralis* [100], *Stellera lessertii* [5].

In different countries halophytes are used as food, fuel, fodder, essential oils, medicines, glue, bread and fiber products [126]. For example; *Salicornia species* are used for vegetable oil production as well as forage crop in Kuwait, U.A.E. and Saudi Arabia [116, 127, 128]. *Suaeda* has been used for extraction of soda for traditional production of soap in Iran whereas young leaves of *Suaeda aegyptiaca* are consumed by people. In some places the extract of *Salsola kali* is used for sterilization of raisins. *Salicornia persica* is used as fodder particularly for goats [129].

According to Khan and Qaiser [60] the species of *Arundo, Rumex, Suaeda, Alhagi, Atriplex, Chenopodium, Kochia, Prosopis, Salsola, Puccinellia, Sporobolus, Arthrocnemum, Salicornia, Tamarix, Plantago, Tribulus, Juncus, Imperata, Phragmites* and *Typha* are used for medicinal purposes, as food, forage and fodder, oil seed crops, and fuel wood.

Different researchers have demonstrated the degree of economic potentiality of aerial parts of some halophytes after examining their phytochemical contents (Tables 6 and 7). Some halophytes are a good source of proteins derived from their leaves. These are used to increase food quality and nutritional values in advanced countries. *Kochia, Salsola* and *Atriplex* are good sources for leaf protein production together with the *Salicornia*. *Salsola* is also used for the production of bioactive compounds and the *Juncus* species for paper, pulp and fiber production [135]. *Alhagi graecorum, Salsola baryosma, Aeluropus lagopoides, Aeluropus*

Table 5 Halophytes with fodder potential in the East Mediterranean

Botanical name	Camel	Sheep	Goat	Bird	Poultry	Potential fodder	Source
Acacia cyanophylla		x	x				[117]
Aellenia species	x	x	x				[50]
Aeluropus species	x	x	x				[10]
Alhagi maurorum	x		x				[5]
Anabasis species	x	x	x				[5]
Arthrocnemum species	x						[101]
Astragalus squarrosus	x	x	x				[5]
Atriplex species	x	x	x				[10]
Beta vulgaris ssp. maritima						x	[83]
Capparis spinosa	x		x				[5]
Centaurea postii	x	x	x				[88]
Chenolea arabica	x	x	x				[5]
Chenopodium species				x	x		[5]
Cynodon dactylon	x	x					[11]
Girgensohnia oppositifolia	x	x	x				[5]
Halimione portulacoides						x	[85]
Halocnemum strobilaceum	x	x					[118]
Haloxylon articulatum		x	x				[75]
Helianthemum lippii	x						[5]
Hyparrhenia hirta						x	[5]
Inula crithmoides						x	[96]
Malcolmia grandiflora	x	x					[5]
Polypogon monspeliensis				x			[76]
Prosopis farcta	x	x	x				[5]
Puccinella distans						x	[5]
Reaumeria alternifolia	x	x	x				[106]
Ruppia maritima				x			[5]
Salicornia europaea						x	[5]
Salsola crassa	x						[5]
Salsola jordanicola	x	x	x				[5]
Salsola kali		x	x				[119]
Salsola tetrandra	x						[5]
Salsola volkensii	x	x	x				[5]
Sarcocornia perennis	x						[101]
Seidlitzia rosmarinus	x						[50]
Sporobolus virginicus			x				[5]
Stellera lessertii	x	x	x				[5]
Suaeda fruticosa		x	x				[120, 121]

littoralis, Juncus rigidus, Tamarix spp. are also used for forage, fiber, oil, firewood, fuel and timber [136].

In the prehistoric times halophytes have been used as ornamentals and for the production of decorative things like baskets, hats, mats and brooms. In all eight halophytic plants have been identified to be used as ornamentals in the region (Table 8). Nearly the same number has been used widely from the study area as a potential source of natural dyes (Table 9). Particularly red color has been used in coloring mats and has been obtained from *Peganum harmala* [143].

Table 6 Economic potential of some halophytes in the East Mediterranean

Botanical name	Soap	Glass	Fuel	Oil	Detergent	Insecticide	Source
Acacia cyanophylla			x				[117]
Agave sisalana	x						[113]
Aizon hispanicum	x	x					[5]
Anabasis species			x		x	x	[10]
Arthrocnemum species	x	x					[5]
Cakile maritima				x			[85]
Capparis spinosa					x		[86]
Chenopodium album	x						[130]
Gypsophila anatolica						x	[5]
Halopeplis amplexicaulis	x	x					[5]
Matthiola tricuspidata				x			[78]
Mesembryanthemum nodiflorum	x						[100]
Nitraria retusa			x				[101]
Salicornia europaea	x	x		x			[5]
Salsola kali	x	x			x		[119]
Suaeda fruticosa	x	x		x			[4, 79]
Tamarix species			x				[5]

Table 7 Phytochemical composition of some halophytic plants from the study area

Botanical name	Protein (%)	Fiber (%)	Fat (%)	Ash (%)	NFE (%)	Source
Acacia cyanophylla	**12–16**	**20–24**	**6–9**	**10–12**	**–**	[131]
Achillea fragrantissima	**14.8**	**2.6**	**38.3**	**6.7**	**37.6**	[10]
Aellenia species	**16–18**	**24–26**	**–**	**–**	**–**	[50]
Aeluropus littoralis	**8.6**	**2.4**	**17.2**	**29.9**	**41.9**	[10]
Anabasis species	**8.5**	**54.8**	**2.5**	**26.1**	**17**	[10]
Arundo donax	**6.9**	**1.3**	**37.5**	**9.2**	**45.1**	[132]
Atriplex halimus	**14**	**13.2**	**2.4**	**23.6**	**42.2**	[10]
Atriplex leuclada	**12–22**	**22.4**	**0.9**	**15.8**	**44.2**	[10]
Bassia species	**21.5**	**19.7**	**2.4**	**19.2**	**37.2**	[81]
Capparis spinosa	**11.9**	**1.9**	**31.6**	**7.5**	**48.2**	[10]
Chenopodium album	**20.5**	**19.9**	**4.2**	**20**	**35.4**	[81]
Cynodon dactylon	**7.0**	**3.1**	**31.7**	**14.7**	**43.5**	[10]
Glycyrrhiza glabra	**9.8**	**6.3**	**41.3**	**5.5**	**37.1**	[10]
Halocnemum strobilaceum	**6.9**	**2.15**	**17.0**	**40.1**	**33.83**	[133]
Haloxylon articulatum	**18.7**	**3.6**	**20**	**17**	**40.7**	[50]
Hyparrhenia hirta	**3.2**	**1.8**	**38.1**	**12.3**	**45.6**	[134]
Juncus maritimus	**8.6**	**32**	**1.7**	**11.9**	**37.2**	[10]
Medicago marina	**6**	**0.4**	**9.5**	**1.4**	**–**	[81]
Nitraria retusa	**11.3**	**2.55**	**31.5**	**30.2**	**24.45**	[121]
Plantago coronopus	**16**	**2.5**	**17**	**9.1**	**55.4**	[10]
Polygonum maritimum	**1.9**	**0.3**	**3.5**	**35**	**–**	[81]
Prosopis farcta	**14.2**	**4.2**	**34**	**8.6**	**39**	[10]
Salsola kali	**12.3**	**1.8**	**31.7**	**15.2**	**39**	[132]
Seidlitzia rosmarinus	**6.8**	**21**	**–**	**39**	**–**	[50]
Sporobolus virginicus	**7.5**	**0.5**	**48.8**	**7.6**	**35.6**	[10]
Suaeda fruticosa	**12.1**	**5**	**30.1**	**14.2**	**38.6**	[120]
						[121]
Tamarix species	**7.21–8.15**	**23–24.2**	**3.11–3.25**	**20.1–25.2**	**40.54–45.24**	[133]
Typha latifolia	**7–12**	**1.5–3.5**	**–**	**–**	**–**	[111]

Table 8 Ornamentals and other uses of halophytes from the East Mediterranean

Botanical name	Mats	Paper	Basket	Ropes	Fishing pole	Hats	Broom	Musical instruments	Source
Agave sisalana				x					[137]
Agropyron junceum	x	x		x					[5]
Ammophila arenaria	x	x	x	x			X		[75, 138]
Arundo donax	x	x	x		x			X	[106, 139]
Hyparrhenia hirta	x				x				[5]
Juncus maritimus	x	x	x						[75, 87]
Scirpus maritimus	x	x	x			x			[105]
Typha latifolia	x	x	x			x			[89]

Table 9 Potential halophytic dye plants from the East Mediterranean

Botanical name	Part used	Colour	Source
Arundo donax	Pollens	Yellow	[105]
Chenopodium album	Young shoot	Green	[130]
Chenopodium rubrum	Whole plant	Golden-green	[140]
Glycyrrhiza glabra	Leaves	Yellow	[141]
Inula viscosa	Flowers	Yellow	[142]
Matthiola tricuspidata	Flowers	Dark blue/Purple	[78]
Peganum harmala	Seed	Red	[75]
Suaeda fruticosa	Stem and Leaves	Black	[79]

The halophytes identified from the study area and used as ornamentals are; *Pancratium maritimum, Inula crithmoides, Matthiola tricuspidata, Polypogon monspeliensis, Halimione portulacoides, Ipomoea imperati,* and the species of *Arthrocnemum, Halopeplis, Frankenia, Acacia, and Limonium.* Despite the limited diversity of plants in coastal areas, halophytes play an important role in the control of soil erosion, provide food and shelter for many animal species [66]. *Salsola tetrandra, Sporobolus virginicus, Suaeda fruticosa, Agropyron junceum, Puccinella distans* [5], *Arthrocnemum* species, *Sarcocornia perennis* [101], *Haloxylon articulatum, Juncus* species [75], *Ammophila arenaria* [76], *Arundo donax* [106] and *Acacia* species [144] can be used for soil and sand stabilization and erosion control. Most important species in he region in this connection are; *Typha latifolia* and the species of *Tamarix* and *Juncus* [5, 75].

The halophytes can also be used to clean contaminated soils and water. *Salicornia europaea* has the ability to detoxify contaminated soils [145] and *Ruppia maritima* [5] is used for wastewater treatment. Similarly *Cynodon dactylon* [76] and *Ruppia maritima* [5], and *Inula crithmoides* [96] can be used to produce biomass through biosaline agriculture.

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Germination and Early Seedling Growth of Two Salt-Tolerant *Atriplex* Species That Prevent Erosion in Iranian Deserts

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and Todd P. Egan

Abstract

Two experiments were performed to determine the effects of temperature and NaCl concentration on seed germination and early seedling growth of *Atriplex lentiformis* and *Atriplex verrucifera* collected from salt deserts in Isfahan and Shiraz, Iran. These species help prevent soil erosion. Seeds were germinated from 5 to 30 °C at 5 °C intervals. Optimum temperature for seed germination in *A. lentiformis* and *A. verrucifera* was 15 and 10 °C, respectively. Germination was lowest at 30 °C for both species. Seeds were also germinated at 100–500 mMol/L NaCl at 100 mMol/L increments. Germination decreased as NaCl concentration increased from over 85 % germination at 0 mMol/L NaCl to less than 5 % germination at 500 mMol/L for *A. lentiformis*, and from over 60 to 0 % for *A. verrucifera* at the same salt concentrations. Ungerminated seeds in high NaCl concentrations had a higher percent recovery germination in distilled water than seeds in lower salt concentrations. For *A. lentiformis* there was 42.5 % recovery at 500 mMol NaCl, but only 13 % recovery germination at 100 mMol. Similar values were found for *A. verrucifera*. Early growth reflected germination responses in each experimental group. Hypocotyl length was significantly and strongly negatively correlated with salinity.

Keywords

Atriplex • Halophytes • Iran • Recovery of germination • Seed germination • Salinity • Temperature

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_19, © Springer Science+Business Media Dordrecht 2014

1 Introduction

Arid and semiarid lands constitute approximately one-third of the earth's surface [1] and two-third of Iran's area [2]. Many plants in these areas have adapted to high saline soil conditions, and competition in these stressful environments favors species that are able to become established, grow to maturity, and reproduce [3]. These halophytic species are extremely important as forage plants for livestock and wildlife in arid and semiarid regions worldwide [4], as they provide palatable and nutritious feed year-round, and are especially important in winter ranges. Because of their economic importance, halophytes have been studied and used in range rehabilitation far more extensively than most other plants [5–7].

Halophytes are taxonomically diverse and occupy diverse habitats. They can grow inextremely dry to temporarily waterlogged sites and salt marshes. They can tolerate salt concentrations similar to, or even higher than that of sea water (Ca. 500 mM) [8]. In salt deserts and marshes when plant mortality is highest, salinity is often the determining factor for seed germination [9].

In order to thrive under seemingly adverse conditions, halophytes have adapted to salinity in many ways, including dormancy when germination is delayed in dry seasons when water potentials are the lowest [9–11]. A delay in germination of some seeds is predicted to reduce temporal variance and increase individual fitness [12]. For most halophytes, seed germination is highest under non-saline conditions, and germination is strongly inhibited at salt concentrations that are much lower than those at which adult plants normally grow. Although a saline environment may inhibit seed germination, many seeds will resume germination after a high level of salt stress is alleviated. An example of this is increased spring germination when rainfall is high and temperatures are low. Therefore, germination progressively increases with decreases in salinity [8, 13].

Most seeds are located near the soil surface where salt concentration changes the most. This constant fluctuation of salinity levels is due to continuous evaporation of ground water [13]. Rainfall can quickly leach salt from the surface and supply water to seeds; however, when there are only brief periods of rain the soil dries out quickly and seedling mortality increases as soil salinity increases. Therefore, for successful establishment of plants in saline environments, seeds must remain viable in high salinity and germinate when salinity decreases [14–16]. When salt stress is alleviated with distilled water most halophyte seeds will germinate [14, 17, 18].

Atriplex lentiformis (Torr.) S. Wats. and *Atriplex verrucifera* M. Bieb. are two dominant perennial xerohalophytes in desert and semi-desert areas in Iran. *Atriplex lentiformis* is a non-native species with numerous, erect, branches 40–80 cm high that are densely covered with hairs. *Atriplex lentiformis* flowers from August to October. *Atriplex verrucifera* is a native species with numerous gray branches 25–60 cm high. Branches are leafless towards the top and secrete salt. *Atriplex verrucifera* flowers from August to September, and is planted to prevent soil erosion in Iran [19]. *Atriplex* shrubs have adapted to saline environments through physiological mechanisms including the ability to excrete salt from cell and tissues. As a result, they have a competitive advantage over species that lack strategies to deal with salt in the soil [20].

There is little information on the germination biology of these species. Therefore, we studied the effects of temperature and salt stress on different parameters of seed germination and seedling growth. Recovery germination after saline treatments was also determined.

2 Materials and Methods

Mature seeds of *A. lentiformis* were collected from 7 to 10 October 2003 from a natural salt marsh near Darab, Shiraz (28° 38′N, 54°, 15′E). Long term (1975–2003) annual average maximum and minimum temperatures were 29.7 °C and 14.4 °C, respectively. Long term annual mean precipitation was 283.4 mm.

Seeds of *A. verrucifera* were also collected from 7 to 10 October 2003 from a salt marsh at Isfahan (33° 44′N, 50°, 48′E). Long term (1975–2003)

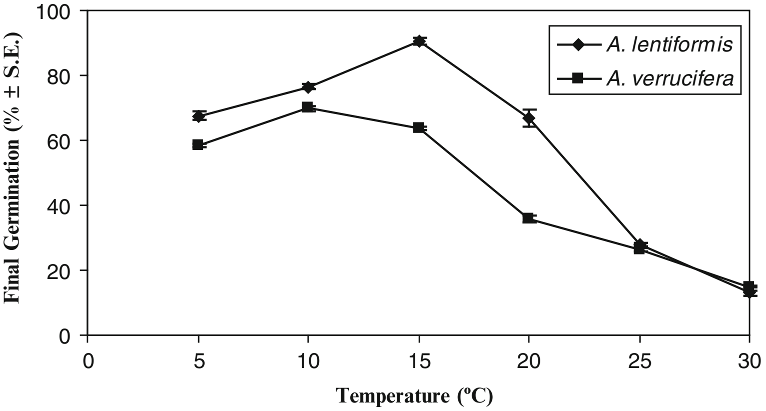

Fig. 1 Final mean germination percentage (±S.E., n=4) of *Atriplex lentiformis* and *Atriplex verrucifera* at 5, 10, 15, 20, 25 and 30 °C

annual average maximum and minimum temperatures were 23.4 °C and 9 °C, respectively. Long term annual mean precipitation was 121.1 mm. These averages reflect the entire year.

Seeds were stored at the Seed Technology Laboratory of Shiraz University at approximately 25 °C between collection and experiments. Germination studies were started in May 2004.

2.1 Determination of Optimal Germination Temperature

For the germination experiments seeds of both species were treated using the fungicide Phygon©. Petri dishes were sterilized with 2.5 % sodium hypoclorite and placed in a 120 °C oven for 2 h. Seeds were incubated in 9 cm diameter Petri dishes on No. 3 Whatman® filter paper with four replications of 25 seeds per replicate.

Distilled water (5 ml) was added to dishes which were then sealed with Parafilm® to prevent solution evaporation, and placed in a dark incubator (Germitator-EYELATRONFLI-301©) for 20 days. *Atriplex verrucifera* seed germination is not inhibited by a lack of light [19], and many species of *Atriplex* germinate well at comparatively constant temperatures [21]; therefore, optimal temperature for germination and early growth of both species was determined by calculating percent germination at constant temperature of 5, 10, 15, 20, 25 and 30 °C. Seeds were considered germinated when the radicle protruded through the seed coat [22].

2.2 Germination Tests at Different Saline Concentration

From experiment one, optimal germination temperatures for each species were determined to be 15 °C for *A. lentiformis* and 10 °C for *A. verrucifera* (Fig. 1). Seeds were then germinated at varying NaCl concentrations at the appropriate optimum temperature. Treatments groups had 5 ml of 0 (distilled water control),100, 200, 300, 400, or 500 mMol/L NaCl in each replicate. To prevent solution evaporation, Petri dishes were sealed with Parafilm® and placed in an incubator (Germitator-EYELATRONFLI-301©) in the dark. Seeds were considered germinated when the radicle protruded through the seed coat [22]. Germination was determined at 24 h intervals for 20 consecutive days. Fresh salt solutions were added periodically to each Petri dish to maintain proper moisture levels throughout the experiment. The following germination values were calculated: (1) final germination percentage, (2) number of days to first germination (when the first seed germinated), (3) number of days to final germination (when the last seed germinated), (4) germination rate using Khan and Ungar's [23] modification of Timson's [24] index of germination velocity ($\sum G/t$), where G is the percentage of seed germination at 2 day intervals and t is the total germination period. (5) mean time to germination ($MTG = \sum n_i d_i / N$) where n is the number of seeds germinated at day i, d is the incubation period in days, and N is the total number of seeds germinated in the treatment) [25]. (6) mean daily germination (MDG = final germination percentage/number of days to final germination percentage) [9]. These assays were calculated to get the best understanding of how environmental variables affect the germination of these two species.

2.3 Salinity Effects on Seedling Growth

To investigate the effects of salinity on radicle and hypocotyl length in each treatment, radicle and hypocotyl lengths of germinated seeds were measured to the nearest millimeter after 20 days. All seeds that germinated did so within 20 days of treatment. Other researchers have found that a large number of halophytes will germinate within 20 days of treatment [26].

2.4 Recovery Experiment After Salt Pre-treatment

After 20 days, un-germinated seeds from the NaCl treatments were transferred to distilled water in new Petri dishes to analyze recovery germination. Germination was recorded at 2 day intervals for 20 days in the dark at optimum temperatures for each species (15 °C for *A. lentiformis* and 10 °C for *A. verrucifera*). Total emergence of the radicle was used as the germination criterion. Germinated seeds were counted and removed daily during this period. This experiment was carried out to determine if the saline treatments inhibited germination by osmotic pressure and/or a specific ion toxicity. The recovery percentage (RP) was calculated as reported previously [8, 17], where $RP = [(a-b)/(c-d)] \times 100$, and the Timson's index of recovery, where $T = [d/(a-b)] \times 100$. In both equations a is the total number of seeds germinated after being transferred to distilled water, b is the total number of seeds that germinated in saline solution, c is the total number of seeds, and d is the Timson's index for seeds in distilled water.

2.5 Statistical Analyses

Statistical analyses were carried out using SPSS version 10.0 [27]. Data were examined using the Kolmogorov-Smirnov test for normality and the Levene test for homogeneity of variance. Data were arcsine $\sqrt{\%}$ transformed before statistical analyses were performed to correct for heterogeneity of variance of the raw data. These statistical analyses were followed by one-way ANOVAs (F-test) and Tukey HSD, post-hoc tests for the identification of significant differences among treatments. Pearson coefficients were calculated to assess correlation between different variables.

3 Results

3.1 Optimal Temperature for *A. lentiformis* and *A. verrucifera* germination

Seeds of *A. lentiformis* and *A. verrucifera* germinated under a wide range of temperatures from 5 to 30 °C. However, germination peaked at 10–15 °C for both species and was reduced at higher temperatures (Fig. 1).

3.2 Germination Test at Different Saline Concentrations

Increasing salinity slowed and decreased germination (Fig. 2), while seeds of both species germinated rapidly in non-saline controls at their optimum temperature. Almost 75 % of the *A. lentiformis* control seeds and 60 % of the *A. verrucifera* control seeds had germinated after 7 days. Germination reached its maximum after 10 days for *A. lentiformis* and after 12 days for *A. verrucifera* in the absence of salt.

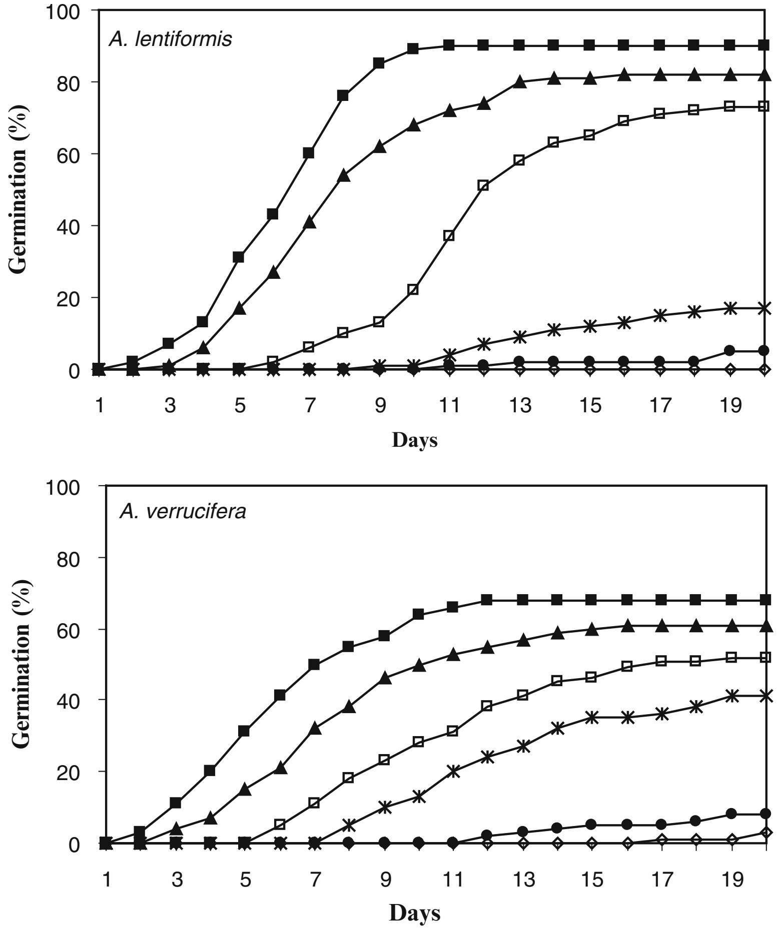

Fig. 2 Cumulative mean germination percentage in 0(■), 100(▲), 200(□), 300(★), 400(●) and 500(◇) mM NaCl at optimum temperature for two *Atriplex* species during 20 days (n = 4)

A one-way ANOVA indicated that germination characteristics for both species under optimal temperatures were significantly affected by salinity. In both species, final germination percentage was highest in distilled water, followed by the 100 mMol/L NaCl treatment. Increased salinity progressively inhibited germination of *A. lentiformis* and *A. verrucifera* (respectively, $F = 160.14$, $F = 28.1$, $P = 0.0001$). No seeds of *A. lentiformis* germinated in 500 mMol/L NaCl (Fig. 2). The number of days to first germination of *A. lentiformis* ($F = 29.14$, $P = 0.0001$) and *A. verrucifera* ($F = 37.75$, $P = 0.0001$) increased with salinity from 3.0 ± 0.40 to 14.3 ±2.40 days and from 2.2 ± 0.25 to 18.5 ± 1.50, respectively. Likewise, the number of days to final germination of *A. lentiformis* ($F = 216$, $P = 0.0001$) and *A. verrucifera* ($F = 11.1$, $P = 0.0001$) increased with salinity from 10.0 ± 0.4 to 19.0 ± 0.0 days and from 11.2 ± 0.9 to 20.0 ± 0.0 days, respectively. With increased salinity, mean daily germination decreased from 9.0 ± 0.02 to 0.26 ± 0.10, and mean time of germination increased from 6.4 ± 0.47 to 16.6 ± 1.20 for *A. lentiformis* ($F_{MDG} = 324.5$, $F_{MTG} = 88.2$, $P = 0.0001$). For *A. verrucifera*, as salinity increased mean daily germination decreased from 6.25 ± 0.62 to 0.15 ± 0.09 and mean time of germination increased from 6.10 ± 0.48 to 19.3 ± 0.75 ($F_{MDG} = 23.48$, $F_{MTG} = 39.2$, $P = 0.0001$). In both species, the rate of germination as

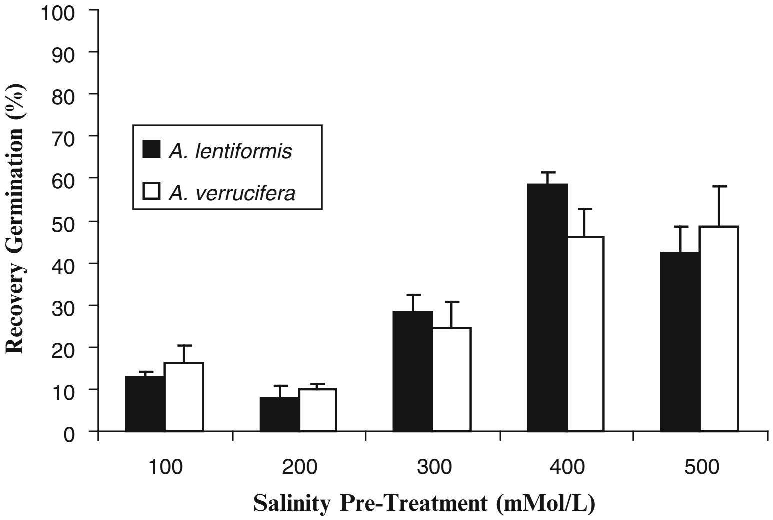

Fig. 3 Recovery germination (±S.E.) of *Atriplex lentiformis* and *Atriplex verrucifera* after replacing treatment NaCl solutions ranging from 100 to 500 mMol/L with distilled water. Seeds were allowed to germinate for 20 days ($n=4$)

determined by the modified Timson's index showed that the germination rate was similar under low and moderate salinity, but was significantly reduced at the highest salinity concentration (Fig. 2). For *A. lentiformis* and *A. verrucifera*, percent germination ($r^2=-0.95$ *A.l.*, -0.97*A.v.*) and germination rate ($r^2=-0.95$*A.l.*, -0.97*A.v.*) were significantly ($p=0.01$) and negatively correlated.

3.3 Recovery Experiment After Salt Pre-treatment

After 20 days, seeds that had not germinated in the saline treatment were transferred to distilled water in new Petri dishes to assess recovery. Seeds exposed to high salinity demonstrated a significant increase (approximately 43–45 %) in germination (Fig. 3). Conversely, recovery of *A. lentiformis* and *A. verrucifera* was affected by salinity pre-treatment (respectively, $F=32.1$, $P=0.0001$; $F=7.9$, $P=0.001$) and correlated with it (respectively, $F=0.785$, $F=0.752$, $P=0.0001$). However, percent recovery in all treatments was lower than final germination in the control group of the original experiment.

In recovery germination, the number of days to first germination was significantly affected by salt pre-treatment for *A. lentiformis* ($F=32.8$, $P=0.025$) and *A. verrucifera* ($F=3.6$, $P=0.03$). Seeds in the highest salt treatments had the fastest recovery. Therefore, the seeds exposed to higher salinity showed rapid germination compared to other treatments. For *A. lentiformis*, MDG significantly increased from 2.60 ± 0.1 seeds per day for seeds previously treated at 100 mMol/L to 6.80 ± 0.4 seeds per day for seeds previously treated with 500 mMol/L. For *A. verrucifera*, MDG significantly increased from 3.16 ± 0.1 seeds per day for seeds previously treated at 100 mMol/L to 7.94 ± 0.8 seeds per day for seeds previously treated with 500 mMol/L. However, MTG did not significantly increase with salinity pre-treatment in *A. lentiformis* ($F_{MDG}=37.4$, $P=0.0001$; $F_{MTG}=1.03$, $P=0.318$) or *A. verrucifera* ($F_{MDG}=9.4$, $P=0.0001$; $F_{MTG}=1.1$, $P=0.4$). Recovery germination rate was higher in seeds that were exposed to higher salinity (Fig. 4). Therefore, the greatest GR occurred at the 500 mMol/L NaCl pre-treatment in *A. lentiformis* and *A. verrucifera* (respectively, $F=33.8$, $P=0.0001$; $F=8.31$, $P=0.001$).

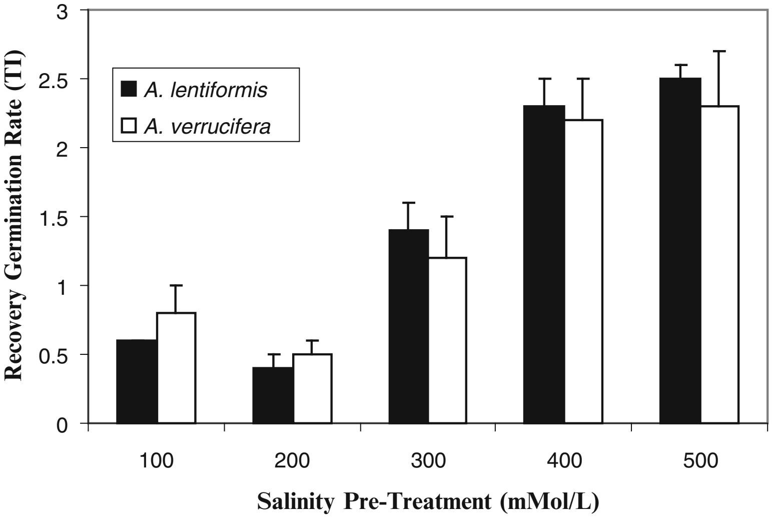

Fig. 4 Recovery germination rate (Timson's index, ±S.E.) of *Atriplex lentiformis* and *Atriplex verrucifera* after replacing treatment NaCl solutions ranging from 100 to 500 mMol/L with distilled water. Seeds were allowed to germinate for 20 days (n=4)

All characteristics of germination recovery were significantly correlated to salinity, except MTG for *A. lentiformis* and final day and MTG for *A. verrucifera*.

3.4 Effects of Salinity on Seedling Growth

Hypocotyl and root length were determined for both species after 20 days. Hypocotyl growth in *A. lentiformis* and *A. verrucifera* showed a clear sensitivity to salt stress (respectively, $F=126.5$, $F=100.3$, $P=0.0001$). In *A. lentiformis* hypocotyl root length was reduced from 27.5±0.9 mm in the control to 0.0±0.0 mm in mMol/L 500 NaCl. In *A. verrucifera*, hypocotyl root length was reduced from 17.42±0.1 mm in the control to 0.37±0.2 mm in mMol/L 500 NaCl. Hypocotyl length was statistically significant and strongly negatively correlated with salinity (respectively, $r=-0.991$, $r=-0.975$, $\alpha=0.0001$). The control group demonstrated the greatest hypocotyl growth for both species. In the control group almost 90 % of *A. lentiformis* seedlings reached the two leaf stage, and almost 85 % of *A. Verrucifera* seedlings reached the two leaf stage. Hypocotyl length at 100 and 200 mMol/L NaCl was almost 35 % for *A. lentiformis*. and 33 % for *A. verrucifera*. All seeds remained in the cotyledon stage at 500 mMol/L NaCl (Table 1).

Sodium chloride significantly inhibited root growth for *A. lentiformis* and *A. verrucifera* (respectively, $F=115.3$, $F=127.7$, $P=0.0001$) at all concentrations. In the control group, the roots were significantly longer than for the other treatments for both species. Root length for *A. lentiformis* at the control was 24.7±1.5 mm, however, at 500 mMol/L NaCl root length was 0.0±0.0 mm. Root length for *A. verrucifera* at the control was 15.55±0.2 mm, however, at 500 mMol/L NaCl root length was 0.0±0.0 mm. There were no significant differences between the 100 and 200 mMol/L NaCl treatments for *A. lentiformis* ($P=0.064$). Root length for *A. lentiformis* and *A. verrucifera* was correlated with salinity (respectively, $r=-0.924$, $r=-0.956$, $\alpha=0.0001$) (Table 1).

As salinity increased from 0 to 300 mMol/L NaCl, differences between hypocotyl length and root length increased for both species, but at higher salt concentrations this difference decreased (Table 1). Therefore, the differences between hypocotyl length and root length in

Table 1 Root length (R), hypocotyl length (H), and differences between hypocotyl and root length (H-R) of two *Atriplex* species in 6 salinity treatment for 20 days

Salinity (mMol/L)	*A. lentiformis*			*A. verrucifera*		
	H	R	H-R	H	R	H-R
0	27.5±0.9	24.7±1.5	2.85±0.4	17.42±0.1	15.55±0.2	1.65±0.1
100	19.5±0.5	11.7±1.5	5.67±0.6	13.34±1.1	9.54±0.8	3.80±0.2
200	13.2±1.7	8.00±0.9	9.40±0.7	11.04±0.4	5.87±0.3	5.30±0.4
300	8.50±0.9	2.70±0.4	5.00±0.8	9.21±1.0	2.00±0.8	8.20±0.5
400	3.30±0.4	1.00±0.2	2. 0±0.5	1.12±0.6	0.13±0.1	1.25±0.3
500	0.00±0.0	0.00±0.0	0.00±0.0	0.37±0.2	0.00±0.0	0.22±0.1

Note: Values are mean±S.E. (n=4)

the non-saline control versus 400 mMol/L NaCl were similar. There was no significant difference between these groups for *A. lentiformis* and *A. verrucifera* (respectively, $P = 0.892$, $P = 0.962$).

4 Discussion

During the Iranian summer heat, seeds of *A. lentiformis* and *A. verrucifera* cannot germinate even after rainfall. After a rainfall in the cooler autumn, seeds of both species will grow quickly. The results of this study indicate a number of things. *A. lentiformis* germinated best at 15 °C, while *A. verrucifera* germinated best at 10 °C. Our results are in accordance to those found in *Haloxylon ammodendron* in which best germination was observed at 10 °C [18]. Germination percentages were lowest at 30 °C for both species. Germination of *A. lentiformis* and *A. verrucifera* decreased with increasing salinity and was substantially inhibited at higher NaCl concentrations. Similar results were reported for *Haloxylon ammodendron* [18], *Limonium stocksii* [16], and *Arthrocnemum macrostachyum* [9].

Atriplex species vary in their ability to tolerate salinity at the germination stage of development, from 300 mMol/L NaCl for *A. stocksii*, [28] to 600 mMol/L NaCl for *A. triangularis* [23]. We found the effect of an increase in salinity on the germination of *A. lentiformis* and *A. verrucifera* was different. Percent germination under 0, 100, and 200 mMol/L NaCl for *A. lentiformis* was higher than for *A. verrucifera* for the collected populations. However, the native species *A. verrucifera* was more salt tolerant overall than the introduced *A. lentiformis*. Germination significantly decreased to 17 % for *A. lentiformis* at 300 mMol/L NaCl while *A. verrucifera* demonstrated 41 % germination.

Exposure to high saline concentrations not only inhibited seeds from germinating, but also decreased the germination rate of seeds that did germinate. Both species suffered a delay in the start and the end of germination that was correlated with salinity. Similar results were obtained when studying germination rates in different halophyte species [9, 14, 16, 28].

Early seedling growth was also significantly reduced with increased salinity. Seedling growth was highest in the control group, indicating that salinity is not necessary for optimum growth of *A. lentiformis* and *A. verrucifera*. Increased salinity decreased root growth more than hypocotyl growth; therefore, at high salinity levels there was a greater ratio of hypocotyl/root growth than at lower salinities. Similar results were obtained by other workers for *A. triangularis* [23] and for *A. griffithii* [28].

Tolerance of seeds to salinity should be considered at two levels [29]: (1) the ability to germinate under high salinity, and (2) the ability to recover and germinate following the removal of saline conditions. With regard to the second consideration, our investigation demonstrated that *A. lentiformis* and *A. verrucifera* seeds that were exposed to higher salinity (400 and 500 mMol/L NaCl) had a greater germination percentage in the recovery experiments (about 42–58 %). Conversely, seed viability and germination capacity were not affected by pre-treatments of up to 500 mMol/L NaCl, and the saline treatments did not induce a specific ion toxicity in either species. This is a common feature of the seeds of halophytes which usually survive long periods of exposure to high saline conditions in the soil. Prior rainfall, causing a reduction in the salinity of the soil surface layers, is necessary for successful germination. For both species, seeds exposed to higher salinity showed faster germination rates and a lower mean time germination in the recovery experiments. Similar results were found in *Haloxylon recurvum* [14] where seeds exposed to high salinity (400 and 500 mMol/L NaCl) had approximately 40–50 % recovery germination. A quick recovery has been reported for other halophytes that were previously exposed to high salinity [8, 9, 16, 17] reported similar results. This increase in germination rate in the recovery experiments contradicts research by other authors that indicates that exposure to high salinity decreases the germination rate [13, 30, 31].

The osmotic potentials of the soils supporting the natural communities promote enforced dormancy in the seeds of both species, but when osmotic stress is alleviated, germination recovers and growth is stimulated. The native species *A. verrucifera* demonstrated higher resistance to salinity compared to the non-native species *A. lentiformis*.

Understanding the germination ability of different halophytes at different latitudes can contribute to a general hypothesis of halophyte seed responses. To study natural halophyte communities further, researchers must also explain the gap between a seed's inherent ability to recover after pre-treatment at reduced osmotic potential and the low number of seeds that germinate in natural field conditions.

Acknowledgements The authors gratefully acknowledge the Seed Technology Laboratory of Darab, Faculty of Agriculture and Natural Resources, Shiraz University, for allowing us to use their facility. We also thank Mr. Taheri for assisting us with laboratory work, and Dr. J. Forrest Meekins for assisting us with manuscript preparation.

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Salt Marshes and Biodiversity

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Abstract

Estuaries and coastal lagoons around the world are wetlands of great importance and they are regularly targeted as prime conservation sites. Many include wildlife refuges and have nature reserves that were set up in areas preserved from development in order to keep valuable species and habitats, while maintaining traditions and sustained use.

Tidal wetlands are often mentioned in the literature as natural habitats with high biological productivity. The net primary production in a salt marsh is often higher than in temperate or tropical forests and this productivity is directly linked to the important role halophytes play in estuaries, in terms of the value-added.

Salt marshes may be a sink of heavy metals. The ability to phytostabilize contaminants in the rhizo-sediment is an important aspect in the self-remediative processes and biogeochemistry of this ecosystem, and will help filtering natural and anthropogenic loads of nutrients and pollutants discharged into the wetland.

There is also a provision of rare and unique habitats, which support nursery grounds for commercial fish and wildlife, including vital feeding grounds for many migratory birds. Rediscovered as a new source of amenity and leisure activities for the population living in urban areas, salt marsh halophytes and estuaries have an important role in the preservation of biodiversity.

In this paper we discuss the support of the salt marsh ecosystem to the estuarine birds, and consequently its contribution for biodiversity.

The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_20,

1 Wetlands and Civilization

The wealth of life in estuarine systems has been known to our early ancestors and wetlands of this type were source of food and amenities to groups of hunter-gatherers, many thousand years before the foundation of cities and permanent human settlements.

Wetlands were also instrumental to the rise of Civilization. High biological productivity means better feeding opportunities and easier food-gathering. This allowed free time after completing the basic tasks of picking up food enough for survival, therefore leaving room for abstract thinking and other elaborate uses of the human mind.

This connection has deep roots and includes amazing examples. For instance, let us consider the Epic of Gilgamesh, the oldest-known example of written literature in the world, telling the saga of a king in the early Sumerian city of Uruk (ca. 2500 BC). Successive versions of this 4,000-year-old poem with a surprisingly actual plot have been recovered from archaeological sites in the territory of modern Iraq, where the standard version was discovered by Austen H. Layard in 1849. It was kept in the library of Ashurbanipal in Nineveh and did survive from the seventh century BC written in clay tablets manufactured from sediments presumably extracted from wetland soil. The story was written in cuneiform characters, tiny wedge-shaped symbols pressed on the wet clay by expert hands holding a blunt-shaped piece of reed used as a stylus [1].

The people from nearby Egypt also knew well about the biological wealth associated to wetlands. Gifted artists left us lively scenes of wildfowl hunts in the papyrus beds of the Nile Delta. Papyrus itself was harvested extensively for manufacture of their prime writing material, a time-honored ancestor of the paper this book is printed on.

2 Wetland Fees and Services

Wetlands have great ecological value, and they deliver a wide range of ecosystem services that have been evaluated as some of the most valuable services for humanity [2–4]. Services associated to estuarine and salt marsh ecosystems in a global scale include: nutrient cycling, primary production, habitat for wildlife, and shoreline stabilizers. The most important benefits are obtained in the fields of sea defense, immobilization of pollutants, and the provision of rare and unique habitats, which support nursery grounds for fish and breeding/feeding grounds for birds.

Salt marshes are listed as sensitive habitats that must be protected under the European Habitats Directive [5]. Their important role has been confirmed by the recent inclusion of these ecosystems in the Water Framework Directive (WFD). Multiple services of wetlands and their value are well known. Vascular plants in salt marshes are crucial to the dynamics of the estuarine ecosystem, strongly influencing the processes of retention of pollutants, reduction of eutrophication, and mitigation of carbon dioxide release to the atmosphere. We know that the major carbon sink of the planet are the oceans (38,630 Pg C), followed by the terrestrial zones. Considering the terrestrial sink only (1,400 Pg C), the more productive habitats and most important zones retaining carbon are in wetlands, which contribute 1/2–1/3 (455–700 Pg C) to this component of the world carbon sink [6].

Areas of salt marsh in estuaries are very important N sinks associated to the production of plant biomass (i.e. the incorporation of N in standing biomass, detritus, litter, and sediments) [7–10] and also through denitrification [11]. Therefore, these processes may contribute to counteract eutrophication in coastal areas [12]. In fact, most of the land-derived nitrogen that loads to coastal environments, in non-human-impacted environments, could eventually be denitrified in estuarine and shelf regions [13, 14].

Wetlands of the estuarine type are often mentioned in the literature as prime examples of natural habitats with very high values of net primary production, directly linked to the important role they play in estuaries, in terms of the value-addition. The net primary production of a tidal salt marsh can be higher than net primary productions of the temperate or tropical forests. Typical values for Net Primary Production in a tropical forest may reach 2.50 kg m^{-2} $year^{-1}$ and in a temperate forest it will stay at 1.55 kg m^{-2} $year^{-1}$. Wetlands of the tidal salt marsh type in the Tagus estuary have Net Primary Production between 1.18 and 3.50 kg m^{-2} $year^{-1}$ [15], in line with production figures around 3.00 kg m^{-2} $year^{-1}$ for coastal wetlands in NW France [16]. Higher values are not uncommon elsewhere, up to an impressive 8.00 kg m^{-2} $year^{-1}$ in the southern Coastal Plain of North America [6]. These figures stand well above typical production values for most other habitats, including fertilized crops in cultivated areas [6, 16].

There is no miracle to this. The modern ecologist knows that wetlands are so productive when compared to most ecosystems because they are blessed with a rare combination of key environmental factors that are essential for plant growth. Carbon dioxide is readily available from the atmosphere, and in tidal wetlands water is seldom a limiting factor. There is often a regular supply and adequate recycling of nitrogen, phosphate and other nutrients. Sunlight needed to photosynthesis reaches near to the ground uncluttered by overhead vegetation canopies and it penetrates also the water column, travelling down to the limits allowed by turbidity and other factors. Due to their high productivity, these ecosystems have great importance concerning the recycling of organic matter by the microbial decomposers, in order to maintain ecological balance [17].

There is however one major drawback. Water masses involved in estuarine circulation typically hold dissolved salts in concentrations that far exceed the tolerance levels of most vascular plants. The salinity of water in estuaries is a complex issue and depends on the interaction of many factors, including the amount of marine water entering and leaving the estuary associated to the tidal cycle, the input of freshwater transported in the river flow upstream, and the local balance of precipitation versus evaporation.

3 Life in Wetlands

Living in wetlands requires special adaptations and environmental constraints faced by the estuarine organisms are often most demanding. Many estuarine organisms are in fact euryhaline and those living in the tidal areas must also be able to withstand abrupt changes to their physical environment. This includes cyclic submergence by tidal water alternating with periods of exposition to the atmospheric agents at low tide.

Fish and invertebrates in the water column may simply move in with the incoming tide and later leave with the receding ebb. However, the vascular plants and any organisms with limited capacity for locomotion must take in situ the changing conditions to their environment. An array of well-known adaptations is described in virtually any textbook dealing with wetland ecology [6, 18] and may include burying deep into the substrate, perhaps combined with an increase in the relative size of underground structures, when compared to those parts left aboveground.

Most vascular plants are unable to tolerate the high salt concentrations usually present in the tidal areas within estuaries and so they are excluded from the local vegetation. But for the few species with comparatively high salt tolerance (halophytes) there is an increased opportunity to establish viable populations and to expand their area around and colonize a bigger share of this habitat.

When compared to nearby areas free from the direct influence of saline tidal water, saltmarsh vegetation typical from estuaries of the temperate zone has only a limited number of species, therefore making for reduced biodiversity within these habitats. However, these halophytes compete to cover a larger share of the substrate available to them and in this process they originate a complex mosaic of salt prairies and open shrubby vegetation. Patterns in species distribution and density may be discernible and are formed according to the combined action of factors like water permanence and subtle gradients in topography [6].

When saltmarsh habitats are considered on a broader scale there is however a very substantial biodiversity increase to be gained from their presence in estuaries. Halophytes with their unique adaptations are able to colonize vast areas that otherwise would be devoid of significant vegetation. Therefore they bring increased habitat complexity and greater species diversity to the regions where they occur.

There is another and perhaps more important effect. The exceptionally high biological productivity rates which are so typical of most saltmarsh areas often result in a generous supply of detritus, food particles and nutrients that may be exported to nearby estuarine habitats and eventually into coastal waters [11].

Extensive mud flats and other sediment deposits in the tidal fringe of estuaries are by no means the barren wastes they usually look like. In fact, the influx of detritus and organic particles originating at nearby saltmarsh habitats allow these vast open spaces to support exceptionally rich invertebrate communities. There are many annelid worms, small crustaceans and shellfish (Mollusca) that spend most of their lives crawling underwater or buried into the sediments when they are exposed at low tide, and may therefore escape easy detection by the inexperienced [18].

Due to the extreme environmental constraints in estuarine habitats these invertebrate communities usually comprise a comparatively small number of species (hence they have reduced intrinsic biodiversity), but may have in turn huge populations with vast numbers of individuals, making up for a large biomass of food items that are preyed upon by many waders and other wetland birds [18].

Saltmarsh vegetation in estuaries also provides living habitat for animal communities. In the temperate regions there is a profusion of aquatic invertebrates (crustaceans and gastropod molluscs) among the strands of halophytes, and these communities may also include small spiders (Arachnida), insects and other terrestrial arthropods.

This bounty of food items attracts the larger consumers that may just move in to feed as appropriate, coming from different habitats in the adjoining areas. There are also migratory birds that occur seasonally and visit at specific times in the year, according to their own routines and long-range movements.

Shall we try to integrate these elements and see how they fit together in a case study highlighting the connections of saltmarsh halophytes, migratory birds and wetland conservation in areas close to important population centers.

4 The Tagus Estuary: Saltmarsh Halophytes and Birds

4.1 Study Area

The Tagus estuary is a large body of transitional water with a NE-SW direction on the western shore of the Iberian Peninsula, SW Europe (Fig. 1). The estuary spans 16 km across at maximum width and covers a total area of 320 km^2 (from aerial surveys) which include ca. 97 km^2 of tidal flats. The overall volume is 1,900 × 10^6 m^3 and water residence time averages 25 days. The tides are semi-diurnal and there is a tidal range of 2.6 m from the lowest neap tide to the highest spring tide [19].

Water depth may reach 46 m in small areas on the entrance channel but mean water depth in the Tagus estuary is only 10.6 m [19]. Sediment beds in shallow water are therefore common and up to 30 % of the estuarine area may become exposed at low tide. Mudflats predominate in the tidal areas but there are also large sand flats and vast deposits of dead oyster shells.

Most of these sediments hold no vascular plants but extensive tracts of saltmarsh vegetation are present in fringes along the margin and in small islets nearby. Saltmarsh vegetation covers a total of *ca.* 17.24 km^2 and colonizes *ca.* 18 % of the tidal areas on the Tagus (based on remote sensing) [20].

The northern (right) bank of the estuary is straight and narrow, contrasting sharply to the left bank (on the eastern and southern sides) in open lowland, with smaller bays and inlets allowing ample room for the development of saltmarsh vegetation.

Communication to the Ocean is made through a narrow channel oriented ENE-WSW (about 10 km long and 2 km across) opening to a sheltered bay and affording protection against

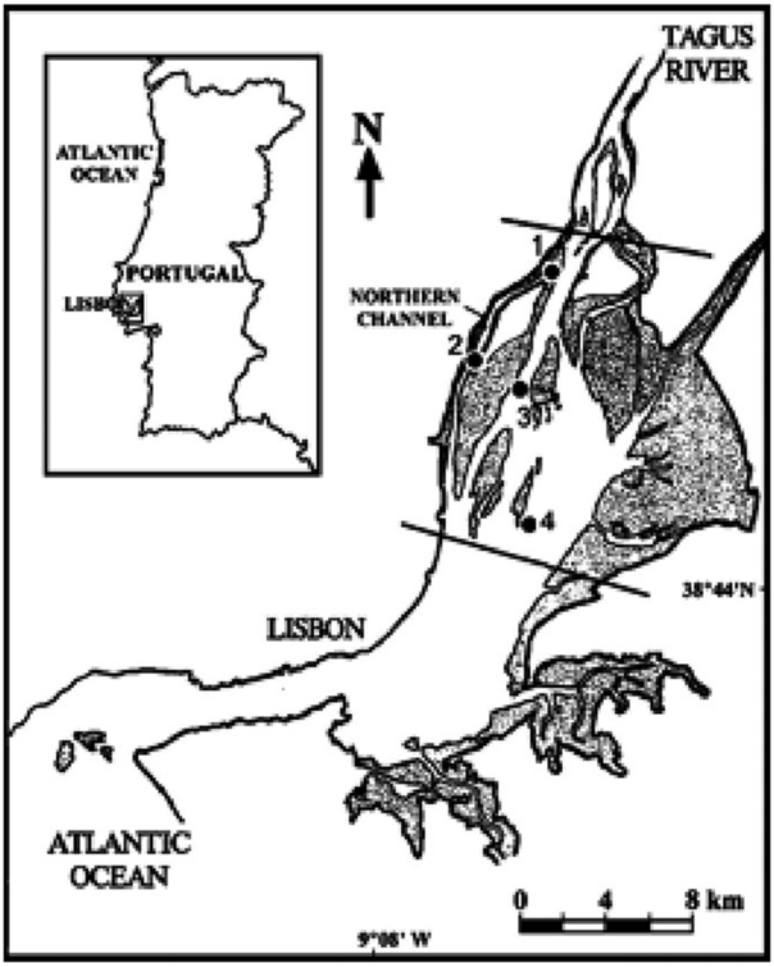

Fig. 1 Map of Portugal with the Tagus estuary area enlarged (Reprinted from Ref. [19])

high-energy oceanic waves. This makes for an exceptionally good natural harbour inside the estuary and was instrumental to the very existence of Olisipo (the classic Roman name for Lisbon city, allegedly established centuries before by the legendary Greek sailor Odysseus). It helped also the initial settlement associated to fishing activities and marine trade that reached historic predominance in the region, and later expanded to the point of making major contributions to the World's maritime history.

Unfortunately, some important areas colonized by halophytes in the estuary have been lost to industrial development and land reclamation projects starting around 1960. Often this was caused by inadequate evaluation of the economic and social relevance of these habitats. There was also competition for space coming from the salt industries in the past and many saltmarsh areas in the Tagus have been managed to make saltpans were tidal water was evaporated in order to concentrate the salts. These were subsequently used for commercial purposes, including keeping dried codfish brought into the estuary by the overseas fishing fleet, until the fisheries were lost in recent years and widespread refrigeration became a viable alternative. Many traditional saltpan complexes retain great ecological value within the estuary but were abandoned by economic reasons and now they are much sought after for quick conversion to industrial fish farms.

Table 1 Mean Biomass values in kg m^{-2} ($n = 5$) ± standard deviation for the period considered. The corresponding NPP and biomass losses, $p < 0.01$ (From Ref. [17])

	Oct	Dec	Feb	Apr	Jun	NPP	Losses (%)	Turnover (year^{-1})
S. fruticosa								
Leaves	2.83±0.97	0.63±0.15	0.05±0.02	0.07±0.02	0.08±0.02	2.79±0.96	98.23±1.11	0.98±0.01
Stems	1.62±0.70	0.70±0.21	0.21±0.07	0.12±0.05	0.11±0.03	1.61±0.50	92.90±4.76	0.93±0.05
Roots	4.37±0.50	4.57±0.18	7.18±0.37	5.35±0.47	4.25±0.16	3.01±0.50	40.65±3.36	0.42±0.05
S. perennis								
Leaves	0.17±0.04	0.06±0.02	0.04±0.00	0.04±0.00	0.06±0.01	0.13±0.04	77.38±6.66	0.77±0.07
Stems	0.42±0.04	0.15±0.06	0.08±0.00	0.04±0.02	0.08±0.02	0.38±0.04	89.80±4.02	0.90±0.04
Roots	3.90±0.33	4.17±0.43	4.55±0.21	4.86±0.09	4.09±0.15	1.01±0.25	16.35±2.33	0.21±0.05
H. portulacoides								
Leaves	0.21±0.06	0.07±0.02	0.06±0.01	0.05±0.00	0.06±0.02	0.17±0.05	78.22±3.97	0.78±0.04
Stems	0.73±0.12	0.32±0.05	0.19±0.05	0.18±0.05	0.19±0.03	0.57±0.15	77.58±8.07	0.78±0.08
Roots	4.13±0.11	3.58±0.28	4.48±0.27	4.42±0.07	4.39±0.23	1.02±0.29	16.84±8.64	0.23±0.06
S. maritima								
Leaves	0.15±0.06	0.06±0.02	0.00±0.00	0.10±0.02	0.08±0.02	0.15±0.06	97.33±1.09	0.97±0.01
Stems	0.28±0.07	0.15±0.03	0.34±0.07	0.27±0.05	0.18±0.08	0.22±0.04	55.01±19.17	0.65±0.07
Roots	2.56±0.60	1.51±0.06	3.68±0.49	3.39±0.62	3.21±0.37	2.83±0.35	38.10±16.06	0.99±0.20

4.2 Salt Marsh Halophytes

There are many densely populated areas and industries around the Tagus estuary. Lisbon city has the largest metropolitan area, in the north side, but there are also major industrial and urban zones around Barreiro, Seixal and Montijo cities in the south side. This geographical setting makes this estuary vulnerable to discharges from industries and effluents of activity sources. Particularly in the south side there are large areas of salt marsh with a dense vegetation of halophytes. The local distribution of these species shows a zonation, evident in transects from the upper marsh areas to the lower marsh and mudflats [8].

Halimione portulacoides (L.) Aellen (Amaranthaceae) is one of the more abundant species in the upper marsh and coexists with *Sarcocornia* species, while the lower marsh is dominated mostly by *Spartina maritima* Loisel (Poaceae). Length of the submersion period and the physical-chemical characteristics of these two distinct areas, along with inter-specific competition among halophytes, are the major factors that contribute to this zonation. Different plant coverage in the upper and lower marsh also represents an important factor that will influence sediment characteristics like contaminant retention and sediment redox state [21]. A strong seasonal variation of plant biomass in these ecosystems (Table 1) together with a variation in metal concentrations in plant tissues (Fig. 2), indicates a possible similar variation in the metal biogeochemistry [17].

These areas of salt marsh are subjected to long periods of submersion and their sediment is often waterlogged and with low levels of oxygen, being adverse to plant growth [22]. However salt marsh plants are well known for pumping oxygen from the atmosphere to the sediment, turning the redox conditions of the root zone oxidative [23].

All these sediment – plant interactions are very important when considering contaminant retention. Tidal flooding of the salt marsh supplies considerable amounts of heavy metals from nearby urban and industrialized areas, which tend to accumulate in the sediments and in plant tissues. These metals retained in the sediment are present in various forms [24] depending on the bonds they establish with the different sediment components (Fig. 3). This is a dynamic process and very much influenced by the sediment and external factors (hydrodynamics, weather and seasonal variation), but also by the vegetation that

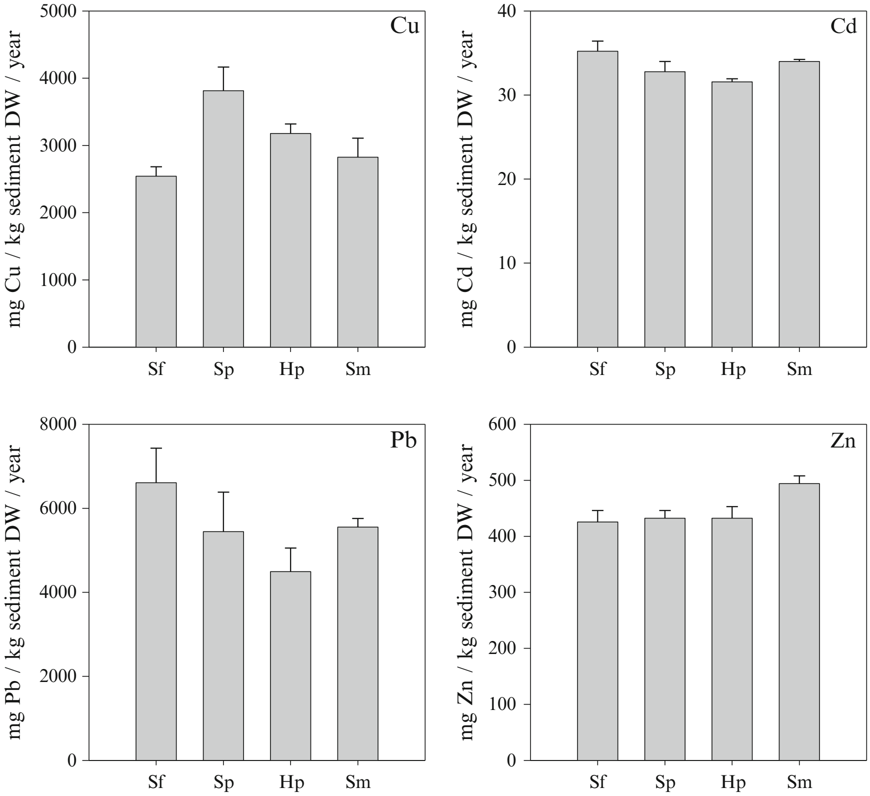

Fig. 2 Average metal concentrations in the sediments from the Tagus estuary, studied for 1 year in salt marsh areas colonized by four halophyte species (Sf – *S. fruticosa*, Sp – *S. perennis*, Hp – *H. portulacoides*, Sm – *S. maritima*) (From Ref. [17])

colonizes the area [26]. There is also evidence that microbial activity may influence metal speciation, through interaction with metal ligands [27–29]. These modifications include reactions of metal precipitation by metallic sulfides and redox reactions with changes on the metal specie and associations [30].

From the ecosystem point of view, metal cycling provides a better understanding on the role of plant detritus in the trophic transport of metals, and also on the processes involved in the contamination of a salt marsh and adjoining estuarine areas (Fig. 4). This helps establishing the paths of cycling metals within the salt marsh, and is no longer restricted only to the fluxes between plants and sediment, but considers also the whole trophic web. These results further support observations from previous studies that point out salt marshes as a sink of heavy metals, and give better insight on the major cycles of metals studied in the two more important metal retaining matrixes [31].

In the Tagus as elsewhere, the exceptionally high biological productivity so characteristic of the estuarine halophytes is often harvested in adjacent habitats. This includes the traditional captures of migratory fish and cephalopods of high commercial value, but there is also a crucial link between the primary production of halophytes on the Tagus saltmarsh and the vast numbers of migratory birds using regularly this estuary [32].

4.3 Birds

Birds are unique among all terrestrial vertebrates because most of them have exceptional capacity for travelling quickly over long distances and for their ability to reach remote spots that remain

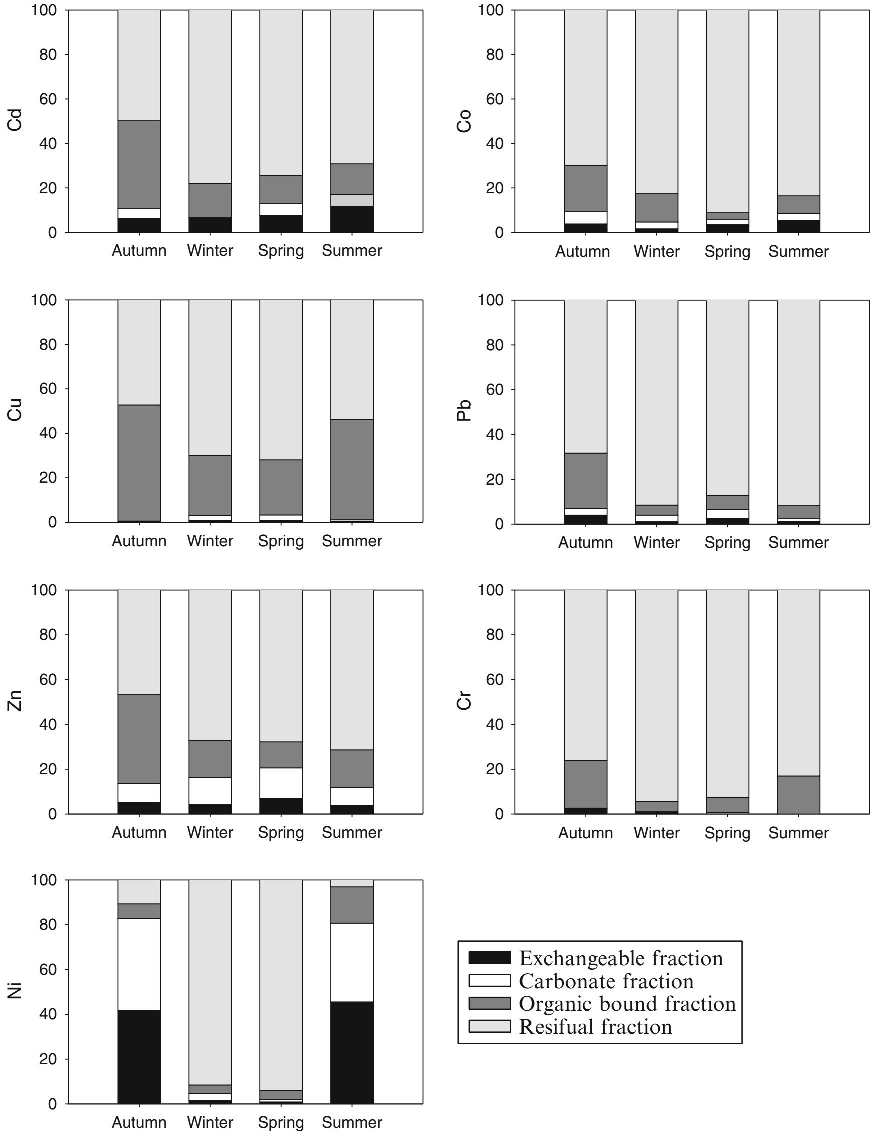

Fig. 3 Metal speciation in the rhizosediments of *H. portulacoides* surveyed for 1 year in the salt marsh areas of the Tagus estuary (From Ref. [25])

virtually inaccessible to non-flying animals. Migratory birds put these capacities to best use and many species turn up regularly in estuaries and other wetlands, where they feed upon the wealth of prey available from tidal areas and sheltered waters.

Estuarine birds are usually grouped into categories that remain widely used despite having no taxonomic value. The Waders (or Shorebirds) include many small to medium size Charadriidae and Scolopacidae that have in common characteristic body shape and similar feather patterns, but are most notorious for their habit of walking on mudflats and other tidal habitats with their feet pressing directly onto the wet ground. Waders are included in the Waterfowl, a broader informal group of species also living in aquatic habitats that includes the herons and egrets (Ardeidae), the Ibises and Spoonbills (Threskiornithidae), together with smaller families. As a group however, the

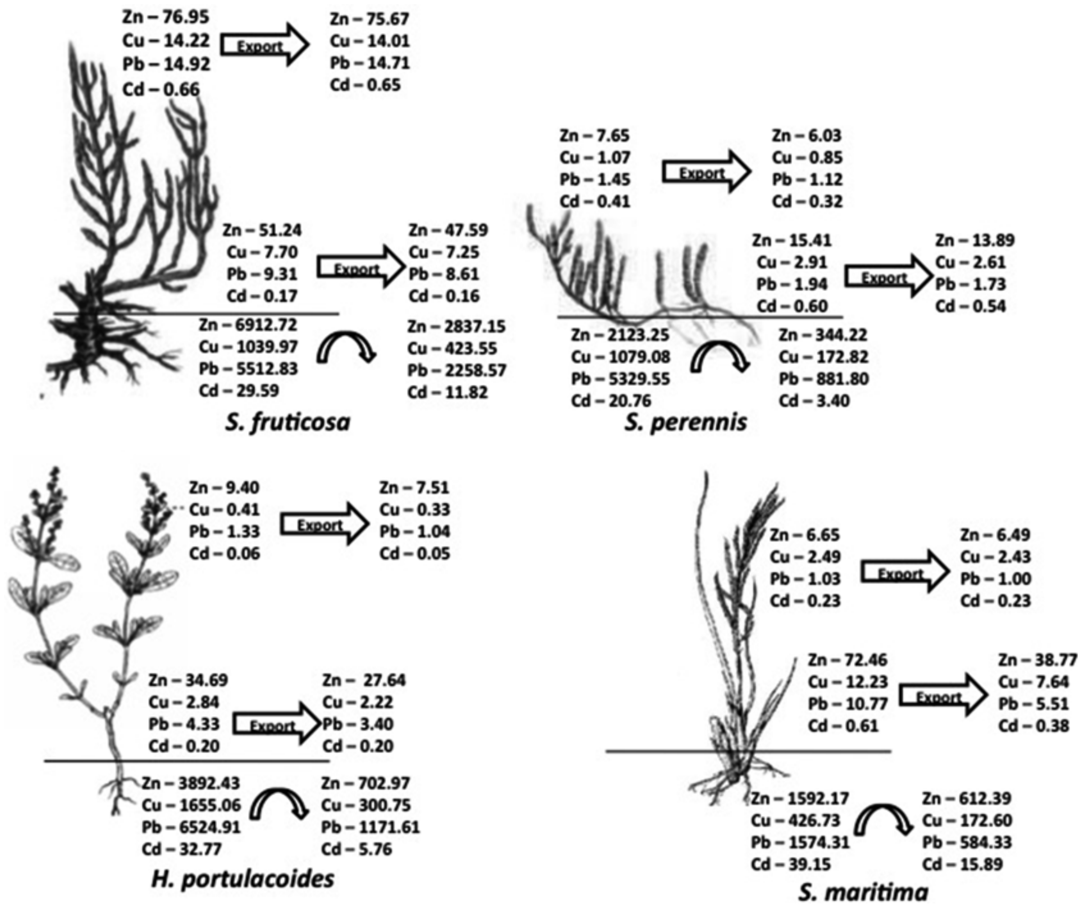

Fig. 4 Metal Primary Accumulation (MPA, mg) and losses due to litter generation for the species and plant organs studied in salt marsh areas on the Tagus (Sf – *S. fruticosa*, Sp – *S. perennis*, Hp – *H. portulacoides*, Sm – *S. maritima*) (From Ref. [17])

term waterfowl is often associated to the vast array of duck, geese and swans (Anatidae).

Most waterfowl species are highly migratory and they travel long distances every year. Waders are especially noteworthy and include some of the most extreme examples of long-range migrations in the animal kingdom. In the northern hemisphere they usually fly north in spring to reach the breeding areas (mostly in the northern tundra or in wet meadow habitats) and raise their offspring. They come back again a few months later, flying south to reach wintering areas located mostly in estuaries and coastal lagoons [32].

The Tagus is the largest estuary in Iberia and one of the most important wetlands in Europe. It stands out as a key site for migratory waterfowl on the Eastern Atlantic Flyway, and plays a strategic role as a staging area straight in the path of extremely busy migration routes in the Western Palearctic [32]. With its vast tidal areas supporting rich invertebrate communities, there is no surprise to find the Tagus regularly listed among the top wetlands for migratory waterfowl in the region.

Waterfowl populations are monitored on the Tagus estuary since the late 1960s [33–35], and there is an historic background with almost four decades of regular standard midwinter counts available for the most important species there [32, 36].

The Tagus estuary regularly holds large wintering populations of migratory waterfowl (ca. 45,000–116,000 birds were counted there in January, 1992–1996) and for many species it stands out clearly as the most important wetland in Portugal. Results of the January counts available for wader populations in the Tagus demonstrate that some species occur regularly in numbers that stand clearly above the threshold of international importance, based on the technical criteria that were set up by the International Waterfowl and Wetlands Research Bureau. According to an early version of these criteria [37], the status of international importance is reached when a wetland regularly supports a population of at least 20,000 waterfowl, or where data on population are available it regularly supports 1 % of the individuals in a population of one species or subspecies of waterfowl.

The 1 % criterion was initially developed as a tool for selecting wetlands that are key sites for the populations of migratory waders and has been further refined to become "Criterion 6" under the umbrella of the Ramsar Convention. This updated version states that "A wetland should be considered internationally important if it regularly supports 1 % of the individuals in a population of one species or subspecies of water bird". It must be stressed that this 1 % threshold is applicable throughout the range of that population and at any time of the year [32].

The Tagus estuary is a very important stopover site for many long distance migratory species in the Palaearctic-African bird migration system [32, 38] and the post-breeding passage of some wader populations may be quite impressive there on occasions.

Most of the migratory waders on the Tagus estuary feed primarily in vast tidal flats and prey upon the rich supply of small invertebrates that live buried in (or crawling on) the sediments of the tidal fringe. Small *Hydrobia* snails (Gastropoda, Mollusca), *Nereis* worms (Polychaeta, Annelida) and small *Carcinus* crabs (Decapoda, Crustacea) have been identified as important food items, but other prey occur in the area and may also be taken.

Most wader species will take prey from sediments slightly covered by tidal water but they are able to use these areas only at certain periods in the tidal cycle, when prey is accessible and water depth is not excessive. The vast majority of wading birds must in fact walk, and they will keep their feet on the ground. Therefore they have to retreat before the advancing tide, and must fly to dry spots in higher ground. When the high tide sets in, and as long as their feeding areas stay submerged, waders must wait for the tide to turn and will concentrate (often in large flocks) at high tide roosts inside the estuary.

High-water roosts are essential features in the life-cycle of waders but other estuarine birds may also need them eventually. These roosts often occur in extensive areas of halophyte vegetation, including large man-made saltpans that remain comparatively free from human disturbance. Small islets of halophytes may be very important in the tidal cycle and they are often used as temporary roots around high water, while they are not covered yet by the incoming tide and can still provide safe haven to the waders perching on them above water (Figs. 5, 6, and 7).

In contrast, duck do not have such a dependence on high water roosts because they are able to float buoyantly and may swim around on the water surface while waiting for the tide to turn. Within the estuary they feed primarily on small size food particles sieved from the water column or from the surface of wet sediments in tidal flats, and they will sometimes concentrate in large flocks at the outer edge of halophyte stands. There are wonderful adaptations to this mode of feeding and a noteworthy example is provided by the Shoveler *Anas clypeata* with its broad spoon-shaped bill lined with filtering lamellae.

Duck populations on the Tagus estuary are mostly migratory (except for the Mallard *Anas platyrhynchos*) but they tend to travel shorter distances than the waders. Some of them move to the estuary later in the season, when feeding habitats further north in Eurasia are temporarily lost due to winter freezing [39].

Flamingos *Phoenicopterus roseus* are now a familiar sight in many tidal flats and saltmarsh areas on the Tagus estuary and they occur also in other coastal wetlands in Portugal. They made a spectacular comeback to the area, increasing from only a very few birds in the remotest parts of the estuary around 1974 [40], to a remarkable

Fig. 5 Grey plover *Pluvialis squatarola* flocking at high water on a temporary roost in the Tagus estuary. The waders are perched on halophytes growing in old saltpan complexes, and must wait for the ebbing tide to resume feeding in the tidal flats (*Photograph by A. Teixeira*)

Fig. 6 Waders flocking at high water on this temporary roost in the Tagus estuary must perch on halophytes, but waterfowl like Mallard *Anas platyrhynchos* (foreground) may just swim on the water surface (*Photograph by A. Teixeira*)

1,321 birds in 1981 [41] and their numbers keep high in recent years. This situation reflects increased protection to waterfowl species on the Tagus estuary, and results from successful recovery of the Western Mediterranean and North African populations [42, 43].

Avifauna of the Tagus estuary is not restricted to the aquatic species only. Predators like Osprey

Fig. 7 Waders follow the receding tide and leave their high water refuges to feed again in mudflats around halophytes in the Tagus estuary salt marsh. Most of the birds in this picture are migratory Dunlin *Calidris alpina* (*Photograph by A. Teixeira*)

Pandion haliaetus, Marsh Harrier *Circus aeruginosus* and Peregrine *Falco peregrinus* are common there but they are unable to swim and will not walk on wet ground.

Halophytes in Tagus salt marshes are habitat to some Passerine birds but these tend to be overlooked and even ignored by the non-specialist because they are small and unobtrusive. Some of these species are common and may be found in nearby habitats, simply moving into the areas colonized by halophytes to collect small invertebrates and maturing seeds. These food items are often picked up from hedges of *Atriplex halimus* in the upper marsh, and from tall bushes of *Sarcocornia fruticosa* and *Inula crithmoides*. Common passerine species on the Tagus include Fan-tailed Warbler *Cisticola juncidis*, Mediterranean Warbler *Sylvia melanocephala*, and House Sparrow *Passer domesticus*. Such birds occur regularly in habitats around the estuary and most of them are resident, making a sharp contrast to the long-distance migratory waders feeding in the tidal flats.

There is a notable exception however. The Bluethroat *Luscinia svecica* is a migratory passerine found in the autumn and winter months in the Tagus salt marshes, where they hide mostly in dense thickets of *S. fruticosa* from the upper tidal areas and in hedges made up from bushes of *A. halimus*. They feed on a mixed diet of small aquatic invertebrates and terrestrial arthropods. These food items are picked from the halophytes or directly from the sediments, in areas of dense salt marsh vegetation penetrated by an intricate network of tidal creeks [8]. Bluethroats on the Tagus are part of a population with special habitat needs, associated to salt marshes. Described as *Luscinia svecica namnetum* [44] they breed typically in halophytes around salt-pans in Brittany, NW France [45] but later they migrate SW to their wintering grounds, mostly in the Portuguese estuaries [46]. The salt marsh halophytes on the tidal areas of the Tagus estuary are therefore a key habitat for the winter populations of this endangered migratory bird [47].

Estuaries are often biodiversity hotspots because they offer plenty of food opportunities and may attract many visiting species. Even though the local communities of halophytes and estuarine invertebrates may have only a limited number of species (well adapted to survive in this unique environment) they often comprise very large populations made up from vast numbers of individual organisms. They bring increased diversity, and new habitat types that may not be available anywhere else in the region.

In the Tagus estuary there are just a few species of halophytes, and their combination makes for the patchwork vegetation in the salt marsh areas. The top ten species in the list are (in no particular order): *Spartina maritima; Halimione portulacoides; Sarcocornia fruticosa; S. perennis; Atriplex halimus; Suaeda vera; Arthrocnemum glaucum; Inula crithmoides; Aster tripolium,* and *Juncus maritimus.*

These halophytes increase biodiversity on a regional scale and help keeping in the Tagus juvenile fish and other marine organisms that rely on abundant food and increased protection from predators provided by the estuarine habitat [48]. They are a driving force to the attraction of large numbers of migratory birds.

In a recent study carried out on a sheltered bay at Seixal, on the southern part of the estuary, from a total of 94 bird species observed in the area during the annual cycle there were 42 species occurring in typical estuarine habitats (tidal banks/salt marsh/open water). This figure corresponds to an important 45 % of the total number of species in the area, and compares to only 23 species (24 %) observed in the non-estuarine habitats. It is worth noting that another 29 species (31 %) were using both habitat types, on an opportunity basis [49].

Recent studies have contributed valuable information to help demonstrate the importance of the Tagus estuary as biodiversity hotspot [20, 31] and they further support the outstanding role of this wetland as staging post for long-distance migratory birds travelling in the Eastern Atlantic Flyway, including Palearctic waders and waterfowl wintering in the area [32, 40, 50]. Within the estuary, halophyte vegetation and adjacent beds of tidal sediment are often the key areas for these bird populations, and usually they are attractive to many different species that occur in vast numbers [49, 51].

A Nature Reserve has been declared on the Tagus estuary in 1976 to afford adequate protection to an area of 14,192.44 ha. Created first in the national legislation (Decreto-Lei n° 565/76, from July 19th) it was included subsequently in the Ramsar list as a prime contribution to the goals of the Convention on Wetlands of International Importance, especially as Water-fowl Habitat when the Portuguese Government decided to join that Convention in 1980. It was no surprise and made a logical outcome to the many efforts deployed worldwide to protect wetlands and to keep salt-marsh areas working as important bird sanctuaries.

Portugal has joined the European Union in 1986 and some wetland areas in the Tagus estuary were later included in a Special Protection Area (SPA) declared under article 9 of the Wild Birds Directive (79/409/CEE). The SPA included all the areas already protected by the Nature Reserve (established one decade before) but covered also new areas and parts of adjacent habitats.

However, the practical outcome of this increased legal protection was not straightforward. Strict measures were adopted to help protect important species and habitats, but their application became later the subject of intense negotiation, and adjustments were made to allow building important structures and large transport facilities helped by EU regional funds. The environmental questions were eventually settled, and improved territorial planning has emerged from this process.

Attitudes of people living in urban areas around the estuary have changed dramatically in recent years. Compared to only a few decades ago (ca. 1970–1980) there is now widespread public awareness for environmental issues and many citizens praise activities that put lasting value to healthy estuarine ecosystems. These include many different uses, like kayaking, bird watching, and jogging on the water front. Shooting small birds or otherwise molesting protected species has been illegal for many years, but nowadays these practices are virtually banned around the estuary. Birds of prey also become respected by the public and they are no longer seen as mere targets for extermination. Hunting waterfowl lost terrain to other activities. All these results did come from sustained investments at environmental awareness and education that were deployed by the public services and by dedicated organizations for many years.

Sometimes leading, but often riding in the wake of these changes in public attitude, most local authorities and managers around the estuary have come to appreciate the potential for using the estuarine habitats as complementary spaces to their urban amenity gardens. In fact, most halophytes remain "green" all year round and they need no freshwater irrigation or routine gardening for maintenance (these are costly items and represent a growing burden to the stressed budgets of local administrations). The potential for using these sites has been there for many years [52], but now there is a public perception of their value, with a fashionable "wild" look associated to the salt marsh areas and presence of waterfowl species in the tidal flats.

Complementary to the official designation of the Nature Reserve in 1976, there is growing action from the local authorities to have smaller "nature reserves" designated in areas of great natural value within their administrative boundaries. Legal protection for these spaces may now be granted merely on the basis of municipal decisions and some new "local nature reserves" have been approved already in wetlands around the Tagus estuary. This new attitude is far-reaching and must be considered a welcome departure from the traditional goals of local powers, usually fighting for more "economic development measures" irrespective of long-term consequences and environmental cost.

5 Conclusions

Salt marsh halophytes and estuaries have an important role in the preservation of biodiversity: (i) Salt marshes are among the most productive ecosystems in the world and perform important ecological functions, namely in terms of primary production and nutrient recycling. (ii) Salt marshes are important sinks of pollutants, including heavy metals. The ability to phytostabilize contaminants in the rhizo-sediment is an important aspect in this ecosystem self-remediative processes and biogeochemistry, and will help filtering natural and anthropogenic loads of nutrients and pollutants to the wetland. (iii) There is a provision of rare and unique habitats, which support nursery grounds for commercial fish and wildlife, including vital feeding grounds for many migratory birds.

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Distinctive Features and Role of Sulfur-Containing Compounds in Marine Plants, Seaweeds, Seagrasses and Halophytes, from an Evolutionary Point of View

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Abstract

Many seaweeds, seagrasses and many halophytes, grow in the tidal zone in similar environments. Their every-day-life and their life cycle are influenced by regular flooding during high tide and exposure to the air at low tide. Therefore they are confronted with similar daily changes in the osmotic potential and need to take up nutrients from the water and/or from the sediment. In addition, coastal zones and estuaries are often contaminated with high loads of some nutrients and heavy metals. Sulfur-deficiency is a major issue for land-based agriculture, whereas seawater act as a global sulfur reservoir and sulfur does not limit growth of marine plants. Sulfur-containing compounds and proteins seem to play a pivotal in the adaptation to these environmental conditions. This review highlights the putative roles of sulfur-containing compounds in a comparative way in seaweeds, seagrasses and halophytes. Can we observe similar metabolic and proteomic adaptations in regularly flooded coastal plants? The role of sulfur-containing proteins and of sulfur-containing secondary metabolites and their responsible set of enzymes will be analyzed from an evolutionary point of view. New strategies to increase salt-tolerance in higher plants based on sulfur-containing compounds are discussed.

1 Introduction

Although halophytes represent only 2 % of terrestrial plant species, they are present in about half the higher plant families and represent a wide diversity of plant forms [1]. The seagrasses developed three to four times from land plants within the order Alismatales to salt-adapted marine plants. Marine algae, we would like to focus here on seaweeds, belong even to very

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_21, © Springer Science+Business Media Dordrecht 2014

different higher taxa: the Phaeophyceae (brown algae) belong to the subgroup Stramenopiles or Heterokontophyta in the eukaryotic supergroup Chromalveolata, whereas Rhodophyta (red algae), Chlorophyta (green algae) and plants are divisions in the Archaeplastida [2].

Sulfur-deficiency is a major issue for land-based agriculture. Many soils become sulfur-deficient, especially when high nitrogen fertilizer is used. In freshwater and soil interstitial waters the sulfate concentration varies from 0.09 to 1.4 mM. Seawater contains about 28 mM or 8 % sulfate salts [3], equivalent to about 900 ppm sulfur, mainly as $MgSO_4^{2-}$. Thus seawater acts as a global sulfur reservoir whereas the nitrogen content accounts for only 16 ppm (http://ocean-plasma.org/). Sulfur is the element with the 6th highest concentration in marine environments. Therefore sulfur does not limit the growth of marine plants at all. Since 1.5 Bio years the composition of seawater has not changed much except local variations and anthropogenic contamination.

There are several examples that sulfur-containing compounds and proteins play a pivotal role in the adaptation to the marine environment. This review highlights the putative roles of sulfur-containing compounds in a comparative way in seaweeds, seagrasses and halophytes. One could assume that during evolution similar metabolic and proteomic adaptation mechanisms were established in marine plants. The role of sulfur-containing proteins and of sulfur-containing secondary metabolites and their responsible set of enzymes will be analyzed from an evolutionary point of view.

It will be interesting to see whether there are specific compounds in different taxonomic groups. These results could be used for chemotaxonomy in combination with genetic data. Some of the secondary compounds might be interesting from an economic point of view. Based to the availability of the complete genome sequence from the seaweed *Ectocarpus siliculosus* (Dillwyn) Lyngbye [4] comparative analysis became more meaningful, however, so far there are only fragmentary genome sequences of seagrasses and halophytes, except *Thellungiella salsuginea* (Pall.) O.E. Schulz and *Thellungiella parvula* (Schrenk) Al-Shehbaz and O'Kane available on the market. Unlike algae, seagrasses have roots and vascular tissue allowing them to absorb and translocate nutrients from soft sediment. In low nutrient environments this provides seagrass with a competitive advantage over algae as they can access the higher nutrient concentrations available in the sediment compared to the overlying water. On the other hand, in contaminated sediments seagrasses need good strategies to avoid accumulation of toxic compounds in their tissue. Halophytes form extensive root systems including tap roots which allows them to exploit also deeper sediment layers with different elemental composition.

2 Selected Sulfur-Containing Metabolites with Specific Functions in Salt-Tolerant Plants

2.1 Analysis of Sulfated Polysaccharides

2.1.1 Abundance of Sulfated Polysaccharides

Sulfated polysaccharides (SP) comprise a complex group of macromolecules with a wide range of important biological functions. These anionic polymers are widespread in nature, occurring in a large variety of organisms. SP are found in vertebrates and invertebrates [5, 6] and in seaweeds [7]. Recently, they were also identified in halophytic angiosperms and in a salt-tolerant pteridophyte [8] and even in freshwater plants [9]. In this review we would like to focus on the occurrence of SP in seaweeds and angiosperm plant species.

The most well known SP in red algae are carragenans and agarans. Brown algae possess fucan and fucoidan SP. SP found in green algae are usually heteropolysaccharides. However, there is a predominance of one monosaccharide at the expense of others in several algal orders [10]. In a previous study, correlation between SP and salinity in plants was investigated [8]. Different halophytic aquatic plants were used: marine angiosperms (*Ruppia maritima* L., *Halodule wrightii* Ascheson, *Halophila decipiens* Ostenfeld), mangrove angiosperms (*Rhizophora mangle* L., *Avicennia schaueriana* Stapf & Leechm. ex Moldenke), and the salt-tolerant pteridophyte *Acrostichum aureum* L.. The results reveal that in these halophytic aquatic plants exposed to different salinities the concentration of SP was increased. Also the degree to which they were sulfated correlated positively with the concentration of salt in the environment. The effect could not be found in the terrestrial angiosperms *Zea mays* L., *Oryza sativa* L. and *Phaseolus vulgaris* L. (glycophytes). Interestingly, *O. sativa* did not induce the biosynthesis of SP but increased the concentration of carboxylated polysaccharides [8]. Recently, a study revealed the presence of SP also in the three freshwater plants *Nymphaea ampla* L., *Hydrocotyle bonariensis* Comm. ex. Lam. and especially in *Eichhornia crassipes* (Mart) Solm, known as water hyacinth [9].

2.1.2 Description of Sulfated Polysaccharides

The most well known SP in red algae are carragenans and agarans, which are sulfated galactans. SP from brown algae are homo- and heteropolysaccharides containing α-L-sulfated fucose called fucan and fucoidan, respectively. SP found in green algae are usually heteropolysaccharides containing a mixture of xylose, galactose, arabinose, mannose, glucuronic acid or glucose [11, 12]. SP of examined plants are built up differently. Those of seagrass species are composed of galactose units. SP of mangrove species contains arabinose and galactose, and the pteridophyte contains glucose units [8]. Galactose, glucose and arabinose are the main monosaccharides found in the SP from *E. crassipes* [9], comparable with the monosaccharide composition of green algae (Table 1).

Table 1 The composition of sulfated polysaccharides of halophytic plants and algae

Plant	Species	Units of sulfated polysaccharides
Marine angiosperm (seagrasses)	*R. maritima*	Galactose
	H. decipiens	
	H. wrightii	
Mangrove angiosperm	*R. mangle*	Galactose, arabinose
	A. schaueriana	
Freshwater angiosperms	*E. crassipes*	Galactose, glucose, arabinose
Pteridophyte	*A. aureum*	Glucose
Brown algae	*E. siliculosus*	Fucose
Green algae		Galactose, arabinose, glucose
Red algae		Galactose

Modified after Ref. [8] with data from Ref. [9]

2.1.3 Biosynthesis and Evolution of Sulfated Polysaccharides

The brown algal cell walls share some components with plants (cellulose) and animals (sulfated fucans), but they also contain some unique polysaccharides (alginates) (Fig. 1, Table 1). Analysis of the *E. siliculosus* genome failed to detect homologues of many enzymes known from other organisms involved in alginate biosynthesis and in remodeling of alginates, fucans and cellulose, indicating that brown algae have independently evolved enzymes to carry out many of these processes. The biosynthetic route for sulfated fucans is an ancestral pathway, conserved with animals [2]. A number of polysaccharide-modifying enzymes, such as mannuronan C5 epimerase, sulfotransferases and sulfatases, were identified [4]. Probably the biosynthesis of sulfated galactans starts with a precursor of lower molecular weight and degree of sulfation suggesting that glycosyltransferases and sulfotransferases may function simultaneously during the biosynthesis of sulfated galactans, at least in *R. maritima* [8].

Interestingly, green algae, the ancestor of higher plants [13], possess all units of SP as also found in all investigated halophytic aquatic plants (Table 1). This finding suggests that the production of SP is conserved throughout the plant evolution from green algae [8]. It is speculated that the activation and inhibition of glycosyltransferase genes alters the composition of SP among the different phyla [8].

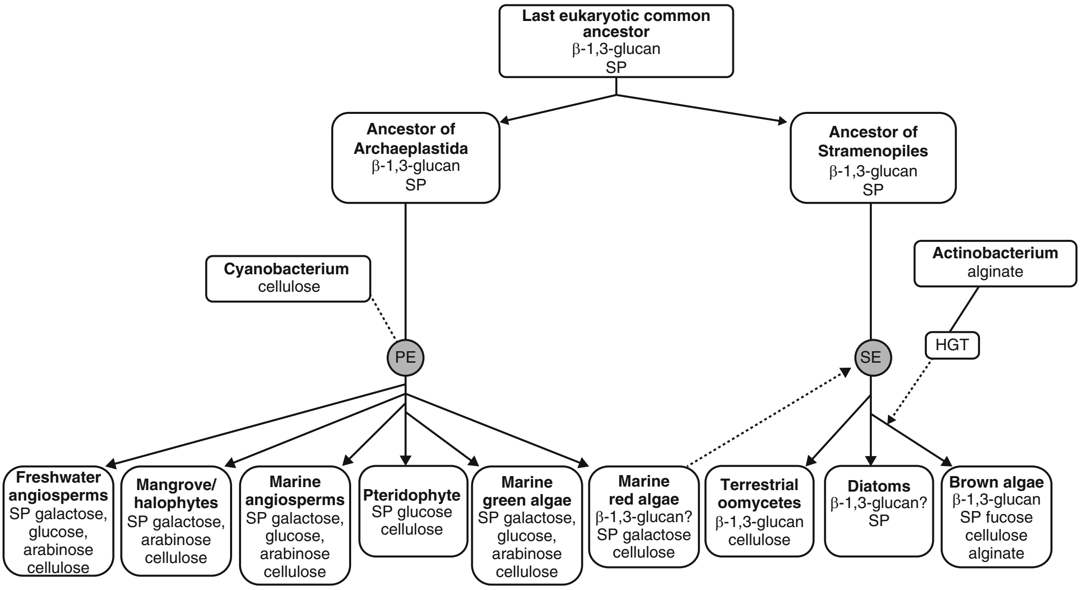

Fig. 1 Scheme illustrating the origin and evolution of the main extracellular matrix polysaccharides in the Archaeplastida and Stramenopiles. Endosymbiotic events are indicated by dotted lines. PE, plastid primary endosymbiosis; SE, plastid secondary endosymbiosis; HGT, horizontal gene transfer; SP, sulfated polysaccharides (Modified after Ref. [8] with data from [9])

The current view about the origin and evolution of the main extracellular matrix polysaccharides in the Archaeplastida and Stramenopiles by [2] is extended including the newest published data (Fig. 1, Table 1). The recent evidence of SP in terrestrial plants can be further differentiated: In seagrasses SP with galactose, glucose and arabinose units, in halophytes and mangroves SP with galactose and arabinose units, and in freshwater angiosperms the same composition as in seagrasses and in green algae were determined.

2.1.4 Function of Sulfated Polysaccharides

In seaweeds, SP are found in the extracellular matrix. SP might protect against dehydration occurring at low tide, they are important both in terms of resistance to mechanical stresses and as protection from predators [4]. The function of SP in the plant cell wall in high salt environments is still unclear. It is speculated that SP increase the Donnan potential [14], supporting ion transport at high salt concentrations [8].

It was shown that in *E. siliculosus* enzymes involved in the desulfatation of SP were induced in low salt medium while two sulfotransferases involved in the synthesis of the cell wall SP were induced in seawater [15]. Therefore modifications of SP by enzymes like sulfatases and sulfotransferases are likely to modify the phytochemical properties of the cell wall, influencing rigidity, ion exchange and resistance to abiotic stress [4].

SP were found in 15 aquatic species of invertebrates [5] and in six halophytic aquatic plants [8] with a positive correlation between SP and water salinity. Obviously, the production of SP is correlated with salinity in the environment. If this is the case it remains an open question, what is the biological function of SP in freshwater plants [9].

Species being able to survive in both saline and freshwater conditions might be well suited study objects to analyze the function of SP. Salt-tolerance and adaptations to low salinities in a freshwater strain compared to the sequenced marine strain of *E. siliculosus* on physiological and molecular levels was examined. It exhibited profound, but reversible, morphological, physiological, and transcriptomic changes when transferred to seawater. This indicates that for the colonization of freshwater, genomic alterations have occurred that produced permanent changes in the metabolite profiles, among them SP to stabilize the transition [15]. Also in the marine angiosperm *R. maritima* SP were not found when the plant was cultivated in freshwater [8].

In summary, the current state of knowledge suggests that the presence of SP in plants is an adaptation to high salt environments, which have been conserved during plant evolution from marine green algae. In future practical approaches to use the potential of SP in engineering salt-tolerant plants should be investigated in more detail.

2.2 Sulfur-Containing Compatible Osmolytes

Compatible osmolytes decrease the water potential of the cell, act as chemical chaperones and play a role in the solubilization of molecular complexes. It was shown that next to brown, red and green algae several angiosperms produce the compatible tertiary sulfonium osmolyte dimethylsulfoniopropionate (DMSP), derived from amino acids, being uncharged at neutral pH and of high solubility in water. DMSP is broken down by marine microbes to form two major volatile sulfur products, each with distinct effects on the environment. Its major breakdown product is methanethiol is assimilated by bacteria into protein sulfur. Its second volatile breakdown product is dimethyl sulfide (DMS). Atmospheric oxidation of DMS, particularly sulfate and methanesulfonic acid, is important in the formation of aerosols in the lower atmosphere. Probably these aerosols act as cloud nucleation sites. Therefore DMS is thought to play a role in the Earth's heat budget by decreasing the amount of solar radiation that reaches the Earth's surface [16].

However, the presence of high concentrations of DMSP in higher plants is limited to a few salt-tolerant species such as *Spartina* spp. (>50 μmol DMSP g^{-1} fresh weight in the leaves) [17]. In seagrasses different DMSP concentrations have been found: *H. wrightii* 3.3 μmol g^{-1} fresh weight, *Syringodium filiforme* Kutz. 0.10 μmol g^{-1} fresh weight, *Thalassia testudinum* Banks ex. Konig between 0.18 and 4.0 μmol g^{-1} fresh weight in epiphytized and non-epiphytized leaves and very low amounts in the rhizome [18]. These results indicate that the degree of epiphytization plays a major role in the contribution of seagrasses to the total DMSP production. In comparison, seaweeds contain between 0 and 85 μmol g^{-1} fresh weight dependent on the region and conditions they have been collected [19]. The regulation of the biosynthetic pathway of DMSP in seagrasses and halophytes needs to be elucidated to clarify the overall contribution by salt-tolerant angiosperms to the DMSP production. Another sulfur-containing osmolyte is choline-*O*-sulfate. So far this compound has only been found in the family Plumbaginaceae, such as the genus *Limonium* [20]. It would be interesting to follow the distribution and roles of this sulfur-containing compound in more halophytic plant species.

3 Is Metal-Binding the Only Function of Phytochelatins and Metallothioneins?

3.1 Metals in Marine Tidal Environments

Phytochelatins (PCs) and metallothioneins (MTs) are Cys-rich metal chelators that represent the two principle groups of metal-binding molecules found across most taxonomic groups [21]. What is their particular role in plants grown in saline environments?

Both essential and non-essential transition metal ions can easily be toxic to cells. The physiological range for essential metals between deficiency and toxicity is therefore extremely narrow and a tightly controlled metal homeostasis network to adjust to fluctuations in micronutrient availability is a necessity for all organisms. Heavy metals are predominantly released into environment through anthropogenic activities and farming, then accumulated in sediment with different levels [22]. These heavy metals in higher concentration which have contaminated large areas of land due to use of sludge, pesticides, fertilizers, residues from metalliferous mines and smelting industries are for plants the most toxic substances [23]. Coastal areas were considered as places which receive huge pollutants and heavy metals contribute massively [24]. Halophytes contribute a huge role in terms of heavy metal accumulation in their tissue [25]. Several results indicate that heavy metal concentration in the plant tissue is much higher than in their environmental ambient. Heavy metal concentration differs also from organ to organ as well as from species to species. The ability to respond to potentially toxic levels of heavy metal ions appears to be ubiquitous in biological systems. Heavy metals are taken up and accumulated by seagrasses [26], mangroves [27], marine algae [28] and other salt-tolerant plants [29].

There are at least three options to cope with heavy metals in salt-tolerant plants, dependent on the species compartmentation, metal excretion through salt glands or chelation in the extracellular space [30]. In all processes PCs and MTs might play a role. In seagrasses, oxygen is transported to rhizomes and roots of seagrasses during periods of light when photosynthesis releases oxygen into aerenchyma. Around the roots an oxidized zone is formed and oxygen diffuses into the anoxic sediment. By night almost all oxygen transport stops and alcoholic fermentation starts in roots [31]. The oxygenated rhizosphere of seagrasses during photosynthesis might create a special environment for the uptake of limiting nutrients with the help of nutrient/metal-binding and the detoxification of toxic elements by oxygenation and/or binding to chelating compounds.

3.2 Abundance and Putative Function of Phytochelatins

PCs, glutathione-derived metal binding peptides, usually with the structure of $(1'\text{-Glu-Cys})_n - \text{Gly}$ $(n = 2 - 11)$ are enzymatically synthesized peptides known to be involved in heavy metal detoxification, mainly Cd and As, which has been demonstrated in plants, algae and some yeast species grown at high heavy metal concentrations. PCs are translocated within the plant, transported to the vacuole as low molecular PC-metal complexes and are stored as high-molecular weight PC-metal complexes in the vacuole [32].

The current model of PC biosynthesis by phytochelatin synthase (PCS) starting from glutathione in a substituted enzyme mechanism is shown in Fig. 2. It has become apparent that PCS genes are far more widespread than ever anticipated. PCS expression can be found in representatives of all eukaryotic kingdoms and the presence of PCS-like proteins in several prokaryotes. The constitutive expression of PCS genes and PCS activity in all major plant tissues is still mysterious. It is unclear, how the extremely rare need to cope with an excess of Cd or arsenic ions could explain the evolution and distribution of PCS genes [32, 33].

In the last years substantial accumulation and tolerance to Pb and Cd by some aquatic plants have been reported [34–36]. Experiments done under Hg stress showed that PCs are synthesized in *Hydrilla verticillata* (L. f.) Royle and *Vallisneria spiralis* L. plants and play a role in Hg detoxification even though the accumulation of Hg was differently distributed in the plant [37].

H. verticillata plants also tolerated higher concentrations of AsV and AsIII than normally present in contaminated areas. Toxicity appeared only at the respective highest exposure concentrations of both As species after prolonged treatment. In view of their fast growth, high biomass and adequate As detoxification system, the authors propose that *H. verticillata* plants have great potential for remediation purposes [38]. The occurrence of the metal-complexing thiol peptides in natural populations of brown, red and green seaweeds was studied [39]. Concentrations of PCs and its precursor glutathione were measured. During heavy metal exposure PCs may also be limited by glutathione availability and, on the other hand, an excessive activity of PCs may lead to glutathione depletion causing oxidative stress to the cell [40]. The non-protein thiols were identified and quantified in seaweed extracts and the molecular structures of PCs were confirmed. The authors concluded that for the first time PCs are reported in native brown algae (*Fucus* spp.), red algae (*Solieria chordalis* (C. Agardh) J. Agardh) and green algae (*Rhizoclonium tortuosum* (Dillwyn) Kützing) but not in thalli of *Ulva* spp. and *Codium fragile* (Suringar) Hariot (green algae) [39]. The results clearly showed that natural assemblages of seaweeds, belonging to disparate phylogenetic groups produced PCs when exposed to a mixture of metals in their environment. However, the involvement of thiol peptides in metal homeostasis, detoxification and resistance varies between seaweed species that are grown under the same environmental conditions [39].

The production of PC-like compounds by *Fucus vesiculosus* L. in response to Cd exposure suggests that marine macroalgae detoxify this metal by a similar mechanism as land plants, freshwater algae and yeasts. The response tended to the depletion of the intracellular glutathione pool but lead to a decreased ability to display other stress responses that depend on glutathione at higher heavy metal levels.

In the seagrass *T. testudinum* (Hydrocharitaceae) the heavy metal accumulation and thiol compound synthesis induced by Cd exposure were studied. Shoots were exposed to several $CdCl_2$ concentrations. Levels of Cd, Cys, glutathione, γ-glutamylcysteine (γ-EC), and PC-like peptides were determined in green blades, live sheaths and root/rhizomes tissues. The detected metal accumulation was dependent on the Cd

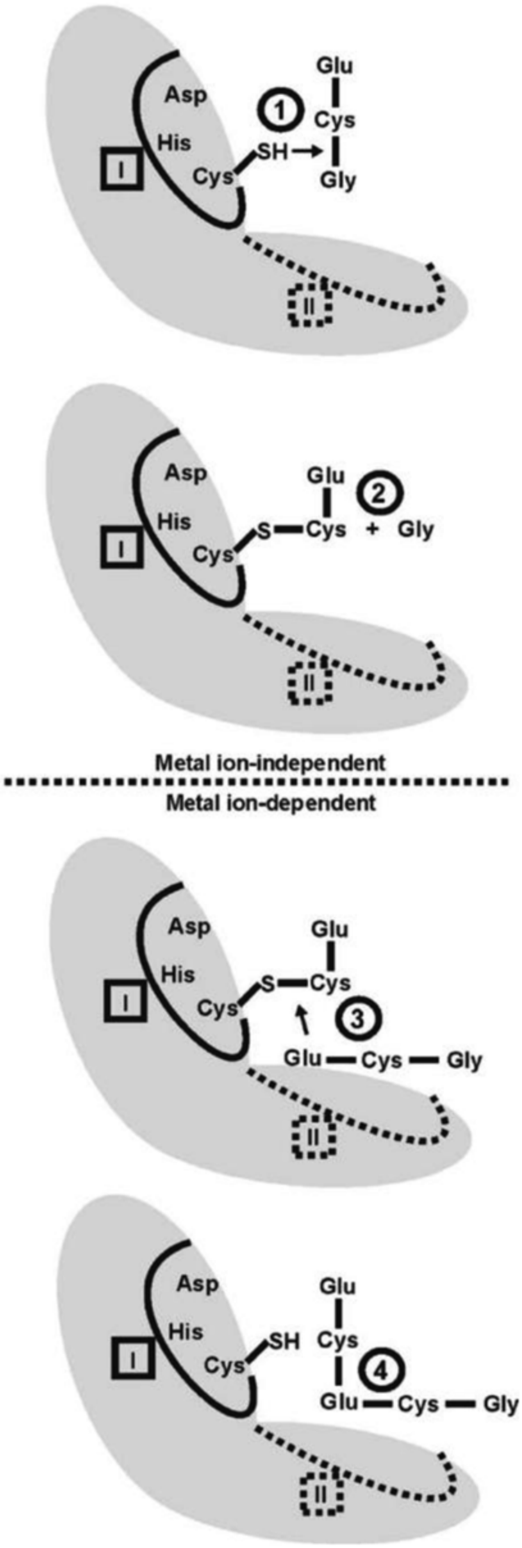

Fig. 2 The hypothetical mechanism of phytochelatin synthesis. PCS probably carry two substrate binding sites (I and II). Acylation of binding site I (step 1) occurs at a conserved Cys which forms together with a His and an Asp the catalytic triad typical for Cys proteases. Gly is cleaved off (step 2) and the resulting γ-glutamylcysteine dipeptide is transferred onto another glutathione (or a PC molecule) (step 3). A new peptide bond is formed (step 4). Steps 1 and 2 are metal ion-independent. Acylation of site II and peptide transferase activity require metal ion activation and/or the binding of a metal–glutathione complex (The figure is taken from Ref. [33])

Table 2 List of halophytic species and their phytochelatin synthases

Plant	Species	Type	GB number	Sources
Marine algae	*E. paludosa*	n.k.	CBP94207	–/–[a]
	E. paludosa	n.k	CBP94206	–/–
	N. palea	n.k	CBP94204	–/–
	E. siliculosus	n.k	CBJ32985	[4]
	M. pusilla	n.k	EEH55879	[42]
	Micromonas sp	n.k	ACO65712	–/–
	T. pseudonana	n.k	EED94631	[43]
	T. pseudonana	n.k	EED91948	–/–
	T. pseudonana	n.k	EED89626	–/–
	M. vaginatus	n.k.	EGK88687	Unpublished
Mangrove species	*A. germinans*	1	ABA43317	[44]
Other halophytes	*T. salsuginea*	n.k	BAJ34584	[45]
Non halophytes	*B. juncea*	1	BAB85602	–/–[a]
	L. sativa	1	AAU93349	[46]
	A. sativum	n.k	AAO13809	–/–[a]
	A. thaliana	n.k	NP_199220	–/–[a]
	A. thaliana	2	NP_171894	[47]

n.k. not known

[a] Direct submission to GenBank, unpublished

concentration and the type of tissue in which green blades showing the highest content followed by live sheaths and root/rhizomes. All tissues experienced an increase in thiol-containing compounds resulted from Cd exposure. The lower glutathione content together with comparable higher PC-like Cd inducible peptides in green blades indicated the enhanced glutathione demand induced by Cd stress under which glutathione is directly used for handling the oxidative stress, and indirectly for thiol peptide synthesis [40]. Live sheaths showed the highest levels of Cys, glutathione and γ-EC [40].

Previous report indicated that plant tissue of *Posidonia oceanica* (L.) Delile and *Zostera marina* L. significantly accumulated high levels of heavy metals when growing on heavy metal-impacted water [41]. When treated plants were compared with control plants it was shown that foliage leaves and sheaths contained two to over six times higher amounts of Hg. It was not referred how these plants accumulated heavy metals.

Plants usually described which accumulate PCs are freshwater plants or halophytes living terrestrial. Few articles are published about PC (or PC-like compounds) in seagrasses or plants living in the tidal zone till up to now. The detailed way of metal accumulation has not been described.

The protein sequence for a putative PCS (Table 2) available from the halophyte *T. salsuginea* (BAJ34584) has been used for the search of additional PSC in halophytes (Fig. 3). Obviously, the PCS are abundant and functioning in salt-tolerant plants. Keeping in mind the high potential of halophytes for heavy metal accumulation one should think about the profit of phytoremediation in soils and sediments containing high salt contents. Genome sequencing of more salt-tolerance plants and parallel physiological analysis of their PCS could help to select the best species for phytoremediation processes.

3.3 Abundance and Putative Function of Metallothioneins

Although PCs have been shown to play an important role in the detoxification of certain heavy metals in both plants and animals [52; see Sect. 3.2], the role of MTs in this process has not been

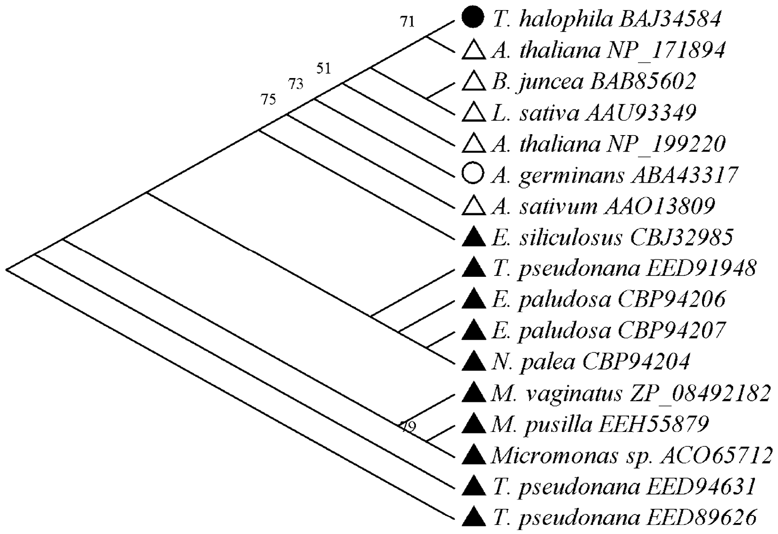

Fig. 3 Molecular phylogenetic analysis of phytochelatin synthases. The evolutionary history was inferred using the Neighbor Joining method [48]. The bootstrap consensus tree inferred from 1,000 replicates is taken to represent the evolutionary history of the taxa analyzed [49]. Branches corresponding to partitions reproduced in less than 50 % bootstrap replicates are collapsed. The percentages of replicate trees in which the associated taxa clustered together in the bootstrap test (1,000 replicates) are shown above the branches [49]. The evolutionary distances were computed using the Dayhoff matrix based method [50] and are in the units of the number of amino acid substitutions per site. The rate variation among sites was modeled with a gamma distribution (shape parameter = 1.92). The analysis involved 17 amino acid sequences. All positions containing gaps and missing data were eliminated. There were a total of 50 positions in the final dataset. Evolutionary analyses were conducted in MEGA5 [51]. ▲: Marine algae, ○: Mangrove species, △: Non halophytes; ●: Other halophytes

conclusively shown in plants [21]. Originally, MTs were identified in animals by their ability to protect against Cd toxicity but MTs have also been reported to play a role in other cellular processes, including the regulation of cell growth and proliferation, DNA damage repair, and scavenging of ROS but also in providing zinc [53]. Thus, although the importance of MTs throughout the life cycle of a plant has been demonstrated it is not clearly understood how they fulfill these roles [54].

3.3.1 Definitions, Classification and Functions

MTs are a group of proteins with low molecular mass and high Cys content that bind heavy metals and are thought to play a role in their metabolism and detoxification [32]. In recent studies, the criteria that define a protein or peptide as MT are: (i) low molecular weight (<10 kDa), (ii) high metal and sulfur content (>10 %), (iii) spectroscopic features typical of M–S bonds and (iv) absence or scarcity of aromatic amino acids [55]. However, often they are called MT-like proteins because one or more criteria do not apply.

Based on the arrangement of Cys residues, classes of MT proteins are grouped including class I: MTs contain 20 highly conserved Cys residues and are found in mammalian and vertebrates. MTs without this strict arrangement of Cys residues are referred to class II MTs and include all those from plants and fungi as well as non-vertebrate animals. In this MT classification system, PCs are, somewhat confusingly, described as class III MTs [32, 56]. Plant type II MTs are divided into four types, based on their Cys arrangement [32]. All four types were experimentally shown to be capable of acting as metal chelators [57]. Interestingly, the MT protein sequence from the marine alga *F. vesiculosus* does not fit easily into any of these four plant types [58, Table 3]. Hence, further studies

Table 3 List of halophytic species and their class II metallothioneins

Plant	Species	Type	GB number	Sources
Brown algae	*F. vesiculasus*	n.k.	CAA06729	[58]
	E. siliculosus	n.k.	CBJ32637	[4]
	E. siliculosus	n.k.	CBJ27567	[4]
Seagrass	*P. oceanica*	2	AJ249602	[59]
	P. oceanica	2	AJ249603	–/–
	P. oceanica	2	AJ628138	[60]
	P. oceanica	2	AJ628139	–/–
	P. oceanica	2	AJ628140	–/–
	P. oceanica	2	AJ628141	–/–
	P. oceanica	2	AJ628142	–/–
	P. oceanica	2	AJ628143	–/–
	P. oceanica	2	AJ628144	–/–
	P. oceanica	2	AJ628145	–/–
	P. oceanica	2	AJ628146	–/–
Mangrove species	*S. apetala*	2	ABQ42032	[61]
	S. ovata	2	ABQ42031	–/–
	S. caseolaris	2	ABQ42030	–/–
	S. alba	2	ABQ42029	–/–
	B. gymnorrhiza	2	ABF50984	[62]
	A. marina	2	AAK11269	–/–[a]
	A. marina	2	AAG61121	–/–[a]
	A. marina	2	AAG50080	–/–[a]
	A. marina	2	ABQ63078	[63]
	K. candel	n.k.	ABD75757	[64]
	A. germinans	2	AAY59706	[44]
Other halophytes	*S. portulacastrum*	2	AEK87151	–/–[a]
	M. crystallinum	n.k	AAC27531	–/–[a]
	M. crystallinum	n.k.	AAB61212	–/–[a]
	L. bicolor	n.k.	ABL10086	–/–[a]
	P. tenuiflora	2	AFF18618	–/–[a]
	A. tripolium	1	AB090882	[65]
	S. brachiata	2	AEF01492	[66]
	T. salsuginea	[b]		[67]

n.k. not known
[a] Direct submission to GenBank, unpublished
[b] Translated from DNA sequence: BQ060316

are needed to determine the diversity of the MT gene family.

Some data suggest a metal-binding capacity [57] and MTs may play a role in the homeostasis of essential metal ions and also the detoxification of heavy metals [21, 60, 68]. However, other studies showed that additional functions of MTs are still unknown and unclear [21, 55, 69]. Interestingly, MTs are highly expressed in seagrasses even in normal conditions when growing in uncontaminated sediments. In a heat stress experiment a MT with unknown function was the most abundant transcript but its expression was decreased by high temperature (3–15 %) [69, EST database http://drzompo.uni-muenster.de/].

3.3.2 Abundance of Metallothioneins in Halophytes

The seaweed *F. vesiculosus* is member of the brown algae family and it was shown that this species contains the gene for MT [58, Table 3]. The filamentous brown algae *E. siliculosus*

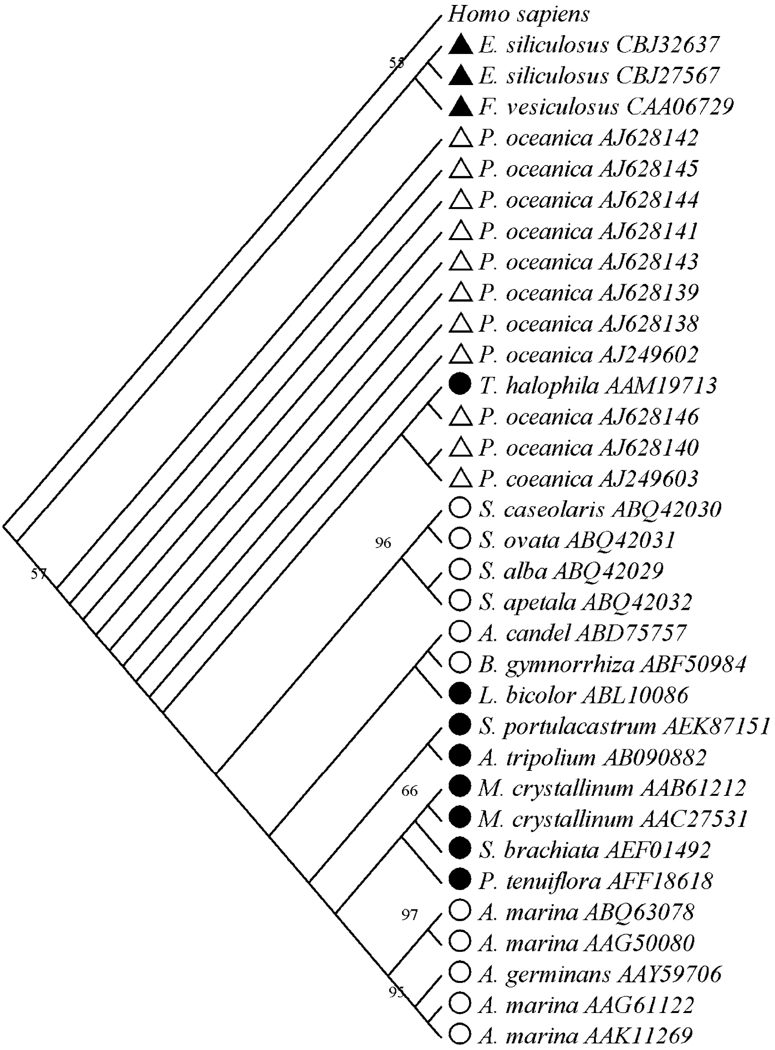

Fig. 4 Molecular phylogenetic analysis of type II MT. For explanation see Fig. 3. ▲: Marine algae, ○: Mangrove species, △: Seagrasses; ●: Other halophytes. A MT sequence of *Homo sapiens* was used as out-group

contains at least two genes encoding MTs (own analysis). Nine MT-like sequences from Cu or Cd treated *P. oceanica* were isolated and classified into two subgroups [60]. Type II MT genes were also found in several mangrove species [27]. With respect to other halophytes, a type II MT gene was isolated from *Salicornia brachiata* L. [66]. This species is an extreme halophyte growing luxuriantly in the coastal marshes and is frequently exposed to various abiotic stresses including heavy metals. Expression of SbMT-2 gene was up-regulated concurrently with Zn, Cu, salt, heat and drought stress, down-regulated by cold stress while unaffected under Cd stress suggesting a role not only in metal binding. Type II MT also occurred in several other halophytes (Table 3). However, their function has not been analyzed so far. Phylogenetic relations of MTs isolated from halophytes so far are shown in Fig. 4. There is no clear pattern visible corresponding to the respective taxonomic group. The MT sequences from halophytes and mangroves have similarities with brown algae and also with seagrasses. One can assume that different types of MTs were taken for analysis. Therefore, as long as not all species included in the tree are completely sequenced a final conclusion about the distribution of different groups of MTs in different taxa is not possible. In addition, more metal binding studies need to be done.

4 Conclusions

More and more data reveal the specific functions of sulfur-containing molecules in the marine environment. The high sulfate content of marine water bodies was obviously used as a positive selection pressure to develop adaptation to the high salt content. The algae use SP since a long time and the seagrasses remembered their old set of enzymes to produce new cell wall components during their way back to the sea. Probably in seagrasses the function of MTs was modified during adaptation. And the same is true for some halophytes which also contain in comparison to terrestrial plants unusual sulfate-containing polysaccharides which are interested from an applied point of view because they have some pharmacological activities among them they could be used as efficient anticoagulant with smaller side effects. These compounds constitute another treasure of the ocean. The same might be true for MTs because their unusual high abundance in seagrasses indicate a new role for MTs.

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The Chemical Composition and Technological Properties of Seagrasses a Basis for Their Use (A Review)

N.A. Milchakova, Benno Böer, L.I. Boyko, and D.V. Mikulich

Abstract

Seagrasses (*Zostera marina, Z. noltii, Ruppia cirrosa*) and other higher marine plants (*Potamogeton pectinatus,* etc.) are widely distributed in the ocean, and they occupy large areas of shallow gulfs and bays of the Black Sea. The usage survey of seagrasses in agriculture, industry and pharmacology has been completed, and the results of experiments on the uses of Black Sea seagrass in the diet of livestock are described, including the chemical composition. *Zostera marina* contains a significant amount of organic matter and nutrients with valuable trace elements whose concentrations are higher than in most terrestrial food plants. However, its organic matter does not have a high nutritional value due to the low protein content, the imbalance of its amino-acid composition and poorly assimilated lignin. The potential for economic seagrass utilization is mainly based in aquaculture, because seagrasses are keystones of the coastal ecosystems, and many of them are protected by various conventions and agreements, and they are biological ocean "hot spots". Seagrass aquaculture can play a role in biodiversity conservation of the native communities and populations from their extraction for commercial use.

The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_22, © Springer Science+Business Media Dordrecht 2014

1 Introduction

Seagrasses are higher plants (class Monocotyledoneae) that flower and seed beneath the water, having evolved from terrestrial origins and re-entering the sea millions of years ago [1]. There are 72 seagrass species that are known [2]; their communities represent one of the key-elements of the coastal habitats in the ocean [3]. Extensive seagrass meadows occur in every continent except Antarctica; their distribution and diversity are greatest in the tropical zone [2, 4].

Seagrass communities contribute to the ecosystem-functioning and health of coral reefs and mangroves, salt marshes and oyster reefs [5, 6]. Seagrasses have a high primary productivity and are the basis of many marine food webs; it is the food of dugongs, manatee, and some species of sea turtles [4, 5], as well as numerous fish and other marine species. The value of marine macroalgae and seagrasses ecosystems has been estimated at US$ 34,000 per hectare per year; this is three times more than coral reefs and 10 times more than tropical forests [7, 8].

Anecdotal data about the use of seagrasses is available since ancient times; for example, dry leaves of *Zostera marina* were found in the Egyptian pyramids; the layers of these leaves were also found in the foundation of many burial mounds of the Bosporus Kingdom in the Kerch Peninsula, Crimea, sixth century B.P. [9]. In the Middle East some information about the use of seagrass must have occurred more than 2,000 years ago [10]. According to Chinese manuscripts, the powder from *Zostera* spp. leaves was also used as a medicinal substance from the second century B.P. [9].

Seagrasses are still used in some countries to manufacture heat-insulating materials, as a fire-resistant durable filling, as noise-proof material, and to thermo-insulate agricultural constructions, and for production of household items such as mats, rugs and baskets [11–13]. These products have a non-porous surface with a naturally smooth texture and sheen quality; they are allergy-free, strong and they withstand dust-abrasion. They are commonly used in some regions of southern Asia, Australia, southern Ukraine, some European countries and Africa [14–17].

At the present time the interest in seagrass utilization for agriculture, industries and medicine is increasing. It is a fact that the utilization of seagrass and their commercial use is not just an economic issue but also an important part of sustainable development and functioning of coastal ecosystems. On one hand, the coastal zone needs protection because of the diversity of life inhabiting the beach-casts and adjacent areas [13, 15, 18, 19]. On the other hand, it needs regular collecting of fresh remains of cast-out seagrass plants with numerous decaying algae. This could be solved through legal regulations for collecting only leaves freshly washed ashore during the summer months, which is already practiced in Ukraine [9, 11]. This approach allows the conservation of perennial seagrass communities in situ.

The expansion of seagrass use has a significant limitation for the ecosystem too; the living resources of seagrasses should not be collected and harvested directly from natural habitats because of their biological “hot spot” value in the ocean and coastal ecosystems. Nearly ten seagrass species are classified as threatened, and 27–30 % of world’s seagrass habitat disappeared in the last hundred years; this is the greatest threat causing habitat-loss for the seagrasses and losses to marine biodiversity, fisheries, water quality, shoreline stability and ecosystem richness [8, 19–23]. Seagrass communities are under protection in 80 % of MPA in the Mediterranean (total number greater than 200, www.mpaglobal.org) and 50 % of them are in the Black Sea (total number 43, [12]; they are in the list of keystone communities of Natura 2000 and the European network of protected sites (www.eea.europa.eu/…eunis-database; Habitats Directive (92/43/EEC). The diversity of algae, invertebrates and fishes is astonishingly high in seagrass communities, and they are under protection of various international conventions and agreements (Bern Convention 1979, Annex 1; The Convention on Biological Diversity (CBD), Rio de Janeiro 1992; The Pan-European Biological and Landscape Diversity Strategy (PEBLDS), Sofia 1995; The Strategic Action Plan for the Environmental Protection and Rehabilitation of the Black Sea, Sofia 2009, and etc.).

Any increase of the commercial utilization of seagrasses must base on sustainable resource utilization principles; in this case, they could become the object of aquaculture. But cultivation of seagrass is a very difficult process; it still has small positive results with a significant economic cost, according to data from many regions of the world [24–29]. Therefore at the present time, the cultivation of seagrass cannot be viewed as an opportunity to obtain a stable resource for their commercial use. Therefore, research and development of seagrasses as part of coastal zone management and seagrass conservation is very important [8, 9, 22, 23, 30–32].

2 The Chemical Composition and Technological Properties of the Black Sea Seagrasses

The investigation of the chemical composition of Black Sea seagrasses and higher plants (*Zostera marina, Z. noltii, Ruppia cirrosa* and *Potamogeton pectinatus*) has shown their valuable elemental composition and potential use as sources for alimentation, fodder and medicine [33–40].

2.1 *Zostera marina*

The composition includes extractives, minerals, nitrogen-bearing materials, carbohydrates and lignin. The content of the ether solution is insignificant; however, it oscillates over a wide range and it depends on the season and growth conditions. A very high content of dry matter (>50 %) contains carbohydrates; the percentage of free sugars is less than 2 %, as their contents change during plant growth. The easily hydrolyzed polysaccharides of eelgrass are constructed from oddments of glucose, xylose, arabinose, galactose, uronic acid and other sugars (Table 1). The content of some monosaccharides (glucose, arabinose and xylose) in the easily-hydrolyzed polysaccharides are greater in eelgrass than *R. cirrosa* and *P. pectinatus*. Under the content of hard-hydrolyzed polysaccharides (mostly cellulose), eelgrass does not differ from terrestrial grasses.

The hydrolyzed protein matter in eelgrasses is valuable as an amino-acidic composition. Among 16 amino-acids produced of *Z. marina*, proline, glycine, aspartate, glutamine and phenylalanine dominated – 3.4; 0.8; 0.7; by 0.5 % in dry matter, respectively. *Z. marina* has four times greater content of essential amino-acids than alfalfa and corn leafage. The amounts of some micro- and macronutrients of *Zostera* spp. are much higher, than those in some terrestrial fodder – grass flour, corn and sunflower silage [34–38].

Table 1 The composition and content (g/100 g of dry matter) of easily hydrolyzed polysaccharides in *Zostera marina, Ruppia cirrosa* and *Potamogeton pectinatus* from the Black Sea

Monosaccharides	*Zostera marina*	*Ruppia cirrosa*	*Potamogeton pectinatus*
Galactose	3.51 ± 0.33	4.43	4.2
Glucose	11.13 ± 0.87	8.9	8.3
Arabinose	3.61 ± 0.31	2.85	3.05
Xylose	4.20 ± 0.45	3.15	3.0
Rhamnose	3.50 ± 0.33	2.08	2.1
Uronic acids	6.35 ± 0.44	3.04	2.9

Table 2 Nutrient value of *Zostera marina* (the Black Sea)

Index	Content (in dry matter, %)	Index	Content (in dry matter, %)
Crude protein	11.18 ± 0.92	Hard-hydrolyzed polysaccharides (HHP)	44.88 ± 2.52
Crude fat	1.41 ± 0.08	Easy-hydrolyzed polysaccharides (EHP)	22.80 ± 1.02
Crude ash	16.22 ± 1.20	Caloric value 100 g, kcal (kJ)	149 (623)

The pectin substances of *Z. marina* (about 14 %) have gelatinous properties; their solutions can prepare sufficiently strong jellies. The soluble nitrogenous share is as high as 44 %; proving its high nourishing value. The entire nourishing value of an eelgrass was determined on general "gross" parameters (indexes) – protein, fat, carbohydrates, mineral substances, and this is the base for calculating their caloricity (Table 2). On the other hand, the alimentary value of a "crude" protein (the index is generally equal to N nitrogen) determines an amino-acidic composition and the ratio of amino-acids [41].

As a whole, the dry organic matter of eelgrass has a low nutrient value, because hard-hydrolyzed polysaccharides are dominant. The degree of the dry matter digestion is compounded at 49.2 %, for protein – 40.7 % and for polysaccharides – 36.4 % [33]. According to FAO/WHO standards [41], the status definition and usage directions were completed by researching the alimentary value of each nutrient component within human food. In an estimation of the alimentary value of eelgrass protein on an amino-acidic composition, the ratio of amino-acids has shown that *Z. marina* contains a trivial set of amino-acids, and the essential acids in its composition comprise 30 %. But the standard imbalance of proteins and the limit is determined by cysteine, methionine and tryptophan.

By definition, the alimentary value of eelgrass dry matter contains biogenic macro- and microelements (Table 3). Some of these values are much higher than in wild fodder grasses; they are three times greater than in *Sorghum sudanense*, and four to six times greater than in *Phleum* sp.

The content of Fe and Co is 40–50 times as much as in hay from *Poaceae* and *Fabaceae* grasses. *Z. marina* contains 6.65 mg Co (per 1 kg dry leaves), compared with flour from *Vicia* sp. and *Medicago* sp. that contain only 0.352 mg and 0.296 mg Co, respectively. The role of elements such as Cr and Co in animal feed and human food has not been sufficiently studied. Some data suggests that the main function of Co is its participation in the formation of blood, the processes of metabolism, growth, synthesis and functional activity of some enzymes. Comparison of the macro- and microelements structure of eelgrass with wild grass flour testifies to eelgrass's unique capacity to concentrate mineral substances and elements at rates twice higher or more than terrestrial grass [42].

Table 3 The macro- and microelements composition (in dry matter, %) of *Zostera marina* (the Black Sea) and fodder flour from wild grass (southern part of Ukraine)

Biogenic macro- and microelements	*Zostera marina*	Fodder flour (wild grass)
Ca, g/%	2.48	0.58
Mg, g/%	1.15	0.33
Na, g/%	1.0	0.25
К, g/%	0.7	0.82
P, g/%	0.17	0.31
S, g/%	0.6	0.19
Fe, mg/%	450	9.90
Mn, mg/%	82.8	6.63
Co, mg/%	0.62	0.06
Cu, mg/%	3.55	0.29
Zn, mg/%	9.36	2.27
I, mg/%	Traces	0.09

Eelgrass concentrates a valuable complex of biogenic trace substances, except for iodine [42]. The organic matters of eelgrass, as a whole, have no high nutritional and alimentary value because of the low-level contents of protein, unbalanced by amino-acidic structure, the low contents of lipids, and also the extremely high contents of polysaccharides which are hard to digest. One of the options for obtaining valuable supplements of storm cast-outs of seagrasses is the biotransformation of organic matter and poorly assimilated lignin in eelgrass into high-protein, digestible fungal mycelium.

The alimentary value of eelgrass is provided through biologically active microelements (Fe, Cu and Co) that adjust all physiological processes. As a whole, the rich chemical composition makes *Zostera marina* a valuable fodder additive for livestock.

2.2 *Ruppia cirrosa* and *Potamogeton pectinatus*

The chemical composition and the properties of *R. cirrosa* and *P. pectinatus* from the Black Sea have not been studied as well as those of *Z. marina*. In a soluble nitrogenous structure, protein matters dominate the non-protein forms of nitrogen. The hydrolyzates of protein matters contain many valuable amino-acids; the content of crude protein is 10.3 % in *P. pectinatus* and 16.8 % in *R. cirrosa*. The main part of N is in a difficult solution form; dry matter is represented by a significant amount of the vitamins B group (Table 4).

Table 4 The chemical composition (in dry matter, %) of seagrasses and higher plans from the Black Sea

Species	Crude protein	Ash	Ether solution matter	EHP
Zostera marina	11.31	19.2	2.4	22.8
Ruppia cirrosa	11.94	16.78	0.87	24.6
Potamogeton pectinatus	14.0	13.9	0.85	23.0

Note: *EHP* easy-hydrolyzed polysaccharides, for EHP – quantity of reducing matters is multiplied by 0.80

Table 5 The content of vitamins (mg per 1 g of raw matter) in the Black Sea higher plants and some fodder types (the southern part of Ukraine)

Species, fodder	B_1 (thiamine)	B_2 (riboflavin)	Carotin
Zostera marina	1.13	0.22	0.63
Ruppia cirrosa	0.80	0.11	0.27
Potamogeton pectinatus	1.26	0.75	0.20
Meat-bones flour	0.90	5.3	–
Fish flour	1.0	6.2	–
Alfalfa flour	3.3	14.3	150–300
Wild grasses	1.5	4.8	40–80

By comparing the quantity of vitamin B_1 (thiamine), seagrasses do not differ greatly from traditional forages (Table 5). The content of vitamin B_2 (riboflavin) is greater in *P. pectinatus* than in *Z. marina* and *R. cirrosa*.

3 The Commercial Use of Seagrasses in the World

3.1 Agriculture

The most rational application of eelgrass is as a component of traditional fodder, supplying Cu, Co and Zn to regions with deficits of these elements. It has been established that the production of the complex fodder mix is perceptively based on eelgrass and algae containing iodine [38–40]. However, the high content of poorly assimilated lignin causes difficulty in calculating the proportion of additives in the forage [36, 37, 43].

Tests of algal components and *Zostera marina* in milk-cow feed were conducted in some agricultural regions of Ukraine. The highest parameter of physiological condition of the animals, in yield and quality of milk production, were obtained by the use of mixed fodder, which contains 500 g of eelgrass and 100 g *Phyllophora* spp. (after the extraction of carrageenan) on one head of animals per day. For some regions (for example the Carpathian Mountains) the mixed fodder was covered the deficient of iodine at 2.5–7.5 times, Co at 2.5–4 times, Cu at 16–30 %, Zn at 17–33 % in fresh hay. As a result, the yield of milk increased by 12 %, and the protein contents increased by more than 3 %. The quantities of valuable amino-acids in protein and polyunsaturated fatty acids in the lipids were also increased. At the same time, the content of cholesterol in milk was decreased (54.99 ± 1.38 to 30.15 ± 2.05 mg %).

The activation of the physiological processes is demonstrated in animal too. The live weight of cows was increased by 10 %; the blood protein contents were basically increased at the expense of a fraction of γ-globulin, while the contents of free cholesterol have decreased by 24 %. This milk production had high nutrient and dietary properties, and it was recommended for prevention of diseases that are endemic for the Carpathian region of Ukraine, for example, atherosclerosis and illnesses of the thyroid gland. These scientific researches have shown the importance of seagrass and macroalgae as a mix-food supplement to improve milk quality, nutritional value what is very important for human health.

In the southern part of Ukraine (Odessa, Kherson and Nikolaev agricultural regions) these tests registered similar results. The addition of 50–250 kg of eelgrass to one ton of ensilaged hay becomes enriched through its valuable micro- and macronutrients. In the experimental group of cows, where only eelgrass has been added to the basic diet, the extra weight has compounded to 4.75 kg per one head and, where the eelgrass is in an additive along with urea, it was 5.22 kg per one head. The daily portion of milk was increased by 13–15 % (Table 6), and the mean weight of the neonatal calves was up by 200–300 g. The length of wool fibers was increased by 0.9–1 cm in an experimental group of sheep. The wool padding from one head of sheep increased by 300 g; the weight of sheep grew by 20–30 %, and by 10–15 % for pigs. The increase in chicken egg production and density of egg shells are also registered. Apart from that, the introduction of the fodder components from eelgrass and marine macroalgae in forage promoted the strengthening of muscle walls and normal metabolism of the animals. Flour made from eelgrass may become a part of animal rations, preferably applied in granulated form after pretreatment.

Table 6 Data on experiments with *Zostera* spp. admixed to the combined forage (winter rye and wild grasses) given to milk-cows (Odessa region, Ukraine)

Parameters	Unit of measurement	Animal groups	
		Control	Experimental
Livestock number	No. of animals	242	873
Duration of the experiment	Days	120	120
Consumption of *Zostera* spp.	100 kg	–	62.7
Cows receiving the forage	No. of animals	242	873
Cows ceased receiving the forage	No. of animals	242	873
Increasing of average yield of milk per cow (per day)	kg	539	633

As a whole, the fodder components of seagrasses and algae slow down the allocation of calcium and, therefore, accelerate ossification processes for the livestock. For this reason, introducing algae and seagrasses into their forages ration has a most favorable effect on the growth of young, pregnant and suckling animals.

Among other aspects of seagrass uses are the production of substances for the granulation and briquetting of mixed fodders, known as agents for the conservation of juicy forages, which have high content of hemicelluloses and pectin. Apart from that, seagrasses can also be used as fertilizer, to prevent the development of fungi and helminth eggs, weed seeds and they often contain high amounts of micro- and macronutrients. The eelgrass has a high moisture capacity (up to 3,000 %) and can be used for the fertilizer efficiency prolongs, and irrigated soil retains it for a longer time.

There are several data about uses of seagrass as a fertilizer in Mediterranean countries, although this is probably more applicable for algae and other marine organisms entangled within the seagrass mat, than for the seagrass itself [13, 44, 45]. *Posidonia oceanica*, when mixed with lime and phosphates, was used in Mediterranean countries as a meal for feeding poultry [44]; this was also experimented with in South Australia, although only on a limited basis. Washed up seagrass litter is used commercially to make garden mulch, although there is speculation that this is largely for bulk [15, 46].

3.2 Use in the Household and Crafts

Seagrasses still have many traditional uses in manufacturing household items, etc. Seagrass leaves with extremely strong and durable properties are woven into different types of furniture (armchairs, headboards, display shelves, bookcases) and some decorative items (rugs, baskets and mats).

The slabs and mats from eelgrass are often used for thermo-insulation in the constructions for cattle and granaries, because they have flame-retardant and heat-insulating properties, and they are resistant to decay. It is conditioned by the high contents of calcium salts that cause the high osmotic pressure, making habitation unacceptable for the insects and small rodents [11, 12]. They are still used for filling mattresses, roof covering, house insulation and garden fertilizers (after excess salts have been washed off).

Investigations conducted in Ukraine point out that heat-insulating slabs made of *Zostera* spp. are replacing synthetic ones in agriculture constructions and granaries; in addition, *Zostera* mats enrich the calcium salts, and the correspondingly high osmotic pressure makes them a hostile environment to various pets [9, 11, 16]. Until as recently as half a century ago, dry leaves of *Zostera marina* and *Z. noltii* had been a filling stuff for mattresses in local regions of Ukraine and Russia (http://mebel-dekor.ru/mattress/; http://uteplitelya.net/photo/2010-08-26x758920.html).

Dried seagrass material was commonly used as housing insulation in the USA, until well into the 1960s. One of the major beneficial properties of seagrass as insulation was that it was non-flammable, because of its high silicon content. A popular form of insulation in the USA was called Cabot's Quilt, named after its inventor. This was a mat of dried seagrass material, inserted into the walls of houses. The material was also used to sound-proof radio studios in the USA and the UK [47, 48]. *Zostera marina* has found use as a substitute for horse hair in Europe and the USA, as a material for stuffing pillows, mattresses and upholstery. The crab industry in Chesapeake Bay used seagrass as a packing-material for exporting crabs from the region [48, 49]. Seagrass leaves were used to bind clay and soil in embankments; for example, in the dikes of the Netherlands. This use has found a translation into modern times, with seagrass litter being used to produce mulch applied to sand dunes to help its stabilization [1, 48]. Seagrass dry leaves as material were popularly used to thatch roofs in rural coastal areas in Europe and the UK.

During the Second World War, seagrass fibers were used as a substitute for cotton in the manufacture of nitrocellulose in Germany. In the UK, experiments were carried out on the use of seagrass fibers for paper making [14]. In Eastern Australia, the leaf fibers of *Enhalus acoroides* were possibly used to make nets and cord before European migration, and matting and bed mattresses were made during the Second World War. At the same time, *Posidonia angustifolia* leaves from the beach were used for fertilizer, soil conditioner and compost mixes, but now such activities are illegal in many parts of Australia, because live and dead seagrass plants are under protection [46].

In Micronesia, Polynesia, Melanisia and southeastern Africa seagrasses are traditionally used for making baskets, burning for salt, soda, as well as thermo-insulation, bedding, roof thatch, packing material, fertilizer, insulation for sound and temperature, fiber substitutes, piles to build dikes, for cigars and for children's toys [12, 50–52]. *Enhalus acoroides* fiber is also reportedly used in the construction of nets. In Japan, some species of seagrasses are used as fiber for rope or padding (tatami mats, cushions for train seats and horse saddles, traditional fisherman's skirts) or as agricultural compost [53]. Japanese fisherman used *Phyllospadix iwatensis* as a material for making wet weather gear up to the 1930s, when it was replaced by rubber as the prime material for this purpose.

3.3 Medicine

Many seagrasses have antimicrobial activity; in addition the polysaccharides of eelgrass have shown a biological potency in relation to some oncologic diseases [54–57]. It was also found that zosterin pectin from *Zostera marina* manifested a higher reduction in antitumor activity compared to the medicines mildronat and emoxipin, against Ehrlich carcinoma [58, 59]. They have also been used in traditional medicine (against skin diseases) in the Mediterranean region and in Africa [17]. The residents of some regions of Thailand use dry seagrass leaves and rhizomes for the treatment of diarrhea [52].

The substance "Zosterin" made from *Z. marina* growing in the coastal zone of the Russian Far East has demonstrated high biological activity over many trials [57]. This polysaccharide is of a pectin nature and belongs to the group of natural organic sorbents that have versatile cleansing effect (gastrointestinal tract and blood), and improve of epithelial regeneration and also enhance the effect of other medicines; its effect is slightly diuretic and is easily dissolved in water, while retaining useful substances [56, 57]. Zosterin stimulates T- and B-cell responses, increases the abundance of antibody-forming cells in the spleen; it intensifies an immune-modulating activity; and induces spontaneous splenocyte proliferation. Zosterin-containing medications are essential prophylactics for tanker crews, oil refinery, lead-and-zinc factories and construction industry personnel that work with products with high contents of heave metals [57]. Also, screening of *Halodule* spp. and *Halophila stipulacea* have shown high contents of biological active substances for; at present, extracts from many other species are being screened for biological properties [52].

In investigating the possibility of *Zostera marina* as a dietary fiber for immobilization of lactic-acid bacteria and receiving health care products (eubiotics) that were found in the substrates of eelgrass, it was found that they have antibacterial properties and completely inhibit the growth of *Lactobacillus acidophilus* and yeast *Saccharomyses cerevisiae* in nutrient environments [39].

The additional use of seagrasses for perfumery and cosmetics has increased exponentially. In particular, seagrass-based cosmetics including Zosterin cream, Zosterin moisturizing cream with vitamin E, mineral masks and tonics, and cooling Zosterin cream-mask with antioxidant effects that are popular in Russia (http://www.headnet.ru; http://www.rusmedserv.com).

4 The World's Seagrass Resources

There are two global estimates of seagrass area, 124,000 and 177,000 km^2, which included only clearly mapped polygons and also unmapped polygons of seagrass area, correspondingly [4, 23]. Seagrasses cover the biggest area in Southeast Asia and Australia, 55.9 % of the global coverage area. A more exact determination of the global extent of seagrasses is difficult because many of their meadows have not yet been mapped [2]. Floating seagrass litter (detached leaves and other parts) often forms in the shallow bays and gulfs and it is then washed up on beaches.

Seagrass beds belong to the highest productive chain of the coastal ecosystems; the average standing stock of seagrass is 460 g per m^2 (dry weight) and an average growth rate of 5 g dry weight per m^2 per day [60]. It has been estimated that carbon fixation of seagrasses constitutes up to 1 % of the total carbon fixed in the oceans, and they store 12 % of the ocean's carbon [19].

At the present, seagrasses are declining globally [8, 19, 22, 23, 61], and their habitats have been disappearing at a rate of 110 km^2 per year between 1980 and 2006 [23]. Declines of *Posidonia oceanica* meadows that once covered an area between 25,000 and 45,000 km^2 in the Mediterranean Sea have been estimated to have declined by 5–20 % [22, 62].

The further urbanization of coastal areas will be followed with declines of seagrasses and other estuarine and coastal species and their habitats. Seagrasses grow close to the shore and coastal areas and are naturally dynamic towards pressures of development and recreation; the decline of seagrass habitat is a significant threat to ecosystem services, essential for sustainable human living. Seagrasses also have a strong influence on global climatic changes [63, 64]. Eutrophication, dredging, excavation of recourses, damaging fisheries practices such as trawling and aquaculture, introduced species, hurricanes and erosion are all factors contributing to the loss of seagrass habitats; therefore, the development of technologies of seagrass cultivation is an important ecological task [2, 5, 8, 13, 32, 45, 63, 65–69]. The loss of *P. oceanica* meadows in the Mediterranean Sea, for example, is a result of the cumulative effects of various anthropogenic factors, including increasing aquaculture practices in many regions [45, 69].

Loss of livelihood and food resources in less developed parts of the world are directly linked to reduced seagrass habitats, where gleaning and fishing on the seagrass flats is a major source of protein [50, 70]. Many small subsistence fishing practices, such as those practiced in Zanzibar (Tanzania), are totally dependent on seagrass meadows for their fishing grounds [17]. Fisheries resources are reduced at the same time as seagrass habitat is being lost, because seagrasses provide nursery grounds and habitat for commercially important fish [51, 53, 61].

The difficulties of conservation and restoration of seagrasses are also connected with low recruitment rates (generation length) of many seagrass species, ranging from 0.5 to 35 years; only 1–10 % of the total seeds become seedlings, and the horizontal elongation rate varies from 0.02 to 2.0 (m year^{-1}). Species with low elongation rates like *Zostera marina* may attain a high potential for colonization by balancing species with a high reproductive effort.

Due to adverse anthropogenic factors, some seagrass species are threatened with extinction; data from the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species show that ten seagrass species are at an elevated risk of extinction, with three species classified as endangered [8, 71].

At the present time, one of the biggest areas of seagrass recourses (*Zostera* spp., *Ruppia cirrosa,* and other higher marine plants – *Potamogeton* *pectinatus, Zannichellia major*) is in the Black Sea and the Azov Sea. Extensive seagrass meadows cover almost every shallow bay or gulf of Ukrainian coastal zone. *Zostera* spp. prevails at depths from 1 to 5 m, and some plants occur at depths below 20 m, across a salinity gradient of 0.3–26‰ [11, 12, 16]. Three decades ago the total biomass of *Zostera marina* and *Z. noltii* in the Black Sea was estimated to be approximately 1.13 million metric tons (wet weight) [72]. In the north-western part of the Black Sea (Ukrainian coast), the total amount of storm cast-out of *Zostera* spp. leaves and shoots are estimated at 35,000–50,000 metric tons (wet weight) [16, 72]. The leaves of *P. pectinatus, R. cirrosa* are also included in the cast-out, but their percentage is much smaller than *Zostera* spp. About 10 % of it is due to the casts after the leaf-fall that extends from late July to October. During this period, the leaves of the seagrasses have the best chemical and mechanical properties as animal fodder supplement [35, 39]. Huge seagrass casts (about 125 kg per km, of a 1-m wide strip a year) were also registered along the Mediterranean coast, including leaves of *Zostera noltii* and *Posidonia oceanica* [13]. Accordingly, due to the key role of seagrass in the coastal ecosystems and their ecosystem service, their harvesting should be based only on fresh, annual storm cast-outs before forming inshore communities [9, 16].

Seagrass restoration is a globally important management strategy of the coastal ecosystem. It must be admitted that re-colonization and aquaculture of seagrasses are at economic costs that require considerable effort, and even with success in most cases, the area that is restored falls well short of the area that requires restoration. Moreover, the transplantation of seagrasses relies on the destruction of otherwise healthy meadows, which are reported to have extremely slow recovery rates, and it is generally expensive [18, 25–28, 30]. Facilitation of natural recruitment of seagrass ramets or seedlings is more effective, along with aiding the recovery of seagrasses through the provision of natural sources of nutrients [27]. If restored populations have a high number of genotypes, outcrossing rates and fitness increase and the possibility for populations to adapt to environmental changes will be enhanced [66, 73].

Apparently, versatile seagrass utilization should develop mostly through progressing aquaculture. Among the positive effects of seagrass aquaculture are environmental enhancement, and the protection of the native communities and populations of seagrass for ecosystem services and commercial use.

One of the existing suitable spaces for seagrass-cultivation may be the extensive coastal sabkha ecosystems that occur in the world’s hot and dry deserts, located slightly above the high-tide mark, and where seawater for irrigation is ready available, in a natural environmental setting of hyper-aridity, and a lack of freshwater. It may be highly valuable to initiate seagrass research and development projects in these sabkha systems, to test their environmental contribution, economic feasibility and benefit for man-kind.

Acknowledgements The research leading to these results has received funding from the UNESCO, UNESCO Doha Office, the Permanent Secretariat to the Commission for the Protection of the Black Sea Against Pollution (Contract No:07.201/2006/455221/SUB/D2) and the European Community’s Seventh Framework Programme (FP7/2007-2013) under Grant Agreement No. 287844 for the project “Towards COast to COast NETworks of marine protected areas (from the shore to the high and deep sea), coupled with sea-based wind energy potential” (COCONET).

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Short Communication: Seagrass Terraces for Food Security and Carbon Sequestration

Benno Böer

Abstract

Somebody started developing rice-field terraces a long time ago, and rice is now one of the most important cash crops in the world. Who will try the same with seagrasses under seawater irrigation? Seagrasses can provide highly valuable cash products under full strength seawater salinity. This is a highly valuable research prospect for coastal dry land countries that wish to develop food-security without depending on freshwater.

1 Rice Fields as an Inspiration to Turn Coastal Deserts Green

Asian rice probably originates from the wild rice (*Oryza rufipogon*) in China, and has been consumed by humans already ca. 12,000 years BP. Rice domestication probably begun around 8,000–10,000 years BP, and is as old as agriculture itself. Somebody started developing rice-field terraces more than at least 2,000 years ago, for example the rice-terraces of the Philippine Cordilleras, which is a UNESCO World Heritage Site. Rice (*Oryza sativa* L. and *Oryza glaberrima* Steud.) is now the grain with the second highest production after maize, making it one of the most important cash crops in the world. It is the most important grain for human nutrition, and grown in 112 countries. This success-story is based on the availability of wild rice combined with ancient human ingenuity.

Who will try the same with seagrasses under seawater irrigation?

1.1 Enhancing Food Security in Dry Lands

Dry land countries suffer significantly from food insecurities, fluctuating market prices, and often depend on large percentages of food import, which is costly and has a high carbon intensity. The State of Qatar, for example, currently imports more than 90 % of its food. Qatar wishes to enhance these figures, in order to improve the country's food

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_23, © Springer Science+Business Media Dordrecht 2014

security. This is the main reason, why it established the Qatar National Food Security Programme, which recently (11/2012) hosted the *International Conference on Food Security in Dry Lands*. Several countries attended this important event, because they have similar concerns and hopes.

Many dry lands do have vast natural resources available, which are currently not being used for food production, but which can potentially be used, if we only developed the required methods and conducted and documented the necessary research and experiments: dry lands have tens of thousands of square kilometers of hyper-saline soils (sabkhat), which are not believed suitable for agriculture. In addition there are at least 2,200 salt-tolerant plant species (halophytes) in the world, and the seagrasses in the Gulf are among them. And, of course, there is an abundance of seawater available, and, for example, all countries in the Arab Region have this resource available.

The seagrasses are currently not used for human consumption or agriculture, even though, they are the staple diet of marine reptiles, mammals, and fish. The seagrass beds in the Gulf are known to be among the highest productive ecosystems on our planet.

One of the possible contributions to enhance food security is via developing proto-types of seagrass terraces in non-productive salt-deserts. Three seagrasses are known to occur in the Gulf (*Diplanthera uninervis* (Forssk.) F. N. Williams, *Halophila ovalis* (R.Br.) Hook.f., and *Halophila stipulacea* (Forssk.) Asch.). They are tolerant to full strength seawater and do not require any fresh water.

It is theoretically possible to grow seagrass in coastal sabkhat, provided they remain permanently submerged, receive adequate light and temperature, and sufficient nutrients.

It is theoretically possible to use the seagrasses that are being produced in such man-made biosaline agro-ecosystems for the production of fish, livestock fodder (camel, goat, sheep), poultry (ostrich, turkey, chicken) and possibly other cash crop products (floor carpets, mattress fillings, insulation materials and others).

The Asian rice-terraces could provide an inspiration for the design: seagrass terraces could be established perpendicular to the coastline in the vast stretches of coastal hyper-saline sabkhat. Seawater could be pumped permanently from beach-wells under the coastal oceans through non-corrosive irrigation pipes inland, until reaching the highest point of the seagrass terraces. The required power for pumping could be provided by solar or wind energy. From here the seawater could be released from the pipes and flow into the seagrass terraces, to provide the required moisture and water-flow, following gravitation until finally reaching the sea. This way, salt-accumulation through evaporation would be avoided.

Research needs to be conducted in order to unfold and measure the full potential. Proto-types should be developed, and studied.

1.2 Carbon Sequestration by Seagrass Terraces

The United Nations recently organized the COP 18 Climate Conference, and debated about carbon emissions and other related issues. Seagrasses are well known for their potential as atmospheric carbon sinks. Therefore, the natural seagrass beds should receive adequate conservation protected by laws, and seagrass terraces should be studied for their carbon sequestration potential, versus methane emission.

2 Conclusion

Seagrasses are flowering plants thriving, and developing their entire reproductive cycle in the marine environment under full strength seawater salinity. If we could elevate seagrasses to supratidal sabkha environments, we could convert low productivity natural ecosystems into high productivity man-made cash-crop agro-ecosystems in dry lands, without the dependency of limited fresh-water resources. The question is: which seagrass species are of economic potential, and how should we approach the idea to develop them into economically feasible systems that produce cash crops under marginal soil/water conditions? This short communication aims to inspire serious investors to provide the necessary funding for scientists to try and turn non-productive salt-desert dry lands into highly productive systems enhancing food-security based on available resources.

Floating Mangroves: The Solution to Reduce Atmospheric Carbon Levels and Land-Based Marine Pollution?

Benno Böer, Chanthy Huot, and Mark Sutcliffe

Abstract
The international environmental conservation communities know about the immeasurable service-value that mangrove ecosystems provide for ecosystem functioning. Globally mangroves are seriously and rapidly declining in area coverage. The coastal zones are narrow in width, and therefore offer rather limited space for mangroves. UNESCO's innovative technology offers a new idea that has not yet grasped the attention of the international community: Floating Mangroves for carbon sequestration. A small-scale model has been developed. This concept can reduce atmospheric carbon levels, reduce land-based marine pollution, generate biofuel and other cash crops without any dependency on freshwater, and it can generate jobs and income.

1 Introduction

Members of the international scientific and biodiversity conservation community know about the immeasurable service-value that mangrove provide for its ecosystem functioning, and services, including primary productivity, and the immense capacity for carbon sequestration in the biomass and soils. Many attempts are ongoing to better conserve mangroves in coastal zones, where the majority of them are naturally occurring, and where they are seriously and rapidly declining in area coverage globally. Mangrove area coverage is estimated to have been reduced from ca. 32 million ha to 15 million ha. Figure 1 shows one of the largest inter-tidal mangroves and salt marsh stands in the Gulf, at Al Khor, on the western side of the Qatari Peninsula, where the sea water salinity levels are suitable for mangroves. The vegetation consists of *Avicennia marina*, *Arthrocnemum macrostachyum*, *Suaeda sinus-persica*, *Salicornia iranshari*, as well as *Halconemum strobilaceum*, and *Halopeplis perfoliata*.

The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_24, © Springer Science+Business Media Dordrecht 2014

Fig. 1 Natural inter-tidal vegetation in Al Khor, Qatar (Photo: Benno Böer)

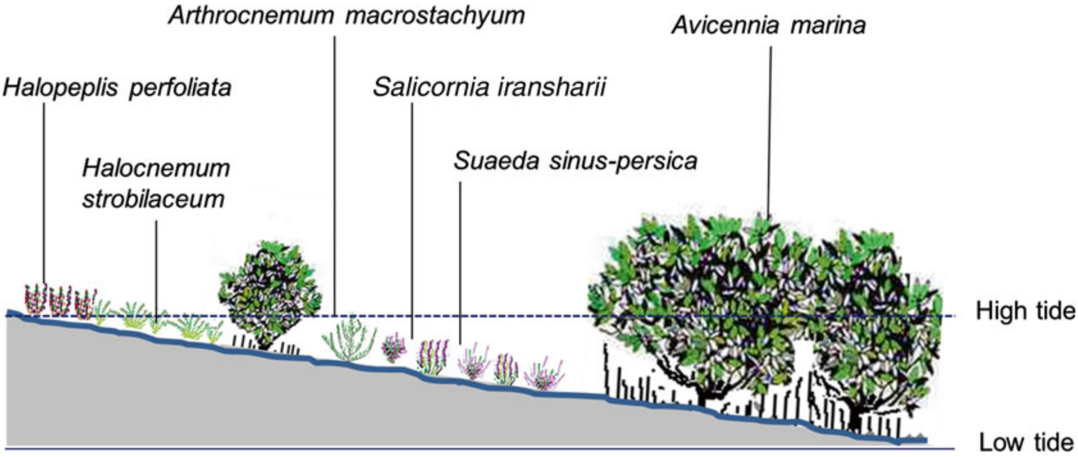

Fig. 2 Inter-tidal vegetation zones in Al Khor, Qatar, from the most seaward edge of *Avicennia marina* mangroves to the most landward salt-marsh zone of *Halopeplis perfoliata* (Graphic by ©: Chanthy Huot & Benno Böer)

Figure 2 offers an insight of a typical cross-section through the inter-tidal vegetation at Al Khor. The most landward edge is often dominated by *Avicennia* mangroves, and followed by a belt of *Arthrocnemum* salt marsh, sometimes with a mélange of annual *Suaeda* and *Salicornia*, and, more landwards with *Halocnemum*, interspersed with *Limonium* axillare, and most landwards *Halocnemum*. Above the high water line is sometimes an additional zone of *Sporobolus ioclados*, *Suaeda vermiculata*, *Tetraena qatarense*, *Biennertia sinus-persica* and *Aeluropus lagopoides*.

The coastal zones are narrow in width, and therefore offer rather limited space for mangroves, which naturally depend on tidal fluctuations. Some experts, supported by decision makers, have succeeded to increase localized mangrove coverage, for example in Abu Dhabi, and in Eritrea, in coastal zones. Others have suggested producing large amounts of mangroves in inland deserts under sea water irrigation, as a cash crop, to make the deserts green, and to sequester atmospheric carbon levels, which is of great importance for the climate change issue. This is a controversial approach, since some experts have warned against irreversible soil salinization, salinization of fresh ground-water resources, as well as the loss of naturally important desert habitats, valuable for biodiversity conservation.

This short communication offers a new idea that has not yet grasped the attention of the climate change movement: Floating mangroves for carbon sequestration. It is planned to develop a proto-type of floating mangroves and salt-marshes to sequestrate large quantities of carbon in delta, coastal, and oceanic environments in the tropics and sub-tropics. The innovative suggestion to connect floating mangroves to carbon sequestration might be a real blessing to influence atmospheric carbon levels in the best interest of mankind.

2 Methods

A small-scale model of floating mangroves was developed in September 2012 (Fig. 3), in partnership between UNESCO, Lusail Real Estate Company, and Mourjan Marinas. Seeds of the mangrove (*Avicennia marina* (Forssk.) Vierh.) were collected from the natural mangrove stands in Al Khor and Al Dhakeera, Qatar, and placed in floating boxes with semi-permeable membranes (Fig. 4), that keep the sandy substrate inside the floating boxes, and that allow for sea water intrusion into the root-zone of the mangroves, in order to supply sufficient water and nutrients. The boxes are being kept afloat by air-filled plastic containers below the floating mangroves. These containvers allow for the adjustment of the buoyancy. From September to November, 2012, the containers were supplied with 10 l of fresh water twice a day, once in the morning and once in the afternoon. In December, 2012, the irrigation was

Fig. 3 Floating mangrove experiment on floating boat-jetty, Lusail City, Qatar, 2012 (Photo: Benno Böer)

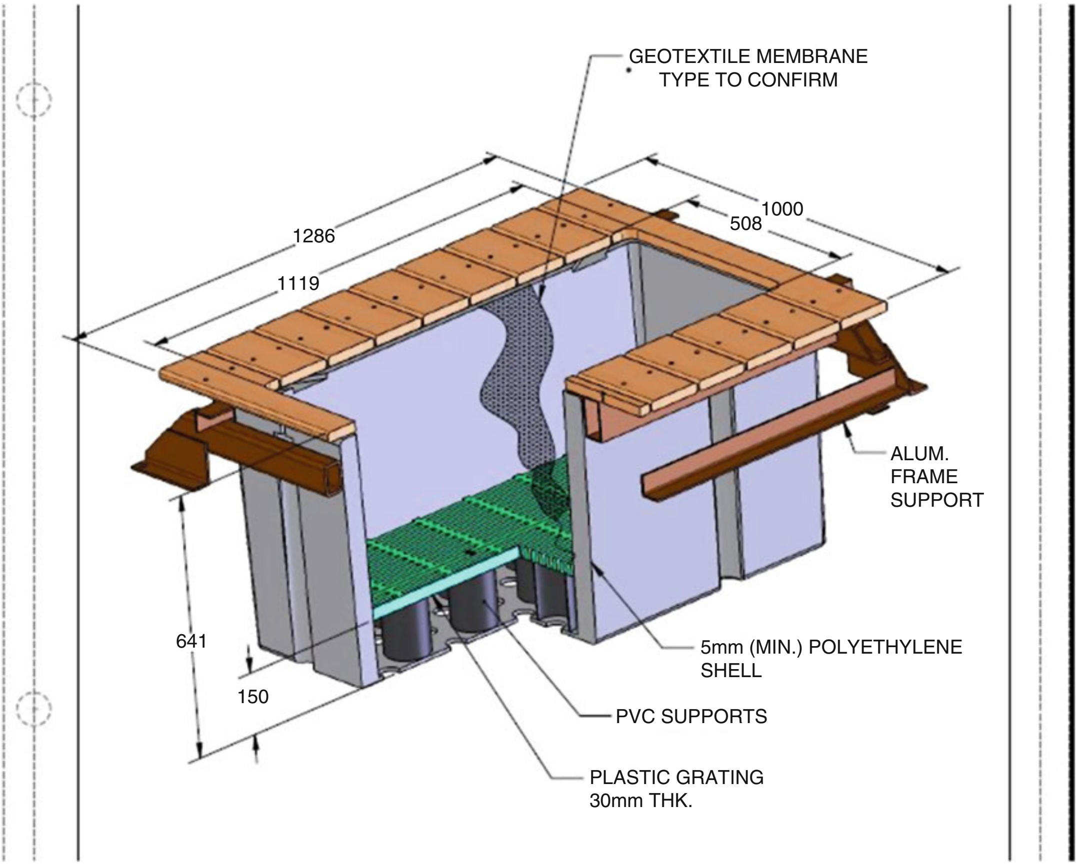

Fig. 4 Design of a proto-type container for floating mangroves (Graphic by Mourjan Marinas)

switched to a mixture of 5 l fresh water and 5 l sea water, in order to make the plants adapt to salinity. From January, 2013 onwards, the floating mangroves were irrigated only with sea water, three times a day (10 l each time). Since the soil volume is rather small and the sandy substrates might have sufficient nutrients compared to the coastal areas where the germination of natural mangroves usually take place, a spoon of NPK fertilizer was added to each container in November, and then 5 kg of dry compost fertilizers was also supplied in December, to maintain the plants to grow well before their roots can take up the nutrients from sea water.

The same experiment was made with *Arthrocnemum macostachyum* (Moric.) K. Koch salt-marsh plants, which were produced from cuttings (Fig. 5). The cuttings were collected from Al Khor in October 2012 and rooted in fresh water. A small amount of salt was added to the water after the cuttings had developed roots to make the plants adapt to sea water before transplanting in the box on December 24, 2012.

3 Results

The plants of both plant species germinated and developed very well, and they are now growing inside the floating containers, without any utilization of fresh-water, purely based on sea water. The detailed data on *Arthrocnemum macrostachyum* has not been available yet since the cuttings was transplanted in late December 2012. In this short communication, therefore,

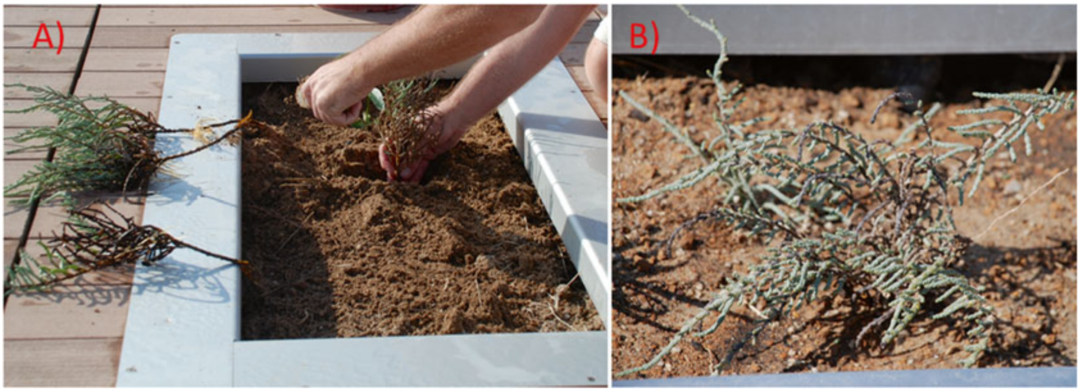

Fig. 5 (**a**) Rooted cuttings of *Arthrocnemum macrostachyum* transplanted into a proto-type container, and (**b**) the cuttings at four weeks after planting (Photo: Chanthy Huot)

Table 1 Survival rate of the mangrove seedlings at 16 weeks after sowing

	Number of germinated seeds	Number of surviving seedlings	Survival rate (%)
Box 1	36	33	92
Box 2	34	26	76

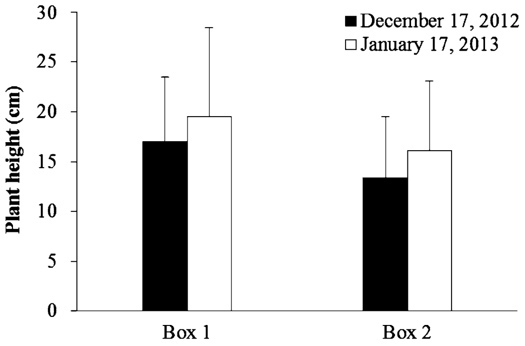

Fig. 6 Plant height (mean ± std, Box 1, N = 33 and Box 2, N = 26) of the mangrove seedlings measured 12 and 16 weeks after sowing

we would like to show information only for the mangroves (*Avicennia marina*), based on data collected during 16 weeks after sowing. The survival rates of the seedlings were high (Table 1). The rate in the Box 2 was low compared to Box 1, because some plants were damaged physically by soil stirring as well as strong-force watering made by the gardeners, and probably strong wind. The average plant height was shown in Fig. 6.

We also observed that some seedlings were yellow since germination (Fig. 7a), and then died when they grew bigger. In addition, we observed leaf-yellowing (chlorosis) and curly dry leaves with dead tissues or black spots showed in Fig. 7b, d. If these occurred to young plants, they mostly died soon after that. Without any damage, the plants looked healthy like in Fig. 7c.

4 Discussion and Prospects

The experiment is promising. The plants survived and grew in large numbers. If it works on a larger scale as good as in the small-scale experiment, it might be a real blessing to influence atmospheric carbon levels in the best interest of mankind. This needs to be tested and refined in a proto-type. The challenge will be to identify reliable partner institutes and funding resources, even though the costs to develop a proto-type and required technical, ecological and economic data are estimated at 2.5 million US$, this amount of money is nothing in comparison to climate-related catastrophic events, such as for example, the tropical hurricane Sandy, that occurred in the year 2012, or the tropical cyclone Gonu, that occurred in 2007, where human losses were tragic and material losses in the range of billions of US$.

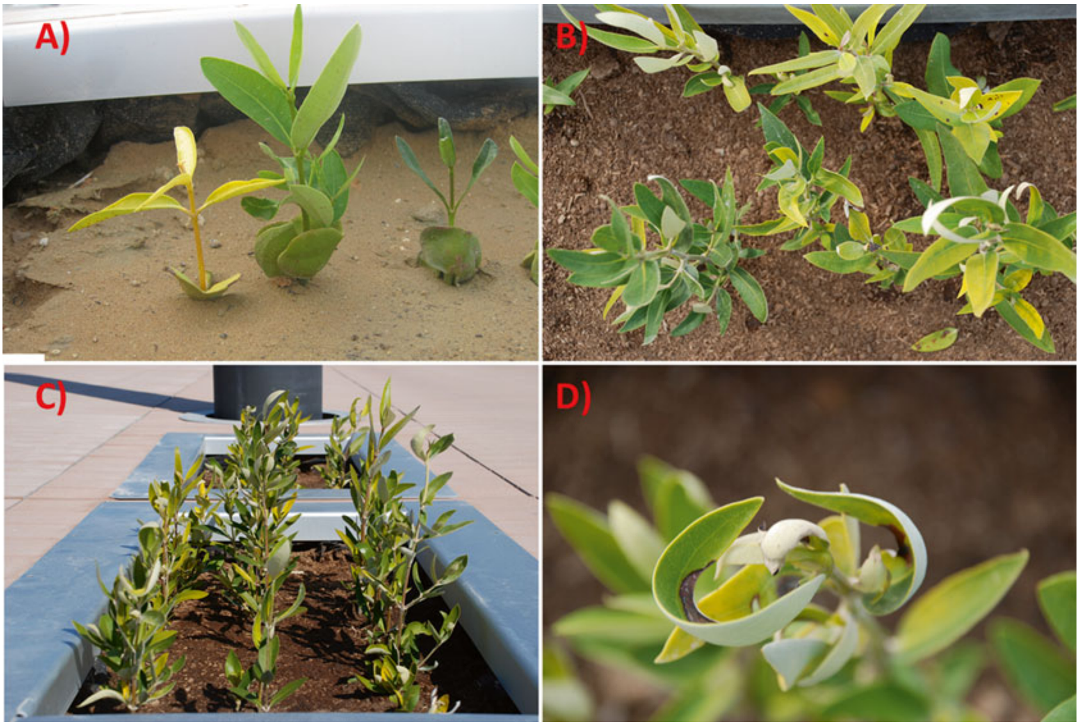

Fig. 7 (**a**) a yellow seedling developing since germinating, (**b**) in homogeneity, in terms of leaf colors, of the plants growing in the same box, (**c**) Well-growing floating mangroves at 16 weeks after transplanting, and (**d**) the development of curly and dry leaves (Photo: Chanthy Huot)

Based on this idea and experiment, it is our aim, to produce as a next step one or several proto-types of larger (20×20 m) floating mangroves, explicit ecological and economic data, one or several M.Sc. and Ph.D. holders, and associated thesis, and several peer-reviewed scientific papers on carbon sequestration, uptake of marine pollutants, cost-benefit, or relevant other topics.

5 Environmental and Economic Considerations

Whilst the immediate focus of this study will concentrate on the potential for sequestering carbon, it is important to stress the substantial ancillary benefits of mangroves which could be realized as floating mangroves. As highlighted by Partick Rönnbäck in his paper *'The ecological basis for economic value of seafood production supported by mangrove ecosystems'* [1], there are major benefits which mangroves contribute to, and whose contribution may carry over as floating mangroves.

Floating mangroves could reduce land-based marine pollution by intake of potassium, nitrogen, and phosphates, which will possibly reduce harmful-algal-blooms, and they could generate jobs, income and profit for people, based on livestock-fodder, clean biofuel, and other profitable products.

Considering the extreme fresh-water limitations in dry lands, where decision makers and politicians are increasingly concerned with water-supply and food-security, floating mangroves could be a real blessing, contributing to food supply (based on livestock fodder, and possibly based on associated fish and shrimp production units) because they assist redressing the dependency on fresh-water in regions of fresh-water shortages, yet surrounded by an abundance of sea water.

The true extent of their benefits remains uncertain, but the potential opportunity cost of not doing so urges further inquiry.

Lastly, as much as there may be scope for optimism, it is also important to understand the potential costs associated with floating mangroves, because this project is not the first time the concept of floating mangroves has been put forward. From hobby fish keepers experimenting with floating mangroves [2], to existing smaller floating islands (Spiral Island [3–5]) and master planned city proposals [6], the idea of using floating mangroves is emerging as a solution to many existing problems, and it is important that we learn more about the potential impacts they might bring.

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World Halophyte Garden: Economic Dividends with Global Significance

Benno Böer, M. Ajmal Khan, and Kenneth B. Marcum

Abstract

Developing biosaline agriculture more intensively will result in seriously enhanced global food-security, especially in dry land countries. It will assist generating jobs and income. Certain successes have been achieved over the past five decades. However, much more attention is needed, including a full collection of wild halophytic plant species. This short communication suggests that the world needs a World Halophyte Garden.

More than 50 years have passed since Boyko [1] re-invigorated a scientific debate on the utilization of an abundant resource in agriculture: saline waters. Numerous scientists have attempted to embark on the process of bio-saline agriculture, with food-security, cash crop development, and freshwater conservation in mind. Conferences were held, scientific books produced, and institutes established, with several halophytes, such as *Sesuvium portulacastrum*, *Avicennia marina*, and *Salicornia* spp. having now achieved a visible application in coastal and dry-land landscaping. Certain successes have been achieved; however, much more attention is needed for coordination, networking, involvement of stakeholders and decision makers, sponsors and producers. More support is required from international and regional donor agencies. Through this communication we would like to illustrate the need for a world halophyte germplasm collection, allowing researchers and developers easy access to germplasm of existing halophyte species, thereby circumventing the considerable expense in time, energy and funds for initial collection of wild halophytic plants, which every research, restoration, or development project faces. In short, the world needs a "World Halophyte Garden".

Previously provided lists of world's halophytes, include above seawater-tolerant, medium, and low

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The original version of this chapter was revised: The book title has been revised. The erratum to this chapter is available at: http://dx.doi.org/10.1007/978-94-007-7411-7_26

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M.A. Khan et al. (eds.), *Sabkha Ecosystems*, Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7_25, © Springer Science+Business Media Dordrecht 2014

salinity-tolerant plant species [2, 3]. Currently, approximately 2,500 halophyte species are known, depending on definition and salt-tolerance, but this does not even include the marine and coastal macro-, and micro-algae. Taking into consideration that a large part of mankind is dependent on food import, with food shortages increasing in frequency and severity in many parts of the world, it is of vital importance to find new ways to produce food. World population pressures and climate change are accelerating both freshwater shortages and salinization/degradation of the world's productive arable land. However, there are thousands of square kilometers of hyper-saline soils with low natural productivity in the world's coastal regions, with an abundance of seawater and other saline water resources, and the above-mentioned 2,500 species of halophytes which can utilize this water. Development of novel saline agricultural production systems utilizing saline water/ecosystems and existing halophyte species may play a tremendous role in helping to alleviate world food and freshwater shortages. The establishment of a "World Halophyte Garden" would ensure the availability of halophyte germplasm, both for the research and development of cash crop halophyte production systems, as well as for ecosystem restoration. Our hope is that the first "World Halophyte Garden" will be established in the near future, thereby promoting research and development of novel biosaline agricultural production systems. An ideal location for this halophyte center would be in the Arab States of the Gulf, a region characterized by severe freshwater shortages and abundant saline ecosystems, as well as a large number of undeveloped native halophyte species.

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ERRATUM

Sabkha Ecosystems: Volume IV: Cash Crop Halophyte and Biodiversity Conservation

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M.A. Khan et al. (eds.), *Sabkha Ecosystems: Volume IV: Cash Crop Halophyte and Biodiversity Conservation*, Tasks for Vegetation Science 47, DOI 10.1007/978-94-007-7411-7,
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DOI 10.1007/978-94-007-7411-7_26

The Book Title was incorrect in PDF and is corrected now. The Book title reads as:

Sabkha Ecosystems

Volume IV: Cash Crop Halophyte and Biodiversity Conservation

The updated original online version for this book can be found at
http://dx.doi.org/10.1007/978-94-007-7411-7

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M.A. Khan et al. (eds.), *Sabkha Ecosystems,* Tasks for Vegetation Science 47,
DOI 10.1007/978-94-007-7411-7, © Springer Science+Business Media Dordrecht 2014