Environmental Footprints and Eco-design of Products and Processes

Subramanian Senthilkannan Muthu
Editor

Environmental Implications of Recycling and Recycled Products

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Preface

Recycling is a familiar term these days and it's becoming popular amongst everyone. The importance of recycling is now being felt where the environmental concerns on landfilling are increasing and the space available for landfilling is getting scarce in every country across the globe. Almost all of the countries have started promoting recycling through various options and one can see recycling bins around in any country. Environmental and economic gains of recycling are becoming familiar to every individual through various resources and recycling is being practiced in almost all the industrial sectors. In fact, recycling has become an inevitable option in the manufacturing and waste management sectors. In most countries these days recycling is being taught in early schooling. Many supermarket brands are rewarding the public to promote recycling behavior.

It is becoming commonplace to recycle almost every product produced on Earth and also every individual material in any form (complete product or waste) due to the environmental and economic gains. At the same time, resources are becoming scarce day by day and eventually recycling is becoming an inevitable option. Any material which is decided to be discarded has to reach a recycling centre now due to these environmental and economic gains as well as to address the scarcity of virgin resources.

There is an ample amount of research happening in many faces and facets across this important topic, that is, recycling, and it's been applied in almost all the industrial sectors as mentioned earlier. Environmental implications of recycling and recycled products deserve special attention for discussion by means of a book and hence this book was planned. This book discusses this important topic with the aid of 10 very informative chapters that disseminate the maximum information on this title. These 10 chapters cover the environmental implications of recycling and recycled products in various industrial sectors dealing with different products and processes. I hope that the readers will get a concrete idea of this area from this book. I take this opportunity to thank all the authors who have contributed the various chapters for their time and efforts spent.

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The Role of Reverse Logistics in Recycling of Wood Products

Michael Burnard, Črtomir Tavzes, Aleksandar Tošić, Andrej Brodnik and Andreja Kutnar

Abstract Consumer awareness, strengthened by legally imposed green constraints, has led to the need for the safe return of products from the field, as well as more environmentally friendly products. As a result, logistics planning must now consider both forward and return flows of products, parts, subassemblies, scrap, and packaging. Reverse logistics is the continuous logistic process through which shipped products move from the consumer back to the producer or recycling enterprises for possible reuse, recycling, remanufacturing, or disposal. The purpose of a reverse logistics process is to regain the value of returned materials or to provide the means for appropriate disposal. The transition from waste management to resource and recycling management, along with increasing price pressure and resource scarcity has required improved quality and efficiency from logistics systems. This applies to businesses from commercial and municipal waste management, as well as industry, trade, and service enterprises with in-house waste disposal tasks. The reverse supply chain includes a series of activities required to retrieve a used product from a customer and either dispose of it or reuse it. The design of efficient transport chains and the optimisation of complex logistics networks, similar to the optimisation of waste collection, waste transport, and waste handling, to give just a few examples, must be applied in the recycling management of all goods. In this chapter a case study of reverse logistics of waste wood and wood products is presented as the coordination and control; physical pickup and delivery of the material, parts, and products from the field to processing and

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recycling or disposal; and subsequent returns back to the field where appropriate. This includes descriptions of the services related to receiving the returns from the field, and the processes required to diagnose, evaluate, repair, and/or dispose of the returned units, products, parts, subassemblies, and material, either back to the direct/forward supply chain or into secondary markets or full disposal.

Keywords Cascade use · LCA · Logistics · Recovered wood · Reuse · Upgrading

1 Introduction

In recent times, the emergence and availability of inexpensive materials and advanced technology led societies to mass consumption and subsequent waste generation and landfilling. At that time, environmental impacts and sustainable development were not a matter of concern. In the early 1970s, however, the need to transition to a sustainable civilisation became apparent. During the following decade, environmental disasters reminded academicians, politicians, the media, and society in general of such issues. By the 1990s, especially in Europe, this was accompanied with legal enforcement of product and material recovery or proper disposal. Terms such as recycling, reuse, resource efficiency, environmentally responsible manufacturing, and green products began to be familiar to all of us. A number of forces seem to be the drivers behind this increase in the need for reverse logistics activities.

Consumer awareness and environmental legislation have led to the need for the safe return of products from the field, as well as more environmentally friendly products. As a result, logistics planning must now consider both forward and return flows of products, parts, subassemblies, scrap, and packaging. Reverse logistics is the continuous logistic process through which used products move from the consumer back to the producer or recycling enterprises for reuse, recycling, remanufacturing, energy production, or disposal. Reverse logistics can be described as the process of planning, implementing, and controlling the flows of raw materials, in-process inventory, and finished goods, from a manufacturing, distribution, or usage point to a point of proper disposal. The purpose of a reverse logistics process is to regain the value of returned materials or to provide the means for proper disposal.

An entirely new spectrum of goods has emerged at what was once considered the end of the supply chain. The transition from waste management to resource and recycling management, along with increasing price pressure and resource scarcity has required improved quality and efficiency from logistics systems. This applies to businesses from commercial and municipal waste management, as well as industry, trade, and service enterprises with in-house waste disposal tasks. The reverse supply chain includes the series of activities required to retrieve a used product from a customer and either dispose of it or reuse it. The design of efficient transport chains and the optimisation of complex logistics networks, similar to the optimisation of waste collection, waste transport, and waste handling, to give just a few examples, must be applied in the recycling management of all goods. Successful reverse supply chains also require careful facilities and business planning to enable cost-efficient and environmentally sound processing. These novel business concepts require innovative reverse logistics, operational transport, and material flow planning to optimise their plant logistics, especially in the field of renewable biobased resources.

Both on the European and global levels, actions are required to increase efficiency significantly in the utilisation of renewable biobased resources. The preferred options aim to extend the overall life cycle of a material by using it in multiple product lines beyond its first use for materials, when functional life permits it. Intelligent concepts for the reuse and recycling of valuable materials at the end of single product life will reduce the amount of waste destined for landfills. Reusing the components of large structures made with engineered solid wood products after their first life cycle is a valuable source of already graded and dried wood to be collected and reprocessed for further use. At the end of their first product life, the majority of wood-based products retains material qualities and quantities that would allow for further use in solid or stepwise disintegrated form (as strands, particles, or fibres). Despite this, recovered wood is currently mainly burned in waste incineration plants, or—with higher power efficiencies—in special wood combustion facilities. However, this ignores the preferred option to hold the biobased, carbon-storing wooden materials at their maximum quality level by reuse in solid form and subsequent recycling of reclaimed wood in as many steps of a material cascade as possible. In the wood product sector, until now the potential for efficient material cascading of engineered solid wood products has been largely underdeveloped. However, recent and ongoing projects are beginning to develop much needed solutions and technologies that will allow more efficient reuse and recycling of reclaimed wood.

Used wooden products, at the end of their service life, will be increasingly treated and recycled to produce 'raw' materials, which will compete with freshly harvested and produced forest products. This presents an opportunity for new and existing businesses to provide products, services, and materials to forest products related companies. Moreover, logistics companies and material processors will have to cooperate to solve challenging and increasingly complex logistic problems to be efficient and profitable. These challenges, along with high material costs, have led to enhanced quality and efficiency requirements for logistics systems. In addition, legal frameworks, the market, and client requirements change permanently. Efficient and economically sound logistics offers companies competitive advantages, and can make recycling enterprises a profitable resource trade. However, reverse logistics networks are complex and require the application of suitable methods of (mathematical) optimisation, each modelling the specific requirements of the value creation chain. This includes independent and comprehensive analysis, planning, and optimisation of material and information flows, as well as waste disposal processes (e.g., container locations, emptying cycles, accumulation sites, decontamination sites, and processing plants).

The aim of this chapter is to discuss the needs for effective waste wood reuse and upgrading. Furthermore, it presents a case study of reverse logistics using waste wood and wood products in Slovenia as an example. It closely examines the coordination and control; physical pickup and delivery of materials, parts, and products from the field to processing, recycling, or disposal; and subsequent returns back to the field where appropriate.

This chapter first introduces European legislation and the role of wood and wood products in the bioeconomy, and then continues with a description of waste wood reuse and upgrading concepts, which includes cascading wood use, classification of hazardous and nonhazardous waste wood, and material considerations for recovered waste wood. The presentation of waste wood flows in Slovenia is followed by a detailed description of a reverse logistics model to collect and process recovered wood.

1.1 European Legislation

Climate change is a global issue, which must be addressed worldwide. Many of the world's political and economic decisions are increasingly determined by resource and energy scarcity in addition to climate change. In these circumstances, a balance must be achieved between multiple aspects of sustainability including economics, ecology, and social well-being. In Europe, several strategic documents, directives, and initiatives were launched with the aim of developing a low-carbon economy in the European Union (EU). Among these documents are the EU Sustainable Development Strategy (SDS, European Commission 2009), which was published in 2006, and reviewed in 2009; the EU Roadmap 2050 (European Commission 2011; European Parliament, Council 2008); and the recycling society directive (Directive 2008/98/EC, European Parliament, Council 2008). Another important document is the Europe 2020 Strategy for smart, sustainable, and inclusive growth, where one of the headlines relates to climate and energy. Furthermore, in 2012 the European Commission launched a strategy entitled Innovating for Sustainable Growth: a Bioeconomy for Europe (COM (2012) 60 final). The Commission states that Europe needs to change radically its approach to production, consumption, processing, storage, recycling, and disposal of biological resources in order to cope with increasing global population, rapid depletion of many resources, increasing environmental pressures, and climate change. Furthermore, the European Commission adopted the communication, 'Towards a circular economy: a zero waste programme for Europe' (COM 2014 0398 final) to establish a common and coherent EU framework to promote the circular economy. The deliverables of a circular economy include: boosting recycling and preventing the loss of valuable materials; creating jobs and economic growth; showing how new business models, ecodesign, and industrial symbiosis can move us towards zero waste; and reducing greenhouse emissions and environmental impacts.

The forest-based sector is a key pillar of Europe's bioeconomy. Using wood products can contribute to significant CO_2 savings in terms of greenhouse gas emissions, embodied energy, and energy efficiency (Hill 2011). The goals of sustainable development are to increase economic efficiency, protect and restore ecological systems, and improve human well-being. Working towards these goals is expected to lead to new concepts, products, and processes that optimise the reuse and stepwise use of forest-based resources. Life cycle analysis, industrial ecology, and the cradle-to-cradle concepts will be used as key tools in sustainable economic development. These tools will also lead to new business opportunities through innovative products optimised for end-of-life reuse requirements and sustainable resource utilisation.

The European Commission has published a new EU forest strategy for forests and the forest-based sector (COM 2013 659 final). One action within the new EU forest strategy is dedicated to innovation and research and to rural development. Among other aspects, the EU forest strategy underlines the importance of building with wood and the importance of considering innovation and research activities in the whole forestry–wood chain. The strategies, envisioned tasks, and measures within have influenced both public funding for research, development, and innovation, as well as research and industrial community readiness and receptiveness. The former is well reflected in the new framework programme of the EU Commission, 'Horizon 2020'. Within 'Horizon 2020' the topic Societal Challenge 2 'Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the Bioeconomy', as well as the goal 'waste as a resource, recycle and reuse, competitive low-carbon energy' of Sustainable Process Industries (SPIRE), Sustainable Industry Low Carbon II (SILC II), Factories of the Future, and Nanotechnologies and Advanced Materials And Production (NMP) research and innovation roadmaps. Together these provide a pathway for the process industry to decouple human well-being from resource consumption and achieve increased competitiveness in Europe by enhancing product ecodesign, ecoinnovation, and life-cycle management. The industry members are represented by the Forest-based Sector Technology Platform which with its Strategic Research and Innovation Agenda for 2020 of the Forest-based Sector (FTP 2013a) and the Horizons—Vision 2030 for the European Forest-based Sector (FTP 2013b) sees this sector as a key actor and enabler of the biobased society.

The new Cohesion Policy 2014–2020 Programming Cycle expects national and regional authorities to develop research and innovation strategies aimed at their 'smart specialisation'. Therefore, concomitant to the EU-level, the EU member states and associated countries have developed their own strategic documents, which have and will continue to have an influence on reverse logistics and wood products recycling.

The Smart Specialisation Strategy of Slovenia, in its 'Pillar II: Value Chains and Networks' foresees several 'Priority areas of use' (PAU) addressing these areas. The PAU SI_industry 4.0/'Smart factories' prioritzes an engaging and creative environment that fosters innovations, which will result in value-added products, processes, and systems initially and primarily for the forest-based value chain.

The innovations should support sustainable building, and provide the necessary optimised complex multifunctional and multicomponent systems that would develop the next generation of renewable building materials (PAU Smart buildings and homes, and PAU Smart resource utilisation). Increased resource efficiency and extended product lifetimes as well as better value side-stream utilisation by process optimisation, reverse logistics, and biorefinery should minimise the negative environmental and human health impacts thus enhancing human well-being (PAU Smart resource utilisation and PAU Health).

The new German Hightech-Strategy 2020 provides the pillar, ‘prioritization of future challenges relative to prosperity and quality of life’, within which the sustainable economy and energy are strongly emphasised. In the German national strategy, ‘City of the future’ (*Zukunftsstadt*), one of the major topics is sustainable development that includes building planning, use, and recycling. The German bioeconomy strategy highlights striving for self-sufficiency in energy and raw materials, as well as the need to invest strongly in developing green technology. Furthermore, one area of action in the German Forest strategy 2020 is dedicated exclusively to ‘Raw materials, use and efficiency’. Furthermore, the new German High-Tech Strategy aims to find solutions for challenges in such areas as sustainable urban development, environmentally friendly energy, individualised medicine, and the digital society (BMBF 2014). One of its five pillars is prioritisation of future challenges relative to prosperity and quality of life. Within this pillar, a focus is on the sustainable economy and energy: the manner in which we produce and consume needs to become more resource-efficient, environmentally friendly, and socially compatible.

Italy’s strategies include: advanced manufacturing systems, advanced materials, and smart manufacturing and construction and technology environments, where the requirement for optimised resource use (reverse logistics and recycling) is a horizontal theme.

The Finnish bioeconomy strategy estimates timber construction to account for a significant share of urban construction. It notes that the growth outlook for timber construction as part of ecological housing and other construction is very positive in Finland and globally. The greatest prospects for timber construction are envisioned to be in large-scale buildings: solutions for residential blocks of flats, office buildings, halls, and various kinds of wooden structures as well as environmental buildings, also including construction-related services (including cradle-to-cradle (C2C) design, reuse, and recycling).

Norway is not a member of the European Union, and has not yet implemented ‘smart specialisation’ strategies in its regional policy framework. However, both national and regional policy initiatives emphasising wood construction and wood as a construction material have recently been developed. An official White Paper was issued on construction politics (KOG 2012) and two national initiatives Bygg21 (DFB 2014) and Skog22 (Innovasjon Norge 2013) have contributed strategies for developing knowledge-based, sustainable, and efficient construction and forest industries. In both Bygg 21 and Skog 22, the strong importance of a forest-based bioeconomy and the importance of timber construction in the future Norwegian economy are emphasised. Areas of particular interest for future wood construction are identified as: multistorey structures in the urban environment, industrialised production and prefabrication, and environmentally sound and energy-efficient buildings.

On the international level, the issue of wood recycling is mostly connected to tackling climate change. Amongst other mitigation strategies, the Intergovernmental Panel on Climate Change (IPCC), in their Fourth Assessment Report (WG3 Chap. 9), lists 'increasing off-site carbon stocks in wood products and enhancing product and fuel substitution using forest-derived biomass to substitute products with high fossil fuel requirements, and increasing the use of biomass energy to substitute fossil fuels' as an option (IPCC 2007). Sustainable production of timber, fibre, or energy from sustainably managed forests is considered to provide the best long-term mitigation benefit. However, in the Special Report of the IPCC 'Renewable Energy Sources and Climate Change Mitigation' (IPCC 2012) the conclusion of Chap. 2 emphasises that in order to achieve the high potential deployment levels of biomass for energy, increases in the competing demand for fibre must be moderate, land must be properly managed, and forestry yields must increase substantially. Expansion of bioenergy in the absence of good governance and close monitoring of land use carries the risk of low greenhouse gas (GHG) benefits. Furthermore, conflicting demands for virgin fibre between the wood-based composites sector and the biomass energy sector are probable and could undermine efforts to mitigate GHG emissions. However, burning virgin fibre may not be the best option when compared to multiple use and long-life products, which are only incinerated at their end of their service life. The correct choice requires detailed and careful analysis, but a reverse logistics system for recycling wood-based products is among the most optimal, albeit currently underutilised, options.

1.2 The Role of Wood and Wood Products in the Bioeconomy

Wood is a natural, renewable, reusable, and recyclable raw material that can play a major role in minimising the negative effects on the climate and environment when it is sourced from sustainably managed forests. Forest biomass is currently the most important source of renewable energy and now accounts for around half of the European Union's total renewable energy consumption (COM 2013 659 final). Wood products contribute to climate change mitigation throughout their entire life cycle. While in the forest, trees naturally draw CO_2 from the atmosphere. During their service life wood products store CO_2 in products and components of the built environment; with extended service lives, the amount of carbon stored in these wood products exceeds the energy required to harvest and produce them. When substituted for fossil fuels at the end of their service life, wood products release their stored carbon back to the atmosphere and provide significant energy returns.

The amount of carbon released during conversion to energy, however, was already incorporated in the woody biomass in forests during the extended service life of the timber products used for energy recovery (Werner et al. 2006).

Letureq (2014) studied effective ways of using wood production from the perspective of climate change mitigation. Two major opposing concepts were compared, carbon sequestration and biomass carbon neutrality. The former advocates that woody resources are regarded as 'renewable' and their use as an energy source is 'neutral' with respect to the greenhouse effect. The carbon sequestration concept calls for increasing the carbon stock in forests, wood products, and other long-term wood storage. Comparison of the heat generation carbon footprint between wood and other fuels has revealed that the intrinsic carbon emission factor for wood is the highest among all fuels in common use. However, this concept of wood carbon neutrality neglects the possibility of carbon storage in long-life wood products (e.g., through reuse or in the built environment). Furthermore, Kim and Song (2014) compared life-cycle assessments of two wood waste recycling systems, particleboard production and energy recovery, and concluded the particleboard production scenario has a greater environmental benefit in reducing greenhouse gas emissions. However, upcycling (retaining wood in the largest possible dimension) offers even greater carbon saving potential through sequestration than downgrading recovered materials to particles for particleboard.

2 A Concept for Reuse and Upgrading of Waste Wood

2.1 Cascade Use of Wood

Efficient resource use is the core concept of cascading, which is a sequential use of a certain resource for different purposes (Tavzes and Kutnar 2012; Höglmeier et al. 2013). This means that the same unit of a resource is used for multiple high-grade material applications (and therefore sequestering carbon for a greater duration) followed by a final use for energy generation and returning the stored carbon to the atmosphere. Intelligent concepts for reuse and recycling of valuable materials at the end of single product life will reduce the amount of waste to be landfilled. For example, the steps of a hypothetical wood cascade might be: (1) collecting, remanufacturing, and reusing large solid or engineered timbers from large structures as many times as possible; (2) when the structural value of the recovered timbers is no longer useful, they may be used for flooring, in solid wood furniture, in window frames, or moulding; (3) chipping, stranding, or otherwise breaking the material down for use in composites such as OSB, LSL, or particleboard, and so on; (4) and, finally, burnt for energy. Although legal frameworks exist to support this process, the necessary industrial facilities and logistics networks remain underdeveloped.

Höglmeier et al. (2013) discussed the potential for cascading of recovered wood from building deconstruction. The study focused on recovered wood from the building sector in large dimensions and without contamination that should first be used to produce timber of smaller dimensions, such as lamellas, which can be chipped after their service life and used in the next cascading step as particles or fibres, and finally as energy. The study concluded that in Southeast Germany 45 % of recovered wood from building deconstruction is potentially suitable for use as raw material for particle or fibreboard production. Furthermore, 26 % of the recovered wood is suitable for reuse and 27 % could be channeled into other high-value secondary applications. The results showed that utilisation of recovered wood in a cascade could increase the duration carbon is stored in wood products and consequently minimise its contribution to greenhouse effects.

The amount of carbon dioxide released into the atmosphere when wood is burned or decomposes is the same as that absorbed by the tree during growth. Still, incineration of wood products at end of life provides various environmental benefits. The use of woody biomass as feedstock for biofuel production helps to avoid the food versus fuel debate for alternative energy, which makes it more attractive from an environmental perspective (Wang 2005). However, Rivela et al. (2006a, b) applied a multicriteria approach in order to define the most suitable use of wood wastes. The study concluded that based on the environmental, economical, and social considerations the use of forest residues in particleboard manufacture is more sustainable than their use as fuel. The results of an LCA study might differ due to the type and management of raw materials, conversion technologies, end-use technologies, system boundaries, and reference energy systems with which the bioenergy chain is compared (Hall and Scrase 1998). Furthermore, Kim and Song (2014) included temporary biomass carbon storage and used the LCA methodology based on ISO 14040 and ISO 14044 and demonstrated that particleboard production from wood wastes produces 428 kg CO_2 eq. less compared to particleboard from fresh wood and that energy production using wood wastes is 154 kg CO_2 eq. less compared to that of the combined heat and power generation process. The results clearly show that cascading through several life cycles prior to incineration is a better option.

2.1.1 Carbon Storage in Wood Products

Trees capture atmospheric carbon dioxide via photosynthesis and a proportion of this sequestered carbon is stored in the aboveground woody biomass. Wood is composed of three main biopolymers (cellulose, hemicellulose, and lignin) and atmospheric carbon accounts for a minimum of 40 % of the dry wood mass (increasing somewhat as lignin content increases). The net benefit of this ability to store atmospheric carbon depends upon the length of time before the material is subsequently oxidised and the carbon is released back to the atmosphere (Kutnar and Hill 2014). In all situations where carbon flows and stocks are considered, it is essential that a distinction be made between biogenic and fossil carbon sources. Even with biogenic carbon it is important to differentiate between carbon that is held in long-term storage (such as in an old-growth forest) and that derived from newer managed or plantation forests.

2.2 Classification of Hazardous and Nonhazardous Waste Wood

Although the cascade use of wood was proven the superior option in wood material flow, several considerations and restrictions need to be made to optimise the cascade and prevent undesired, potentially negative, impacts on human health and the environment. To prevent its decay, or to enhance or achieve properties that are not inherent to solid wood, the wood may be impregnated or surface-coated with several inorganic or organic preservatives and/or coatings.

Therefore, wood from the products at the end of their primary-use service life, or as side-stream from various wood processing needs to be classified and sorted upon arrival to waste-processing facilities, prior to recycling and eventual reuse (the latter discussed in more detail in Sect. 2.3). Table 1 shows classifications of wood and wood-related wastes, selected from a more comprehensive table of all wastes, as defined by the European Commission (Commission Decision 2000/532/EC) and transferred into Slovene legislation (Slovene Decree on waste 103/2011).

Table 1 Classification list of hazardous and nonhazardous waste wood (Commission Decision 2000/532/EC)—all included in the Slovene Decree on waste (103/2011): Annex 4—Classification of wastes

Hazardous waste wood	Nonhazardous waste wood
02—Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing	
/	02 01 07: wastes from forestry
03—Wastes from wood processing and the production of panels and furniture, pulp, paper and cardboard	
03 01 wastes from wood processing and the production of panels and furniture	
03 01 04*: sawdust, shavings, cuttings, wood, particle board and veneer containing	03 01 01: waste bark and cork
Dangerous substances	03 01 05: sawdust, shavings, cuttings, wood, particle board and veneer other than those
	mentioned in 03 01 04
	03 01 99: wastes not otherwise specified
03 03 wastes from pulp, paper and cardboard production and processing	
	03 03 01: waste bark and wood
	03 03 08 wastes from sorting of paper and cardboard destined for recycling
	03 03 10: fibre rejects, fibre-, filler- and coating-sludges from mechanical separation
	03 03 99: wastes not otherwise specified
15—Waste packaging; absorbents, wiping cloths, filter materials and protective clothing not otherwise specified	
15 01 packaging (including separately collected municipal packaging waste)	

(continued)

Table 1 (continued)

Hazardous waste wood	Nonhazardous waste wood
15 01 10*: packaging containing residues of or contaminated by dangerous substances	15 01 01: paper and cardboard packaging
	15 01 03: wooden packaging
17—Construction and demolition wastes (including excavated soil from contaminated sites)	
17 02 wood, glass and plastic	
17 02 04*: glass, plastic and wood containing or contaminated with dangerous substances	17 02 01: wood
17 06 insulation materials and asbestos-containing construction materials	
	17 06 04 insulation materials other than those mentioned in 17 06 01 and 17 06 03
19—Wastes from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use	
19 12 wastes from the mechanical treatment of waste (e.g., sorting, crushing, compacting, pelletising) not otherwise specified	
19 12 06*: wood containing dangerous substances	19 12 01 paper and cardboard
	19 12 07: wood other than that mentioned in 19 12 06
20—Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	
20 01 separately collected fractions (except 15 01)	
20 01 37*: wood containing dangerous substances	20 01 01 paper and cardboard
	20 01 38: wood other than that mentioned in 20 01 37

* Any waste marked with an asterisk (*) is considered as a hazardous waste pursuant to Directive 91/689/EEC on hazardous waste, and subject to the provisions of that Directive unless Article 1(5) of that Directive applies

Although most of the categories are straightforward to identify and interpret, some additional explanation needs to be made for better understanding of legal requirements in wood recycling, and actual mechanisms thereof. In Slovenia, waste from category 17 is not collected as bulk or municipal waste as is true for wood from other categories from 15 to 20 (Table 1). For construction and demolition wastes (category 17), the Decree on waste from construction sites is in place (34/2008), whereas for all the clarifications that are not in this Decree, the Decree on waste (103/2011) is used. All construction wastes are the responsibility of the investor, who must (1) temporarily store construction wastes separately; (2) ensure the removal of construction waste—by turning it over to a collector or contractor of construction waste processing, or taking it to the waste collection centre—unless the amount of produced wood waste (at the construction site) is below 10 m^3. Alternatively, the investor can process construction waste, if an environmental permit has been obtained in accordance with waste management regulations.

Further criteria apply to waste wood classification and sorting (Table 2). The waste wood can, within each category from the classification list (code number from classification list of wastes, Table 1), be further classified into four categories

Table 2 Criteria for wood waste *classification* into four categories (Decree on the recycling of non-hazardous waste into solid fuel, 57/2008—Annex 1, Part 2—Criteria for classification of wood waste into four categories)

Code number from classification list of wastes	Description of waste	Additional description of waste wood, suitable for preparation of solid fuel
03 01 05	Sawdust, shavings, cuttings, wood, particle board and veneer other than those mentioned in 03 01 04	1. Waste wood category 1: sawdust, shavings, cuttings of natural solid wood; 2. Waste wood category 1: sawdust, shavings, cuttings of wood composites and processed uncontaminated wood, if the content of hazardous substances does not exceed maximum values for natural wood from Annex 2 of this Decree; 3. Waste wood category 2: sawdust, shavings, cuttings of wood composites and processed uncontaminated wood, if the content of hazardous substances does exceed maximum values for natural wood from Annex 2 of this Decree.
15 01 03	Wooden packaging	1. Pallets: – Waste wood category 1: pallets of solid wood, such as Europallet, industrial pallets of solid wood, – Waste wood category 2: pallets of wood composites, – Waste wood category 3: other pallets containing adhesives; 2. Transport crates: – Waste wood category 1: transport crates and dividers of natural wood, and crates for fruits, vegetables, decorative plants, etc., of natural wood, – Waste wood category 2: transport crates of wood composites; 3. Cable reels: – Waste wood category 1: cable reels of solid wood
17 02 01	Wood	1. Wood from construction materials: – Waste wood category 1: natural solid wood,

(continued)

Table 2 (continued)

Code number from classification list of wastes	Description of waste	Additional description of waste wood, suitable for preparation of solid fuel
		– Waste wood category 2: wood composites, glued wood, processed uncontaminated wood; 2. Used wood from demolitions and adaptations: – Waste wood category 2: planks, beams, sidings for interior decoration of uncontaminated wood; door panels and frames of uncontaminated wood; interior decoration wall panels, ceiling panels, decorative mouldings, etc. of uncontaminated wood; plywood shuttering panels, – Waste wood category 3: uncontaminated construction timber (beams), wooden latticework and rafters, and other uncontaminated demolition wood.
17 02 04*	Glass, plastic and wood containing or contaminated with dangerous substances	1. Used wood from demolitions and adaptations: – Waste wood category 4: contaminated construction timber (beams), latticework and rafters of contaminated wood, windows, window frames and outdoor doors, impregnated construction wood for outdoor use, contaminated construction and demolition wood; 2. Impregnated wood from outdoor use: – Waste wood category 4: railway sleepers, installation poles, gardening articles and impregnated garden furniture, articles used in agriculture; 3. Used industrial use wood: – Waste wood category 4: industrial flooring, cooling towers; 4. Used wood from hydraulic engineering: Waste wood category 4;

(continued)

Table 2 (continued)

Code number from classification list of wastes	Description of waste	Additional description of waste wood, suitable for preparation of solid fuel
		5. Used wood from ship and railway carts scrapping: Waste wood category 4; 6. Used wood from incidental events (fire-damaged wood, etc.): Waste wood category 4; 7. Final fraction from used wood processing for the production of wood composites: Waste wood category 4
20 01 38	Wood other than that mentioned in 20 01 37	1. Waste wood category 1: furniture of natural solid wood; 2. Waste wood category 2: furniture of uncontaminated wood; 3. Waste wood category 3: furniture of contaminated wood
20 03 07	Bulky waste	Wood waste: Waste wood category 3

Table 3 Limits on the content of hazardous substances in the wood that is treated with preservatives (Annex 2 of Decree on the recycling of non-hazardous waste into solid fuel)

Parameter	Maximum content for natural wood (mg/kg)	Maximum content for treated wood (mg/kg)	Content for contaminated wood (mg/kg)
Boron (B) and its compounds	15	30	>30
Arsenic (As) and its compounds	0.8	2	>2
Fluorine (F) and its compounds	10	30	>30
Copper (Cu) and its compounds	5	20	>20
Mercury (Hg) and its compounds	0.05	0.4	>0.4
Chlorine (Cl)	100	150 without PVC coating and 350 with PVC coating	>150 without PVC coating and >350 with PVC coating

(Waste wood category 1–4, Table 2), using the limits on hazardous substances content set out in Annex 2 of the Decree on the recycling of nonhazardous waste into solid fuel (Table 3).

Wood waste subclassifications depend on the criteria listed in Table 3. Generally, waste wood category 1 contains natural solid wood and sawdust, shavings, cuttings, and the like derived thereof, and processed uncontaminated wood (and its side-products, e.g., sawdust, shavings, etc.), if the content of hazardous substances does not exceed maximum values for natural wood. Waste wood category 2 contains wood composites and processed uncontaminated wood (and sawdust, shavings, etc. thereof), if the content of hazardous substances does exceed the maximum values for natural wood. Waste wood category 3 contains different wood products (e.g., furniture) and composites, which do not exceed the maximum values of contaminant content for treated wood and uncontaminated construction timber (beams), wooden latticework and rafters, and other uncontaminated demolition wood. Waste wood category 4 contains contaminated wood (values exceeding the minimum content allowed for contaminated wood), mainly as code number 17 02 04* from the lists of wastes classifications.

2.3 Material Considerations for Recovered Waste Wood

Unlike wood products recycling, paper recycling is well explored and established both scientifically and economically. Paper products recycling has become commonplace in most industrialised nations and paper products are typically designed with recycling in mind. Furthermore, in many regions of the world, indicating the recyclability of items (especially paper products) is a legal requirement. Correspondingly, it is simple for users and companies to know what is recyclable and what is not. Though many nations have established specific rules related to wood products recycling (Slovenia's rules for wood and wood products recycling are presented in Sect. 2.2), identifying and sorting the highly usable and desirable materials from the less desirable and contaminated material remain difficult. Many of the complications with wood recycling relate to contaminants present in the recovered material. These contaminants range from chemical treatments and adhesives to foreign objects such as nails and screws (Table 4). Nonetheless, the recoverable material present in recovered wood products is considered a valuable resource of raw wood material if it can be effectively utilised (Bejune 2001; McKeever and Falk 2004; Höglmeier 2013).

According to European projects examining the topic (e.g., DEMOWOOD 2015, CaReWood 2015; FPS COST Action E31 2011), there is great potential to expand wood recovery for uses beyond energy and particleboard production (the two most common uses). Many solutions have been proposed to simplify and automate contaminant detection and then sorting and cleaning of the contaminated materials (DEMOWOOD 2013; Hasan et al. 2011). In addition to manual visual inspection and sorting, these solutions utilise a conglomerate of technologies. To detect and separate metals and other solid materials magnets, gravity sorting, rollers, and sieves may be utilised (DEMOWOOD 2012). X-ray fluorescence systems (XRF), near-infrared spectrometry (NIR), laser-induced breakdown spectroscopy (LIBS), ion mobility spectrometry (IBS), and spectrally resolved thermography can be used

Table 4 Common contaminants in recovered wood (adapted from DEMOWOOD 2013)

Contamination Type	Common examples	Sources in recovered waste wood
Chemical	Halogens (e.g., chlorine, bromine)	Preservative treated wood, coated wood (i.e., with polyvinyl chloride (PVC))
	Heavy metals (e.g., cadmium, mercury)	Painted or preservative treated wood
	Volatile Organic Compounds (VOCs) (e.g., formaldehyde, naphthalene)	Wood-based composites using formaldehyde based adhesives, creosote treated wood
Physical	Metals (iron, brass, steel, aluminium)	Fastened wood (e.g., with nails, screws, or plates)
	Glass	Windows
	Plastics	Windows, fastened wood, framing lumber
	Plasters, insulation materials	Framing lumber, indoor wood (e.g., moulding, cabinetry)

to identify chemically treated wood waste (DEMOWOOD 2012). Once these technologies are implemented in a sorting facility, wood waste containing chemical compounds that are limited by law (see Table 3, Sect. 2.2) can be effectively identified and removed from processing. Chemically contaminated wood products of sufficient size may be resawn or planed to a smaller size, removing the contaminated (or otherwise damaged) surface(s) if the chemical penetration is not too deep. To re-enter the market, the newly produced timbers must be graded to certify their fitness for use. Removing physical contaminants such as nails or screws may require manual interventions, or sawing to remove heavily damaged or contaminated cross-sections (e.g., where large fasteners such as bolts, have left large holes).

2.3.1 Outputs of Processed Recovered Wood

The most beneficial use of recovered wood is the highest quality use for which it is suitable (Fraanje 1997). Clean, solid construction timbers, for example, may be resawn and shaped to a smaller size, then used again in solid timber construction. If well protected, wood timbers can be utilised in this fashion for multiple cycles, until the recoverable size is no longer useful. When this eventuality occurs, the timber may be broken down into smaller sizes for other uses such as strands for oriented strand board (OSB), flakes or chips for animal bedding, particles for particleboard panels, and eventually can be burnt for energy. This concept of subsequent use of recovered resources in the highest quality product is called material cascading and significantly extends the service life of materials extracted from natural resources while reducing pressures on raw material sources such as forests (Fraanje 1997, Höglmeier et al. 2013).

3 Flows of Waste Wood—a Case Study of Slovenia

Sources of waste wood in Slovenia include construction residues, demolition wood, household items (e.g., furniture), wooden packaging, and so on. However, wood (as the primary load-bearing material) housing construction accounts for only 3 % of dwellings in Slovenia (Table 5; Statistical Office of the Republic of Slovenia 2004). Housing using a combination of materials likely contributes significantly to the total available stock of recoverable wood from construction as well. Furthermore, many dwellings other than those built with wood may contain wooden elements such as windows and roof trusses that contain recoverable wood. Wood housing construction has expanded since 2002 and is expected to continue expanding as new technologies and products, as well as green building paradigms, influence material selection (Kitek Kuzman 2010; Kušar 2010). Dwellings and other buildings represent a major future source of recovered wood. When these buildings are demolished for new construction, the wood materials that have been protected in their structure and interiors can be collected, cleaned, and reprocessed into new materials. Demolition wood from housing and other buildings, because of its size and condition (i.e., dry and often untreated), presents the simplest form of waste wood to process into new high-value products.

A potentially significant stock of high-quality recovered wood is imminent in Slovenia. Prefabricated houses built before 1992 must be renovated by 2020 to meet thermal transmittance requirements for external walls (Kitek Kuzman and Kutnar 2014). Though the exact quantities are unknown, the renovation process of these homes will produce an influx of materials that must be collected, transported, and processed. Ideally, the recovered waste wood will be preserved in its highest value state and reused in a second long-life product that retains the carbon stored in long-life products. However, the processing infrastructure to maintain the greatest value of the recovered wood is not currently in place.

Municipal waste wood and wooden packaging is collected and transferred to one of Slovenia's 50 waste collection facilities where basic sorting is done to extract recoverable fractions. Between 2008 and 2013 the quantity of these materials

Table 5 Dwellings in Slovenia by building material type in 2002 (Statistical Office of the Republic of Slovenia 2004)

Building material	Number of dwellings	Percent (%) of total[a]
Brick	279,352	60
Concrete, reinforced concrete	28,375	6
Stone	56,586	12
Wood	*13,962*	*3*
Combination	77,695	17
Other	7,059	2
Total	463,029	100

[a]Rounded to nearest whole percent

Table 6 Municipal waste wood and wooden packaging collected and recovered in Slovenia from 2008 through 2013 in tonnes (Statistical Office of the Republic of Slovenia 2014b)

Code*	Category Name*	Year					
		2008	2009	2010	2011	2012	2013**
15 01 03	Wooden packaging	489	849	1,676	2,181	2,370	11,553
20 01 37	Wood containing dangerous substances	221	–	–	–	910	4
20 01 38	Wood other than 20 01 37	10,875	11,110	12,890	19,104	20,634	19,096
Total		11,585	11,959	14,566	21,285	23,914	30,653
Recovered (t)***		5,423	6,852	8,341	14,505	17,148	24,343
Recovered %***		47 %	57 %	57 %	68 %	72 %	79 %

* For more details on codes and categories, see Table 1 in Sect. 2.2

** The significant increase in wooden packaging collected in 2013 is due to a change in the way collections were measured that year

*** Recovered is the amount of the total waste wood collected that was used again for another purpose; this could be burnt for energy, used for particles in particleboard production, chipped for ground cover, or other uses. This value is rounded to the nearest whole percent

collected increased by approximately 19,000 tonnes (nearly a 260 % increase, Table 6). During the same time, the quantity of wood-based material recovered from municipal waste categories also increased by 19,000 tonnes (a 430 % increase in material recovery, Table 6).

Approximately 50 % of wood waste produced by wood-based manufacturers (e.g., such as pulp, paper, sawmilling, and panel producer, List of Wastes category 03; see Table 2) is accumulated and utilised by the manufacturers in further production or burned for energy (Statistical Office of the Republic of Slovenia 2014a, c). The remaining fractions are delivered to other manufacturers or energy producers in Slovenia, delivered abroad, or temporarily stored for later processing (Statistical Office of the Republic of Slovenia 2014a). The quantities of waste wood produced by the wood-based production industry has declined from a peak of 741,047 tonnes in 2006 to 314,947 tonnes in 2013 reflecting the decline in production that followed the economic downturn (Statistical Office of the Republic of Slovenia 2014a).

Large fluctuations in the availability of waste wood, both from industry and produced by the public, affect the ability of businesses that rely on the material to plan their production. Combined with the variety in dimensions and quality, a robust system for collection and processing is necessary to achieve the greatest economic and environmental value from recovered wood. A transnational logistics network is one solution that may enhance the sustainability of a wood-recycling enterprise due to the relatively small national market in Slovenia. A system for collecting and processing used materials from consumers is called a reverse logistics network. A model reverse logistics network for recovering and processing used wood-based materials is described in detail in Sect. 4.

4 Models of Reverse Logistics

A paper by Vandermerwe and Oliff (1990) was one of the early influential contributions to reverse logistics and delivered a systematic analysis of product recovery, but mainly focused on business implications. The authors considered an alternative concept from the existing "buy–use–dump" method common then and now. The proposed concept of reconsumption cycles also emphasised the need for a bidirectional logistics infrastructure.

A year later Stock (1992) published an article focused on the role of reverse logistics in waste reduction. The article emphasised four major issues: resource reduction, recycling, substitution, and disposal. A study by Kopicki et al. (1993) stressed that the opportunities for reuse and recycling were supplemented with market aspects of reuse and extended product life. Stock (1998) published a more detailed book on the implementation of reverse logistics and business practices.

As interest in the field of reverse logistics grew quickly, a comprehensive and systematic overview of the rising issues was published by Fleischmann et al. (1997). The article aimed to provide a general framework for reverse logistics and divided the field into three main areas: distribution planning, inventory control, and production planning. The article provided a summary of some of the basic mathematical models such as the original facility location model (Kaufman et al. 1977) and featured models that included collection, transportation, recycling, and disposal (Gottinger 1988; Caruso et al. 1993).

A warehouse location problem (WLP), sometimes known as the facility location problem (FLP), in its most general form is an optimisation problem concerned with trying to find an optimal placement of facilities or warehouses while minimising transportation costs. Once placed, the facilities, transportation, vehicles, and supporting systems form a supply chain network or simply network. Originally, WLP models were used for forward supply chains where delivering goods directly to each customer creates large delays and transportation costs. The solution is to use warehouses as an intermediate buffer. Similar to the forward supply chain, in a reverse logistic system (sometimes referred to as backward supply chain) retrieving used goods or material directly from customers is infeasible. In most cases, implementing a reverse logistic network requires additional facilities that accumulate returned goods or materials and transport them in bulk. Reverse logistics models usually inherit from the basic WLP and extend them with domain-specific knowledge. In the beginning of the 1990s a vast number of variations were introduced. Clegg et al. (1995) explored the effects of recycling and remanufacturing with linear programming models of production to analyse the viability of the recovered parts in manufacturing.

Barros et al. (1998) presented a network for recovering and recycling sand from construction waste. Their model included placing two intermediate facilities. The first was a regional depot for receiving recovered sand, testing its pollution level, and storing clean sand. The other facility received polluted sand and cleaned it. Their model is a multilevel capacitated warehouse location problem (CWLP), which is an extension of the basic WLP problem that takes into account the capacities of the warehouses and optimises both facility placement and distribution to meet those capacities. Indeed, our model also reflects on their work.

These models were supplemented by Spengler et al. (1997) who developed a mixed-integer linear programming (MILP) model for recycling industrial by-products, which they applied to the German steel industry. The model included allocating recycling plants, calculating their capacities, and made economic considerations as well. Andel (1995) proposed a cost-efficient design method for transportation routes, which included centralising returns through a third-party provider who also handles sorting and regional transportation. Young (1996) described a closed-loop reverse logistic system for the disposal or reuse of the products. Young noted the important role of distributors with regard to waste removal, handling methods, and warehousing costs.

By the end of the 1990s most reverse solutions addressed specific problems and therefore lacked generality. However, in 2001 Fleischman proposed a new definition: '[R]everse logistics is the process of planning, implementing and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain directions for the purpose of recovering value and proper disposal'.

The most generic model was first proposed by Fleischman et al. (2001) and was called a recovery network model (RNM). The model considered the forward flow along with the reverse flow and optimised both distribution and recovery. A mixed-integer linear programme formulation was proposed to enhance the traditional WLP model with two integrated models. One modeled the forward chain connecting production facilities to customers through warehouses, and the other modelled connecting customers to production facilities through disassembly centres. A later article by Isabel (2007) argued that although the model offered generality it was missing three important aspects encountered in real-world implementations of reverse logistics networks such as production/storage capacity limits, multiproduct production, and uncertainty in demand/return flows. Their work proposed an improved mixed-integer linear programme formulation accompanied by a case study for an Iberian company. Some articles explored evolutionary algorithms such as genetic algorithms combined with a MILP model (Hyun and Gerald 2005). Simons (1998) described a system adopted by a company that produced wood panels and other building materials. The company supplied construction sites with special containers for their wood products, and picked the containers up from the construction sites. However, the company hired third-party companies to handle the logistics (e.g., pick-up, transport, and delivery). Additionally, the company recovered the pallets on which their products were delivered. As with the containers, the company hired third-party companies to do pallet collection. Materials that could not be recycled were burned. Although this implementation of a reverse logistic model might have worked well for this specific case, it still cannot be generalised to all wood-based building materials and products.

4.1 A Model of Reverse Logistics for Wood Recovery

In its simplest form, a reverse logistics network for wood product recovery and processing is a generalised CWLP problem augmented with additional model entities to reflect some specific requirements of wood recovery. The purpose of the model we describe is to determine the optimal location and quantity of processing facilities based on the location of existing accumulation facilities (waste collection sites in Slovenia), costs, and ecological impacts.

4.1.1 Model Entities

Our model for reverse logistics reflects the steps in the wood recovery process. Unfortunately, the path recovered wood products must take involves activities that are either not present in conventional primary manufacturing or that must be modified to accommodate recovered wood (cf. Sect. 2.1). Waste wood comes in different sizes, shapes, qualities, and amounts, and therefore requires assessment before its future use is determined. First, it is collected and stored in a suitable environment (i.e., protected from rain) that we model as accumulation facilities (**A** in Fig. 1). In Slovenia's recovery system a number of accumulation centres already exist and, moreover, they also perform basic sorting of waste wood into "junk" wood (unrecoverable wood destined for landfilling, **J** in Fig. 1), into low-quality wood for energy production (burning, **E** in Fig. 1), and in some cases into wood for further processing.

Next, in an implemented wood recovery network, the wood selected for further processing is sorted either manually or by machine into different categories (cf. Sect. 2.2) at sorting facilities (**S** in Fig. 1). In many cases, before further processing, the wood must be decontaminated (e.g., removing fasteners, such as nails and screws, or removing painted or other finished surfaces; cf. Sect. 2.3) at decontamination facilities (**D** in Fig. 1). Depending on economic concerns and business objectives, decontamination and sorting facilities may be combined (**D/S** in Fig. 1).

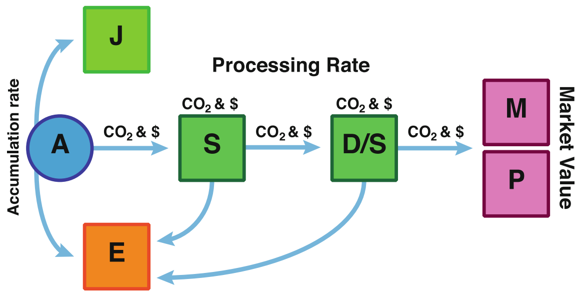

Fig. 1 Model entities and their relationships

Sorting facilities sort waste wood into the following general categories: wood that meets the size and quality requirements for further processing, wood best suited for energy production (**E**), and wood that must be landfilled (**J**). Finally, the highest quality waste wood is ready for further processing (**P** in Fig. 1) or, in some cases, may be sent directly to the market as a raw material (**M** in Fig. 1).

To set up model equations, we associate a number of attributes with each entity. These are: **P** denoting a Boolean value indicating if a facility exists or not (e.g., $A_i^{(P)}$ for accumulation facility **i**); **C** denoting the facility's capacity; **O** for the annual operational cost of the facility; **S** as the production capability of a facility; and **X** denoting the construction cost of the facility.

Furthermore, each facility has geographic coordinates that are used to calculate the distance between them and the transportation cost (**$** in Fig. 1), as well as the carbon footprint of transportation ($\mathbf{CO_2}$ in Fig. 1). To simplify the modelling we define distance matrices separately for facilities **A** and **S**—as a matrix **X**—and for facilities **S** and **D**—as a matrix **Y**.

4.1.2 Optimization Problem

The model we described is a basic model of reverse logistics and is represented by a mixed-integer linear programme. The model is divided into two main parts, one for the placement of facilities determines the optimal location for each entity (accumulation centres, decontamination centres, and sorting centres). The other part models the transport routes from one facility to another. Finally, a single MILP is constructed for the optimisation of cost and carbon footprint subject to a set of restrictions obtained from the described model entities.

Currently this model is specific to the Slovenian ecosystem, and considers only three types of waste wood: wood suitable for reuse, wood of poor quality used for energy (**E**), and wood destined for landfilling (**J**). In other countries, these categories will be defined through the national and regional legal frameworks, building traditions and methodology, and cultural considerations that affect material choices as well. Increasing the number of categories or changing their definitions will only minimally affect the model's results. The mathematical formulation of the criterion function, the constraint functions, and variable descriptions are provided in Eqs. (1) to (5), where

$$\min \begin{pmatrix} \sum_i \left(A_i^{(X)} A_i^{(P)}\right) + \sum_i \left(S_i^{(X)} S_i^{(P)}\right) + \sum_i \left(D_i^{(X)} D_i^{(P)}\right) + \\ \sum_i \sum_j \left(X_{ij} A_i^{(P)} S_j^{(P)} S_j^{(S)}\right) + \sum_i \sum_j \left(Y_{ij} S_i^{(P)} D_j^{(P)} D_j^{(S)}\right)(1 - E - J) + \\ \sum_i \left(A_i^{(O)} A_i^{(P)}\right) + \sum_i \left(S_i^{(O)} S_i^{(P)}\right) + \sum_i \left(D_i^{(O)} D_i^{(P)}\right) \end{pmatrix} \tag{1}$$

subject to

$$\sum_i A_i^{(C)} \leq \sum_i \left(\sum_j S_i^{(P)} A_j^{(P)} \right) S_i^{(S)} \tag{2}$$

$$\sum_i S_i^{(C)} \geq \sum_i \left(\sum_j S_i^{(P)} A_j^{(P)} \right) S_i^{(S)} \tag{3}$$

$$\sum_i A_i^{(C)} (1 - E - J) \leq \sum_i \left(\sum_j D_i^{(P)} S_j^{(P)} (1 - E - J) \right) D_i^{(S)} \tag{4}$$

$$\sum_i D_i^{(C)} \geq \sum_i \left(\sum_j D_i^{(P)} S_j^{(P)} (1 - E - J) \right) D_i^{(S)} \tag{5}$$

The criterion equation (Eq. 1) is a function that minimises the building cost, transportation cost, and operation cost. The building cost is composed by the cost of building all the facilities (**A**, **S,** and **D**) that we will need to process the waste wood in our accumulation centres. The transportation costs consist of the cost of moving all the wood from **A** to **S**, and the cost of moving the wood to be decontaminated from **S** to **D**. The last part of the criterion equation is the operating cost of each facility, which our MILP will position. Next, we define the constraints.

The first constraint (Eq. 2) guarantees that the amount of wood that we are going to process in the sorting centres is the same as the amount of wood we have in our accumulation centres. The second constraint (Eq. 3) restricts the amount of wood being processed in a sorting centre to the centre's maximum capacity. This is followed by the third constraint (Eq. 4), which mandates that all the wood that must be decontaminated is processed in the decontamination centres. Finally, the fourth constraint (Eq. 5) caps the amount of wood processed in the decontamination centres at their capacity.

The evaluation of the MILP gives us the optimal facility placement and best transportation routes based on cost considerations, material accumulation, processing rates, and associated greenhouse gas emissions.

4.2 Implementation of the Model

This section describes technical implementation of the reverse logistics model for wood recovery. The user interface and some processing steps are implemented in Web-based frameworks to provide familiar and highly customisable interactions for users.

4.2.1 System Architecture

The systems architecture follows the basic client–server type architecture (see Fig. 2). The server side is hosted on the 8-core i7 3820 CPU with 32 GB of RAM and running Debian-based Linux. Furthermore, both the front-end and server-side applications contain several different technologies to support scalability and stability. The underlying software layer on the server side is an Apache2 http server (version 2.2.22) hosting an open source PHP framework called CodeIgniter (version 2.2.1) following a 'model-view-controller' architectural pattern. The PHP framework ensures security and serves as an interface between the database and the model. A MySQL database is used to store all inputs and outputs of each computed instance of a model. The model itself was implemented in MATLAB® (version R2014a) with an optimisation toolbox containing an integer and mixed-integer linear programme solver using the branch-and-bound method.

The connection between the server and client sides uses a REST protocol. The client side was implemented using Google's AngularJS library (version 1.3) with modern HTML/JavaScript bindings. Location-based data are rendered using the Google Maps API (version 3). The graphical interface was built with the Bootstrap front-end library (version 3).

Once the model data are prepared on the client side, we utilise the REST interface to queue computation jobs on the server side. We decided to implement the job queue to support multiple simultaneous users committing different instances of a model for computation. Furthermore, this also solves possible race conditions and minimises the impact on limited hardware resources. The jobs from the queue are processed using MATLAB in a first in, first out fashion. After the computation is complete the result is parsed using a PHP script, saved into a local MySQL database, and finally the client is notified about the results to be viewed and inspected.

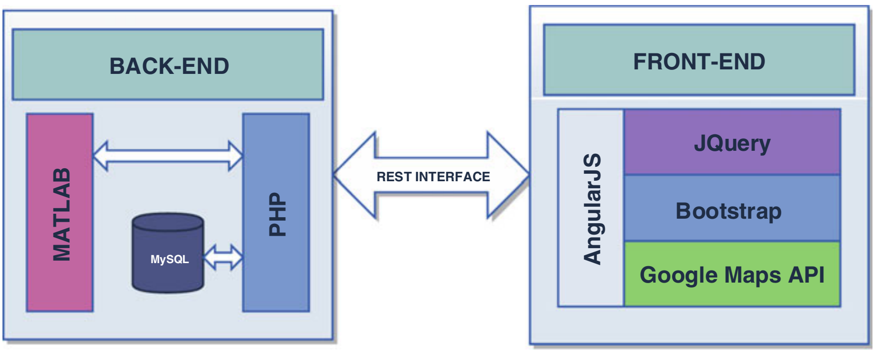

Fig. 2 Application architecture

4.2.2 Using the Application

The application was designed as a ‘wizard’ guiding a user through the necessary steps of building the model. In this section we take a more detailed view of the client side of the application and steps that need to be taken to build a custom model successfully.

Entering the Model

In the first step, the user sets global parameters such as costs associated with building sort and decontamination centres, as well as transportation costs. This step is followed by adding accumulation centres, their locations, and capacities (Fig. 3).

In the third step, the user defines the possible locations for decontamination centres (Fig. 4). Note that these are potential locations as the evaluation of the model will either place them or not based on the value of $\mathbf{D}_\mathbf{i}^{(\mathbf{p})}$. The sorting facilities are currently considered to be at the same locations as decontamination centres (cf. **S** vs. **D/S**) although in the future they may be treated separately from them. Note that this sets the distance matrix **Y** to 0. Furthermore, the user also has to set the expected processing capacity of individual decontamination centres. In this case, capacity is the centre’s annual throughput capability. The total sum of the capacities of all possible decontamination facilities must be equal to or greater than the sum of all waste wood collected.

After all accumulation and decontamination locations are entered, the user also has to enter their contact details so that the system will notify them upon successful completion of the computation. Before sending all the data be computed, the application calculates the distance matrix **X** (note, the matrix **Y** = 0). It is calculated

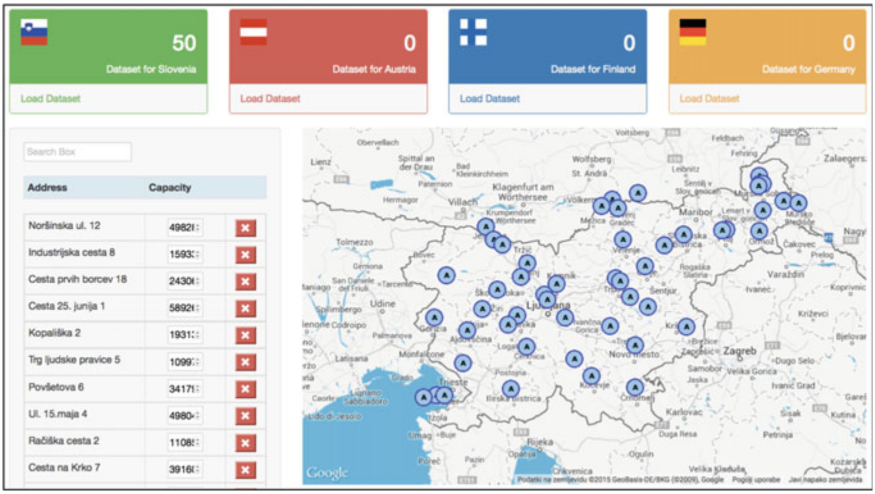

Fig. 3 Step two—adding accumulation centres (circles with an “A”)

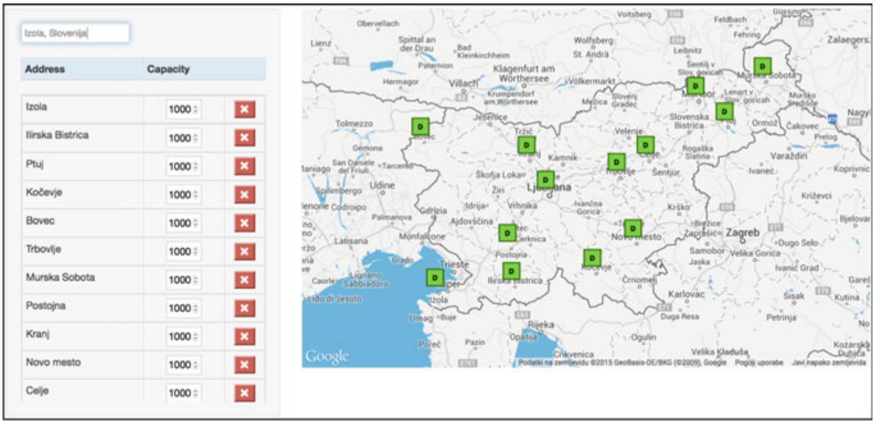

Fig. 4 Step three—adding decontamination centres (squares with a "D")

using distances from the Google Maps API. Moreover, to speed up the computation process the distances are cached and possibly reused.

Finally, the application stores all previously entered models, which can be reused by simply selecting them from a list (Fig. 5).

The Result of a Computation

When the computation on the server is completed, the user is notified that the results are ready for examination. The results are displayed on a map with more detail about each accumulation centre presented in tabular form below the map.

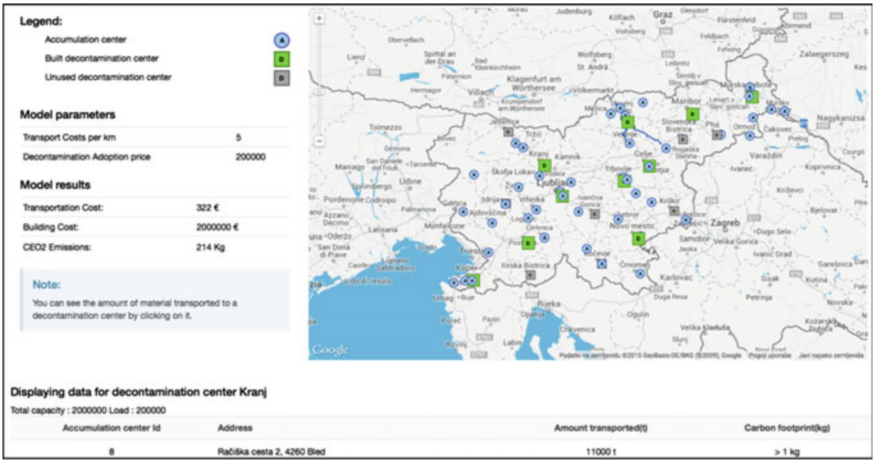

Fig. 5 Computation results. Note that to improve legibility the of accumulation centres is cut after the first centre

The system renders the decontamination centres that should be constructed in green and the unselected locations are rendered in gray. The model parameters are located on the left sidebar with some additional outputs of the model including the total value of the minimisation function cost in € and CO_2 emissions on yearly basis. The CO_2 emissions do not include operating emissions, as these data are not readily available and must still be collected.

By clicking on a placed decontamination centre a table containing more details is displayed below the map. This table contains a list of accumulation centres and the amounts of waste wood that will feed the selected decontamination centre.

For improved visualisation the routes taken for transporting waste wood from an accumulation centre to a decontamination centre are emphasised.

5 Discussion and Conclusions

The forest-based sector can become a leader in achieving the European Commission's ambitious CO_2 emissions reductions goal (Roadmap 2050) with innovative production technologies, reduced energy consumption, and increased wood products recycling. The use of forest products in products with long service lives, such as in the built environment, allows for the possibility of extended storage of atmospheric carbon dioxide.

Forest-based industries are continually developing advanced processes, materials, and wood-based solutions to meet evolving demands and to increase competitiveness. Furthermore, new advanced wood-based materials with improved intrinsic properties that promote efficient product reuse, recycling, and end-of-life use can pave the way to a low-carbon economy. Interactive assessment of process parameters, product properties, and environmental impacts should be used to aid development of innovative wood processes and manufacturing technologies, existing and planned, which embrace the cradle-to-cradle paradigm. Recycling, upcycling, and end-of-life disposal options need to be integrated in a fully developed industrial ecology. Intelligent material reuse and upcycling concepts could reduce the amount of waste destined for landfills or downcycling. However, in order to develop and/or optimise waste-wood processing to minimise environmental impacts, much more information must be gathered about relevant process factors. This includes the development of chain of custody procedures throughout the entire life cycle, including a robust reverse logistics system, which present new or expanded business opportunities to logistics operators and wood processors.

Building decontamination and sorting facilities is a costly infrastructural investment that might not be profitable if done in less than optimal fashion. For this reason, the developed model can and should be further improved by including a return on investment calculation for placed facilities. In addition, the model will be extended transnationally to include other European countries and cross-border cooperation. The model should be modified to include legal parameters that define new categories and quality assessments in each of the entities.

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Recycling Potential of Building Materials: A Review

Himanshu Nautiyal, Venu Shree, Sourabh Khurana, Niraj Kumar and Varun

Abstract All buildings have a specific lifetime which can be divided as construction, operation, and demolition phases. A lot of energy and capital are required in the construction phase of a building inasmuch as a large variety of materials is required for building construction. A high amount of waste material is generated in the construction and demolition (C and D) phases of a building. Due to this fact the dumping of C and D waste materials for landfill is neither economical nor environmentally friendly due to the many environmental impacts associated with it. Thus it becomes quite important to think about the reuse of C and D waste of a building. Recycling and reuse of waste material reduces the requirement of fresh and virgin materials in construction of new buildings. Along with the requirement of fresh material, it increases energy requirements as well as externalities. As we know, many GHG emissions are associated with procurement, manufacturing, transportation of building material, and on-site construction activities which can be reduced by reuse of waste materials in new building construction. This chapter reviews the recycling potential of different types of building materials as well as the energy, economic, and environmental impacts on construction of buildings.

Keywords Building · Material · Construction · Recycling · Waste

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1 Introduction

In the present era, the effect of climate change has been observed in various parts of the world. The world's population has been increasing dramatically in the last few decades and the consumption of natural resources also has increased to a higher level. Climate change problems and the high amount of greenhouse gas (GHG) emissions are accompanied by continuous consumption of resources (Sharma et al. 2011). The excessive consumption of primary materials shows adverse environmental effects. This is because destruction of landscape areas is associated with the extraction and mining of scarce materials. In addition to this, excessive consumption of the resources leads to scarcity of resources for the future. Therefore it has become quite important to think about protection of scarce and valuable materials/resources. There is a huge demand for these materials in the building construction sector. With the growing world population, the construction rate of buildings is also rising. Buildings have become the basic need of society because they provide shelter, security, and a comfortable indoor life. A noticeable increase of the construction rate of buildings is coming up in almost every nation in the world to accommodate their populations.

As the world building sector is increasing at a massive rate the environmental impacts associated with it are also rising. Buildings consume a high amount of energy during their life cycle, that is, from the stage of extraction of raw materials to final demolition. It has also been concluded in many studies that a large amount of energy consumption is associated with the construction phase of the building which includes extraction of raw materials, processing and manufacturing, transportation, and so on (Sharma et al. 2011; Varun et al. 2012; Devi and Palaniappan 2014). Apart from energy consumption, buildings consume an excessive amount of materials and resources during their construction phase. The demand for building construction materials is increasing dramatically throughout the world which leads to fast depletion of resources and raw materials on Earth accompanied with the contamination of water and air. In addition to this, a high amount of GHG emissions are released during the construction, operation, and demolition phases of a building which can be measured in terms of carbon footprints. Excessive use of construction materials and their extraction, processing, and transportation contributes a lot of GHG emissions to the atmosphere (Shree et al. 2015). Thus it now becomes important to understand the need for protection of these resources and control of the environmental impacts associated with their excessive use.

One method to solve the above problems may be the optimum and limited use of available resources. But the world population demand is becoming so high that it is quite difficult to cut down on the massive use of virgin materials in building construction. Another solution of this problem is reuse of an entire building structure by shifting the entire structure to other locations. This concept may be effectively possible for small houses but is not suitable for large building structures made up of concrete, bricks, and other heavy elements (Jeffrey 2011). Therefore the effective method to save new and fresh construction materials is recycling. During the construction and demolition phases of a building a large amount of waste is generated and dumping this waste to landfills clearly means the wastage of all embodied energy invested on them. The use of C and D waste in landfilling is not suitable from an environmental aspect because they require large landfill spaces and also contribute to worsening valuable lands. Instead of excessive landfilling, resulting waste materials can be recycled and reused in other construction works so that excessive consumption of new virgin materials in building construction and the problem of large landfill space can be reduced considerably (Chini and Goyal 2012). In addition to this, the recycling of building materials is also an important issue for sustainable development.

The recycling of building waste material can also help significantly to reduce the environmental effects associated with the building sector. As the entire world is focusing on sustainable development, it becomes the key issue among all areas of social, economic, and environmental points of view. Therefore, in order to achieve sustainable development in buildings, they must be designed with minimum energy consumption and GHG emissions during their entire life cycle. Recycling helps in conserving embodied energy associated with construction materials and reducing their carbon footprints. However, the amount of recycling depends upon material type and its condition and life as waste. The present work is focused on the need for recycling and its importance for sustainability and it also reviews research work carried out in the field of recycling of C and D waste generated by buildings. The chapter begins with a discussion regarding the importance and requirements of recycling. After this, different methods of recycling and associated processes are discussed. The materials used in building and their recycling potential are also discussed with the work carried out by various researchers on waste management through recycling of building materials.

2 Materials Used in Building Construction

A building is a structure that uses various types of material during its construction. This includes resources such as sand, masonry, timber, and the like, and materials prepared through various processing and manufacturing techniques. Several manufacturing units were established throughout the world for the production of construction materials including cement, glass, and so on. Earlier mud, clay-type biodegradable and ecofriendly materials were used to build small homes; then wood became the sole material to construct homes (small homes, cottages, etc. exist in the present time also) but with the passage of time new construction materials with different properties were introduced by human beings. Nowadays concrete, bricks, metals, glass, composites, and plastics, among others are commonly used in building construction (Fig. 1). These man-made materials are not as biodegradable as mud, clay, and wood but due to their construction-favourable properties they are popular in large scale throughout the world. Not only in developed urban areas, but also in villages, these materials have become preferable for building construction.

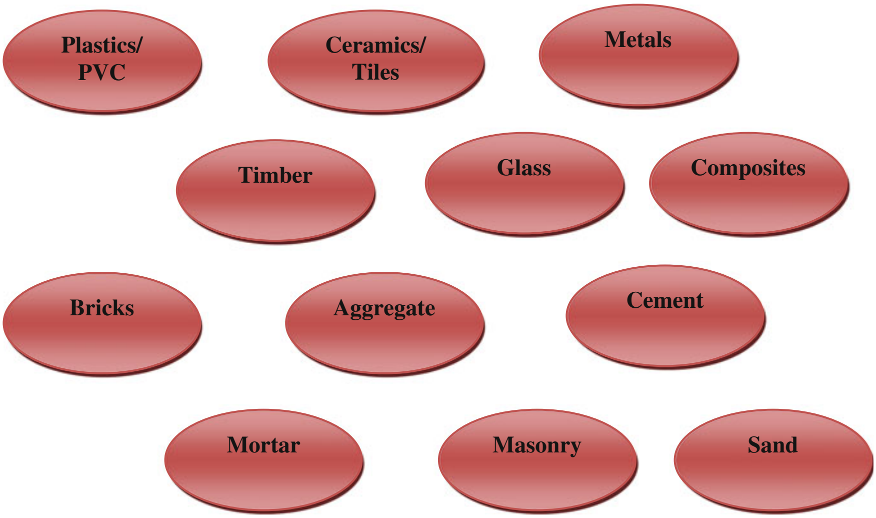

Fig. 1 Commonly used materials for building construction

Today, concrete is popularly used in almost all building construction works and is prepared by aggregate and cement which acts as a binder. Portland cement is a commonly used material and it is widely available at low cost. The concrete is also used with steel bars to increase its strength, commonly known as reinforced cement concrete (RCC). Other fibrous materials such as fibreglass and carbon fibres are used as cement composites. In addition, sand is also used with cement to prepare the concrete mixture. Gypsum concrete is another building material and is made up of gypsum plaster, Portland cement, and sand. Bricks are also important building materials used in our present age and produced in various types and classes. Fired clay bricks are popularly used in bulk and considered a strong material in construction. Air-dried bricks made up of mud and clay are known as mud bricks. Earlier mud and clay were used to build walls directly, not in the form of bricks. Masonry such as rocks and stones is also a strong and long-lasting material which is commonly used in walls, foundations, and the like. These are quite dense and heavy and also were a good choice of ancient civilisations in past ages. Ceramics and tiles have found applications in flooring, sidings, walls, roofing, ceiling, and so on. Tiles are a good choice of architects and engineers in today's building construction due to their special properties including moisture, scratch and stain resistance, light weight, good textures, and finish. The use of ceramic tiles is very common in buildings, however, metal and glass are also being used to manufacture the tiles.

Timber and wood are products of trees and have been used as building materials for several years in framing, doors, and windows, for example. Even some small homes and cottages are still built using wood today. A variety of timbers and woods are available for building construction depending upon the type of tree and also the cost. In addition, metals are used for the structural framework to provide sufficient strength and support to a building. Steel is widely used in building construction due to its strength, flexibility, and long-lasting properties. Tin and aluminium alloys provide better corrosion resistance and light weight making them a good choice in construction. Copper also has good building material properties including corrosion resistance, light weight, and so on, but it is more expensive than other building materials. It is used in roofs, domes, vaults, cladding of walls, and so on. Apart from the structural use, metals are also used in sanitary fittings, electrical fittings, and appliances. Another important man-made building material is glass which is brittle in nature and is prepared by mixing sand and silicates in a furnace. Nowadays it is used in windows and doors in large-scale building construction. In addition to this, it is even being used to cover complete walls and façades of buildings. Other man-made materials include plastics, and PVC, which are the product of polymerisation and used to make pipes to carry electrical wires, water, and sewage-like products. They are widely accepted in building construction due to their light weight and high plasticity.

The materials discussed above are common and widely used building materials, nevertheless there are many other materials that are important components of building construction including paints, distempers, asbestos, and asphalt. Some special materials are also used in various miscellaneous applications such as moisture protection, insulation, and waterproofing. In addition to this, new building materials are being introduced with advances in materials technology due to which building construction becomes far better.

3 Recycling of Building Materials

It has been discussed in previous sections that several materials and construction techniques are involved in making a building that result in a lot of waste material during the construction phase and it can be referred to as construction waste. Likewise when the building life is over and the demolition process is carried out, the building structure is converted into a big mass of material waste that can be referred to as demolition waste. As a matter of fact, the amount of demolition waste is greater than the waste generated in the construction phase. In general, demolition activities often produce 20–30 times more waste then construction (Jeffrey 2011). About half of the material used and wasted throughout the world is associated with the building sector (Department of sustainability, environment, water, population and communities 2012). Construction and demolition waste associated with a building depends upon the materials used and construction techniques involved. Site management, manufacturer, procurement, supplier, contractor, designer, owner, and logistics are the main contributors of C and D waste (Thomas and Wilson 2013). Earlier, for convenience the C and D waste was often used for landfill, but the landfill or dumping of the combined C and D waste is not beneficial from economic and environmental points of view. The problem of land requirement and wastage of valuable land and high capital are associated with disposal of debris and making it an unsuitable method for waste management. Also, large landfill areas can become a big source of methane which is not easily acceptable from an environmental point of view. A lot of embodied energy is always involved in extraction, manufacturing, and processing of raw materials; that's why dumping of materials waste clearly means the wastage of energy and capital invested on them (Sharma et al. 2011). In addition to this, other environmental effects are also associated with C and D waste such as land wastage and contamination of fresh water and soil (Chini and Goyal 2012). These factors compel us to think of reusing the C and D waste so that associated embodied energy wastage and environmental impacts can be reduced significantly.

Recycling of waste materials is the most promising method to control the impediments associated with management of C and D waste. Today almost all nations of the world are concentrating to promote recycling of waste. Yuan and Shen (2011) presented a review on the studies of C and D waste management and found significant contributions of developed countries to the research in this field. The developing countries are also trying to give an effective contribution to promote C and D waste management. The research on C and D waste management is becoming an important matter of concern worldwide. Also, more research in this field is anticipated from developing countries due to major construction activities. The study also concluded that survey and case studies are popular methods for data collection and a descriptive analysis approach is mostly used to process the data.

Many energy consumption and environmental impacts can be reduced by recycling and reusing C and D waste in new construction. Figure 2 shows the various phases of building where waste produced after the construction and demolition phases can be recycled and reused to be the part of further building construction and other uses. Apart from recycle and reuse, C and D waste can also be reduced by finding and measuring the potential waste in the initial stage of the design process. However, if it is not done, the entire C and D waste management depends upon recycling and reusing only. Reduce, reuse, and recycle are the 3Rs of waste management and provide effective solutions to deal with waste and the environmental impacts associated with it (www.sustainabledevelopment.un.org). C and D waste is accumulated in a construction or demolition site and is always a mixture of raw materials, thus it is important to separate them to reuse again. Poon et al. (2001) presented the need of separating the C and D waste into its constituents before disposing to landfills and public filling areas. The study was carried out to analyse waste-sorting methods on construction sites of buildings in Hong Kong and found that source separation needed less effort to separate inert (bricks, sand, concrete, etc.) and noninert (wood, paper, plastics, etc.) materials in C and D waste.

The separation of C and D waste can be carried out by manual selection of materials but it requires a great deal of manpower and time. The reduction in size of waste materials and the use of conveyors, mechanical equipment, and machinery makes the selection and separation more efficient. Sometimes toxic and hazardous materials may be present in construction or demolition sites; it then becomes necessary to identify and separate them out. Also some materials are not suitable for landfill and disposal depending upon their impacts on surroundings. All these

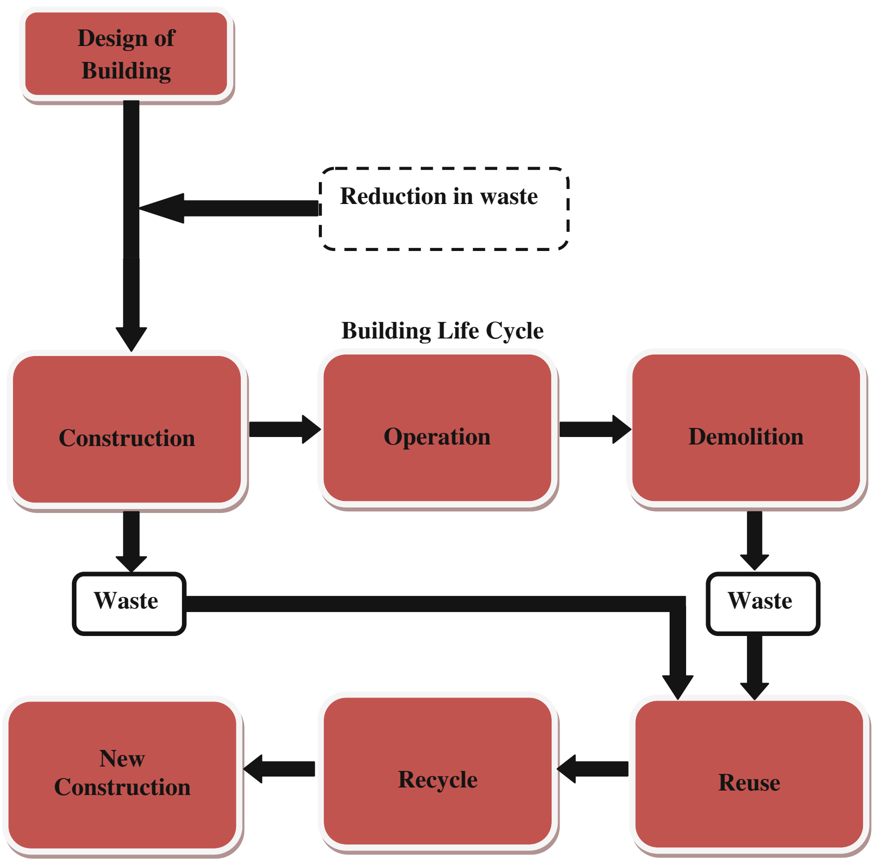

Fig. 2 Recycling of C and D waste from buildings

materials may require special handling and proper techniques to recover and separate them out. Therefore, proper identification and separation of materials from C and D waste is necessary before further reusing and recycling. As discussed above, recycling of debris is a promising alternative to deal with building materials waste instead of disposal, therefore it is necessary to recycle all C and D waste as much as possible. However, all C and D waste cannot be recycled completely so the material waste that cannot be recycled has to be disposed of or used in landfill.

Several research works and studies have been carried out on the methodologies and techniques for the management of C and D waste because quantification and estimation of such waste are essential for proper implementation of waste management techniques. Wu et al. (2014) have presented a review of existing methodologies to quantify C and D waste generation. Comparison was carried out by site visit, generation rate calculation, classification system accumulation, variables modelling, and other particular methods in the study. A decision tree was also presented to select the most appropriate method to quantify waste under different scenarios.

Huang et al. (2002) have carried out an analysis covering technical and cost-benefit analysis for a mechanical sorting process for recycling of C and D waste with respect to three different product streams and discussed their recycling feasibilities. Melo et al. (2011) have carried out a study on C and D waste generation and management in the Lisbon, Portugal metropolitan area. On the basis of construction activities and movement of waste loads, C and D waste generation was estimated for the year 2006 and 2007. The study found a considerable amount of C and D waste generation in the Lisbon metropolitan area and especially in the Lisbon municipality.

Yuan et al. (2011) have carried out a study and discussed 'energy theory' to analyse the efficiency of recycling of C and D waste and to include social, environmental, and sustainable aspects along with the cost benefits in it. Applying this theory to the Chinese construction sector, it was found that a closed loop recycling method is better than an open loop recycling for C and D waste management. Study shows that this theory can also be applied to other construction industries to analyse techniques of waste management.

Yuan et al. (2012) have estimated the deficiency of approaches which considered dynamics and interrelation of variables within the waste reduction system. A model is discussed which was based on system dynamics to integrate the major variables related to reduction of C and D waste. Tests were carried out to check the validity and reliability of the model. The study found that the dynamic model can be effectively used to evaluate strategies of C and D waste reduction under different scenarios and helps to discover the best management strategy.

VilloriaSaez et al. (2014) have carried out a study and analysis of various building sites to quantify the generated C and D waste. It was found from the results that a reduction of C and D waste up to 15.94 % per m^2 of built surface with the use of plasterboard walls is obtained as compared to traditional brick partitions. A model is also discussed for the accumulation of C and D waste during a project and described that the C and D waste mainly accumulated in the middle phases of the project. The study also allowed discovering the amount of C and D waste generated in a project site and space needed to manage the waste properly.

Wang et al. (2004) have discussed a system analysis tool for C and D waste management that helps contractors, processors, and regulators to analyse their decisions on managing wastes. The estimation of selected C and D waste material generation was also included in the model. The study concluded that cost-effective improvements of the waste management system can be obtained with the presented model.

VilloriaSaez et al. (2013) have presented a study to analyse viability and effectiveness of 20 best practices measures for management of C and D waste. With the help of the results three effective best practices during the design stage and five effective on-site best practices have been identified. The study concluded that the analysis can help construction stakeholders in making decisions to use an effective and sustainable procedure of waste management and to promote the concept of zero building-waste generation.

Ding and Xiao (2014) have discussed a methodology to analyse and estimate C and D waste generated by the building sector in Shanghai. It was found that wastes of about 13.71 million tonnes were produced in Shanghai in 2012 out of which 80 % waste was of bricks, concrete, and blocks. The study concluded that proper management of C and D waste is quite beneficial for Shanghai from economic and environmental points of view.

Dantata et al. (2005) have carried out a study to compare cost analysis in deconstruction of residential buildings and demolition in the commonwealth of Massachusetts. The analysis was done using two different deconstruction projects previously discussed in other studies. The results showed that demolition cost could be 17–25 % lower than the cost of deconstruction with respect to the current scenario in Massachusetts. Parameters were identified regarding labour cost, disposal cost, and resale of deconstructed materials and ranked them on the basis of their effects on cost. It was found that labour cost is the main parameter affecting the total cost in deconstruction of buildings. It is then followed by salvage value and disposal cost, and disposal cost was found to be the most sensitive parameter in the total demolition cost of buildings. In addition to this, a sensitivity analysis was also carried out to find the breakeven points of the parameters. The study concluded deconstruction is an effective method to decrease the C and D waste generation of buildings, however, there may be variations in some cost parameters related to deconstruction in different regions.

4 Environment and Economic Importance

Recycling of building materials plays an important role in reducing environmental impacts and achieving sustainable development. Table 1 shows the benefits of recycling of one tonne of brick, concrete, asphalt, and plasterboard in terms of environmental indicators such as GHG emissions, energy consumption, water use, and solid waste. The data show that noticeable benefits can be obtained by promoting recycling of C and D waste. A study carried out by Coelho and Brito (2013b) shows considerable environmental benefits from a recycling facility

Table 1 Benefits of recycling of tonne of construction materials (www.epa.nsw.gov.au)

Material	GHG emissions in tonnes CO_2	Cumulative energy demand in GJ (Lower heating value)	Water use in kL of water	Solid waste in tonnes
Brick	0.020	0.28	1.26	1.07
Concrete	0.024	0.35	1.28	1.09
Asphalt	0.030	2.38	0.88	1.06
Plasterboard	0.028	0.55	−0.03	0.98

operation for C and D waste, even in conditions such as low input mass, high transportation cost, and the like. The study was carried out on a C and D waste recycling plant in Portugal in which primary energy consumption and CO_{2eq} emissions were taken as environmental impact performance indicators (Coelho and Brito 2013a). Coelho and Brito (2012) have carried out a study to analyse the effects of C and D waste management on environmental impacts associated with a building's life cycle through a life-cycle analysis (LCA) approach. It was found from the results which were based on real building measurements and construction activities that reduction in environmental impacts cannot be achieved through shallow, superficial, and selective demolition of buildings. The study concluded that considerable reduction in environmental impacts can be achieved using core material separation in the demolition phase and its recycling and reuse.

A lot of embodied energy is associated with building construction materials during raw material extraction, processing, manufacturing, and transportation. In addition to this, a high amount of GHG emissions is also released into the atmosphere (Department of sustainability, environment, water, population and communities 2012). As discussed earlier, a building structure consists of several materials; however, glass, cement, sand, bricks, wood, PVC, and the like are commonly used materials in almost all building construction. Red brick masonry is highly used in building structures and has the embodied energy of 2141 MJ/m^3 (Reddy and Jagdish 2003). A large amount of fuel is required in manufacturing bricks and a high amount of emissions is consequently released into the atmosphere. A study carried out by Kumbhar et al. (2014) showed that a high amount of emissions is released in manufacturing bricks directly at the site due to large coal combustion in the kiln as well as the combustion of fuel in their transportation. In the study, a case was considered of brick manufacturing at kilns in India and it was concluded that acidification value is increased due to the use of low-grade fuel having high sulphur content. The embodied energies associated with some commonly used materials according to the Indian database are shown in Fig. 3. It can be observed from the figure that glass and PVC have high embodied energy due to the

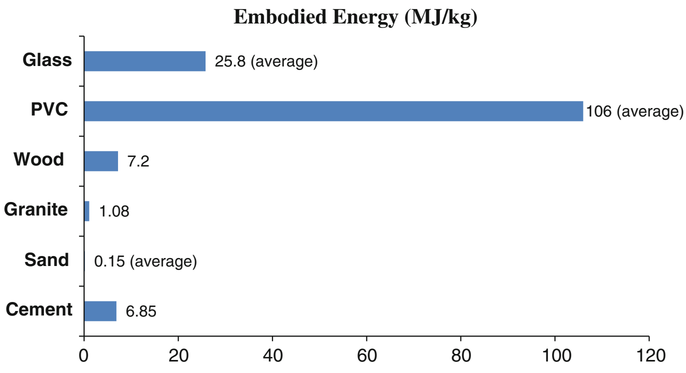

Fig. 3 Embodied energy of building materials (Devi and Palaniappan 2014)

various processes and techniques involved during their manufacture, whereas for sand and granite it is comparatively low.

Thormark (2002) has estimated the energy usage from a building life cycle and concluded that about 37–42 % of the embodied energy used in buildings can be recovered using recycling (life of a building was assumed to be 50 years). Also, the recycling potential was found to be about 15 % of the total energy associated with the building's lifetime. The study also concluded that there is a great need to promote the recycling of building materials and emphasis must be given to the energy intensity of these materials. Also, the study suggested promoting the use of recyclable materials in building construction and avoiding the use of construction whose disassembling is difficult so energy consumed in buildings can be recovered more effectively. In addition to this, maintenance is important to increase building life and about 12 % of the total embodied energy is associated with maintenance. It was suggested to promote the use of materials with low embodied energy to reduce the energy consumed in maintenance.

In addition to embodied energy associated with construction materials, release of a high amount of GHG emissions is also associated with them. These emissions have been estimated in several studies in terms of carbon footprints. Therefore, recycling of building materials clearly leads to saving of their embodied energy as well as the GHG emissions associated with them; consequently environmental impacts are effectively reduced. Klang et al. (2003) have carried out a study of a model to analyse the contribution of waste management systems for sustainable development which includes social, economic, and environmental aspects. It was found that recycling of steel and reuse of sanitary porcelain gave a potential contribution in all aspects of sustainable development. Also the largest potential was associated with brick preparation for reuse but it had negative effects on sustainability also from a social point of view. The study also suggested that the discussed model can be used to compare the different activities and uncover the results concerning allocation of resources. It was shown that the model is also helpful for designing waste management and recycling strategies.

Blengini (2009) has discussed the results of an LCA study on a demolition of a residential building in Turin, Italy. The building was demolished in 2004 using controlled blasting. The results showed that recycling of building waste material is economical, profitable, and sustainable for achieving low energy consumption and low environmental impacts. The study also discussed that another benefit from the environmental point of view associated with recycling is to reduce and avoid the landfilling problem which is very important to save valuable land especially in countries such as Italy which are densely populated. The study also suggested considering the issue of land wastage in further research on LCA analysis including suitable quantitative indicators.

Now, another example can be taken of metals used in building construction. As discussed earlier, metals and alloys are important building construction materials and widely used in frameworks to provide sufficient strength. Figure 4 shows life-span impacts of stainless steel, copper, and aluminium. It can be noticed that the life span of stainless steel and aluminium is the same but embodied energy and

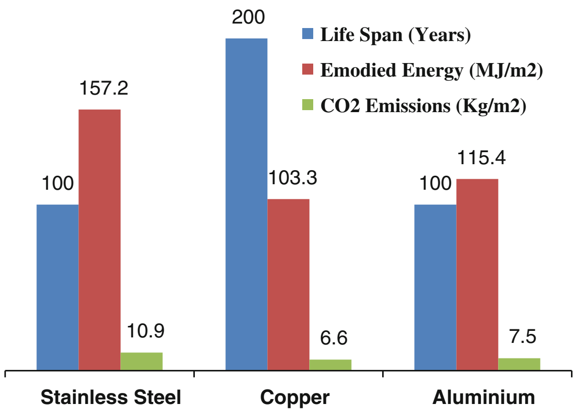

Fig. 4 Life span and impacts of metals (www.copperconcept.org)

GHG emissions associated with stainless steel are higher than copper and aluminium. The life span of copper is quite high and embodied energy and GHG emissions associated with it are considerably lower than aluminium and steel. Therefore, the choice of metals and selection also affects the environmental impacts of the building and if the proper material has not been selected for building construction then the need for recycling of that material will become quite important to reduce its environmental impacts considerably.

The other important benefit of building material recycling is conservation of resources. As already discussed, the depletion rate of natural resources on earth is increasing due to the fast-growing population of the world. In this regard, recycling can play a big role in conserving the scarce resources, minerals, and so on. Also wastage of valuable land is reduced by promoting the recycling of building materials. The dumping of C and D building waste and landfilling is not an effective and economical solution to manage the waste. Hazardous materials present in the waste also contaminate soil, air, water, and so on, and environmental problems are increased consequently. Gao et al. (2001) have presented a study to analyse savings through the materials and products produced from the recycled materials. Three different types of residential buildings with different construction techniques were studied to estimate the reduction in energy use and resources after using recycled materials. These studied residential building designs were conventional wooden construction, wood frame construction, and light steel construction. For most of the materials used in buildings, it was discovered from the results that energy required to reproduce building materials from recycled materials is lower than that consumed to make new building materials. It was discovered that in all cases of the studied buildings, energy use of building materials can be reduced to at least 10 % through recycling and simultaneously a reduction of about 50 % of the resources in terms of mass of building materials can be obtained. In addition to this, the study also concluded that aluminium and steel products are the key materials for recycling.

Thormark (2001) has carried out a study to analyse energy and natural resource conservation and material saved using recycled building waste materials in Sweden.

In the study two scenarios,' maximal material recycling' and 'maximal reuse', were discussed and compared to estimate the energy conservation by recycling of building waste materials in 1996. The results showed that recycling of building materials can be effectively used to save energy and natural resources and this saving of energy was about 20–40 % depending upon the recycling type. The study concluded that the recycling of bricks, stone, wood, metals, and minerals is important to save energy as well as natural resources. In addition to this, the study posited a need for studies on the possibilities of increasing the recycling of building wastes effectively.

Huang et al. (2013) have carried out a study to estimate raw material requirements and environmental impacts associated with buildings in China from 1950 to 2050. The effects of prolonging a building's life and increasing building material recycling on raw material demands, waste generation, and CO_2 emissions were studied. A considerable reduction was found in raw material demand and CO_2 emissions for new construction over the next years. The study concluded that low waste generation, fewer emissions, and reduction in raw materials demand can be achieved by prolonging building life and promoting recycling of materials.

It can be observed from the above discussions that emissions, energy consumption, and harmful releases in manufacturing and processing units of building materials can be reduced through recycling of building materials which leads to the minimisation of environmental impacts associated with the building sector.

5 Recycling Potential and Its Feasibility

In order to increase the use of recycling of building materials it is very important to develop methodologies to measure the recycling potential of building from its construction phase. Also, it is quite necessary to take recycling of building materials into consideration during the design stage of a building, therefore there is a great need to change the design criteria of buildings to make efficient use of recycled building materials. This can be done by assembling step by step building materials in the construction stage in order that during the demolition phase of the building disassembling of materials can be performed in reverse order. This can help to reduce wastage as well as degradation of the building materials (www.lub.lu.se). The C and D waste generation can be recycled and reused in several applications. For example, the amount of concrete, aggregate, and masonry present in C and D waste is quite high and can be used in roads, driveways, pavements, pipe bedding, landscaping, and so on. Metal parts present in waste can be remelted and converted into secondary material to use in structural steel or piping, for example. Timber can be reused in making furniture, doors, or fencing, among others. Also, plastics materials in waste can be further used as secondary material for benches in parks or playgrounds. Glass can be crushed and reused for compaction fill. Bricks, tiles, and sanitary fittings can be salvaged and resold for further use (www.zerowaste.sa.gov.au).

Industrial materials which are the by-products of various industrial processes can also be used in building construction. Materials such as waste solid fuel (e.g., coal), slags, used tyres, and the like are produced in high amounts as industrial wastes and have valuable properties so they can be recycled and reused efficiently. Many energy, economic, and environmental benefits are associated with the recycling of industrial materials. The use of coal ash in cement manufacturing, use of fly ash and slag in concrete, and recycled gypsum to produce drywall, for example, save energy consumption and emissions in building construction (www.epa.gov).

In order to carry out the recycling of C and D waste to produce appropriate recycled materials for construction, it is quite important to find the recycling potential of materials present in C and D waste. Also, the suitability of the recycled materials in new construction and other uses must be checked before using them in place of virgin materials. Several studies on recycling potential have been reported by researchers. Townsend et al. (2004) have carried out a study to analyse the suitability of screened soil or fines (a product recovered from recycling of C and D waste debris) to use as fill materials in construction projects in place of natural soil. Vefago and Avellaneda (2013) have carried out a study and discussed new concepts related to building elements and materials. In this work the potential of recyclability has been evaluated. The study suggested that treatment of materials which maintain their properties over their life cycle should be different from those that lose their characteristics over their life cycle. It was found out that these concepts are more appropriate for the current situation. The results also concluded that recyclability of buildings is the appropriate way to achieve sustainability in buildings.

Bravo et al. (2015) have carried out a study to evaluate the mechanical performance of concrete used with recycled aggregates from C and D waste from different places in Portugal. Various physical and chemical tests were carried out to study the composition of recycled aggregates. Tests including compressive strength, splitting tensile strength, elasticity, and abrasion resistance were performed to evaluate the performance of concrete. It was found that the recycled aggregates, especially fine aggregates, deteriorate the properties of concrete. But improvement in abrasion resistance was found with the use of coarse recycled aggregates.

Pytel (2014) has presented a detailed study to analyse the potential applications of recycled moulding and core sands for manufacturing ceramic building materials. The study concluded that it was possible to dispose of the used moulding sand in the production of ceramic materials for construction. However, processing treatment and removal of casting remnants of waste are necessary for this. Also, waste materials can be used in components of plastic bodies in the production of construction materials and recycled sand can act as an additive in it.

Ulsen et al. (2013) have presented a study to discuss a technique by which high-quality sand from C and D waste can be produced inasmuch as the present waste recycling technologies for construction are mainly focused on producing coarse recycled aggregates. It was found out from the results that the discussed technique allows the production of sand with low porosity and can change the present recycle model for construction. Soutsos et al. (2011) have carried out a study to analyse the potential of using recycled aggregate from demolition waste for the production of precast concrete building blocks. In addition to this, replacement of quarried limestone aggregate with recycled aggregate from C and D waste was also studied. No significant reduction in strength was found if recycled aggregate was used in concrete blocks which leads to no increase in cost because there is no requirement of additional cement for increasing strength of the block.

Hoglmeier et al. (2013) have proposed that a significant amount of wood can be recovered from building waste and used in cascades. The study was carried out to analyse and estimate the quantity of used wood in the building stock of Bavaria in southeast Germany. The study found that about 26 % of recovered wood was appropriated for reuse and 27 % could be utilised for other secondary applications.

The selection of building materials also affects the quantity and quality of C and D waste generation. There are many studies in which emphasis is given to the selection of appropriate materials for construction. Saghafi and Teshnizi (2011) have presented a study and described that the selection of materials in terms of recycling potential is the most controversial job in achieving sustainable construction. A method was presented to estimate the savings in energy consumption through the use of recycling building materials. Selections of materials, construction, and deconstruction technologies plus recycling frequency were taken into account. The study concluded that the results of the analysis can be used in assessment/estimation tools. P-factor (in terms of potential recycling energy per unit of embodied energy) is suggested for the interactions and relations between potential recycling energy and embodied energy and for comparison and proper selection of materials.

Thormark (2006) has carried out a study to analyse the effect of material selection on the total energy requirement and recycling potential of a building. The case of cost-efficient passive houses in Gothenburg, Sweden was considered in the study. There were 20 apartments in 4 two-storey rows with 120-m^2 floor area of each apartment. The building lifetime was considered to be 50 years. It was shown that the embodied energy was 40 % of the total energy of the building which can be approximately decreased by about 17 % and increased by 6 % through substitution of different materials. The study concluded that selection of materials and recycling aspects of a building are of great importance to reduce the total energy consumption during the building life cycle. In addition to the recycling potential of a building material, types of recycling and the provision of disassembly must be considered. The study also recommended developing and promoting new construction with respect to material selection and design procedure. Takano et al. (2015) have carried out a study to analyse the influence of materials selection on life-cycle energy balance using a case study of a hypothetical building model in Finland based on current building codes and service systems of the country. The building was two storeys and the gross floor area of the building was 120 m^2. Three categories—structural frame, surface components, and inner components—were selected to study the effects of selection of materials. It was found that materials selection for a structural frame shows the larger effects as compared to surface and inner components. In some cases the combination of different materials for a structural frame appeared to be effective. Also it was discussed that selection materials for surface and inner components have a larger effect than others in applications such as thermal insulation, sheathing, and exterior cladding. In addition to this, the study concluded that the recycling benefits of woods and plastics have large effects on the building's life-cycle energy balance.

Duran et al. (2006) have carried out a study and discussed a model to analyse the economic feasibility of C and D waste in Ireland. The impacts of amount of C and D landfilled and aggregate extraction were discussed and it was found that recycling of C and D is effective to reduce environmental impacts in terms of reduction in landfill and amount of primary aggregate. The study showed that it is important to crush the C and D wastes and use as recycle aggregates to reduce the negative environmental effects of landfilling. The study suggested the establishment of potential recycling centres at Dublin, Limerick, and a mobile centre. The study also concluded that the recycling is economically viable if landfill cost is greater than cost associated in bringing the waste to the recycling centre and the cost of primary aggregate use is greater than recycled aggregate. The study also demonstrated that an increase of scale of the recycling centres gives a reduction in recycling costs which leads to the benefits of economies.

Nonavailability of appropriate markets and industries is an important factor for the impediments of large landfill and less recycling. That's why it becomes important to promote waste management industries and the availability of good markets to increase the use of recycled materials. Pappu et al. (2007) have presented a study on the generation of solid waste in India and their recycling potential and environmental implications. The study showed that there is a big scope of establishment of secondary industries for recycling and using the solid waste in construction materials. The study also suggested that there is a need to estimate physical, chemical, engineering, thermal, mineralogical, and morphological properties to use the wastes effectively. Also it was suggested to establish technology enabling centres for entrepreneurs and commercialisation so that effective use of building materials recycled from solid waste can be increased. In addition to this there is a considerable scope to produce new building components from the construction materials generated and recycled from agro-industrial wastes, due to which cost associated with building materials can be considerably reduced.

Vrancken and Laethem (2000) have performed a study regarding recycling of gypsum present in C and D waste. The impure gypsum present in C and D waste is often disposed of but the sulphur content present in it is important to use as a secondary aggregate for concrete. The study revealed a need of a centralised collection and transportation system to separate and recycle the impure gypsum from C and D waste. In addition to this, the study showed that involvement of contractors, sorting sector, gypsum industries, and the government is necessary to establish a gypsum recycling system.

Zhao et al. (2010) have carried out a study to analyse the economic feasibility of facilities for recycling C and D waste in Chongqing, China and it was found that a large amount of waste is available for recycling and there is a high demand for recycled materials due to the many construction activities going on in the city.

This leads to a high market potential of recycled materials in the construction sector. On the basis of cost and investment analysis, it was found that the recycling centres in the city might face investment risks under the current scenario. The study also concluded that economic instruments and regulations can aid in increasing the economic feasibility of recycling.

6 Conclusions and Recommendation

The growth of the real estate sector is increasing at a high rate and many construction activities are going on throughout the world. A huge amount of waste is generated in the construction and demolition phases of building and it becomes essential to recycle the C and D waste material from economic, social, and environmental points of view. First of all, excessive use of raw materials can be reduced if proper planning and management are done during the design phase of buildings. Also, many studies reported that proper selection of materials for construction leads to reducing the material consumption and increasing the recycling potential of materials after demolition. It is necessary to stop the process of blind selection of material or selection without proper analysis of construction techniques going to be carried out. There should be variation in material selection and construction methods according to the site location and place. In many places local alternatives are available for building construction and much energy, transportation, capital, and emissions can be reduced by using them. In remote and rural areas, there are many biodegradable materials which can be efficiently used in building construction. Also, sometimes traditional techniques are found quite beneficial for building construction. In addition to this, there is a need to reduce those construction materials and techniques in which high energy consumption, cost, and environmental impacts are involved. Reduction of waste and debris after building construction and demolition greatly depend upon the design procedure. It is quite important for designers to introduce efficient design techniques to minimise the extra and waste materials during the construction phase. Also it is recommended to follow stepwise assembling of construction materials so that the same procedure can be reversed during the demolition phase. It helps to improve the recycling potential of the debris after building demolition.

The waste generated due to construction and demolition activities must be recycled to produce materials for new construction and other applications. This helps in conserving the scarce and valuable resources of the Earth and reducing the energy requirements in manufacturing and processing virgin materials as well as environmental impacts. The amount of recycled materials produced from building waste depends on the recycling potential of building materials. One of the major requirements to improve the recycling potential of waste materials is the knowledge of properties of recycled materials and development of new effective methodologies for waste management. This can be done by promoting appropriate research and testing of recycled materials and recycling techniques.

In developing countries the growth of urbanisation and building construction is quite high. For example, in a developing country such as India, a high amount of waste is generated due to the rapid growth of urbanisation, industrialisation, and the infrastructure sector. About half of the total waste generated due to construction activities is recycled and the remainder is used for landfill. Waste generation in India during construction and renovation/maintenance is estimated as 40–60 and 40–50 kg/m^2, respectively. It is quite important to promote the recycling of C and D waste to have sustainable development in India. India has a labour-intensive construction industry and there is a great need to improve the quality standards of the products prepared from recycled wastes (www.waste-management-world.com). Also the proper data of the C and D waste generation must be available for promoting the recycling of C and D waste. In fact there is need of a separate agency dedicated to keeping all records of waste generation and to promote recycling. In addition to this, emphasis must be given on developing an effective mechanism especially for India, based on the country's social, environmental, and economic factors for proper collection, storage, processing, and recycling of C and D waste.

It is necessary to provide a good market and waste management industries to promote the recycling of building materials. Availability of a good market is helpful to increase the use of recycled materials in new construction. There is also a scope of social improvement in the promotion of recycling industries and centres because it provides several opportunities of employment for the people. The role of government is also valuable and important to promote the recycling of C and D wastes. Governments should make an easily adaptable policy and rules for recycling of C and D waste not only for building construction but other bulk construction such as roads, flyovers, bridges, and so on. There must be some compulsory rules for efficient and effective building design, selection of construction materials, and techniques so that the amount of C and D waste can be reduced considerably. The appropriate amount and size of construction materials is also important for minimising the waste. Also there must be research and advancements in building materials and construction techniques so that the goal of sustainable development in the building sector can be achieved. In addition to this, waste management programmes must be initiated to create awareness among the designers, contractors, operators, and the like to maximise the use of recycling and recycled materials. Overall it can be concluded that the recycling of building materials is an essential step to achieving all economic, social, and environmental aspects of sustainable development.

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Recycling of Wastes into Construction Materials

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Abstract Construction activity generates a large amount of waste, causing environmental and economic impacts due to waste elimination without recycling or reusing these materials. In this research, the incorporation of wastes from different sectors (biomass, power plants, construction and demolition process) in concrete with good fire resistance is studied. The chemical composition and grading curve of these wastes are determined. Fire resistance blocks are manufactured with a high percentage of waste in their composition. The new materials are then subjected to several tests in order to analyse their fire resistance, mechanical properties, thermal conductivity, leaching, and radioactivity. A new façade solution is developed by changing traditional materials for some of the new recycled materials, and their technical features are compared. All four wastes studied decreased the density and mechanical strength of a 28-day-old block, and a higher water ratio is needed for block preparation. On the other hand, the blocks' fire resistance increased, decreasing their thermal conductivity. The properties of the new materials validate their possible usage for nonstructural applications such as blocks or prefabricated concrete panels for façades and inside partitioning, showing good mechanical and thermal performance. Their use does not represent a significant risk to the environment.

Keywords Fly ash · Bottom ash · Recycled aggregates · Construction and demolition waste · Fire resistance · Thermal conductivity · Sound absorption · Leaching · Radioactivity

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1 Introduction

The construction industry is not an environmentally friendly activity inasmuch as it causes the depletion of natural resources and generates a large amount of waste. Consequently, the growth of the construction sector is limited by the environment source and sink capacities. Source limits refer to the finite capacity of the environment to provide resources, both renewable and nonrenewable, whereas sink limits refer to its capacity to assimilate the waste that economic growth and development cause.

In this sense, some researchers approach sustainability as a resource management and pollution control problem (Wong and Yip 2002). The 'three-R' principle (reduction, reuse, and recycle) has been widely adopted. First, reduction means minimising waste through planning and design; about one-third of construction waste essentially arises from design decisions, for example, by the selection of nonenvironmentally friendly materials and construction methods (Osmani et al. 2008). Second, reuse means that the final products can be incorporated back into the same cycle or into another cycle without additional material processing. Finally, recycling refers to the recovery of unavoidable waste, involving chemical or mechanical processing (Gomes et al. 2008), into secondary materials which can be reused. Both reuse and recycling reduce the rate of extraction of natural resources.

The use of recycled materials in new construction products constitutes a more sustainable and respectful way to build, simultaneously reducing two major environmental impacts of human activity: the enormous consumption of natural resources and the massive generation of waste. Thus we see how, in the building sector, the proliferation of new building products that incorporate recycled materials (stone, plastic, wood, glass, paper, etc.) is brewing what is already known as a new generation of ecoproducts that combine efficiency and environmental commitment (Pérez Arnal 2008).

Furthermore, when the properties of the waste make its use possible in specific, high added-value applications, these products can successfully compete with products made from primary materials, and reduce the environmental costs of waste disposal. Among the wastes with potential properties for their use in building materials, there are construction and demolition waste (C&D waste) and ashes and slag from different thermal processes.

C&D waste management is a major issue worldwide due to the intensive activity of the construction sector, first in economically advanced countries and now in emerging economies such as Brazil and China (Agamuthu 2008). The environmental problem posed by C&D waste is derived not only from its increased volume, but also from its treatment. Some of the consequences of waste disposal are: contamination of soil and water resources through uncontrolled landfills, landscape deterioration, and above all, the economic impact derived from waste elimination without any recycling or reuse. The tendency in the field of construction is to consider C&D waste as inert waste to be deposited in landfills, and, in some cases, in uncontrolled dumps. However, C&D waste management requires a tendency to change towards the prevention of waste generation and, failing this, towards waste recycling and reuse and/or energy recovery (Mercader et al. 2010).

In Spain, the National Plan of Construction and Demolition Waste developed the Spanish Royal Decree 105/2008 (RD 105/2008; Spain MP 2008), which constitutes specific legislation at the state level for C&D waste production and management. Following the guidelines of the Royal Decree, several C&D waste treatment plants have been established across Spain. These treatment plants manage C&D waste and obtain recycled mixed aggregates as a by-product, generating approximately 5 million tonnes of recycled mixed aggregates per year, which represent 15 % of the total C&D waste produced. This high production makes it necessary for a more suitable application to be found than just deteriorated landscape restoration or landfill recuperation. Furthermore, the recycled material has good characteristics which validate its usage in applications of higher quality.

According to the National Plan of C&D Waste, concrete, bricks, tiles, and ceramics are the most representative components (Spain ME 2001). Oikonomou (2005) analyses the general properties of recycled aggregates from concrete. The use of these aggregates has also been studied in moulded concrete bricks and blocks (Poon et al. 2002). Their results show that the replacement of coarse and fine natural aggregates by recycled aggregates from old concrete at the levels of 25 and 50 % have little effect on the compressive strength of the bricks and blocks, although higher levels of replacement reduced the compressive strength. The performance of the bricks and blocks is also satisfactory in shrinkage and skid resistance tests. Also ceramic bricks proceeding from construction and demolition of buildings have been recycled as pozzolanic material in cement (Lin et al. 2010). There are other studies which determine the performance of masonry mortars made with recycled concrete aggregates proceeding from preselected concrete (Vegas et al. 2009).

When regarding the influence of recycled aggregates from concrete upon the properties of new concrete, Tabsh and Abdelfatah (2009) found that the compressive or tensile strength loss due to the use of recycled aggregate is more significant in weak concrete than in stronger concrete. For example, coarse aggregate obtained from concrete whose strength is equal to 50 MPa results in compressive and tensile strengths of concrete comparable with those achieved when using natural coarse aggregate. Furthermore, Levy and Helene (2004) proved that concrete made with recycled aggregates from old masonry or from old concrete can have the same fresh workability and can achieve the same compressive strength of concrete made by natural aggregates in the range of 20–40 MPa at 28 days.

On the other hand, Corinaldesi and Moriconi (2010) determined that the use of recycled aggregate without water presoaking was detrimental in terms of workability loss, especially when a shrinkage-reducing admixture was used, which is confirmed in the study by Tabsh and Abdelfatah (2009) where similar conclusions were obtained when smashing low-resistance concrete. Rolón Aguilar et al. (2007) demonstrated that recycled aggregate from concrete, due to its hybrid composition (natural aggregate and the mortar bonded to it), has physical and mechanical shortcomings compared to natural materials in terms of porosity, absorption, low density, and compressive strength, although it can be used in mass concrete.

As we can see, results generally show a certain deviation from the properties required by the Spanish Structural Concrete Code EHE-08 (Spain MPW 2008). However, the quality of recycled aggregate can be improved by blending it with natural aggregate, by enhancing the manual removal of gypsum before the crushing process at the C&D waste treatment plant, by immersing the aggregate in water to reduce chlorides, and by particle-size adjustment (Martín Morales et al. 2011).

On the same line, the recycling of fly and bottom ashes (hereafter FA and BA, respectively) from coal combustion power plants into construction materials has been studied. The generation of combustion by-products is a global problem with severe implications for human health and the environment, because elements may leach through the soil to the groundwater, and may cause a negative impact on the terrestrial and aquatic ecosystems. FA may contain some elements of environmental concern, such as arsenic, barium, chromium, cadmium, lead, selenium, and mercury, which can limit potential applications (González et al. 2009). Typically, BA contains relatively small amounts of heavy metals, particularly volatile metals such as cadmium, zinc, and lead (Shim et al. 2005). Moreover, it also becomes a problem for industry due to high storage, transport, and disposal costs, which must be faced by plant operators and waste management companies. In fact, nowadays industry is very interested in recycling FA and BA, in particular for cost-saving reasons, while maintaining product quality and process stability (González et al. 2009).

FA represents about 80 % of coal-ash produced by thermoelectric power plants, and BA accounts for 10–15 %. Around 43 Mt of FA and 5.7 Mt of BA are generated in Europe each year. According to data from 2005, FA reutilisation in Europe is of the same order as that of BA, that is, 48 % from which 5.3 % is used in concrete block manufacturing (Lee et al. 2010; Gonzalez et al. 2009).

The high recycling rates of FA are mainly due to its pozzolanic and cementitious characteristics which allow its use as a binding agent or as a raw material to produce clinker and to replace cement in concrete production (Yeginobali et al. 1997; Bilodeau and Malhorta 2000; Demirboga 2003). Most of these ashes have similar or even better properties than Portland cement, and being the main advantages of cement partially replaced by FA, it results in a lower demand for water and lower generation of hydration heat (González et al. 2009). Some studies have demonstrated the possibility of BA being used as a lightweight aggregate in mortar and concrete due to its low particle density. Eighty thousand tonnes have been applied as fine and coarse lightweight aggregates in Europe per year. BA influences many concrete properties, such as water demand, mechanical strength, and porosity (Lee et al. 2010; Andrade et al. 2007).

It also has been proved that the use of fly and bottom ash additions in mortars can affect the material behavior in a fire (Xu et al. 2001). Some commercial products, used as thermal insulation or passive fire protection in buildings and industrial installations, have a chemical composition and properties similar to fly and bottom ash mixtures (Vilches et al. 2005a, b, 2007; Leiva et al. 2005). Therefore, the behavior in a fire of the proposed new product is expected to be similar to that of the commercial products.

In this sense, recycled materials combining the wastes mentioned above can be found in the bibliography. For example, the utilisation of bottom ash from the incineration of municipal solid waste and recycled mixed aggregates from C&D waste in concrete (Juric et al. 2006) has been characterised. Bottom ash substitutes cement and recycled mixed aggregates substitute gravel. The composition of this aggregate is mainly mineral, around 90 %, whereas other aggregate materials are bitumen, brick, and wood.

There also exist several studies on the production of construction materials using other wastes, such as those described below.

Bauxite red mud is a by-product, released in the Bayer process of aluminium extraction from bauxite ore. In this process, bauxite is reacted with caustic soda under heat and pressure. Red mud has been used as a substitute for ordinary clay for producing bricks. Below 900 °C red mud can be considered an inert component in mixtures with carbonate-rich clays so that the mechanical strength decreases as the red mud concentration increases (Sglavo et al. 2000). Several attempts have been made to recycle red mud not only to avoid environmental pollution, but also to use it in developing polymer composites, wood substitute products, bricks, ceramic glazes such as porcelain, sanitary ware glazes, electroporcelain glazes, tiles, and extraction of metals (Yalcm and Sevinc 2000; Sglavo et al. 2000; Saxena and Mishra 2004).

Moreover, there are slags with a high recycling potential into construction materials. There are three types of slags, namely blast furnace slag, converter slag, and electric furnace slag. The first two are produced by pig iron industries and the third is generated by the steel industry. The blast furnace slag is categorised as group I waste and has been used in the manufacture of blended cement improving its soundness, strength, morphology, and abrasion resistance. However, group II materials, that is, ferro-alloy industrial waste, have not been used extensively, but have great potential for recycling. All these solid wastes have been used in production of Portland blast furnace slag cement, super sulphate cement, as an aggregate in high-strength concrete and lightweight concrete (Gupta 1998; CPCB 2005). The group III materials include the tailings of iron, zinc, copper, and gold ore beneficiation and have been used as fine aggregate or concrete filler material in the construction industries (Bhattacharyya et al. 2004).

Other waste with recycling possibilities is waste phosphogypsum (PG), which is an industrial by-product of phosphate fertiliser production from phosphate ore or fluorapatite. Untreated PG has the limited scope of utilisation in construction materials due to the presence of undesirable impurities such as P_2O_5, fluorides, organic matter, and alkalis (Sing and Garg 1997; Garg et al. 1996). However, PG has been used as a data set controller in the manufacture of Portland cement substituting natural gypsum, as a secondary binder with lime and cement, in the production of artificial aggregates for soil and road stabilisation, and as a raw material for wallboard and plaster after purification or a calcination process (Pressler 1984; Sing and Garg 1997; Singh et al. 2003). A large volume of purified PG can be used by combining with fly ash and lime to produce construction materials such as bricks and blocks (Yang et al. 2009; Kumar 2002, 2003). Fly ash-lime-phosphogypsum bricks and blocks with suitable PG content have shown a better performance in strong sulfate environments (Kumar 2003).

Other studies (Yang et al. 2004) using agricultural lignocellulosic fibre (rice straw)-waste tyre particle composite boards were manufactured for use as insulation boards in construction, using the same method as that used in the wood-based panel industry. The manufacturing parameters were: a specific gravity of 0.8 and a rice straw content (10/90, 20/80, and 30/70 by wt% of rice straw/waste tyre particle). A commercial polyurethane adhesive for rubber was used as the composite binder. The waterproof, water absorption, and thickness swelling properties of the composite boards were better than those of wood particleboard. Furthermore, the flexibility and flexural properties of the composite boards were superior to those of other wood-based panel products. The composite boards also demonstrated good acoustical insulation, electrical insulation, anticaustic, and antirot properties. These boards can be used to prevent impact damage, are easily modifiable, and are inexpensive. They are able to be used as a substitute for insulation boards and other flexural materials in construction.

Finally, the emergence of new types of ash from ecological fuels, such as biomass, unfit to be used in cement and concrete, make the amount of ash recycled insufficient. Therefore it is necessary to find new applications for these products, such as soil stabilisation, manufacture of ceramic materials, fire-resistant materials, or agricultural activities. The ash from the combustion of 'orujillo', a residue from the extraction of olive oil, is the most abundant type of biomass in our region. In this study, the recycling of this type of waste into plasterboard is proposed. Among the main background to this work we can find the research by González-Madariaga and Lloveras-Macia (2008).

In this research, the incorporation of different wastes in concrete with good fire resistance is studied. The wastes under study are: ash and slag from coal combustion, biomass ash, and C&D waste. The methodology consists, first, on determining the chemical composition and grading curve of these wastes. Fire-resistance blocks are manufactured with a high percentage of waste composition, ranging from 20 up to 100 % of fine and coarse aggregate replacement. The new materials are then subjected to several thermal and mechanical tests in order to analyse their fire resistance, mechanical properties, and thermal conductivity. These materials are also put through leaching and radiological tests in order to determine their environmental behavior. Finally, a new façade solution is developed by changing traditional materials for some of the new recycled materials analysed in this research, and their technical features are compared in order to determine the viability of using the new solution in future constructions.

In Sect. 2, the analysis and results of the essays carried out for the different wastes are shown. The aim of this part of the work is to analyse the possibility of recycling industry and C&D waste into building materials of new applications (materials for fire resistance and sound absorption), in order to increase the percentage of recycling of these kinds of waste. In Sect. 3, the comparison of a traditional façade solution and a new one with high recycled content is made, mainly focused on thermal conductivity. Finally, in Sect. 4 some conclusions are drawn from this study.

2 Recycling of Coal and Biomass Fly Ashes, Coal Bottom Ash, and C&D Wastes for Concrete Block Manufacturing

2.1 Materials and Methods

2.1.1 Materials

In this section, several material mixtures for the production of concrete are studied. The various materials which will be combined are: fly ash (FA) and bottom ash (BA) from coal combustion power plants (García-Arenas et al. 2011); fly ash from the combustion of the residual biomass (BFA) present in the waste obtained in the olive oil extraction process from Las Lomas Power Plant in Jaén (Spain; Alba et al. 2012), Portland cement (PC) (CEM II/B-L 32,5 N according to UNE-EN 197-1 (2011)) commercialised by CEBASA S.A., which complies with ASTM Type II; natural fine and coarse aggregates (NFA and NCA), in the form of natural river sand and crushed granite, respectively; and finally recycled fine and coarse aggregates (RFA and RCA) from the ALCOREC treatment plant in San José de la Rinconada (Seville, Spain), which are classified according to their size: 0–10 mm for RFA and 10–80 mm for RCA (Leiva et al. 2013). The recycled mixed aggregates are formed by concrete, ceramic tiles, Arabic tiles, terrazzo, and small gypsum or wood pieces which have been overlooked during the cribbing process. The chemical composition of all these materials, determined by atomic absorption spectrophotometry in accordance with ASTM D3682-13 (2013), is reported in Table 1.

The outcomes of the analysis show that FA is a conventional class-F (ASTM) ash and can be classified as Category A (lower than 5 %) according to its loss-on-ignition values (EN 450-1 2013) and, therefore, may be used in mortar. This parameter clearly differs from the Portland cement samples, which have values higher than 5 %, due not to unburned organic matter, but probably to the $CaCO_3$ and $Ca(OH)_2$ content. The SiO_2 content is greater than 25 % and the $SiO_2 + Al_2O_3 + Fe_2O_3$ content is higher than 70 %, thereby meeting the requirement for the recycling of FA in cements. The alkali content (Na_2O) is lower than 5 %, whereas those of SO_3 and MgO are lower than 3 and 4 %, respectively, also meeting the requirement. BFA has a high proportion of potassium components in the composition of the ash.

NFA and NCA are fundamentally composed of SiO_2, and all other components remain insignificant. RFA and RCA present similar chemical compositions. Their Al_2O_3 and CaO content and loss on ignition are higher than that of natural aggregates due to the Portland cement contained in recycled aggregates.

Table 1 Chemical composition (%) and physical properties of materials

	FA	BA	BFA	RFA	RCA	PC	NFA	NCA
SiO_2	41.77	40.82	36.78	52.60	52.78	13.83	96.21	85.73
Al_2O_3	26.45	23.61	7.01	7.08	9.57	3.53	0.76	4.96
Fe_2O_3	18.79	25.28	3.54	3.06	3.54	2.26	0.22	2.92
MnO	0.05	0.05	–	0.05	0.05	0.06	0.00	0.04
MgO	1.21	1.05	6.28	1.84	2.45	0.70	<0.01	0.30
CaO	5.68	5.17	17.31	18.50	17.89	59.33	0.13	0.46
Na_2O	0.20	0.16	1.52	0.71	0.61	0.08	0.05	1.14
K_2O	1.27	1.05	22.46	1.38	1.87	0.48	0.30	0.99
TiO_2	1.02	0.90	–	0.40	0.50	0.19	0.12	0.23
P_2O_5	0.46	0.31	–	0.09	0.11	0.06	0.01	0.06
SO_3	0.53	0.08	–	0.03	0.42	1.68	0.02	0.03
Cl^-	–	–	–	<0.03	<0.03	<0.03	<0.03	<0.03
Loss on ignition	0.69	<0.01	9.36	12.27	9.19	15.50	0.31	0.95
Specific gravity	2.45	2.17	2.31	1.68	1.62	3.18	2.69	2.48

International standards state that sulphate content must be lower than 1 % (RILEM 1994; BS 8500-2 2006) or 0.8 % (Spain MPW 2008), and RFA and RCA comply with these limits. The chlorine content is lower than 0.05 %, as required by Spanish standards (Spain MPW 2008).

The specific gravity is measured in accordance with ASTM C127-12 (2012); the recycled aggregate specific gravity is lower than that of natural aggregates, and RFA and RCA specific gravities are higher than 1.5, hence they can be classified as Type I according to RILEM standards (RILEM 1994) and Type 4 according to German standards (DIN 4226-100 2002). Figure 1 shows the particle size distribution of the aggregates in accordance with EN 933-1 (2012). The RCA fine content (<0.063 µm) is lower than 3 %, thus being classified as Type I according to RILEM standards (RILEM 1994), and Type 4 (<4 %) according to German standards (DIN 4226-100 2002).

2.1.2 Block Preparation

The mixture proportions tested, as shown in Table 2, end up with a product formed mainly of waste. The final composition of the blocks is obtained by completely replacing the natural fine aggregate with fly ash or RFA, and the coarse aggregate with bottom ash or RCA. The composition of HR3 was obtained using an optimisation process in which three main objectives were taken into account: (1) an improvement in the insulating properties; (2) the need for certain minimal mechanical properties, defined by what the products were ultimately expected to be

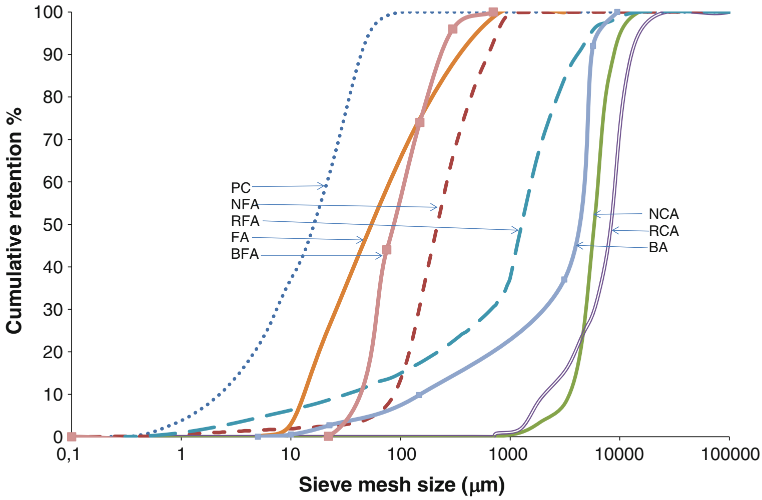


Fig. 1 Grading curves for FA, BA, BFA, RFA, RCA, NFA, and NCA

used for; and (3) the panel density has to be low in accordance with the density of commercial panels (<900 kg/m^3) according with previous studies (Leiva et al. 2009). In HR3, gypsum was used as binder due to its high insulating capacity while it maintained acceptable mechanical properties. To make the material acquire a compressive strength greater than 1 MPa, polypropylene monofilament and glass fibres were added, which improved the material's compressive flexural and impact strengths. Finally, HR3 was configured as follows: ash (60 %), gypsum (30 %), vermiculite (9.5 %), and fibre (0.5 %), with a water/solids ratio of 0.5 (Alba et al. 2012).

Table 2 Mixture proportions of the compositions (wt%)

Mixture	Water/solids ratio	PC	NFA	FA	RFA	NCA	BA	RCA
H0	0.096	20	50	0	0	30	0	0
H-FA20	0.140	20	30	20	0	30	0	0
H-FA40	0.217	20	10	40	0	30	0	0
H-FA50	0.256	20	0	50	0	30	0	0
H-BA20	0.160	20	50	0	0	10	20	0
H-BA30	0.186	20	50	0	0	0	30	0
HR1	0.259	20	0	50	0	0	30	0
H-RFA20	0.12	20	30	0	20	30	0	0
H-RFA40	0.18	20	10	0	40	30	0	0
H-RFA50	0.20	20	0	0	50	30	0	0
H-RCA20	0.14	20	50	0	0	10	0	20
H-RCA30	0.16	20	50	0	0	0	0	30
HR2	0.18	20	0	0	50	0	0	30

The dry components are placed in a planetary mixer until a homogeneous combination is obtained. The water is then added to obtain a homogeneous paste. The pastes with a high fly and bottom ash content need additional water. This water demand is increased because it depends on the fine particle amount, the unburnt material, and the internal water content of the ash (Lee et al. 2010; Andrade et al. 2007). On the other hand, the pastes with RFA and RCA content need additional water due to their high porosity and low specific gravity which increase the water/solid ratio (Wainright et al. 1994; Merlet and Pimienta 1994).

The paste is placed into moulds to manufacture test pieces of various shapes and sizes to be used in the mechanical tests. Specimens are taken out of the moulds 24 h after casting, and cured in a water tank at 25 °C for 27 days.

2.1.3 Insulating Properties

For passive protection against fire, those materials that retain a large quantity of water are more desirable. When the surface of a porous medium with a water content is exposed to a real or simulated fire by means of exposure to a high temperature, part of the water evaporates, which generates overpressure in the pores of the material. Consequently, the evaporated water is transported from the exposed surface as a result of a pressure gradient to the interior of the material, which is cooler, and the water condenses again. A liquid film is thus formed which is progressively displaced towards the unexposed part. Thus, the water content of the material causes an evaporation plateau to appear at around 100 °C in the temperature profile of the unexposed side (temperature vs. time) because the pressure gradients do not significantly influence the saturation pressure of the liquid water in the interphase. This phenomenon is called the evaporation plateau (Vilches et al. 2005a, b).

The standard fire-resistance test described in the European regulation (EN 1363-1 2000), similar to other widely used international standards, is the result of the observation and analysis of several real fires. In order to simulate the fire exposure conditions, the regulation requires that one of the sides of the protective material be exposed to heat according to a standard temperature curve defined by the equation: $T = 20 + 345 \cdot \log_{10}(8t + 1)$, where T is the oven temperature for the test in °C and t is the time in minutes from the beginning of the test.

A special furnace is used to study the insulating capacity of the blocks. This furnace allows the surface temperature of the exposed surface (hot surface, T_{in}) of the block to be recorded by means of an S-type thermocouple, which is also used with a proportional controller to produce the standard temperature curve. On the unexposed surface (cold surface, T_{out}), the temperature is registered by means of a Pt-100 probe with a stainless steel contact surface (see Fig. 2; Vilches et al. 2007). In order to analyse the insulating capacity of the block following the Spanish standards regarding fire resistance, it is also necessary to measure the time taken for T_{out} to reach 180 °C (t180). All the blocks, for every composition tested, are 3 cm thick, 28 cm high, and 18 cm wide.

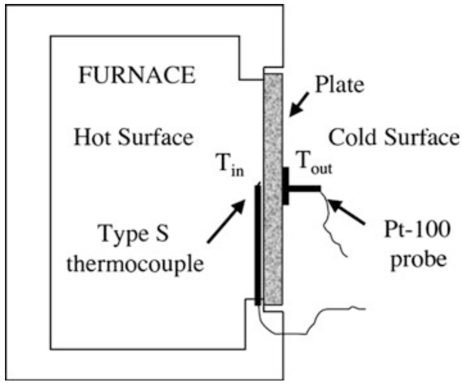


Fig. 2 Insulating capacity test (Leiva et al. 2013)

The thermal conductivity is measured according to the hot-wire (parallel) method (EN 993-15 2005), in the Technological Institute of Materials from Asturias (ITMA). The equipment used is a NETZSCH TCT 426, and the measurements are carried out at a temperature interval from 20 °C to higher temperatures.

2.1.4 Physical and Mechanical Properties

All samples, with different compositions, are characterised. Their physical and mechanical properties are determined through the following tests: density, setting times, volume stability, humidity, and compressive and bending stress. These properties are those required for blocks in construction applications (UNE 136001 EX 1995; EN 12859 2012).

The material density (ρ) is measured by weight and by volume (dimensions). Four specimens of each type are tested.

The next property measured is the volume stability (VS) using Le Chatelier´s apparatus (EN 196-3 2005). VS affects the potential application of the material as a construction product because volume changes with respect to other products can generate construction defects.

The pH, as for the previous property, affects the behavior of the whole construction because it affects the durability of other construction materials, for example, reinforced steel corrosion. The pH is then measured in accordance with European standards (EN 12859 2012). A 2-g sample is taken from the plate and is dissolved into 20 g of water. After 5 min, the pH of the solution is measured.

Another important construction material property is humidity inasmuch as it influences the end-user environment. Humidity (*H*) is also measured in accordance with European standards (EN 12859 2012). The sample mass is measured at room temperature ($M1$), and again after drying at 40 °C when a constant mass is reached ($M3$). The value of humidity is calculated by:

$$H = \frac{M3 - M1}{M1} x100 \quad (1)$$

Finally, the mechanical properties of the samples, that is, compressive (Rc) and bending (Rf) strengths, are evaluated using a compression test machine (Suzpecar, MEM-102/50t) according to ASTM C348-14 (2014) and ASTM E761-92 (2011), respectively. All these properties are determined on 28-day-old samples in three separate samples.

2.1.5 Environmental Study

In order to become construction materials, the new products developed in the present work must present a low toxicity level, which is proportional to the leached metals in the sample. The environmental study, EN 12457-4 (2003), is carried out to characterise the fly and bottom ash, as well as RFA and RCA, and to evaluate the possible applications. Portland cement, a commercialised product, is subjected to the same test in order to compare the leaching results. Furthermore, the most commonly used leaching tests for monolith samples in the waste management field in Europe, the NEN 7345 (1995) diffusion test also known as the tank leaching test, are performed. Similar studies have been performed for other recycled materials (Leiva et al. 2010). Lastly, the metal analysis in leachates is carried out using atomic absorption spectrophotometry and inductively coupled plasma techniques.

2.2 Results and Discussion

2.2.1 Physical, Mechanical, and Insulating Properties

As expected, the density of the 28-day-old block decreases when the proportion of FA or RFA content replacing natural fine aggregate (NFA) is increased (Demirboga 2003; Table 3). This is due to the lower specific gravity of these components (see Table 1) and the wide size distribution of RFA compared to NFA (Fig. 1).

Both compressive and bending resistances (Table 3) of the samples are reduced when adding fly ash to replace NFA due to the lower mechanical resistance and pozzolanic activity of the ashes (Papadakis 1999). These observations are consistent with results of other studies (Bijen and Selts 1993; Babu and Bao 1996; Iam et al. 1998). On the other hand, when adding RFA to replace fine aggregate, the compressive resistance lowers and their bending resistance remains similar, as previously stated in the literature (Evangelista and De Brito 2007, De Juan and Alaejos 2009).

Table 3 Variations of density, and of compressive and flexural strengths of concrete blocks with FA, BA, RFA, or RCA content

Mixture	Density (kg/m^3)	R_c (MPa)	R_f (MPa)
H0	2088	22.7	5.1
H-FA20	1910	20.9	4.2
H-FA40	1650	15.3	2.1
H-FA50	1615	4.9	1.3
H-BA20	1740	11.6	3.3
H-BA30	1660	8.2	3.1
H-RFA20	1790	22.0	5.0
H-RFA40	1750	20.5	4.8
H-RFA50	1710	19.8	4.5
H-RCA20	1820	21.2	4.9
H-RCA30	1500	20.5	4.5

Figure 3 shows the insulating capacity obtained during the fire test for 30 mm-thick blocks with FA and RFA content, respectively. When the fly ash content is increased, the insulating capacity also increases (more slightly in the case of RFA), due to the widening of the evaporation plateau. The mass losses (%) during the fire test in the compositions H0, H-FA20, H-FA40, and H-FA50 are 3.92, 4.39, 4.95, and 5.16, respectively, whereas in H-RCA20, H-RFA40, and H-RFA50 they are 5.05, 5.32, and 5.55. The mass loss is related to the water content, which also produces a wider evaporation plateau (Vilches et al. 2005a, b).

On the other hand, the density of the 28-day-old block decreases when the NCA replacement with bottom ash (BA) or recycled coarse aggregate (RCA) is increased (Table 3). In the case of BA, this is due to its lower specific gravity and higher porosity (Lee et al. 2010), whereas with RCA it is also due to its lower size distribution (Fig. 1).

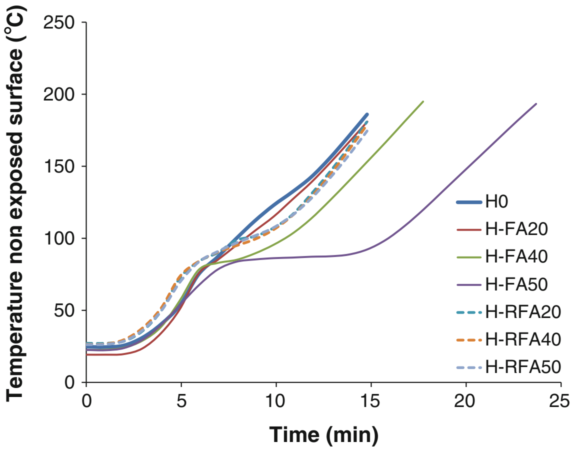


Fig. 3 Fire test on the FA and RFA blocks

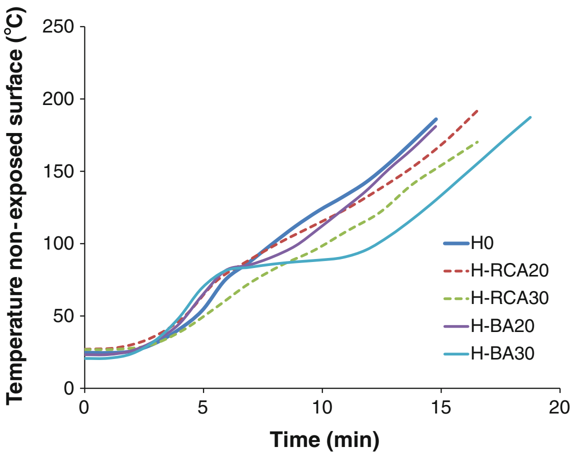


Fig. 4 Fire test on BA and RCA blocks

The mechanical strengths, compressive and bending, of the samples are reduced by adding bottom ash or RCA to replace natural coarse aggregate (Table 3), in a similar way to the previous samples analysed, this being a very slight decrease in the case of RCA. These results are consistent with other studies on bottom ashes (Demirboga et al. 2007; Özkan et al. 2007) and on RCA (Rahal 2007; Etxeberria et al. 2007).

The insulating capacity during the fire test of 30-mm-thick plates is higher for all the samples that contain BA or RCA (Fig. 4). The evaporation plateau widens with bottom ash additions because BA is a porous material with a high capacity to retain water and works as a water reservoir. By increasing the BA content, the block porosity is increased, thereby improving the moisture transport behavior within the block during the fire (Andrade et al. 2007; Lee et al. 2010). When adding RCA, the evaporation plateau disappears, and the fire resistance is then established by the curve slope, because the slope is inversely proportional to the thermal conductivity (Vilches et al. 2005a, b).

The present case is completed with the analysis of blocks made completely with and without recycled material. Table 4 lists the physical and mechanical properties of the blocks without recycled waste (H0), and without fine and coarse natural aggregates (HR1 and HR2).

Table 4 Physical and mechanical properties of H0 and HR

	Density (kg/m^3)	Volume stability (mm)	H (%)	pH	R_c (MPa)	R_f (MPa)
H0	2088	1.0	1.8	11.0	22.7	5.1
HR1	1504.3	0.4	3.1	10.7	12.0	1.9
HR2	1590	0.2	4.0	11.3	20.1	4.5
HR3	800	2.0	6.3	10.2	1.2	1.8

The density of 28-day-old blocks decreases with the addition of FA, BA, RFA, and RCA, inasmuch as these materials have a lower specific gravity than natural fine and coarse aggregates. Furthermore, as expected, humidity is higher in the HR1 and HR2 blocks. Density at 28 days was lower in HR0, HR1, and HR2 panels, and the humidity was significantly higher. The volume stability was lower than 10 mm in all cases, which is required by European standards for other building materials made from waste (EN 450-1 2013).

The volume stabilities of HR1, HR2, and HR3 show little variation, less than 2 mm, complying with the limit in European standards (EN 450-1 2013) for other construction materials with waste (<10 mm). One factor that affects volume stability is the MgO content. At less than 4 %, the samples have practically null volume stability, but in BFA it is higher. Compressive and flexural strengths of HR1 and HR2 are also lower than that of H0 due to the effects of the weaker new materials in the block, less significant with RFA and RCA.

As can be seen, HR compressive resistance was 1.24 MPa, which is a relatively high value in terms of the product application goals as a component of fire-resistant elements such as fire doors and fire walls (Vilches et al. 2007) but lower than blocks with Portland cement. Furthermore, the contribution of the glass fibre had a very positive effect on the resistance to bending values; it tripled the resistance with respect to the same composition without glass fibre. On the other hand, flexural strength decreased in HR3.

The pH is similar in all cases, slightly exceeding the limits with respect to construction gypsum blocks for HR1 and HR2 (<10.5; EN 12859 2012). The insulating capacity of HR1 is higher than that of H0 due to the combined effect of the fly and bottom ashes (see Fig. 5). In HR2, the insulating capacity is also higher. The evaporation plateau widens and the curve slope decreases, especially after 100 °C is reached. These results are similar to those of other construction materials containing different waste types, such as fly ashes (Garcia Arenas et al. 2011; Leiva et al. 2009), biomass ashes (Vilches et al. 2007), solid particles recycled from used truck tyres (Hernández Olivares and Barluenga 2004), and geopolymers produced

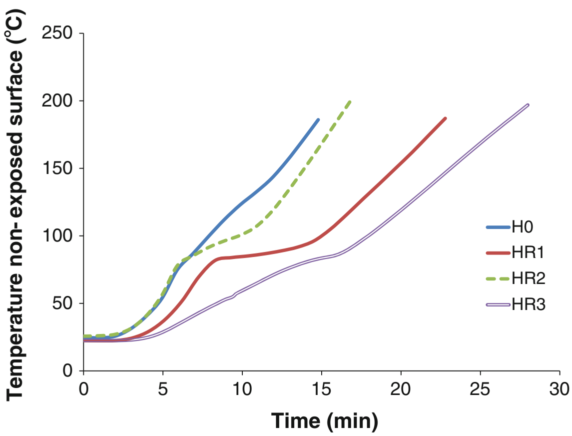


Fig. 5 Fire test on H0, HR1, HR2, and HR3 blocks

by granulated blast furnace slag (Cheng and Chiu 2003). Furthermore, the fire resistance in the HR1 blocks is lower than that of other blocks containing gypsum as a binder (Leiva et al. 2005; Vilches et al. 2005a, b) but the last are not water resistant.

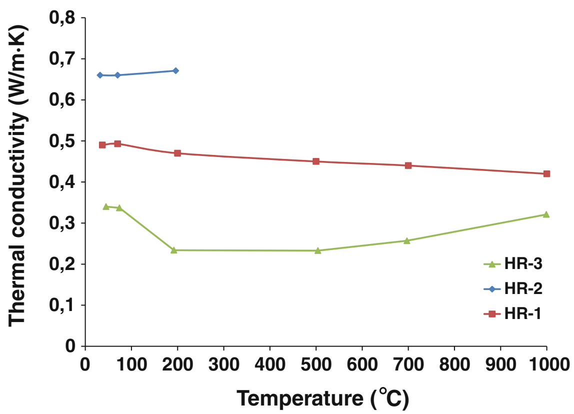
Throughout testing no gas emission was observed. In addition, all the blocks maintained mechanical stability before, during, and after the test, in both the exposed and unexposed surfaces, without appreciable deformation.

The variation of HR thermal conductivity with temperature is shown in Fig. 6. HR3 blocks present a lower thermal conductivity than HR1 and HR2 at ambient temperature and all of them are lower than heavy-weight concrete (1.63 $W \cdot m^{-1} \cdot K^{-1}$) and similar to medium-weight concrete (0.51 $W \cdot m^{-1} \cdot K^{-1}$). This is because thermal conductivity is directly proportional to density (Morabito 1989; Demirboga and Gül 2003).

For HR1 and HR3, between 100 and 200 °C a decrease of thermal conductivity due to the evaporation of water can be observed, which produces two effects on the material causing variations in its conductivity: the thermal conductivity of the gaseous substances generated is very different to that of the solid and, on the other hand, the rapid generation of these gaseous substances produces the appearance of overpressure in the porous materials, which could produce breakages, and the consequent appearance of preferential pathways for the evacuation of the generated steam. This increase in porosity produces a reduction in the density, which results in a reduction of the thermal conductivity (Leiva 2006). The thermal conductivity remains virtually constant from 200 to 700 °C, the temperature at which a linear increase is produced due to the increase in the energy of the molecules that make up the material (Thomas 2002).

As can be seen in Fig. 6, thermal conductivity of HR1 and HR2 is almost constant up to 70 and 200°C, respectively, because their densities are also constant. In HR1, thermal conductivity decreases between 100 and 1000°C because density decreases due to water evaporation (this water also produces the evaporation plateau during the fire test) and to the decomposition of different carbonates and

Fig. 6 Thermal conductivity of H1, HR2, and HR3



calcium hydroxides (Kodur and Sultan 2003). The latter decomposition produces two effects: the gaseous substances generated have very different thermal conductivities to those of the solid substances; and the rapid generation of such gaseous substances produces an overpressure inside the porous material, which could produce breakages, and the consequent appearance of preferential pathways for the evacuation of the generated steam. This increase in porosity produces a reduction in the density which entails a diminution of the thermal conductivity (Kodur and Sultan 2003).

2.2.2 Environmental Results

Leaching

The range of construction materials for which tests have to be developed is very broad (concrete, brick, lime silicate blocks, asphalt, wood, metal roof materials, plastic materials, etc.) as is the variety in 'dangerous substances' (heavy metals, organic contaminants, radio nuclides). Also, the variety in application/impact scenarios is fairly wide (e.g., the release of 'dangerous' substances to the water phase in a drinking water pipe, in a road base application with compacted granular materials, or in the run-off of rainwater from roof material). This implies that it is not easy to find a unique environmental test.

Nevertheless, it is clear that certain types of leaching tests are more suitable than others for use in analysing contaminant emission potential for identified or formulated scenarios. Although there are variations within each category, leaching tests can be grouped into the three categories described below:

1. *Batch leaching:* The discrete particulate material is agitated with a leachant in a container for specific time durations. The concentrations of contaminants in the leachate are measured. Batch leaching tests provide the maximum exposure of waste materials to leachant. The EN-12457-4 belongs to this category.
2. *Column leaching:* In this category of tests, discrete particles of the material are packed into a column with or without compaction. The leachant is introduced, typically into the bottom of the column such that the hydraulic gradient moves it upward through the material. Thus the leachant enters at the bottom and the leachate flows out of the top of the column. The concentration of the leachate and its flow rate or volume are monitored continuously or at specific time intervals.
3. *Monolith leaching:* A cemented mass monolith of the material containing the targeted contaminants is submerged in the leachant. The concentration of contaminants in the liquid is monitored at time intervals. In the most common variation of this test, the leachate which is also the leachant is purged at time intervals ranging from 2 to 90 days. The results are usually analysed to determine the diffusion coefficients of specific contaminants from the monolith to the leachate. The monolith may be fabricated as a cylindrical or rectangular block.

Monolith leaching provides the least surface area for contaminant release per unit mass. The contaminants must diffuse to the surface of the monoliths through much longer travel pathways than in the cases of batch and column leaching. The NEN 7345 belongs to this category.

Although in Spain there is no implemented national legal requirement for the reuse of waste materials such as in the type of products studied here, some regional regulations exist for some residues used in other kinds of applications, apart from the regulations related to the use of pulverised coal fly ash in cement and concrete. For instance, the Autonomous Government of Catalonia and Basque Country has established regional regulations for waste management, including limited recycling for some wastes (metallurgical and MSWI slag) in hydraulic road binders. These regulations require determining the concentrations of some potential pollutants using the EN12457-4 leaching test (Order on Re-Use of Slag 1996, 2003).

In this work, all the materials are subjected to the EN12457-4 leaching test, and they have been compared with the limits stated for different parameters by the European Union and Council directives on the landfill of waste (Directive 2003/33/EC; Council Directive 1999/31/EC), in which the three following waste categories are defined: inert, nonhazardous, and hazardous wastes. Table 5 also includes the slag recycling limits in the construction sector, according to Catalan and Basque regulations.

As can be seen in Table 5, there is a wide variety of essays and local legislation. Some wastes cannot be used because there is no legislation regarding them, and there are even different limits to be met by the same kind of waste depending on the region, thus allowing several wastes to be used only in some regions.

Because all the recycled materials (FA, BA, RFA, RCA) are used as part of blocks, it seems reasonable to pay more attention to the leaching of the conformed product rather than to the components, and for this reason HR1, HR2, and H0 have been subjected to the tank leaching test (NEN 7345) for bound or shaped materials.

Table 5 EN-12457-4 leachability of wastes (mg/kg, dry basis)

	As	Cd	Cr	Cu	Mo	Ni	Pb	Zn	Ba	V
FA	30	3	150	3	574	10	30	55	65	20
BA	30	3	2	3	10	10	30	1	68	20
PC	30	3	436	3	10	10	30	105	313	20
RFA	<5	<1	<2	<1.5	–	<5	<1.5	2	–	–
RCA	<5	<1	18	<1.5	–	<5	<1.5	<1	–	–
NFA	<5	<1	<2	<1.5	–	<5	<1.5	<1	–	–
NCA	<5	<1	<2	<1.5	–	<5	<1.5	<1	–	–
Inert waste	0.5	0.04	0.5	2	0.5	0.4	0.5	4	20	–
Nonhazardous waste	2	1	10	50	10	10	10	50	100	–
Hazardous waste	25	5	70	100	30	40	50	200	300	–
Catalonian limits	100	100	500	2000	–	500	500	2000	–	–
Basque limits	–	0.9	260	–	130	80	80	120	1700	130

The results have been compared with the Dutch Soil Quality Decree (DSQ; Decree on Soil Quality 2007), which contains rules relating to the use of stony building materials and earth in construction. The aim of the DSQ is to prevent pollution of the soil and surface water.

Table 6 describes H0, HR1, HR2, and HR3 metal concentrations and anions in the leachates, where the blocks spent 64 days in the leaching test tank. Practically all HR1, HR2, and HR3 heavy metals analysed lie outside the detection limits. In addition, none of these concentrations exceeds the limit established in DSQ, and are similar to H0 leachate concentrations. Only Mo, V, and As concentrations are significantly higher in HR1 than in H0, but within the admissible limit. According to these results, no important environmental problems are expected from using the blocks developed in this study.

Radiological Test

Building materials contain various amounts of natural radioactive nuclides. For example, materials derived from rock and soils contain mainly natural radionuclides of the uranium (^{238}U) and thorium (^{232}Th) series, and the radioactive isotope of potassium (^{40}K). In the uranium series, the decay chain segment starting from radium (^{226}Ra) is radiologically the most important and, therefore, reference is often made to radium instead of uranium. The worldwide average concentrations of radium, thorium, and potassium in the earth's crust are about 40, 40, and 400 Bq/kg,

Table 6 Leaching test NEN 7345 results (mg/m^2) of blocks compared with the DSQ limits

	H0	HR1	HR2	HR3	DSQ limits
Hg	≤0.2	≤0.2	≤0.1	<0.1	1.4
Se	≤0.4	≤0.4	≤0.4	<1	4.8
Sn	≤0.4	≤0.4	≤0.3	<0.1	50
Pb	≤0.3	≤0.3	≤0.2	9.6	400
Ba	≤3.2	≤3.2	≤6.6	17	1500
Cd	≤0.2	≤0.2	≤0.1	1.0	3.8
Sb	≤0.7	≤0.7	≤0.4	≤0.2	8.7
Co	≤0.2	≤0.2	≤0.1	≤0.1	60
Cr	9.1	9.1	8.9	45	120
V	2.6	41.8	≤3.3	2.5	320
As	0.1	21.4	0.1	9.6	260
Mo	1.7	19.3	≤2.7	≤2	144
Ni	≤1.1	≤1.1	≤0.7	1.9	81
Zn	≤1.9	≤1.9	0.5	29	800
Cu	≤0.3	≤0.3	≤0.2	51	98
Cl^-	693.3	8290	1020.9	–	110,000
F^-	≤33.1	≤33.1	≤28.2	–	2500
$SO_4^=$	2835.4	2435.3	24,442.7	–	165,000

respectively (To remind the readers, the becquerel (symbol Bq) is the SI derived unit of radioactivity, defined as the activity of a quantity of radioactive material, in which one nucleus decays per second; in other words, Bq is equivalent to s^{-1}.).

In Spain, as already mentioned in the leaching tests section, there is no legislation for this kind of product. International recommendations (European Commission 1999) allow choosing an effective dose increment constraint in the range 0.3–1.0 mSv/y for prolonged exposure to natural radiation by a member of the public. The effective dose also takes into account, in addition to the energy absorbed by the body due to exposure to radiation, the relative biological harm and the susceptibility to harm of different biological tissues.

The activity concentrations of radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in typical construction materials and wastes are presented in Table 7. The data give an idea of the variability found in different materials coming from different sources.

For practical goals, the evaluation of the compliance of a specific building material with the limits of international recommendations [35] is carried out using the activity concentration index 'I'. This index is expressed in terms of activity concentrations of the three major natural radionuclides: ^{226}Ra, ^{232}Th, and ^{40}K, according to the equation:

$$I = C_{Ra-226}/300 + C_{Th-232}/200 + C_{K-40}/3000 \quad (2)$$

where $C_{Ra\text{-}226}$, $C_{Th\text{-}232}$, and $C_{K\text{-}40}$ are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in Bq kg^{-1} in the building material tested. To comply with the regulations (based on the annual dose increment constraint of 0.3 mSv/y) the activity concentration index calculated for the product tested must comply with the criterion: $I \leq 1.0$ (European Commission 1999). The results of Table 7 confirm a potential for industrial use of the FGD gypsum because 'I' is under this criterion.

Table 7 Activity concentrations (Bq/kg) of radionuclides ^{226}Ra, ^{232}Th, and ^{40}K and activity concentration index (I) of gypsum samples

	Typical activity concentration (Bq/kg)			Maximum activity concentration (Bq/kg)		
	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K
Most common building materials (may include by-products)						
Concrete	40	30	400	240	190	1600
Aerated and light-weight concrete	60	40	430	2600	190	1600
Clay (red) bricks	50	50	670	200	200	2000
Sand–lime bricks	10	10	330	25	30	700
Natural building stones	60	60	640	500	310	4000
Natural gypsum	10	10	80	70	100	200
Most common industrial by-products used in building materials						
Phosphogypsum	390	20	60	1100	160	300
Blast furnace slag	270	70	240	2100	340	1000
Coal fly ash	180	100	650	1100	300	1500

As can be seen from Table 7, radioactivity concentrations found in wastes can often be significantly higher in comparison with most common building materials. According to these guidelines, the use of wastes containing natural radionuclides in building materials, which could result in activity concentration indices exceeding the values specified in Table 7, should be justified on a case-by-case basis by the states.

3 Recycling of Biomass and C&D Wastes for Façade Solutions

It is given that the studied materials made with waste must be integrated in constructive solutions with other nonrecycled materials. In order to study the influence of these materials on the solutions' characteristics, in this section the integration of recycled materials into traditional constructive solutions is analysed.

3.1 Materials

The materials analysed in this second case study are HR2 and HR3. The characteristics of both solutions for their use in building envelopes are compared with the traditional and most common solution in social housing in Andalusia (Marrero et al. 2013; Mercader et al. 2010), consisting of:

- One-half-foot brickwork of perforated ceramic brick taken with cement mortar M5
- Poor cement mortar layer (CS III W1)
- Unventilated air chamber
- Polyurethane rigid foam
- Aluminium profiles supporting the inner layer
- Plasterboard

In this case study, the main aim is to minimise the environmental impact by developing an alternative façade solution, where the new plasterboard with fly ash from biomass (Alba et al. 2012) is used for the inner layer, and the new recycled concrete plates (Espejo Escudero 2009) replace the outer brickwork.

3.2 Panel Preparation

Prototypes of façade solutions using these materials were built in order to verify their behavior during the installation process. Thus, their hardness and strength on screwing were tested, showing a good puncture resistance even in weaker areas

Fig. 7 Prototype of the 'Plares' gypsum panels (Alba et al. 2012)

(i.e., close to edges and corners). The cut of the plates is done easily and quickly with a simple saw, and they can be directly screwed to the aluminium profiles with relative ease (Fig. 7).

3.3 Comparative Façade Solutions

It is known that the energy balance that can be achieved in a building depends largely on its façade, more specifically on the thermal insulation that this provides. This insulation is quantified by what is known as thermal transmittance (U) of materials, that is, the ability to transmit cold or heat through the material (Spain MH 2009).

As mentioned at the beginning of the case study, the solution of the original façade that is intended to be substituted consists of a double wall with an unventilated air chamber, with its main outer layer made with brickwork and the inner layer made with plasterboard. Inside the air chamber there is a polyurethane rigid foam thermal insulation sprayed on the outer layer (on the left in Fig. 8).

After performing the calculations, the result for the transmittance (U) of the conventional solution is 0.677 W/m^{2}K, complying with the limit of 0.82 for the climatic zone B4, to which the city of Seville belongs according to the Basic

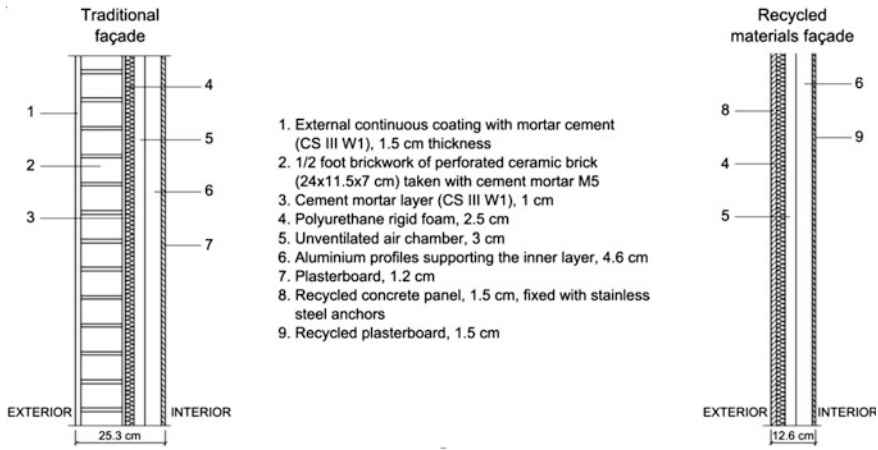


Fig. 8 Traditional (*left*) and recycled (*right*) façade solution (Marrero et al. 2013)

Document on energy saving from the Spanish Technical Code of Construction (Spain MH 2009). In the case of the solution made with recycled materials, the transmittance obtained is 0.761 W/m^2K.

In view of the results, the thermal behavior of the new constructive solution made with plates from recycled material is slightly lower than that of the conventional solution, and it is within the limits set by the Spanish Technical Code of Construction.

4 Conclusions

The following conclusions can be drawn from this research.

1. All four wastes studied decrease the density and mechanical strength of a 28-day-old block.
2. All the new components studied increase the fire resistance of the blocks, which is recorded in the steep slope of the time–temperature curve during the fire test. Thus, the new material has higher fire insulation and lower thermal conductivity than nonrecycled blocks. Both these characteristics improve block quality for certain applications, thereby generating value-added products.
3. Ashes are commonly recycled, but in order to facilitate the recycling of by-products such as those considered here (fly and bottom ashes) an established set of standards is required that clearly regulates their use. For example, fly ashes can currently be used in some Spanish communities but not in others. In all cases, the metal content is similar to that in traditional materials used in construction.
4. Recycled fine and coarse aggregates are used in the same state as they are received from the C&D waste treatment plant, without any previous treatment

such as heating, milling, and sieving. Both show a differentiated chemical composition to that of river sand and crushed granite, respectively.

5. The block preparation differs in water content, because a higher water ratio is necessary in the recycled concrete.
6. The properties of the new materials validate their possible usage for non-structural applications such as blocks or prefabricated concrete panels for façades and inside partitioning, inasmuch as they have similar mechanical properties to materials on the market.
7. From an environmental point of view, in recent years there has been a growing tendency to use new recycled materials with technologically enhanced levels of leaching and radioactivity (e.g., coal, fly, and bottom ash; slag; phosphor-gypsum; etc.). Many of them are valuable industrial by-products having the potential to be reused in construction, however, the problem of their contaminants has to be addressed. In view of this, there is a need to develop and introduce on both international and national levels environmentally safe and economically reasonable standard regulations, which should be based on justified radiological, social, and economics legislation concepts.
8. The use of the developed material does not represent a significant risk to the environment, as it has been determined through leaching tests that despite the high content of residual material, the impact is minimal.
9. The plates made with the new recycled materials show good performance in their use in construction due to their good mechanical properties. Their resistance to bending and compression allow drilling and screwing even in the worst areas without any breakage occurring in the plates.
10. The thermal transmittance of the new constructive solution, the main feature to note on façades, is slightly lower than that of the conventional solution. Although the initial solution had a transmittance U = 0.677 W/m^{2}K, the new solution, with panels of recycled material ('Plares') for the inner layer, and plates of concrete with recycled aggregates for the outer one, presents a thermal transmittance U = 0.761 W/m^{2}K, and it is still within the limits established in the Spanish Technical Code of Construction U_{Mlim} = 0.820 W/m^{2}K.

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Enhancing Crop Residues Recycling in the Philippine Landscape

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Abstract Recycling the crop residues of the two major crops (rice and sugarcane) in the Philippines remains to be achieved. Rice straw burning is still prevalent at 76 % of all rice farms. About 32 % of the 22 million tonnes (valued at PhP 18.41 billion compost) rice straws produced in the 4.4 Mha harvested areas are burned. It will take about 30 years or more to stop rice straw burning in the Philippines at the rate farmers are withdrawing from the burning habit. For sugarcane, 64 % of the trash, at about 3.02 billion kg of sugarcane trash, is still burned. The average annual fertiliser import for the last 10 years was 2.0 million tonnes (50 % of which was nitrogen) valued at PhP 40 billion. Recycling the residues of the two crops (rice and sugarcane) will have a large effect because 50 % of all fertilisers are used for these crops. The total compost fertiliser value of the crop residues of the two crops amounts to about PhP 25 billion (US$569 million) per year. National laws and local ordinances were enacted but monitoring and enforcement should be strengthened. Discussed in this chapter are other paths that must be explored. Farmers could be given incentives and rewards for not burning crop residues instead of the punitive approaches (legal) to enhance crop residue recycling in Philippine landscape.

Keywords Crop residues · Rice straws · Sugarcane trash · Detrashing · Recycling · Composting

1 Introduction

The Philippines is an archipelagic country consisting of 7,107 islands with three major island groups, namely: Luzon (141,000 km^2), Visayas (57,000 km^2), and Mindanao (102,000 km^2). Located between latitudes 4 and 21° north and longitudes 116 and 127° east, the country has a stretch of 1839 km north-to-south off the

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southeast coast of Asia. It is bounded by three large bodies of water: the South China Sea on the west and north, the Pacific Ocean on the east, and on the south by the Celebes Sea and the coastal waters of Borneo. This location leads to the Philippines being frequently visited by many typhoons and it is ranked the third most vulnerable country regarding climate change. The total land area of the Philippines is about 30 million ha, of which, 10 million ha are agricultural croplands. Rice and sugarcane are the two most important crops.

Rice is a staple food to about 80 % of population supplying 40–65 % of food caloric energy (Mendoza 2008). Rice contributes 29 % to agriculture's 16 % contribution to the gross domestic product (GDP), employing about 40 % of the total labor force; nine out of ten farmers are rice farmers (Tolentino 2001; Briones 2014). Rice-farming activities involve the father, mother, their children, and neighbors. Hence, rice farming is more than a livelihood or income source. It is life in a rice-farming community.

Sugarcane continues to be an important sector of the Philippine economy as it contributes about 0.5 million direct and another 5 million indirect employment. Sugarcane is presently grown on about 420,000 ha. In the 1960s to early 1970s, when the country had large sugar exports to other countries, mainly the United States of America, the sugar industry contributed about 20 % of Philippine exports (Zabaleta 1999). At that time, the area planted to sugarcane was about 580,000 ha.

The present agricultural practices for these two major crops can be likened to 'mining the soil' as they are so 'extractive' (Mendoza 1989; Alaban et al. 1990). As such, the soils are impoverished attributed mainly to noncrop residue recycling as they are simply burned on the farms where they are harvested. These two major crops (rice and sugarcane) occupy only about 30 % of the 10 million ha of agricultural lands but 50 % of all fertilisers in the country are used by these crops (Briones 2014). There are other utilisation options for the crop residues as in biofuel or feedstock for gasification but recycling them back on the farm where they are produced is still the best utilisation option (Lal 2005; Mendoza and Samson 2006; Parr et al. 1986). The positive merits of crop residue recycling are well studied and documented. Even farmers in an earlier survey conducted by Mendoza in 1994 had found out that many farmers knew all along of the need to recycle crop residues. Of the 1451 farmer respondents from at least 30 rice-producing provinces of the country, 65 % of them were aware of the need to recycle crop residues (Malasa et al. 2007). Areawise, crop residue burning still dominates the Philippine crop agriculture landscape and 76 % of rice lands and 64 % of sugarcane lands are still burned (Launio et al. 2013; Mendoza and Samson 2000).

Burning crop residues had become not only an agricultural, environmental, and health nuisance but also a social/community problem, hence, a political issue. This chapter reviews and analyses why crop residues are not recycled back on the farms where they are harvested; existing laws and local ordinances are reviewed as to why despite them, burning crop residues still persists and finally, measures on how crop wastes could be productively recycled instead of just serving as environmental nuisance and health hazards in surrounding communities are discussed.

2 Crop Residue Recycling: Why Farmers Don't Do It

For Rice. Rice straw is a valued product in rice production. This is especially true for farmers on rainfed areas that grow rice once a year. Rice is stored as valuable feed during the dry summer months. For those who grow onion and garlic, rice straw is used as mulching material. They preserve rice straw for without this material, their high-value crops such as onion and garlic will not thrive under the summer sun's heat without mulch and it will become water-intensive, requiring frequent irrigation. Pressure to grow more rice due to an increasing population led to massive construction of irrigation facilities to grow rice during the sunshine-rich and typhoon-free but rainfall-less, hence dry, months of summer. Irrigation and the availability of high yielding and nonphotoperiod-sensitive rice cultivars in the 1970s led to two croppings or more per year. This was the start of the farmers' practice of burning rice straw. The dwarf high-yielding rice cultivar (IR-8) was so susceptible to rice tungro virus (RTV) that the farmers were advised to burn rice straw to prevent the further spread of RTV (Mendoza 1994). Also, with irrigation water that allowed farmers to plant rice continuously lands should be prepared quickly. There was a short turnaround time and this required machines. Big and heavy tractors are not appropriate on muddy fields and they are expensive. This facilitated the introduction of small tractors. But rice straws obstruct land preparation using small machines. The easy solution is to burn them. Unlike before, farmers need rice straws for their carabaos but farmers had sold their carabaos to buy small tractors. With the machines around, they did not need their carabaos or the rice straws. Cattle raisers did not want to get and feed their stock rice straws because they were afraid of the insecticide residues from the systemic insecticides (Furadan 3G) that were still used by the farmers at that time.

There are many other reasons why farmers burn rice straws (Mendoza and Samson 1999) and they are as follows: (1) farmers believed that rice straws are a hiding place for rats, one of the damaging vertebrate pests for rice in the Philippines; (2) partially decomposed straws lead to yellowing of newly transplanted rice seedlings although this is temporary (due to nitrogen immobilisation; Narwal 1994); (3) duck raisers burn rice straws intentionally so the remaining rice grains after threshing can be eaten by their ducks after burning; (4) rice straws piled near the roads are burned when passersby throw the cigarette butts on the pile.

It was also pointed out that farmers simply burned rice straws because the government provided subsidies for fertilisers making them unduly cheap. Thus, nutrients lost can be replaced cheaply. It is so much easier to apply chemical fertilisers than spreading rice straws or composting them. The effects of soluble fertilisers on rice growth could be seen in a few days. Sales representatives were given incentives proportional to the number of bags of fertiliser sold to the farmers (Mendoza and Samson 1999).

Burning Rice Straw Has Many Undesirable Effects. Burning rice straw causes air pollution, health impacts, and nutrient loss (Truc 2005; Oanh and Sally 2004; Yevich and Logan 2003). On nutrient loss, burning rice straw causes almost complete N loss, 25 % P, 20 % K, and sulphur (S) losses of 5–60 % (Dobbermann and Fairhurst 2002). The practice of rice straw burning is a major source of air pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), unburned carbon, nitrogen oxide (N_2O), and sulphur dioxide (SO_2; Gupta et al. 2004). Methane is emitted from rice straw burning (Wassman and Dobbermann 2006). Yevich and Logan (2003) estimated 2200 g CH_4 per tonne of rice straw. Regarding health, rice straw burning is also known to emit particulate matter and other elements such as dioxins and furans that affect human health (Torigoe et al. 2000; Gadde et al. 2009). In the Philippines, based on estimates by the Industrial Technology Development Institute (ITDI) of the Department of Science and Technology (DOST), 250 kg of rice straw and 100 kg of rice hull are burned per tonne of rice produced. In 2006, a total of 5,073,880 tonnes of rice straw and rice hull were burned. This contributed to the dioxin and furan releases to air and land of about 187.0457 g TEQ/a compared to the estimated emissions by the transport sector of about 0.12 g TEQ/a (DOST 2006).

Given these negative effects of rice straw burning on the environment, human health, and soil fertility, there were earlier campaigns to stop burning rice straw. These included (1) the research trials conducted on-farm to demonstrate the benefits of rice straw incorporation; (2) a nongovernmental organisation (NGO) campaign on NBS which was done mostly during seminars and training; (3) some NGO/GO or farmer advocates joined the electoral process and successfully got elected. Once elected, they passed local ordinances to stop burning rice straws. Even private companies have joined the campaign. Starting in 2006 Bayer launched a nationwide campaign against rice straw burning, dubbed '*Huwag Sunugin ang Dayami*' (Do Not Burn Rice Straws) with emphasis on improving soil fertility (Fig. 1).

Fig. 1 Burning of rice straws showing the thick smoke. Photo taken at along the North Luzon Expressway, Pampanga, Central Luzon, Philippines, January 5, 2015

3 On Sugarcane, Why Burn?

Just as with rice, burning sugarcane trash is a common practice. Sugarcane growers burn sugarcane fields in two stages, namely the pre-harvest and post-harvest burn. On average, the sugarcane plant produces 25–40 leaves, thus, it is trashy. Sugarcane 'trash' includes the tops, green, and dry leaves. They constitute up to 25 % of the entire sugar cane stalk. If unburned before harvest, much time and labor is used in removing the trash. It was estimated that it could slow down the work by as much as 40 %. Cane cutters oftentimes are in a hurry and they do not fully remove the attached leaves on the cane stalks. This makes the harvested stalks trashy. Trashy canes delivered to the mill suffer a trash penalty or yield reduction. This is because trashy canes affect juice clarification and boiler efficiency. Why burn? Some fields are weed-infested. If the field is too weedy, it is associated with the presence of snakes. The fear of snake bite plus the weeds obstructing the easy cutting of stalks all point to the decision of burning the canes to facilitate harvesting.

Pre-harvest burning, however, was discouraged by the sugar mills. They automatically impose deductions or penalties to burned canes. The reason is that burned canes have to be milled within 24 h. But this is difficult to achieve. During peak harvest, January to March of any given year, the sugarcane growers tend to hurry milling their canes. A large number of trucks line up in the mill yard waiting for their turn to unload their canes. From cutting, loading, and unloading in the sugar mill, it may take up to 5–7 days. In this period, much sugar inversion losses had occurred in burned canes, hence the mill owners' remedy is to exact a penalty or sugar yield reduction (Mendoza 2014).

After harvest, there is still trash remaining which obstructs tillage in preparing the land for new cane establishment and in ratoon-crop establishment. Piling the trash between cane rows to provide space for cultivation and fertiliser application is laborious. Coinciding with this operation is harvesting. The priority is harvesting and to facilitate farm operation, burning is the easy option. Except for accidental fires or burning due to weedy canes, many planters no longer burn before harvesting due to the significant economic losses. But they still find the huge pile of trash difficult to manage in establishing their next crop, be it ratoon or new plant cane (as discussed earlier). Their quick and easy solution is to burn their canes, the post-harvest burning.

Mendoza and Samson (2000) estimated the total area burned at 236,800 ha of the total area planted at 370,000 ha (or 64 %) from CY1998-99. There is no available estimate of sugarcane trash burning as of this this date (2015). Using the same burning coefficient, the estimated amount of trash burned for the 420,000 ha of sugarcane harvested for crop year 2013–2014 is about 1.94 Mt trash (0.64 × 7.12 t/ha × 420,000 ha).

Detrimental Effects of Burning Canes. Burning canes, before or after harvesting, has many agricultural, environmental, and health negative effects (Fig. 2). Burning canes liberates a considerable amount of CO_2 and other GHGs. The estimated direct CO_2 emission from cane burning was 10,410 kg/ha. An additional

Fig. 2 Post harvest burning of sugarcane trash. To quickly burn, a farm worker lights on the trashes from one end to the other end of the field. Photo taken at Nagros Occidental Philippines, February 20, 2015

1791 kg CO_2/ha was estimated from the other gases (CH4 = 467 kg CO_2, CO = 1241 kg CO_2, and N_2O = 830 kg CO_2). This summed up to 12,204 kg CO_2/ha which translates to about 37 % of the total greenhouse gas emissions in cane production on the farm (Mendoza 2014).

On the agricultural side, there are many nutrients lost through the biomass in sugarcane production. Sugar (sucrose) is only 10 % of the total tonnage yield. After evaporating moisture (50 %), 10–15 % of the trash+tops represents the amount that can be recycled back in the farm. Bagasse (25 %) is used as fuel in the mill. When trash is burned, the nitrogen is lost as nitrous oxides. Burned cane trash leads to near total loss of N at an average of 44 kg N/ha/yr. Some of the P and 70–73 % of K are also lost through burning (Ross et al. 2000). The quantity and forgone nitrogen lost varied with the amount of trash burned (Table 1). On a per hectare basis, the peso value of nutrients (N, P, K) of the 7.2 t/ha average trash produced per ha is PhP 5251/ha (US$119.36/ha). Converted into compost as in rice straw, the peso value of compost from sugarcane trash is about PhP 6.65 billion (US$151.2 million) for the 420,000 ha harvested canes for CY 2013–2014 (Table 1).

On the health side, sugarcane workers have been observed to have significantly high rates of mortality due to illnesses attributed to burning canes. A case-control study in the United States suggests that people engaged in sugarcane farm-related occupations have significantly higher rates of lung cancer (Mulvey and Rothschild 1983). According to the US Occupational Health Department (1999) sugarcane workers have an increased risk of lung cancer and this may be related to the practice of burning foliage at the time of cane cutting. Burning of the sugar fields releases fly soot to the atmosphere that contains polycyclic aromatic hydrocarbons that have mutagenic and carcinogenic properties (Zamperlini et al. 1997; Allen et al. 2004). Amre et al. (1999) also found an increased risk of lung cancer for workers employed in sugarcane farms in India. Work involving burning after harvesting and exposure to fibres of biogenic amorphous silica during fieldwork may account for the increased risks of lung cancer and possibly mesothelioma among sugarcane farmers (Poolchund 1991).

Table 1 Nutrient content (N, P, and K) and forgone peso value of burned sugarcane trash (2014 prices)

Item			Sugarcane trash (7.2 t/ha)
Kg per ton of trash[a]	N	2.870	20.664
	P	0.O20	0.036
	K	4.460	22.478
Price per Kg (PhP)[b]	N	53.000	1095.192
	P	77.000	2.772
	K	50.000	1123.920
Price per ha trash (PhP)	2221.884		
Add N-fixation @ 10 kg/ton trash*	72.000		
Value of N-fixed during decomposition	3816.000		
Total (Value of NPK* in the trash+Value N fixed) (PhP)	6037.884		
Value of nutrients per ton trash (PhP)	838.595		
Total value for 420,000 ha (in billion PhP)	1.650		
Total value for 420,000 ha (in million USD)	37.460		
Compost value of sugarcane trash (in billion PhP)[c]	6.650		
Compost value of sugarcane trash (in million USD)[c]	151.200		

[a]Author's own estimates based on data gathered in literature
[b]All N are burned; 25 % of P and 70 % of K are lost when trashes are burned
[c]2014 prices of NPK fertiliser SOURCES (retail store)
[d]Peso value of compost in trash computed as in rice straw (20 bags/ton × 0.65 recovery, PhP 200/bag)
Add N-fixation at 10 kg/ton trash[a]
Fertiliser value of sugarcane trash, per ton (PhP)
Average trash produced in the country is equal to 7.2 tons/ha at 0.12 trash × 60 tons/ha average cane yield

4 Benefits of no Burn Canes

As early as the 1950s, it was already recognised that trash mulching improves the yield of sugarcane. The results of this study were presented at the annual convention of the Philippine Sugar Technologists in 1956, but sugarcane planters did not appreciate the findings. To some, it was just natural but to others, this emphasised the need to recycle nutrients back into the soil. Decades afterwards, it was fully documented that organic fertiliser from sugarcane trash serving as a soil amendment, increases both tonnage and sugar quality (Abrigo 1981). High sugar yields are desirable as they increase mill efficiency and returns to the farmer. Moreover, higher quality canes delivered to the mill reduce the cost per unit of sugar manufactured.

Not burning canes and utilising the trashes in the field has many interrelated benefits to the soil, farmer, human health, society, and the environment (Fig. 3).

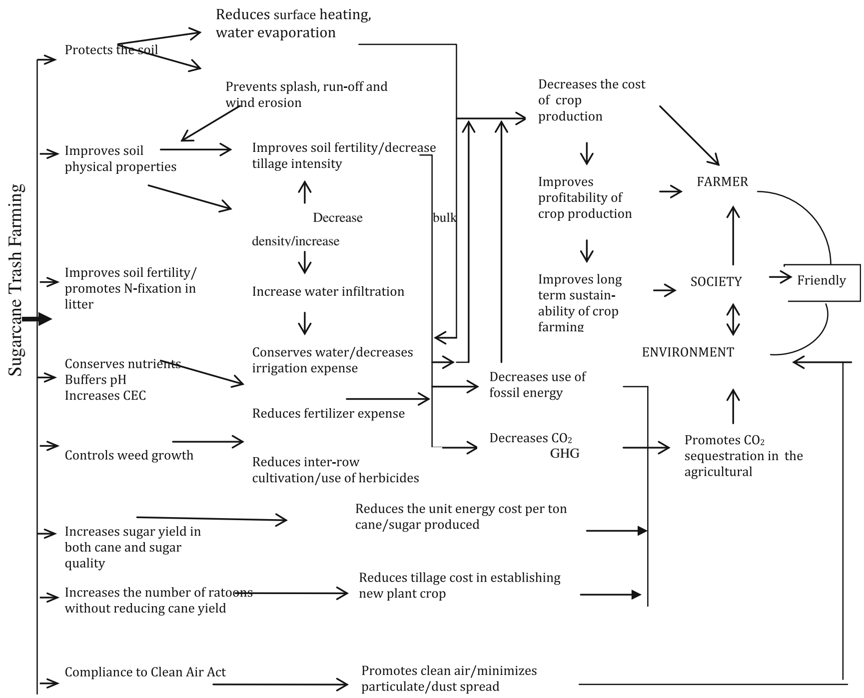

Fig. 3 Summarised interactive benefits of sugarcane trash farming to the soil, farmer, society, and the environment (Mendoza et al. 2003)

Foremost, utilising the trashes as in mulch farming increases sugar content by 11.6 % (Mendoza et al. 1989). Mulching was shown to improve the sugar level of ratoon crops significantly. Long-term fertility improvement of degraded soils through trash farming could lead to an overall increase in sugar levels and boost economic returns. Yields in the ratoon were 33 % higher in the trashed field than the nontrashed fields. There was an increase in both tonnage and sugar quality (Mendoza et al. 1989). A 50 % increase in sugar yields in trash-mulched canes compared with nontrashed farms in small farms was recorded by Delos Santos and Mendoza (2002). Also, trash farming extends the ratooning cycle.

In trash farming, P uptake appears more efficient as the mulch protects the soil from desiccation and permits root proliferation in the soil surface where P levels are high. This suggests that lower P fertilisation rates could be used to maintain productivity. Trash farming not only helps conserve organic matter in the soil during the decomposition process but also encourages N fixation in the sugarcane litter. A highly active system involving a microaerophylic N_2 fixing *Azospirillium brasilense* and adematiaceous fungus *Helicomyces roseus* had been described by Hill and Patriquin (1990). High yields without N fertiliser using cane varieties were associated with greater biological N_2 fixation that involves *Acetobacter* *diazotrophicus*. Trash farming conserves significant amounts of nitrogen in the soil (approximately 30–35 kg N/ha) and gains in soil nitrogen equivalent to 54 kg N/ha/yr over 9 years were reported for unburned cane (Boddey et al. 1995). Nitrogen fixation levels of 50–200 kg N/ha occur in trash-farmed sugarcane fields, with the higher range associated with higher trash levels. A mean value of 125 kg N/ha was recorded when trash farming was established as a practice (Patriquin 2001). In Brazil, where trash farming is frequently practiced, only 60 kg N/ha on average is applied to the crop. About 150–300 kg N/ha are used in most nontrash farming cane-producing countries such as Cuba, Peru, India, and the United States (Boddey 1995). In the Philippines, as high as 300 kg N is applied in Eastern Batangas, Philippines (Mendoza 2014). Trash farming could reduce N-fertiliser by 50 % without reducing sugar yields.

Trash farming improves soil properties. Conserved as mulch, sugarcane trash decomposes into humus, improving soil tilth, and decreasing tillage required. By increasing water infiltration into the soil, water retention is improved, thereby decreasing the need for irrigation. Trash-mulched canes can tolerate the normal dry season and El Niño events better than ratoon crops in burned cane fields, which have no trash mulch cover. This effect is even more evident in long-term trash-mulched fields with higher soil organic matter levels and a permanent surface mulch cover. The effects of mulching on soil fertility have been studied in Vietnam (Mui et al. 1997a, b). In a three-year experiment, it was shown that mulched fields had higher percentages of carbon, phosphorus, potassium, and nitrogen, whereas unmulched fields had lower bacteria, actinomycetes, and fungi. The higher percentage of carbon denotes the unique contribution of mulching in terms of carbon sequestration into the soil, which is important in reducing greenhouse gas emissions (Mendoza 2000).

The cost of fertiliser usage (material plus application) accounts for about 21 % of the total variable costs of production (average for plant and ratoon cane). Trash farming improves the economics of sugarcane production. Where trash farming was implemented, net returns increased by 43 % in the first ratoon crop. The trash-farmed ratoon crop achieved the lowest cost. It was 31 % below the cost of the conventional plant crop and 10.0 % below the ratooned conventional crop. The trash-farmed crop had 20 % higher ratoon tonnage yield (78 t/ha) than conventional cane (65 t/ha).

The increased yield in the trash-farmed cane also reduced the overall energy input of sugar produced. Fertiliser reduction was estimated to be 99–110 kg N/ha. The total fossil energy requirement for the fertiliser in the ratoon crop was thereby reduced to 9.1 GJ/ha (Mendoza et al. 2003). Trash farming reduces direct fossil fuel energy inputs through the following.

1. The most energy-intensive component is primary tillage or deep plowing (40–50 cm) as sugarcane is deep rooted. Extending the number of ratoon cycles from the conventional system of 1P:1R plant crop:ratoon crop to 1P:3R or 1P:4R results in a considerable reduction of energy inputs due to land preparation. A trash-farming scheme of 1P:3R results in a 50 % reduction in tillage

requirements, and a 1P:4R scheme results in a 60 % reduction. This is a considerable amount of energy and cost savings due to reduced demand for diesel and lubricants, and fewer repairs and maintenance costs. About 8.2 GJ/ha of energy could be saved from crop establishment

2. Under trash farming, trash-mulched interrows need no cultivation. As per the trash-farming scheme (Mendoza 1979, 1985), the ratio of nontrash and trash mulched rows is 50:50. This represents a 50 % reduction in interrow cultivation.

The adoption of trash farming is not simply the nonburning of cane. Sugarcane forms many leaves which explains why there is so much trash at harvest. These leaves form part of the total biomass which makes the cane heavier and susceptible to lodging. Cutting stalks close to the ground at harvest is difficult because the base of the stalk is covered. Detrashing the stalk when the cane has formed five to seven internodes (five to seven leaves could be removed) exposed the base of the stalk. Detrashing could be done at least twice before harvesting. The use of self-detrashing varieties (i.e., VMC 86-550) could facilitate detrashing.

Sugarcane planters doing detrashing found the practice beneficial as it provides off-season labor for their workers as detrashing is done between July to September, the nonharvesting/crop establishment period for sugar production. The arrangement between the planter and the workers is that those who detrash the sugarcane (hence making it easier to harvest) will also be the ones to harvest the canes. Cutting is easier and faster as well as loading the canes to the hauling truck. Another incentive attached to detrashing is if the stalks are cut close to the ground there is no longer any need for stubble shaving. The cost of stubble is P1,500/ha (US$34, 1 US $ = PhP 44). This is automatically given to the group of workers who performed detrashing and cut canes close to the ground, thus, no stubble shaving for the ratoon cane establishment.

Many benefits accrue with preharvest cane detrashing:

(1) It minimises the bulky trash to be managed at harvest time (about 12–20 t/ha). With detrashing, fewer trashes (60 %) remain after harvest. It is easier to pile the trashes in between rows (Fig. 4). This could pave the way to stopping burning the trashes completely.

(2) It activates the microbes leading to rapid decomposition of the remaining trash at harvest time if moisture is available. This reduces the need to apply chemical fertiliser.

(3) It improves air (CO_2) circulation leading to sweeter canes at harvest (more sugar per tonne of cane). Detrashing improves cane stands and sugarcane stalks are sweeter (clean canes delivered to the mill are not exacted a trash penalty). There was improved sugar recovery and mill efficiency from cleaner (less trashy and muddy) canes. Detrashed canes had 21.7 % higher recoverable sugar per tonne than trashy nondetrashed canes (Dosayla 1994). Thus, overall sugar recovery improved and sugar yield per ha increased. At about 5–10 kg sugar per tonne cane, this translated to about PhP 15,000–PhP 30,000 per ha.

Fig. 4 Trashes and tops are placed in alternate rows.The trash-free row serves as the row for cultivation to apply fertiliser. The pictures above are first ratoon in a farm in Negros Occidental, Philippines (Photo taken February 28, 2015)

(4) Detrashing facilitates cutting stalks close to the ground; the base of the stalks is still the sweetest part. The two to three inches of stalks left in the field were weighed. They weighed about 4–6 tonnes canes. At about 10 % sugar recovery, this translates to about 400–600 kg of sugar or about P12,000–P18,000 worth of sugar. Cutting stalks close to the ground eliminates the need for stubble shaving worth P1,500 per ha.

(5) Detrashing that paved the way to piling after trash every other row had improved ratoon cane establishment. Trials are underway to prolong the ratoon up to 5. This is a considerable improvement over the plant and ratoon once, then plant again.

(6) Dethrashing recycles some nutrients absorbed, improves soil tilth, water infiltration and water retention, and ultimately increases sugar yield (Mendoza et al. 2003).

Moreover, the conventional practice of burning the trash-then-stubble shaving in the conventional ratoon cane establishment has a hidden cost. Burned tillers that emerge 2 or 3 days after cutting the stalks are the vigorous tillers. To flush tillers out, an additional two to three bags of urea are necessary (PhP 2200–P3300/ha at P1,100/bag of urea, US$1 = P 44).

Detrashing is the key step to a no-burning/trash-farming scheme in sugarcane farming. The estimated financial benefits of detrashing cum trash farming are shown below:

Added income (savings)
No stubble shaving …….. ………………………….. ………………… P1,500
Increase sugar recovery (5-10 kg/tone x 70 tonne/ha x PhP30/kg sugar)…. P10,500 – 21,000
Added sugar due stalks cut close to the ground (400-600 kg/ha x P30/kg sugar)..
=P12,000-P18,000
Savings on crop establishment costs due to more ratoon canes …………… P6,000
Added Costs
Detrashing………………………………………………………………. P1,000 – P2,000
Incentive pay due to cutting canes close to the ground……………………. P1,500
TOTAL……………………………….P2,500 – P3,500
Net Benefits……………………………………… P27,500-P43,000 (US$625-927)
(1US$ = PhP44)

There are two groups of sugarcane planters where detrashing-cum-trashing farming (or no burning canes) is implemented at the farm level. The first group is the conscientious and environment-conscious planters (in fact some of them have started doing it). The second group is the beneficiaries of a government agrarian reform program. About 1,200,000 ha sugar lands are now be distributed to former workers of sugarlands. Trash farming is a cost-saving option for these groups of sugarcane growers. It extends the ratoon (crop establishment costs P25,000–P35,000/ha). Also, it could reduce the application of fertiliser (P20,000–P25,000/ha) and still provide a modest yield of about 70 tonnes of cane per ha (Delos Santos and Mendoza 2002).

Preharvest detrashing along with modified (double) row spacing is suggested as a remedial measure to offset the difficulties associated with trash farming. More on-farm trials should be conducted to explore and promote the benefits of this system. Some Filipino farmers are already practicing trash farming on their farms, therefore their efforts can serve as on-site examples for demonstrations to others.

Wider row spacing to ease trash deposition. Studies on spatial arrangement have been conducted to accommodate trash-mulching in ways that would not require so much handling of the trash. A double row spaced at 0.5–0.75 m and a wider interval space of 2.0 m was found to be suitable for intercropping-cum-trash farming (Mendoza 1979, 1985).

5 Addressing the Challenge of Rice Straw or Sugarcane Trash Burning Through Legal Means

There are at least five laws that had been enacted directly and indirectly related to no burning and they are: Republic Act No. 8749 (1999)-Clean Air Act; Republic Act 9003(2001)-Ecological Solid Waste Management Act; Republic Act No. 10068-The Organic Agriculture Act; Republic Act No. 9729 Climate Change Act of 2009; and Republic Act No. 9275 (2004) Clean Water Act.

The Philippine Clean Air Act of 1999 (R.A. 8749) provides for a comprehensive air pollution control policy. Foremost, it recognises that it is the right of every citizen to breathe clean air. It envisions the reduction of emissions from motor vehicles; improves fuel quality to reduce or eliminate lead in gasoline and sulfur in diesel; and prevents sources of pollution such as incinerators, garbage burning and smoking, burning residues that may contain persistent organic pollutants (POPs), poisonous and toxic fumes, gaseous and vaporous organic substances, ozone depleting substances (ODS), and radioactive emissions. Of the many materials cited in the law, burning of agricultural wastes or residues is not included as a source of air pollutants.

The Ecological Solid Waste Management Act of 2000 (Republic Act 9003), passed in January 2000, declared that it is the policy of the state to adopt a systematic, comprehensive, and ecological solid waste management program which shall ensure the protection of the public health and environment, utilise environmentally sound methods that maximise the utilisation of valuable resources, and encourage resource conservation and recovery. This act includes solid wastes generated in households, towns, and factories. Again, agricultural wastes or residues are not included. But as pointed out earlier, even the Clean Air act did not also include burning of crop residues as a source of air pollution. As cited earlier, burning of crop residues as in sugarcane trashes releases fly soot which contains polycyclic aromatic hydrocarbons (PAH) that have mutagenic and carcinogenic properties, and exposure to airborne particulate matter (fly soot and biogenic amorphous silica) is hazarduous to health. Also, burning crop residues near the road has caused accidents as the thick smoke makes the roadway invisible even at short distances. The Ecological Solid Waste Management Act is directed mainly to solid wastes in the household, municipalities market, and institutions (hospitals, schools, private/public offices). RA 9003 is mobilising barangay officers and their constituents to make material recovery facilities (MRF) or areas for recycling household and towns/municipal waste. It mainly stipulates segregation of wastes and proper waste disposal (biodegradable, nonbiodegradable; recyclable plastics, bottles, tin cans; and nonrecyclable/hazardous waste to be properly disposed of). It complements the organic agriculture act (RA 10068) as biodegradable wastes are decomposed and made into organic fertiliser. Many municipalities are now carrying out this composting project and they distribute the organic fertilisers to the farmers. The two laws (Clean Air and Ecological Solid Wastes Management) disallow wanton burning (although crop biomass is not included), and they also complement the Climate Change Act (burning solid waste emits various types of GHGs, and some toxic gases as well).

Although the national laws cited do not specifically recognise the merits or demerits of crop residues, many local government units (LGUs) had already recognised them. Many provinces and municipalities have issued ordinances prohibiting the burning of rice straw. Of the 82 provinces in the country where rice is grown, most of them have enacted a provincial ordinance of no burning of rice straws (NBS). There are 1493 municipalities and 144 cities where municipal/city ordinances have also been enacted. This is in support of the Organic Agriculture

Act (R.A. 10068). For instance, in Tagum city, in the province of Davao del Norte, a City Ordinance no. 229, S-2006 had been passed. The ordinance stipulated that agricultural wastes, for example, rice straws and corncobs, must not be burned but be stockpiled in a proper location and composted (Scheewe 2012). In Bay, Laguna, the municipal council passed Municipal Ordinance No.05-2011, on October 3, 2011 that prohibited burning of rice straws by the farmers and prescribed the penalties ranging from PhP 500 (first offense) to PhP 2000 (third offense) as payment for burning rice straws.

Still, there are many rice farms (76 % of farm area and 64 % for sugarcane farms) where burning of crop residues is still being done. It is not a question of the absence of laws or local ordinance that guides handling or management of crop residues. As one said 'If our problems could be easily solved through laws, then, we have no more problems in dealing with them!' This is also related to road traffic where traffic lights are already visible. The absence of police officers always leads to violations by many drivers causing serious accidents.

Enacting laws or ordinances is one initiative. Enforcing them is another. Citizen participation is crucial. When the affected communities of rice straw burning raised complaints and signed petition letters to their local officials, they act and caution farmers to stop burning. Some stop but some do the burning during the night. The Philippines is a democratic country where each citizen claims democratic space. China and Vietnam are centrally governed but burning rice straws is also being done by their rice farmers. This suggests that it is governance neutral. No burning implies that it should be decided by the farmers themselves. Citizen vigilance is also necessary, otherwise, NBS will be temporary and location-dependent. There are positive indicators that will stop burning. When the local officials are serious and decisive in implementing the ordinance, then the people follow. Only, come next election, some of them are not re-elected. The elected ones learn their lessons. They either 'go soft' on the alleged violators of the ordinance or simply ignore it.

The cases of no burning canes in some countries are unique. In Western Australia, 90 % of their canes are no longer burned. Only accidental fires (10 %) account for the balance. Harvesting of canes is 100 % mechanised. Sugarcane trashes are fully shredded. Where there is no trashing, shredding of the remaining trash after harvest appears effective (Fig. 5) as done by conscientious sugarcane planters in Eastern Batangas, Philippines. They fully recognise the multiple benefits of NBC (no burning of canes).

Brazil has taken a unique route. The Sugar Cane Industry Union (Unica) had signed an agreement with the state government to ban cane burning in the state by 2017 (http://www.enn.com/top_stories/article/24012). These mills crush more than 50 % of the cane output. Sao Paulo, Brazil is the largest cane producing state and accounts for around 63 % of the national crop.

There are some successes on the campaigns to reduce crop residue burning. Mendoza and Samson (2000) had estimated that about 8.16 million tonnes (average value from 1993–1997) were burned yearly of the total 17.7 million tonnes of rice straws or about 46 %. Data from Launio et al. (2013) were used to estimate the quantity of rice straw burned (2006–2010). Including the rice stubble left after

Fig. 5 Tractor implement shredding the trash into finer pieces allows the tillers in the ratoon to emerge and grow faster. (Photo taken in a ratoon canes at Batangas, Philippines, February 17, 2014)

cutting the stem for threshing, a total of 22.0 million tonnes of rice residues were produced per year. About 32 % of the total rice residues are burned (7.08 Mt divided by 22.0 Mt; Table 2). Quantitywise, there was a 14 % reduction in 13 years. With a linear reduction rate of rice straw burning, it will take about 32 more years to finally stop rice straw burning. Many civil society organisations (CSO) including private organisations are into the promotion of no burning crop residues and compliance with local ordinances that are directly related to nutrient cycling. Their combined efforts remain ineffective or inadequate to stop burning crop biomass. The challenge of enhancing nutrient cycling remains.

Table 2 Rice straws burned in the Philippines.*

Ecosystems	RS burned (%)	Weight (*1000 tons)	Total RS burned	Total by ecosystems	%
Irrigated					
Jan–Jun	0.575	2062	1185.650	4564.540	64
Jul–Dec	0.710	4759	3378.890		
Rain fed					
Jan–Jun	0.420	2055	863.100	2515.080	36
Jul–Dec	0.660	2503	1651.980		
Total burned in two ecosystems				7079.620	–

*Source of Basic data: Launio et al. (2013)

Burned rice straw per ha (t/ha) = 1.61; total rice straw produced × 1000) = 9324.00; rice straw per ha (t/ha) = 2.12; % burned = 75.93; average of 5 years = 2006–2010

6 Exploring Other Paths for Enhancing Crop Residue Recycling

There are already farmers (rice and sugarcane) who recognise the multiple benefits of no burning crop residues. But they are the exceptions. Their numbers remain small in proportion to the many who practice burning crop residues. The causes and/or reasons why rice straws and sugarcane trashes are burned despite the known merits and long-term positive effects of crop residue recycling on soil fertility and productivity are summarised below:

For rice:

- Prevent further spread of disease inoculums (RTV in rice).
- Short turnaround time; rice straws abstract land preparation using small machines.
- Cattle raisers are afraid of the insecticide residues.
- Rice straws are hiding place for rats.
- Yellowing of transplanted seedlings with rice straws.
- Duck raisers burn rice straws.
- Rice straws are burned by passersby near the road.
- Fertilisers are cheap due to government subsidy.
- Extension agents and sales representatives are given incentives proportional to fertiliser rates.

For sugarcane trashes:

- 1956 (Pineda) sugarcane soils were still fertile and fertilisers were cheap.
- Burning cane fields easily transfer to nonburned canes during hot and windy days.
- Cigarette butts are thrown by passersby.
- Harvesting nonburned canes slows down work by 40 %.
- Weedy fields are difficult to harvest and the fear of snakes biting the harvester.
- Trashes obstruct tillage for ratoon and plant cane establishment.
- Piling trashes is laborious; labor demand coincides with peak harvesting which is the priority.
- High risks that piled trashes between rows would be burned including the actively growing canes.

The reported massive burning of rice straws has existed for just four and half decades (1970s) whereas for sugarcane it was as early as the 1950s. This coincided with the expanded sugarcane production after the devastation caused by World War II. There are three interrelated reasons: (1) fertiliser was cheap then (oil prices were relatively cheap) and there was a fertiliser subsidy; (2) fire or burning is a quick method of disposing of crop residues that obstruct subsequent field operations; and (3) recycling or converting the residues into compost is laborious, hence, an added cost.

The era of cheap fertiliser is over. The Philippine government is no longer subsidising fertiliser (Briones 2014). Yet, farmers do not treasure the fertilising value of their residues. On a per hectare basis, the amount burned for rice is worth P 2115 (average of 1.61 t/ha for 5 years, 2006–2010). For the 4.4 Mha harvested rice for those years covered, the total value of burned rice straw was PhP 9.31 billion (US$211.53 million; 1 US$ = P44. Priced as compost fertiliser (P 200/bag and 20 bags compost per tonne and at 65 % recovery per tonne), the value of burned rice straw is equal to PhP 18.41 billion (US $418.36 million). For sugarcane, the calculated values of burned trash are:

- Php 729/tonne trash; P 1.43 billion for the 420,000 ha cane harvested for CY 2013–2014.
- The compost fertiliser value is P 6.65 billion (US$151.20 million).

Farmers complain about the high prices of fertiliser but they burn crop residues. The average fertiliser import for the last 10 years averaged 2.0 million tonnes (50 % of which was nitrogen) valued at PhP 20 billion pesos (Briones 2014). Recycling the residues of the two crops (rice, sugarcane) will have a great effect because 50 % of all fertilisers are used for these two crops. For the two crops (rice and sugarcane), the total value of nutrients totaled P 11.36 billion (US$258.18 million). As compost fertiliser, the value is about P 25.06 billion (US$569.5 million).

The profile or characteristics of farmers who are into soil building, and thus stopped burning crop residues (they also apply manures, do crop rotations) were studied. These are the farmers who own the lands or have a long-term occupancy arrangement with their landowners (Damo and Mendoza 2003). They are educated and highly informed (Mamerto Fontillanan of Cuartero, Capis; Lorenzo Jose of Florida Blanca, Pampanga, Vince Acuna, and Nemy dela Cruz of Negros Occidental; to name a few) and they are concerned about the environment and have good community relations.

For these reasons they do not consider recycling crop residues to be laborious. They find ways to reduce the labor required in spreading/recycling rice straws such as spreading the rice straws while threshing is being done. They do it quickly so straws will not be that heavy and difficult to spread once heavy rains fall. Sugarcane farmers use tractor-drawn trash shredders/cutters to cut the trash into small pieces allowing the emerging tillers to go over the shredded trash. Subsequent cultivation lessens the trash that could be burned, or nothing could be burned anymore.

The government (national, local) recognised the dangers and disadvantage of burning. However, there was no specific mention of no burning crop residues for the two laws (Ecological Solid Waste Management Act and Clean Air Act), but local governments acted on it by passing provincial and/or municipal ordinances.

Except for the accidental fires of 10 % for sugarcane, 64 % are intentionally burned. The colloquial statement ‘a proverbial shot in the arm’ is necessary finally to stop crop residue burning for sugarcane.

Areawise, 76 % of the total 4.4 million ha of harvested rice areas are burned (calculated from the data of Launio et al. 2013). About 7.08 million tonnes (average for 5 years: 2006–2010) or 25 % by weight of all rice straws produced in those years are burned (Table 2). It is important to note that about 36 % (2.52 million tonnes) of the straws burned are from rainfed areas. As pointed out earlier, rice straws before the 1970s were used as carabao/cattle feeds during the drier months.

At 2 person-days for spreading rice straw, for the 4.4 Mha harvested rice area, 8.8 million person-days or P 2.2 billion wages are circulating in the rural economy. For sugarcane (420,000 ha), about 8 person-days for detrashing and 10 person-days for piling trash per ha or about 17 person-days per ha, equals a total of about 7.56 million person-days or P 1.89 billion worth of wages. For the two crops, this totaled PhP 4.09 billion. Recycling crop residues generates on-farm employment so necessary in rural areas to arrest out-migration to congested urban areas.

The impact is enormous if the reduction on fertiliser usage is included. The foregone nutrient value of burned rice straws is P 1314 per tonne (Table 3) and P 729/tonne for sugarcane (Table 1). The Philippines imports about 2.0 million tonnes of fertiliser (average for the last decade worth P 40 billion pesos at PhP 20,000 per tonne (US$910 million; Briones 2014). The compost value of burned

Table 3 Nutrient content (N, P, K) and value of burned rice straws (2014 prices)

Item			Nutrient content per ha
Burned rice straws, tons/ha; 2006–2010 (refer to Table 2)			1.610
Kg per ton of straws[a]	N	5.000	8.050
	P	0.300	0.480
	K	3.570	5.750
	Si	70.000	112.700
			Value per ha (PhP)
Price per Kg (PhP)[b]	N	53.000	426.650
	P	77.000	37.190
	K	50.000	287.390
	Subtotal		751.230
Add N-fixation @ 16 kg/ton of straw*	1365.280		
Total (value of NPK* in the straw + Value N fixed)	2116.510		
Value per ton straws	1314.600		
Total value of rice straws burned in 2013 (in billion PhP)	9.310		
Total value of rice straws burned in 2013 (in million USD)	211.530		
Compost value of rice straws (2013 prices in billion PhP)[c]	18.410		
Compost value of rice straws (2013 prices in million USD)[d]	418.360		

Notes
[a]90 % N are burned; 25 % of P and 21 % of K are lost when straws are burned
[b]2014 prices of NPK fertiliser sources (retail store)
[c]Rice straws burned; 7.08 million tonnes (average for 5 years: 2006–2010; Launio et al. 2013)
[d]Peso value of compost fertiliser

residues for rice is PhP 18.41 billion and for sugarcane at PhP 6.65 billion (a total of about P 25.06 billion = US$569 million).

Why farmers burn crop residues was discussed and summarised above. Based on these issues, the majority of our farmers will not stop burning crop residues unless there are incentives or awards that will be given to them. The farmers should be compensated for not burning crop residues so they will be motivated to stop. It should be treated as payment for their added labor in recycling or composting crop residues. Recycling crop residues will not only benefit them but the world as a whole. Paying the farmers for the equivalent CO_2 sequestered benefits the farm, the community, society, and the environment (Fig. 3). It is simply recognising as well as cost sharing on the part of the farmers who grow rice and sugar, the staple food and basic commodity for Filipinos. The Philippine government (starting from the previous one) had been implementing Conditional Cash Transfer (CCT) for the poor. This program could be improved by having conditionality of helping farmers to spread or recycle rice straws or stop sugarcane trash burning and detrash sugarcane stalks.

The Philippines has an Organic Agriculture Act of 2010 (R.A. 10068). Organic farming starts from nonburning-cum-crop residue recycling. The National Organic Agriculture Board (NOAB) should consider formulating the detailed guidelines for promoting crop residue recycling. The principle that the farm is a food and fertiliser factory at the same time should be promoted.

Meanwhile, monitoring and law enforcement must be done as there are existing laws and ordinances at the provincial and the municipal level that prohibit and penalise crop residues burning.

7 Conclusion

The science and technological basis of crop residue recycling detailing the negative impacts of burning to agricultural crop production sustainability, health, and the environment as well as the merits of recycling crop residues on soil, farm productivity, and economics of production are well known.

The key to enhancing crop residues recycling in the Philippine landscape is citizen awareness to campaign for nonburning them. Active leadership from below and not simply from the top would be instrumental in reducing if not stopping crop residues burning completely.

Giving incentives or awards to the farmers for not burning crop residues should be treated as payment for their added labor in recycling or composting crop residues. Paying the farmers for the equivalent CO_2 sequestered benefits the farm, the community, society, and the environment. It is simply sharing the cost burden and difficulties of the farmers who grow rice and sugar, the staple food and basic commodity for Filipinos.

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Dilemmas of Development and the Reconstruction of Fashion

Karen Shah

Abstract Sustainable development by its nature appears elusive. It seems the more we try to capture and pin it down the more it moves away from us, leading us into murkier waters and all manner of contradictions. No more is this felt than in the fashion industry where we are presented with a number of oppositions. The fashion cycle renders styles obsolete before they have worn out, generating waste and overconsumptive practices. But it can also bring into the fore practices that have resonance to sustainable development in terms of their location, orientation, and consideration for the environment. As studies emerge considering the detrimental environmental impacts of the manufacture and consumption of new clothes, second-hand clothes have become a focus for research endeavours considering how they can be reincorporated into the fashion system and have resonance to an ever 'fashion- hungry' consumer. This chapter discusses methods for the processing of second-hand clothes into fashionable items and, by drawing on the wealth of 'waste' materials through reselling, restyling, and remanufacturing, argues that ways of reappropriating them into a more environmentally focused fashion industry is possible and necessary. It sets out as its hypothesis that the global fashion system has value in its transformative powers but that damaging and exploitative forces are still preventing it from being a force for good. This is due to the nature of the items being produced, the way they are manufactured, and how they are ultimately consumed and disposed of.

Keywords Recycling · Fashion · Social entreprise · Waste · Second-hand clothes

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1 Introduction

Development is a tricky area. Its attainment and use as a source of inspiration can misguide us and render some practices, which in one historical or environmental context seem logical and ‘normal’, as antiquated and bizarre. Within a personal sphere this dilemma is often played out on the body with choices being made between ‘traditional’ forms of dress with those that embody a more ‘modern’ aesthetic. Within the home and our day-to-day life this is made manifest in lifestyle choices, occupation, and social status. Thus fashion and development are linked because our appearance and lifestyle are frequently seen as signifiers for our place within society and where along the developmental line we may find ourselves. We use it to judge how ‘fashionable’ someone is and equally how ‘developed’ on a global scale various nations, lifestyles, and communities are. That’s not to say this is right but rather to highlight the similarities between fashion and development theory. But fashion and development are also quite different. Whilst development is very much seen to operate in a linear progression, fashion moves in a cyclical progression. It frequently renders practices and styles obsolete and then brings them back into the fore as relevant and contemporary again.

Second-hand clothes are interesting objects to look at under the lens of fashion and development inasmuch as they exist as something of the past. In many cases they have been discarded because they no longer represent the original consumer’s sense of self, may no longer fit, or may have worn to the point of not appearing new or fashionable. In a postmodern context this has been viewed as a good thing. Identity can be changed, can be challenged, and old stereotypes can be discarded just by discarding the old identity and replacing it with the new. However, there is also a major downside to this in that waste is generated and energy lost as we discard one identity in favour of another. This chapter considers methods for the conversion of waste materials into saleable garments and in the process analyses the extent to which these practices may have an impact on our clothing consumption, disposal, and reuse. Using a practitioner-led approach it considers design and manufacture responses by the author to local (UK context) and global development and considers methods for the conversion of goods borne from a ‘grobal’ scenario into fashion products understood in a ‘glocal’ context. This entails the evaluation of a number of products made from second-hand clothes and previous initiatives dedicated to the conversion of trash into treasure. It draws on the author’s knowledge and experience relating to clothes recycling and brings into the debate issues to do with sustainable development, globalisation, and design activism. It argues that not only do we need to look into our production systems on a global level but also need to consider what can be done on a local level. This can be achieved by considering our relationship to technology, development, and fashion.

In particular this involves the evaluation of a clothes recycling project established by the author, Ketchup Clothes (Fig. 1), and the opportunities that exist in clothes recycling. In devising a methodology for the research it draws on methods of grounded theory and design activism and proposes techniques that have proved

Fig. 1 Garments made from recycled clothes: ketchup versus antiform: alternative fashion show, London, 2008 (Image: Author's own)

successful in the reappropriation of waste textiles. In the process it is hoped that values pertaining to the construction of fashion may pave the way to more environmentally friendly systems of consumption, use, and disposal and turn processes of horror into ones of joy.

The chapter progresses through a discussion of fashion and the way in which it renders styles obsolete before they have naturally worn out. This sets the context for the discussion of techniques presented within the case study of Ketchup Clothes in which practical issues to do with the physical recycling process are presented. Taking a practitioner-led approach to research this deals with issues encountered in establishing a viable social enterprise and draws on data gathered from financial records and activities carried out from 2006. At the root of the discussion is the idea that clothes made from recycled materials don't necessarily need to symbolise a 'poor' aesthetic but can be celebrated and provide us with alternatives to mass-produced clothing. Whilst production systems place many of the outputs from clothes recycling in a niche and even couture market this doesn't necessarily need to be the case. Changes are needed in our attitudes but with greater understanding of sourcing streams and the salient qualities of recycled clothes greater acceptance of the practice may become more mainstream and widespread. Thus consideration for the global as well as the local environment is needed.

The presentation of data and images, taken from the practice of reusing second-hand clothes, provides for discussion and the recommendations for mainstream adoption. This includes material data on the types of second-hand clothing found to be successful in remanufacture, financial data pertaining to the sustainability of the business model, and viable pattern cutting/manufacturing techniques suitable for mass production. Styling techniques and discussion of the aesthetic of recycled clothing is also provided in order to reflect upon methods for making second-hand clothing 'fashionable' again. These practices are further contextualised within the realms of sustainable development, globalisation, and design activism. These activities are seen as having resonance with advocates of clothes recycling and thus methods of drawing theory into practice are considered.

2 Fashionable Development

In his book *Stuff*, Miller put forward the proposition that 'the problem with viewing clothing as the surface that represents, or fails to represent, the inner core of true being is that we are then inclined to consider people who take clothes seriously as themselves superficial' (Miller 2010, p. 13). These words reflect a view towards fashion and the study of clothing that was generally representative of the academic canon for many years. Despite key studies by social analysts such as Veblen (1973), Barthes (1957), Simmel (1957), and Bourdieu and Nice (1984), fashion writer Wilson (2003) bemoaned how fashion studies were often viewed as frivolous and due to their gender status much maligned in academic contexts. However, studies into fashion, and its associated conduits, 'clothing', have now grown and provide a wealth of investigation and deep thought (Kamamura 2005; Harvey 2008; von Busch 2008a, b; Bruzzi and Gibson 2013). In its abstract form fashion provides a link to forces of development and activism (Wallace 2012; von Busch 2013) and as a production process feeds into notions of social equity and empowerment (Fletcher 2007; Curwen et al. 2013) (Fig. 2).

As clothing changes through the forces of fashion we see written on the cloth, etched into the seams, and sculpted onto the body, the sum of our identities, our development endeavours, and our hopes and dreams (Collin and Godfrey 1998; Miller and Woodward 2011). As stated by Goodrum (2001) the body becomes '… a surface to be inscribed upon, transformed and manipulated by various hegemonic and institutional regimes' (Goodrum 2001, p. 35). This link to hegemony is relevant to a reading of fashion due to the fact that choices over the design, production, and consumption of fashion are primarily based around the proliferation of, mainly, capitalist fashion systems that dictate the materials we have at hand, the technology at our disposal, and the opportunities for dissemination. Thus hegemony as a prevailing force, with the power to restrict and control, is prevalent in all areas of our lives. When applied to the body it is manifest in both our inner and outer selves, with the clothes that we shroud it in being representations of dominant modes of design, manufacture, and consumption.

Hegemonic dress in this context is positioned within a set of ideals, legitimate or not, logical or not, that result in one dominant mode/style taking centre stage. Reaction and resistance to these dominant ideological and practical modes of

Fig. 2 Second-hand clothes market, Zambia, 1998 (Image: Author's own)

production can be both subtle and explicit and it is the aim of this section to discuss alternative and activist approaches to the production of clothes as a way of moving beyond hegemonic dress. Key to this is the extent to which methods of production and consumption can be more sustainable in their execution and feed into models of social equity. To become more sustainable and less hegemonic, it is argued that we need to question existing modes of production and reclaim local design practices as a way of bringing about greater autonomy over what we are able to put on our bodies. To live in a global, predominantly capitalist, world, is to be constantly aware of how our lives and histories merge and this in turn impacts upon our identities as fashion designers, consumers, and global citizens. Thus by analysing the relationship of objects to global processes, and those subsequently conceived in a local studio environment, we are able to comment on the value of social enterprise initiatives and approaches to design activism. To this aim reflection on the author's approach to design and the shaping of 'fashion' inspired objects is provided together with an investigation into how models of development have relevance to both our global and local selves, analysing along the way the trajectory of materials borne of a global context and reshaped within a local context. Being able to read these items can give us insight into just where we are at with sustainability and the lessons that can be learnt from globalisation (Lurie 2000; Fry 2009; Boradkar 2010). A growing number of designers and consumers are moving away from what are seen as restrictive forces on their bodies to ones that are more liberating and meaningful to them as individuals. This involves them becoming active in their clothing choices.

2.1 Liquid Clothes

Bauman (2005) proposed that to live in the world today is to exist within a state of liquidity in which nothing is permanent and our identity, in particular, is subject to extreme 'fluid' forces. In viewing clothing within this context he argued that:

> you must 'lose the ponchos' which were so much en vogue last year, since if you wear a poncho now, 'you look like a camel.' Donning pinstripe jackets and T-shirts is over, simply because 'nobody' wears them. And so it goes, if you don't wish to sink, keep surfing; and that means changing your wardrobe, your furnishings, your wallpapers, your look, your habits—in short, yourself—quickly, and as often as you can manage (Bauman 2005, p 56).

This reflection on modern life proposed that we are now living in an age of liquid modernity. In this context identity has moved from a fixed to a fluid state and old stereotypes have become, if not obsolete, then challenged. Artists and designers, seeing the body as a canvas, have distorted old preconceptions of gender, race, and class and proposed alternative visual spectacles of the self (e.g., see the the work of artists such as Orlan, Sherman, Bowery, Wear, Shonibare, etc.). These visions can provide us with inspiration as fashion designers as we consider the extent to which clothing can distort the body and add to the debate over western versus nonwestern, traditional versus modern, and hegemonic versus nonhegemonic dress. These debates are relevant to the study of clothes made from recycled materials because the basis on which they are created would not exist if it weren't for the effect of fashion on the perception of a garment's quality, value, relevance, and usefulness. This discarding of the old for the new has come at a price though. The manufacture of fashionable items has generated mountains of waste, the export of which has displaced indigenous modes of manufacture and raised serious environmental concerns over the sustainability of such practices (Sinha et al. 2010). As stated by Pickup (2007):

> The detrimental effect of our lifestyles on our natural environment and the widening poverty gap across the globe is causing great consternation in mainstream society … we are beginning to assess with increasing concern the damage we are inflicting on our environment and the disastrous implications of our lifestyle choices for future generations (Pickup 2007, p. 2).

The purchase and use of second-hand clothes has long been seen as a lifestyle choice in the western world and a signifier of beliefs centred upon thrift, make do and mend, and a desire not to waste (Reily and DeLong 2011). The sense of projecting a retro look is also of importance. Thus second-hand clothes have provided the focus for a number of research projects and analysis has been made concerning their environmental benefits (Farrant et al. 2010), their appropriation amongst younger consumers (Reiley and DeLong 2011), and the impact of their export on economies such as Africa (Sinha et al. 2012). As stated by Song and van Dyke (2013):

> It was estimated that the purchase of 100 second-hand clothes would save between 60 and 85 new garments dependent of the place of reuse, The LCA showed that the collection, processing

> and transport of second hand clothing have significant impacts on the environment in comparison to the savings that are achieved by replacing virgin clothing. The reduction of impacts resulting from the collection of 100 used garments ranges from 14 % decrease in global warming for the cotton T-shirt to 45 % reduction of human toxicity for the polyester/cotton trousers. The results of the study thus show that clothes reuse can significantly contribute to reducing the environmental burden of clothing (Song and van Dyke 2013).

Studies similarly concerned with the environmental impact of using second-hand clothes in turn have highlighted ways in which they have been used, in the process proposing models for the incorporation of second-hand clothes into existing global fashion systems (Dissanayake and Sinha 2012; Song and van Dyke 2013). In the main these have led to the conclusion that current rates of overconsumption are unsustainable and to seriously reincorporate waste materials back into the fashion system requires a restructuring of present manufacture and consumption practices. A lacuna does exist within the literature, however, and this relates to knowledge concerning design processes and methods for making second-hand clothes accessible within the mainstream and making them fashionable again. This involves investigation into pattern-cutting techniques and methods of production and consumption (Fig. 3). Examples for their use as couture items do exist (e.g., Guy Harvey, Junky Styling) and companies are emerging that investigate the viability of mass production (AntiForm; Goodone) but further analysis of these practices is needed to assess the extent to which the reuse of second-hand clothes can contribute to environmental, social, and economic sustainability.

Fig. 3 Recycled leather jackets contextualised in a local allotment showing link between fashion and nature, Leeds, 2006 (Image: Author's own)

2.2 Design Activism and Recycling

Part of the issue in clothes recycling is to get a sustainable loop working where waste is increasingly able to be incorporated into manufacturing and consumption systems. This can be problematic, however, especially when distances between production and disposal are often so far apart and stopping clothes falling out of the loop can be so hard. Recycling is one way of entering this loop and for many is viewed as an activist activity (von Busch 2008a, b; Fuad-Luke 2009; Julier 2013). It is often undertaken as an alternative to conventional modes of consuming new clothes and also a way of producing pieces that can be brought to the marketplace in new forms thus prolonging the natural life of the original piece (Ketchupclothes, AntiForm, Good One, Junky Styling, von Busch, Redmuttha, etc.), in Ritzer's terms turning a 'nothing' into a 'something' by a process of glocalisation (Ritzer 2004a). At the root of this activism is often the desire to investigate anticonsumption approaches to clothing design, social enterprise, and ways in which people are able to have without buying, to make rather without consuming. This approach to design and production is often chosen over more conventional forms of make due to a concern with overconsumption and a desire to tackle sustainability at a local level but for a global necessity. As such, a conscious effort is often made to source only found or discarded materials and to practice local production by the establishment of design studios equipped with appropriate machinery. In many ways this form of production conforms to Ritzer's notion of glocalisation by being distinct in nature and similarly subject to pressures of grobalisation in the form of mass acceptance, availability, and price (Ritzer 2004b).

This form of redirective practice also appears consistent with notions of design activism and social enterprise, advocated by writers such as Julier (2013), Fry (2009), von Busch (2009), and Fuad-Luke (2008), who saw value in a reorientation of design practice and the embedding of design thinking as a way of solving wicked problems, in this case landfill, air miles, and unethical practices in global clothing production. For many it is done out of love for the industry and for the creative potential (and relatively low costs) that such design and production entails. Von Busch (2008a), terming his approach to clothing production as 'hacktivism', put this succinctly when he stated that:

> Hacking is a matter of dedicated and systematic curiosity of understanding a system, reverse engineering it, finding a suitable place for intervention, plugging in and keeping the power on. Hacking is to modify and advance a system because you love it, not because you hate it (von Busch 2008a, p. 20).

Initiating change thus appears at the root of many activist definitions. Fuad-Luke, for example, defined activism as '… taking actions to catalyse, encourage or bring about change, in order to elicit social, cultural and/or political transformations' (Fuad-Luke 2009, p. 6). The change here being the way in which we consume, produce, and design. As a designer this has always been part of the game. As we adapt to innovations in textiles and modes of manufacture we change the shape and form of things. We mix up references to give a 'new' take on things and present these to an ever-hungry public. This, of course, in itself is not strictly activism because whilst the catalyst may be to encourage people to wear shorter skirts, for example, in many cases it is not going to be significant to bring about deeper social, cultural, and political change. This is because we are changing the outputs of our endeavours but not altering the underlying implicit system of production and consumption. To do this means radically to change our opinions and structures of design to turn them from things of horror into things of beauty.

3 Sustainable Development and Design

Sustainability as a concern for development has seeped steadily into the human consciousness over the past few decades due to concerns over resource use, environmental degradation, and the fact that for millions on the planet even their most basic needs are not being met despite years of concerted developmental efforts. As such, a wealth of literature now exists concerning the application of sustainability to a range of disciplines from design, geography, engineering, sociology, and politics (Burrall 1996; Charter and Tischner 2001; Christie and Warburton 2001; Dresner 2002; Kutting 2004). At the root of many of these studies is a reflection on the words of the Bruntland Report (1987) which defined sustainable development as ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (World Commission on Environment and Development 1987). Inherent within this quote was the notion that addressing present-day needs should not negatively impact on our ability to address needs in the future. From a design point of view this implied that we needed to look closer at the effects of our present production and consumption patterns and where they have a negative impact seek to address this in terms of design, resource use, and production (Datschefski 2001; Braungart and McDonough 2008; Papanek 1971, 1995; Fletcher 2008).

Sustainable development also embraces the notion that development goals should not be solely focused on economic gain but that less measurable indices such as quality of life, global equity, and empowerment need to be paramount to discussions (Burrall 1996; Datschefski 2001). Much of this work implied a necessity to consider the identification and satisfaction of the needs of development, with the poor at the root of these discussions (Chambers 1997). Papanek (1971), for example, in critiquing the role of advertising and the hard sell of ‘absolute necessities’ replacing luxuries, a result of economic development and globalisation, reflected how ‘most things are not designed for the needs of the people but for the needs of manufacturers to sell to people’ (Papanek 1971, p. 46). He went on further to imply that the pursuit of capitalist and industry-based policies had not impacted upon the poor. In his seminal works, *Design for the Real World* and *The Green Imperative,* Papanek put forward the idea that designers needed to reorient their efforts around meeting the needs of the masses rather than the elites. The reorientation or rethinking of design practices was later taken up by Fry (2009) in his work into design rethinking and the addressing of 'wicked problems'. Logically much of this work focused on a developing world context and a reorientation of design practices around notions of appropriate technology and an involvement of the poor within design decisions.

Much of the debate over sustainability in recent years has also centred on a critique of globalisation that is seen to place power in the hands of the few and has created unsustainable working practices (McLaren 1998; Bell and Morse 1999; Fischer and Ponniah 2003; Ritzer 2000). It is argued that as companies skip around the globe in search of cheaper and cheaper resources (including labour and materials) they leave in their wake fragmented communities and environmental degradation. These globalised practices also undermine local production which it is argued would lead to higher gains in the fight against poverty and would lead to a more indigenous development path. Attention has also been drawn to the problems associated with labour flight as more and more people quit the rural areas, seeking employment in ever more populated towns and cities. Much of this labour is absorbed in the informal sector, which campaigners argued offered little in the way of working rights, conditions, or security. Advocates of globalisation built their assumptions of poverty alleviation on the basis that countries needed foreign investment and intervention to increase economic growth and should therefore embrace free trade. However, opposition to this approach pointed to the inequalities produced through this system and the fact that the gap between the rich and poor both in and between countries is growing. Studies showed how the richest 10 % (US households) had a combined income greater than the poorest 43 % of the world's people (approximately 2 billion people) (Bell and Morse 1999).

This implied that whilst development was occurring for a select few there were still billions around the globe for whom these benefits were not being felt. Worryingly, much of the power of development lay not in the hands of countries but in the organisation structures of corporations. For example, The World Social Forum (2005) emphasising the power of transnationals highlighted how :

> In terms of sheer scale of economic activity, the giant corporations now rival all but the largest countries. Comparing corporate turnover to national GNP, 51 of the world's top 100 economies are corporations. … Using this measurement Walmart is bigger than Indonesia, General Motors is roughly the same size as Ireland, New Zealand and Hungary combined (Fisher and Ponniah 2003, p. 55).

Campaigning groups, nongovernmental organisations (NGOs), and forums such as the World Social Forum sought to quell the growing tide but much of the strength of these organisations knew no boundaries. Antiglobal activists felt instead that there was a need to restrict some of this corporate power at all levels of local, national, and international interaction and increase the power of the majority classes, that is, the workers, family farmers, and small business sector. At many levels this was the result of damning critiques of neoliberal policies. Fisher and Ponniah (2003) continued stating that:

> In a world of rapid globalization, where large corporations grow more powerful in their pursuit of economic expansion and profits, there are growing networks of concerned

> activists who are not dazzled by the promised land of globalization. They are alert instead to the dangers globalization presents to justice, cultural autonomy and the environment … they work to make visible the damage and danger wrought by rampant and unexamined economic expansion (Fisher and Ponniah 2003, p. 2).

The transfer of inappropriate technology, which has displaced vast swathes of labour, the promotion of westernised modes of production and the embracing of a consumer culture were also oft-cited reasons as to how inequalities, conflict, and environmental damage arose. The phenomenon of this drive to mass production and to consumption beyond our basic needs, it was argued, led to the extraction of resources beyond the planet's capacity and studies uncovered some disturbing facts about the future if production and consumption were to continue at their present rates. For example, predicted figures for 2050 highlighted how in order to satisfy Britain's energy (CO_2), we would need just over eight planets to sustain global consumption (McLaren 1998). These thoughts are mirrored in Wackernagel and Rees's study (1996), *Our Ecological Footprint,* which stated how:

> The accelerating resource consumption that has supported the rapid economic growth and the rising material standards of industrialized countries in recent decades has, at the same time, degraded the forests, soil, water, air and biodiversity of the planet. As the world becomes ecologically overloaded, conventional economic development actually becomes self destructive and impoverishing. Many scholars believe that continuing on this historical path might even put our very survival at risk (Wackernagel and Rees 1996, p. 3).

3.1 Design Debates

Readings of sustainable development theory thus led to a conclusion that more needed to be done to incorporate key issues into design practice, particularly where they related to resource use, orientation of design and production processes, and product design. As argued by Datschefski (2001) 'Most environmental problems are caused by unintentional side-effects of the manufacture, use and disposal of products' (2001, p. 16). Thankfully steps are being taken to assess the product design loop fully and as a result interesting research and sources of inspiration have emerged that consider an analysis of all stages of the design process from concept through to finished piece and the environmental impact of these processes. Of key importance and relevance to designers is the life-cycle analysis model (LCA) which looks into resource selection, production, use, and disposal of a product. It also seeks to draw into the design equation impacts on environmental, social, and economic damage (Brezet and van Hemel 1997). This approach, however, entails a closer look at our design practices and the incorporation of other disciplines and interest groups. For example, Fletcher et al. (2001) in their study of sustainable consumption in design reflected on how:

> Lifecycle thinking necessitates a high level of design competence, intelligence and communication, supported by the involvement of new design partners such as community groups, the coming together of formal disciplines as diverse as anthropology and

> environmental science and bonded by the traditional, creative, organizing skills embodied within design (Fletcher et al. 2001, p. 214).

It is generally recognised that the largest impact on sustainability occurs in the use phase of a product (Laffen and Dodds 2003); for example, in clothing it is estimated that almost 100 % of pollution and water consumption occurs in the use of an item due to washing (Fletcher et al. 2001). Organisations and companies have thus sought to develop a toolkit approach from which to make and inform design decisions. This includes a closer look at environmental management systems (i.e., ISO 14001), life-cycle assessment, design for environment, remanufacture, environmental reporting, closed loop manufacturing process, and the supply chain (Shaw 2003). Datschefski (2001), for example, argued that products being developed should adhere to these specifications in manufacture:

> Cyclic - The product is made from compostable organic materials or from minerals that are continuously recycled in a closed loop. Solar - The product in manufacture and use consumes only renewable energy that is cyclic and safe. Safe - All releases to air, water, land or space get taken up as inputs for other systems; Efficient – 'Tomorrow will be Less' – Philippe Starck. The product in manufacture and use requires 90 % less materials, energy and water than products providing equivalent utility did in 1990; Social – Product manufacture and use supports basic human rights and natural justice (Datschefski 2001, p. 5).

Addressing the issue of waste, Braungart and McDonough (2008) argued that:

> 'To eliminate the concept of waste means to design things—products, packaging and systems—from the very beginning on the understanding that waste does not exist' (p. 104).

A very laudable caveat but one that is harder to put into practice after years of relatively wasteful design solutions based on inbuilt obsolescence and fast fashion trends in manufacturing and design. Increasing environmental issues are being aligned to ethical concerns and thus sustainable design can only really be spoken about in terms of its contribution to sustainable development, be this social, economic, cultural, or political.

3.2 Designing for Sustainable Development

Designing for sustainable development entails investigation into the identification of development needs with an emphasis on participatory design methods, to ensure that the products being produced are appropriate to both local and global needs. It is also aligned to ethical design in that it forces designers to reflect on production and trading issues. As such, ethical design is closely related to the power relationship within the process of design, manufacture, and consumption and is most commonly expressed within terms of working conditions, wages, expectations, and job satisfaction. It has been closely linked to fair trade and mainly came to the attention of the public through campaigns into coffee and bananas. This has more recently been applied to other products, namely clothing and handicrafts. Ethical design also aims to redress imbalances between and within trading structures and in particular in the addressing of poverty. Ethical design also seeks to engage consumers in the production of a given design and ultimately make them question the mechanisms through which the product came to be on the marketplace. Within this context issues relating to the distribution of profits, intellectual property rights, and working conditions become paramount. These issues, as it can be imagined, are very complex but are mainly concerned about ways of helping the poor to move out of poverty through trade and not aid and of making a stance against countries and companies that exploit cheap labour and bad working conditions for the sake of profit (Labour behind the Label 2007).

Ethical design, however, makes a few assumptions which can present difficulties in our understanding of what makes something truly ethical. Firstly it assumes that trade and not aid is a laudable goal and secondly that the products produced as a result of this intervention contribute to sustainable development. This causes a problem in our understanding: that is, can we have an ethical china cat arguably embodying western ideals and what significance does this production have on long-held traditions and communication of ideology. Should it not also be about the relationship of the producers to the product, markets, and aspirations? How can we design when we have little comprehension of what the product does?[1] We would argue this is where the fair trade lobby could do more, and especially reorientation towards home markets and developing tools for development that have greater meaning and relevance.

Eco-design follows on from ethical design although an environmental angle is added to the point where it is often defined as a product having limited impact to the environment in terms of emission of toxins, generation of waste, and that the manufacture of any component shouldn't have a detrimental impact on our carrying capacity and sustainability. This implies that the production, consumption, and disposal of the product shouldn't contribute to further environmental degradation. In many cases this would entail a major reorganisation of production and consumption practices, which in most cases have been set up to maximize profit and gain rather than to contribute to sustainable development. It also implies a closer look at the materials and technology employed.

Further design debates that have a resonance for sustainable design and development include issues relating to disposal, remanufacture, and performance. Designing for disposal is greatly influenced by the debates surrounding waste and the need for biodegradability. It entails asking the designer to consider issues relating to the life cycle of a product and how it and its manufacturing components may be disposed of. This thus entails a closer look at materials used and how it may be disposed of in innovative and sustainable ways. This could be aided by product exchange, modification, and modularisation. The use of biodegradable materials, such as corn starch, and the questioning of the nature of inbuilt obsolescence can

[1] Fieldwork uncovered a woman weaving a tablecloth from nettles. She owned no table, little less have an idea of why anyone would want such a thing (Dennis 1999).

also go a long way to ensuring that the products we make and consume today are either treasured and used for their natural life or able to be disposed of safely and without threat to current and future capacity. This area draws on the work by Chapman (2009) and the challenge of developing products that are emotionally as well as technically durable. It makes us question the nature of inbuilt obsolescence and helps us critique the logic of fast fashion. Following on from a need to ensure the safe disposal of products is perhaps the need for products to be remade as certain mechanical and aesthetic elements of a product break down or become obsolete. Interesting outcomes can be achieved through taking this approach.

4 Globalisation and Recycling

Many economists, writers, artists, and philosophers have explored globalisation as a process and critical framework for discussion over the years (Rostow 1960; Shonibare 2004; Bauman 2011). However, the manner and means through which it has been promoted have been strongly criticised and it seems that definitive proof that it has been a success still very much lies in the balance (Papanek 1971; Chambers 1997; Monbiot 2000). It has been argued that globalisation has been akin to Americanisation and that rather than solving the problems it set out to achieve, such as poverty alleviation, employment, and income generation, it has actually exacerbated them (Ritzer 2000; Lee 2005). This has been attributed to the fact that the logic of globalisation has, in many cases, been aligned to the logic of development, which in turn has been aligned to the logic of modernisation and economic growth (Schumacher 1978; Sachs 1992). Tracing its roots back to Rostow's infamous stages of growth, where he charted out the path to mass consumption and leisure, the mantra emerged that you couldn't have development without economic growth and the easiest way to do this was through mass production where economies of scale gave greater profits (Rostow 1960). Bringing down labour bills and penetrating global markets became a priority as companies outsourced to countries where labour was cheap and employed rigorous marketing campaigns on 'undeveloped' nations. Consume our product and you too will become a global modern citizen they seemed to be saying and consume we did. Nowhere has this been more prevalent than within the fashion industry. Globalisation has brought its advantages and allowed for all manner of amazing communications and connections. It has opened up the world and at the same time made it smaller and more accessible. Sharing and engaging with global products has fostered a homogeny that has given an impression of harmony, that we are all the same, that old differences and conflicts are dyfunct; we can be like the 1980s Benetton adverts if only we bow down to the god of globalisation.

Ritzer (2004a) provided a compelling discussion into ways of viewing items made under the guise of globalisation citing two dependent but very distinct processes namely 'glocalisation' and 'grobalisation'. These he argued gave way to the production of 'something' and 'nothing', respectively. The 'something' borne out of 'glocalisation' being 'generally indigenously conceived, controlled and comparatively rich in distinctive, substantive content' whereas the 'nothing' from 'grobalisation' was 'generally centrally conceived, controlled and comparatively devoid of distinctive substantive content' (Ritzer 2004a). This provides an interesting context within which to analyse garments derived from a traditional local setting with those borne out of a global, mass production system churning out millions of the same shade, cut, and finish, dilemmas between the two modes of production having been a source of much discussion by sustainable fashion experts and designers alike (Fletcher 2007; Curwen et al. 2013; von Busch 2013). In seeking to become more sustainable the questions arise over which methods hold the most promise for a more sustainable future.

Grobalisation, Ritzer (2004b) argued, originated from an entity wishing to grow but from a centralised position and usually for economic growth and profit, citing examples such as Starbucks and McDonalds as companies who had adopted this approach. The 'nothing' they produced being defined by its sameness to other products and perpetuated by the establishments of nonplaces, such as shopping centres, nonpeople, such as telesales operators, and nonservices, such as credit cards. Companies such as Primark and H & M, and the clothing they produce seem at home within this context. Glocalisation, attached initially to Japan's appropriation of global products in the 1980s, on the other hand, was defined as a local interpretation of the global resulting in unique outcomes in different geographic areas. It was found more likely to be undertaken under social enterprise structures that placed emphasis on the integrity of the product and its links to social, political, and cultural values of the producer,[2] the resultant 'something' being seen as intrinsically more valuable and distinctive but potentially of much less appeal to a wider audience, usually due to cost, distribution, and availability (Ritzer 2004b). There are obviously value judgements embedded in these thoughts, and critics have highlighted how in many instances the poor, whom globalisation was meant to help, do not perceive the products from grobalisation as 'nothing' and don't have the resources to engage with the glocal products. For them eating in McDonalds or shopping in Primark is preferable, by nature of being accessible and more democratic, to elitist delicatessens and exclusive designer-wear. Also could it not be argued that this is the dream of design for all proposed by Papanek all those years ago (Papanek 1971): positioning people, objects, and places as 'somethings' and 'nothings' merely showing elements of snobbery and elitism, especially when there is such an economic argument to people's access to certain products and services: if you don't have the money you are not in the game. However, of course the potential for a democratic outer has been seen to hide a darker undemocratic inner when we consider the policies and production environment under which they have come about (Ritzer 2000; Monbiot 2000).

We all encounter the 'nothings' from globalisation. They are the drinks container bought to hold our morning coffee only to be discarded 15 min later. They are the High Street bought dress discarded after a few wearings due to changes in body,

[2]Fair trade products could potentially be viewed under this context where emphasis is placed on the locality of production and the unique qualities that arise from this.

identity, or just to keep 'on trend'. They are the many products designed with inbuilt obsolescence in mind shortening their life and condemning them on some distant scrap heap (BAN 2002). They are the things that those concerned with sustainability bemoan and despair against and they are becoming globally more freely available. Writers such as Braungart (2009) were right in their contention that waste needs to be eliminated from the design process and that more needs to be done to tackle issues to do with waste, particularly as they apply to clothing and its production and disposal (Fletcher 2007). Many interested in sustainability within the clothing industry advocated a 'closed loop approach' as the only way to address the vast environmental problems associated with inbuilt obsolescence (Reiley and DeLong 2011). Raising the question of how to get this loop working, especially when distances between production and disposal can be so far apart and stopping clothes falling out of the loop can be so hard. For many this debate extends into the role and use of technology and its impact on our ideology proposes more activist approaches to the incorporation of both aspects into our production systems

4.1 Technology and Ideology

The impact of technology on our production systems and their overall appropriateness to social, political, and economic goals has been a hotly debated topic over the years. From the class struggles outlined by Marx (1873), to the scale of manufacture discussed by Schumacher (1978), to the horrifying yet at the same time beautiful images by Edward Burtynsky (2006) of our manufactured landscapes, it seems that technology, be this hardware (equipment) or software (knowledge bases), has shaped the way we work and play. No longer can we ignore the fact that, through the use of technology, mass production now reigns supreme and we have created systems that are so much more than their component parts. The fashion industry has been both a victim and champion of this approach and as our hunger for consumable goods gets bigger and fashion cycles get smaller, styles and products are duplicated and disseminated by means of technology to an ever-consuming 'client' base. It seems that we cannot escape from the fact that fashion is now an essentially 'mass' production system like any other industry with drivers coming from technical, social, and political imperatives. Under the definitions of ideology the following have relevance to our understanding of how technology works in society, namely:

- A medium through which a culture shapes its world
- A process whereby a culture produces meaning and roles for its subjects
- False values used to keep people under control
- The presentation of cultural constructs as natural facts (Cavallaro 2001, p. 76)

Heidegger (1977) in his quest for the essence of technology provides definition in terms of technology being both a means to an end and a human activity—an instrumentum. Citing causality in relation to technology he proposes four causes, namely *materialis, formalis, finalis*, and *efficiens*. This links to the material or matter of the technology, the form and shape it takes, its end use, and the realised final piece. When these are realised the technology is brought forth into the marketplace and by doing so enters into a process of revelation: 'Technology is a way of revealing' (Heidegger 1977, p. 5).

Research into the adoption and diffusion of what were seen as more appropriate or intermediate technologies highlighted the importance of indigenous development, manufacture, and dissemination to the fulfillment of more social and political concerns. Economic gain also tended to follow but where it related to notions of quality, 'tradition', sustainability, and empowerment it had the most success. Thus we need a rethinking of how we make, consume, dispose of, and engage with 'things'. Recognition that in a fluid ever-changing state of how 'things' can become embedded in a narrative and used as a benefit to society, there are many different modes of making, an investigation into which can point the way to new perspectives on their roles.

4.2 The Global Denim Project: A Detailed Exploration in Recycling

Involvement with the Global Denim Project was centered upon the creation of new denim garments that would allow for a further exploration of how the material of denim could be transformed and the life cycle of the material extended (Miller and Woodward 2011). Jeans discarded by participants of the research project were cut in half with one leg being used to test the physical materiality of the items (i.e., in terms of strength and length of time before the material would naturally degrade) and the other being used to test the psychological materiality in terms of the participant's attachment to the objects. Because all of the participants were discarding the objects a key aim was to convert all of the legs into something 'new' but drawing upon narratives from interviewees as inspiration for the design process. To begin the design process, research and development was carried out to establish inspiration for form and shape and the type of garment to produce. An interview was conducted with a customer who was looking for someone to convert jeans that no longer fitted him, into a garment he could wear on stage and would fit into his lifestyle as a drummer in a band. A waistcoat with a large sheepskin collar[3] was developed and reactions gained (Fig. 4). When questioned, the client expressed his joy at the use of details that to him had been very important on the original pair of jeans. He recounted stories of when he first bought the jeans and details such as pockets and frayed edges become interesting revelations as he tried on the garment and noticed them in unexpected places. He also expressed pleasure at the fact that

[3]The sheepskin was found discarded in a bin and fit perfectly with the 1970s theme and the customer's style and musical tastes.

Fig. 4 Waistcoat made from customers old jeans, 2011 (Image: Author's own)

the jeans were back on his body having been discarded in his wardrobe due to the fact that the fit was now wrong, out-of-date, and they were a little tight.

The design of this initial waistcoat led to the design of garments for the Global Denim Project in that importance was placed on the utilisation of details and also consideration for the narratives that had been gleaned from the interviews carried out by Woodward. Within these narratives were tales of 'outdated' fits, a scruffy aesthetic no longer appropriate to their current lifestyle and in many cases a movement from a casual state into one that focused on their roles within a professional workplace. Within this context their own tired and outdated jeans became part of an old identity and thus destined for the skip or charity shop. Inspiration also came from an old 1980s Leigh Bowery jacket whose work was firmly embedded in the notion of transformation and helped to inform shape and style (Greer 2005). To reinvigorate the material, and in the process the jean legs, a pattern based on a smart fitted jacket was developed to represent this transition from casual to professional. In an attempt to highlight the femininity of the cloth and to move away from the 'unisex' nature of some of the garments that the interviewees had expressed a desire to get away from, bust cups were inserted and a nipped in waist accentuated by pocket details and pin tucks running across the back of the garment (Fig. 5). Working from a flat pattern the jeans legs were cut to lay flat and the process of actually working with the fabric began. It presented several challenges not least because the jean legs were all from different weights and types of denim and also

Fig. 5 Jacket made from research participants 'old' jeans, Global Denim, 2011 (Image: Author's own)

had many design features that needed to be cut around or incorporated into the final piece. However, generally the piece came together well and had merit in its construction and aesthetic appeal.

The waistcoat was developed in a more organic way and really did represent the waste from the research project (Fig. 6) The production of the jacket had utilised larger pieces of denim taken from the lower legs and had left more fixed, functional, and secured design details such zip and fly and waistbands behind. These were presented to the dress stand and manipulated in such as way as to construct a sleeveless jacket. In this state pockets got twisted and a jean waistband became a cowl neck. Working with material and old garments in this way can present challenges for the pattern cutter and maker because there is so much that is unknown about how the pattern will fit onto the fabric available and how details may be incorporated onto the body in places where they wouldn't have originally been, the waist as a cuff feature and pockets on the back of the garment being examples of this. Of course this is also the beauty of this style of making inasmuch as there is always an element of the unexpected, of the garment evolving before your eyes. There are times when a strict pattern is just what is needed and at other times a necessity to get onto a dress stand and mould the material around the body, making it fit and altering finishing details so that the garment looks authentic, as something that has not just been patched together but has its own identity and style.

Fig. 6 Waistcoat, Global Denim Project, 2011 (Image: Author's Own)

We are never able really to leave the original garment behind but in its transformation we are able to learn something about its trajectory and how it may have been conceived and constructed in the first place. The meditative act of sewing also provides us with time to spend with the garment and the material from which it is made, as it was and as it will be. It allows for reflection into just how the items have come our way and what our role as designers may be for the present and future.

5 Putting Theory into Practice

As a designer it was never really expected that my practice would be considered as particularly political but in becoming increasingly aware that the way in which I want to make things and the way in which I want my things to be consumed does have a deeper political and social edge. This was highlighted early on at the Leeds Festival of Design Activism (2009) Practitioner Conference that was '… devised to give voice to designers, artists, architects, students, performers, activists, observers and users of socially and/or environmentally committed creative practices' (http://www.designactivism.org/node/5). Presenting a range of clothes made from recycled materials, and highlighting the issues involved in turning this into a viable enterprise, brought up many sticky problems to do with perceptions of value and quality, democratic design systems, and the all-important question of consumption. It was generally agreed though that within the setup and ethos of the enterprise there existed great potential particularly in relation to the way in which as practitioners we can deal with waste, social issues of exclusion, and harnessing creativity for the many not just the few. Clothing became an important communicator in engagement with the public and a means through which wider social and environmental issues could be discussed and contextualised. Collaborations also helped in the establishment and continuation of similar enterprises that reaped interesting research outputs and conclusions.

So from a simple desire just to be able to make things and with a preferred tool of a sewing machine the salient features of the design process for me have always been tied up with reuse and recycling. It harks back to the days when my mum, an outworker, would spend hours making up grey school uniforms for a local factory; I would collect the off cuts, make them into something, and the habit sort of stuck. The sewing machine became an exciting new friend. One that enabled me to craft out my own individuality and have something ‘new’ to wear that hadn’t cost a fortune but still looked good at the local nightclub. It liberated me and over the years has been a great comfort, a space to retreat to when the going gets tough, and has fostered a familiarity and continuity rivaled only by my desire to get the practice more widely recognised as something that can aid in the fulfillment of development goals, be these individual goals of self-actualisation or more tangible ones of income generation and employment.

My first experience of the connection between clothing production and development came about through my involvement with Oxfam in the early nineties and in particular a project I helped to set up, NoLoGo. Through this initiative I helped out in the workroom and shop in SoHo, London, later set up a store in Leeds, worked with various different tailoring groups in India as part of Oxfam Trading, and conducted a PhD into the role of textile and clothing production within development projects, conducting field visits in India, Nepal, and Zambia (Dennis 1999). It fostered in me a belief that whilst engaged in activities such as sewing and making, other things can come into being. It may be that through an initiative, participants become more social, empowered, and quite often it is not so much what is being made but rather the way in which it is being made. It makes us realise that what we have lost in this mass-produced and consumed world is ability and even confidence to make things and that the space to make has in way become a political space. The following case study presents efforts to make clothes from recycled materials and the various techniques explored.

5.1 *Ketchup Clothes: A Case Study in Recycling*

Clothes on the surface share similar attributes and do very much what they have always done. They cover our body, they keep us warm, they make us feel stylish, they make us feel out of date, they allow us to belong, and they set us apart from the crowd. However, there is growing dissent from various quarters that all is not as it should be in relation to manufacture and consumption in the industry and thus this section examines the phenomenon of fashion and what happens to the waste, the leftovers that get discarded. Drawing on localised design practices, artistic tendencies, and consumption preferences, a collection of garments developed from discarded materials is presented together with data collected between 2006/2007 from activities related to the establishment of a clothes-recycling project. This period of time represents a point in the enterprise's history that was solely focused on its business viability and a period when most of the recycling activity took place. Whilst set back in time it has subsequently formed the basis for the contextualisation of the practice and a setting of it within an academic context. Plans for future development will draw upon findings from this period of manufacture and sales as a method for development of the model.

Ketchup Clothes was set up as an experiment in clothes recycling and social enterprise. The general hypothesis for the research was that current production methods for the manufacture and consumption of clothing are detrimental to the environment and this has resulted in a large amount of waste being produced. Recycling exists as a viable method for the conversion of these unwanted textiles and clothing into viable fashion pieces but the lack of information pertaining to methods of manufacture impact on its viability and sustainability. Opportunities do exist for clothes recycling to become more widespread but more information is needed on how materials can be sourced, manipulated, and ultimately consumed.

The Overall Aims of the Project Were to

- Propose innovative methods for recycling clothes with a view to developing models of good environmental practice and determine factors that influence the disposal of clothing and identify viable sources for materials.
- Appropriate waste clothes and textiles into a viable fashion design collection and in the process investigate the nature of the fashion industry.
- Explore existing consumption and disposal models for clothing and highlight push and pull factors that impact on the generation of clothing waste.
- Establish a viable social enterprise and test the enterprise's sustainability in terms of income generation, poverty alleviation, and empowerment. Use this as contextualisation for the extent to which theory relating to sustainable development can be applied to fashion practice.
- Disseminate information relating to clothes recycling within both academic and nonacademic contexts.

5.2 Methods of Enquiry

Set up as a reaction to environmental concerns, and what is seen as an ever-increasing wasteful approach to clothing, methods of enquiry centred upon how items of clothing become discarded and seen as waste. As such it sought to explore approaches to sustainable design through the remanufacture of existing products, products that were recut to eliminate signs of wear and tear and that, for whatever reason, have been discarded by their previous owners. Set up as a social enterprise Ketchup Clothes also sought to explore alternative business models, particularly where they related to participatory design, ethical production, and community/social involvement. Key methods employed included:

- Defining and sourcing waste clothes and textiles in order to reflect upon how they had come to be disposed of and to source materials for use within recycled items
- Engagement in all stages of design, manufacture, marketing, and consumption of recycling clothes
- Exploration of design and pattern-cutting processes in order to propose modes of production for various scales of manufacture
- Engagement in outreach work in order to collate and disseminate information pertaining to the practice of clothes recycling and the fulfillment of development aims such as poverty alleviation, income generation, and empowerment

5.3 *Definition and Sourcing of Waste Clothes*

In the context of the project waste in relation to textiles and clothes was defined as items either discarded as rubbish, items that were seen as second-hand (i.e., they had had a previous owner), or were no longer wanted by someone for whatever reason. Thus methods for sourcing appropriate materials centred upon the following contexts.

- Discarded: This included items left out with the rubbish bins and on the streets.
- Charity shops/second-hand markets/car boot sales: Main distributors of second-hand clothes to the general public.
- Donated: Old stock, remnants, unwanted items.
- Consumers' own items.
- My own wardrobe.
- Sourced: Where a specialist fabric was required such as fair trade cotton or organic cloth for a specific commission.

Thus an important source of materials was from waste bins, second-hand shops, and consumers' own waste. The following figure illustrates the contribution these different sources made to garments made and sold during the space of a year (Fig. 7).

This demonstrates the predominance of discarded and second-hand materials and the variety of waste materials that can be incorporated into a fashion collection.

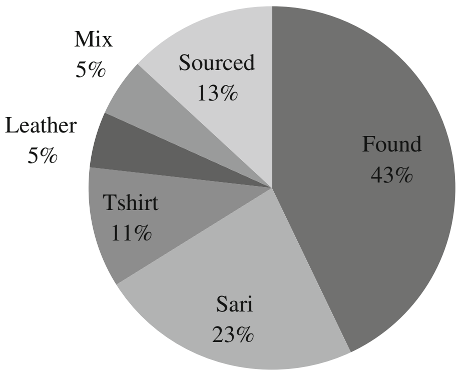

Fig. 7 Distribution of materials/production processes to sales

5.4 *The Design and Manufacture of Recycled Clothes*

A key component for the research was to embed myself fully in the whole range of activities relating to the design, manufacture, sale, and consumption of items made from recycled clothes. Thus once sourcing of material had taken place the task of developing styles and producing them began. It soon became apparent that when dealing with recycled materials, and attempting to develop styles that can be replicated in a variety of manufacture scenarios, several problems present themselves. These include:

- There is a often a lack of consistency in the materials sourced from waste streams and fabric will often vary in quality, surface design, weight, size, and availability.
- Garments are already made up and to get at the fabric that needs recycling necessitates the deconstruction of pieces. This is a skilled job that takes time and expertise.

5.4.1 Rips and Stains

Typical problems with using old T-shirts. These need to be eliminated by cutting out/embellishing over (Fig. 8).

Of course the trick with recycling is to embrace these inherent ‘problems’ and turn them into positives. Thus lack of consistency can translate in design terms as uniqueness and originality. Similarly the mix of different materials can provide a strong aesthetic and also allow elements of what the garment may have been to

Fig. 8 Common signs of wear and tear – rips and stains, 2014 (Image: Author's own)

come through. With recycled fabrics and clothes much of the knowledge about what to make comes from the material itself and thus the design process undertaken can vary from conventional processes. Methods of manufacturing process often directly define and influence the final design and can be used as a source of inspiration within the design process. Examples of responses to recycled materials are presented below.

5.4.2 Remodelled T-shirts

Cotton jersey has a strong affinity to the fashion-conscious consumer. A comfortable, easy to wear fabric, it moves with the body and can be printed, dyed, and manipulated to give a modern aesthetic. It is a fabric that is recognised globally and understood by the consumer. As a choice for recycling it also has great potential and as such was used extensively within the collection. Mainly the jersey came from old T-shirts which were deconstructed, cut to lie flat, and then remodelled into alternative styles such as dresses, trousers, and the like. T-shirts were sorted according to quality, colour, and weight/handle of material. Stains and rips were then cut out and the resultant material was incorporated into a variety of styles. It utilised both flat pattern cutting and moulage (modelling onto a mannequin).

Other techniques included the deconstruction and reconstruction of existing garments into 'new' garments. Often this entailed a rethinking of how and where the garment could be placed onto the body and thus engendered an alternative aesthetic (Fig. 8). The design intent for the items of clothing made from the sourced materials was to produce items of clothing that were democratic in nature, that is, not couture pieces to be consumed by an economic elite but those that were

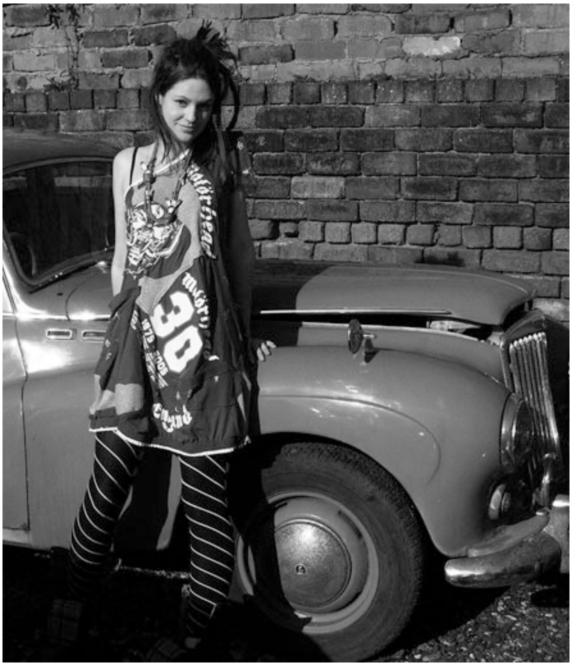

Fig. 9 Example of dress made from recut t-shirts, 2011 (Image: Gemma Barnes)

affordable and understandable to the masses. If we are to counter negative influences, seen to derive from the mass production and consumption sector, then this approach was necessary in order to test how the items' manufacture and consumption may fit into this model. This approach was thus taken to analyse the acceptance of items made from recycled materials within a mainstream, High Street market, and to look at viable production methods for getting the clothes to this market. From a designer point of view there was also greater affinity with this style of clothing and it fit into the author's previous work. Thus pieces were designed with a fashion-conscious consumer in mind, one that was generally aged between 18–45 and one who had an empathy with the production methods used but didn't have masses of disposable income. There was thus a desire to engage with and mimic what was happening on the High Street as a way of positioning the designs and proposing viable manufacturing methods (Fig. 9).

5.4.3 Knitted T-shirts

A T-shirt is laid flat and using a cutting motion up and down the garment a thin ribbon is produced. This is then knitted on large needles to give the necessary aesthetic and handle (Fig. 10).

Fig. 10 Knitted t-shirt top, 2007 (Image: Authors own)

5.4.4 Household Textiles

Opportunities for reusing household textiles including duvet covers, sleeping bags, and tablecloths were explored together with other items such as saris and other lengths of fabric (Figs. 11 and 12).

5.5 Engagement in Outreach Work

Outreach work was seen as a vital method of enquiry as it provided insight into relevant development aims and afforded opportunity to work alongside potential activators of clothes recycling. These included people engaged in financial inclusion projects, schoolchildren, and agencies keen to promote recycling. On the whole outreach consisted of the delivery of practical workshops in recycling skills and the promotion of the outputs of the workshops through fashion shows and exhibitions. These included the display of samples of recycled clothes and the

Fig. 11 Sleeping bag jacket (*left*) and recycled sarees (*right*), 2007 (Image: Authors own)

Fig. 12 Process of reconstruction, men's tailored jacket, 2014 (Image: Authors own)

demonstration of techniques in shopping malls, festivals, market spaces, and within the studio space itself. The place of production of the recycled clothes[4] was located

[4]Leeds 6 is an area close to Leeds University, United Kingdom, and home to many students and a large Asian population. It suffers from many issues relating to social and urban deprivation,

Fig. 13 Recycling workshop, St John's shopping centre, Leeds, 2008 (Image: Author's own)

in what could be described as a deprived area and thus represented the sort of small-scale initiative that could be applicable to other national and international contexts (Fig. 13).

Collaborating with local authorities, similarly minded organisations, NGOs, development agencies, and community groups also provided a source of income for the project and contributed to its sustainability. Spaces of make and interaction thus also formed the platform for the communication of ideas and provided an important source of contextualization and analysis. Within this context it was found that the ways in which participants, particularly under the guise of development and financial inclusion projects engaged with clothing and its remake led the way to a transformation of self. This was also borne out by the ways in which the objects themselves were transformed and inspiration for this process came from the writings of Bauman and practitioners such as Sherman and Bowery (Greer 2005; Bauman 2005; Sherman et al. 2012).

6 Conclusions and Discussion

The drawing up and positioning of conclusions in relation to the value of recycling, local production, and its relevance to sustainability has come about through two dependent methodologies, namely the review of secondary theoretical debate and the examination of reflective thoughts derived from engagement in practical activities that are alluded to in the literature, including recycling, social enterprises,

(Footnote 4 continued)

including poverty, unemployment, and lack of investment. It has a number of small-scale creative enterprises involved in, for example, the music industry and fashion design, operating from small studios and bedrooms.

and activism. Reflecting on the theoretical debate, this has been assisted by the author's engagement with development agencies on a practical level and with producers operating in both the United Kingdom and abroad (including India, Africa, and Nepal). Translating this into practical applications, approaches to development and the role of technology, in particular notions of 'appropriateness' advocated by development critics, has also framed the nature and way in which garments have been designed, produced, and consumed with an emphasis on community engagement, empowerment, and poverty alleviation (Schumacher 1978; Chambers 1997; Fletcher 2008) This has included the establishment of a social enterprise (Ketchup Clothes) to test notions of activism, the production and sale of a wide range of garments made from recycled materials found in the author's locality to gauge customer and market, and the delivery of workshops to disseminate techniques as a way of reflecting on 'sustainable' practices.

The overall aim of this chapter was to present data and literature pertaining to the dilemmas of development and in the process propose methods through which 'fashion' and its associated industry may be 'reconstructed' both in material form and structure. This included the proposal of methods for both the construction of garments made from second-hand clothes but also the need for sustainable practices to be embedded within business models. To live in a global world is to be constantly aware of our own lives and histories and how they may merge and blend with others. Within the context of the fashion industry relationships to modes of production, make, and consumption form the basis for these globalised interactions and provide the focus for an analysis of sustainable practices. Taking a practitioner-led approach to design, and the production of cultural artefacts, this chapter drew on the author's response to clothing waste and provided reflection on almost 20 years of recycling under the guise of a social enterprise, Ketchup Clothes, based in the United Kingdom.

Drawing on a range of global and cross-cultural references this chapter also demonstrated how waste can be transformed into a thing of beauty and in the process provide insight into our relationship to clothes, technology, and modes of disposal, production, and consumption. The jacket and waistcoat developed as a response to the Global Denim project illustrated how the discarded jeans, through a process of deconstruction were converted into something 'new'. This newness grew out of the previous owners no longer having a use for the garments and a contention that they no longer fitted into changing notions of their identity and lifestyles. As such this case study provided insight into the global practices of wearing 'jeans' and the implications of changes in fashion to our perceptions and connection to denim items and fashion obsolescence. Similarly the case study of Ketchup Clothes demonstrated how knowledge of manufacturing methods can lead the way to the development of a commercially focused and 'fashionable' clothing collection.

The relationship of the objects to global processes was thus viewed through the lens of sustainability and it was argued that production methods, especially those based in a studio environment, have the potential to impact on notions of social enterprise and design activism. To this aim reflection on the author's approach to design and the shaping of 'fashion'-inspired objects was provided together with an investigation into how models of social enterprise may be developed to have relevance to global processes. Theories relating to aspects of liquid modernity and global identities also framed discussion into how objects become personalised and lead to a transformation of the self. Our relationship to development is also crucial particularly as it relates to our concept of the future. To this end we can draw on readings of the future from popular culture and consequently fashion (Piercy 1979; Martin Margiela 2010; Chalayan 2008). In this we often see two dialectically opposed scenarios, namely utopia and dystopia. We imagine that sustainability lies within the utopian realm of our world and thus dystopia becomes our foe.

In her utopian world and recounted in her book, *Woman on the Edge of Time*, Piercy (1979) prophesied how clothing would perform two functions: it would be hardwearing, functional, and made from natural materials. Agriculture and bioscientists paving the way for innovations in fibres that come naturally dyed and finished. The other function related to the need for attractiveness, uniqueness, and individuality and to this end Piercy proposed extravagant and elaborate structures that were either vintage pieces shared around the community or one-off pieces that naturally biodegraded. In the dystopian world the distorted and exaggerated body forms dictated more by stereotypical renderings, were covered by garments that were derived from digital and virtual contexts and all about portraying an ever-changing identity.

Whilst this is just a story, a piece of fantasizing about the future, it does make us think about what is possible and just how far away from a sustainable future in fashion we may be. Elements of the story have come true: we can grow leather, we know which materials biodegrade, organic cotton is readily available, clothes swaps proliferate on the outskirts of the mainstream, and much has been done to adjust modes of production to be more equitable and less polluting. However, we also have elements of dystopia within the system. Workers' rights are still routinely ignored, mountains of waste litter the road on the quest to be 'fashionable', and materials and finishes are not developed with the environment in mind. We have the knowledge but it seems that the political and social will to change things is still dormant.

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Chitosan Derivatives as Effective Agents in Recycling of Textile Dyes from Waste Waters

Shahid-ul-Islam and Faqeer Mohammad

Abstract Textile wet processing involves tremendous use of different classes of structurally diverse dyes such as acidic, basic, disperse, azo, diazo, anthraquinone, and metal complex dyes for many applications from simple colouration to multifunctional finishing of a wide variety of textile materials. Unfortunately, the presence of dyes in effluents generated in wet processing has been continuously polluting waters due to the formation of toxic chemical sludge or carcinogenic compounds. This chapter covers the advancements taking place in the treatment of dye effluents involving the use of chitosan and its derivatives extracted from crustaceans and some fungi. Their advantages are mainly excellent sorption capability, low toxicity, high availability, better biodegradability, and compatibility with the environment. By combining the valuable information about chitosan and its derivatives as well their application in treating wastewaters, this chapter is of high potential value to researchers engaged in the development of products and processes for recycling of dyes from wastewater effluents.

Keywords Dyes · Effluents · Recycling · Chitosan

1 Introduction

Disposal of coloured wastewaters from many industries such as dyestuffs, textile, food, leather, paper, pharmaceuticals, paint, petroleum, electroplating, and plastics have introduced substantial amounts of potentially toxic organic substances into the atmosphere and into the aquatic and terrestrial environments (Crini 2005;

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Kadirvelu et al. 2003; Bailey et al. 1999; Oliveira and Airoldi 2014). The discovery of synthetic dyes in 1856 by William Henry Perkin and their advantages further increased the importance of synthetic colourants for dyeing and finishing a variety of textile materials including nylon, wool, silk, leather, and cotton (Islam and Mohammad 2014; Islam et al. 2013, 2014; Shahid et al. 2013). Despite their advantages, synthetic dyes often pose serious environmental and health concerns. About 50,000 tonnes of dyes are discharged into the environment worldwide every year (Lewis 1999). Over the past few decades, a variety of methods, including physico-chemical and biological methods have been investigated in the treatment of water and wastewaters containing different classes of structurally diverse dyes such as acidic, basic, disperse, azo, diazo, and anthraquinone-based and metal complex dyes (Forgacs et al. 2004; Fu and Viraraghavan 2001; Ali 2010). Some of the conventional methods commonly employed for dye removal from wastewaters are depicted in Fig. 1. The chemical structures of some commonly adsorbed synthetic dyes are shown in Fig. 2.

Natural biological materials are considered nowadays as emerging alternatives towards achieving safe and effluent free water supplies (Errais et al. 2011; Meshko et al. 2011; Özcan et al. 2006; Poots et al. 1976; Annadurai et al. 2002; Noroozi et al. 2007). Of all the natural materials investigated, chitosan which is a natural linear polyaminosaccharide biopolymer synthesised by alkaline deacetylation of chitin and chemically composed of glucosamine and N-acetylglucosamine units linked by 1–4 glucosidic bonds has drawn special scientific attention. In addition to its biocompatibility, biodegradability, and bioactivity, the presence of reactive amino groups and primary and secondary hydroxyl groups along the backbone confer to it interesting properties for application in agriculture, biomedicine, biotechnology, textile, and food industries. However, the main barrier to hinder the use of chitosan is its poor mechanical strength, low specific gravity, easy agglomeration or gel formation, and insufficient solubility in dilute acids. To overcome this, chitosan has been chemically modified in several ways to obtain a wide range

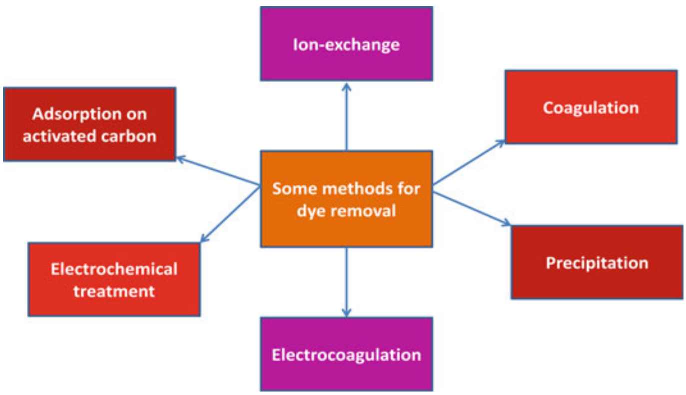


Fig. 1 Some methods to remove synthetic dyes from wastewaters

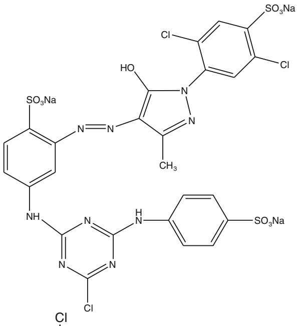
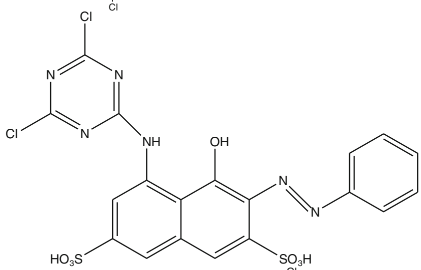
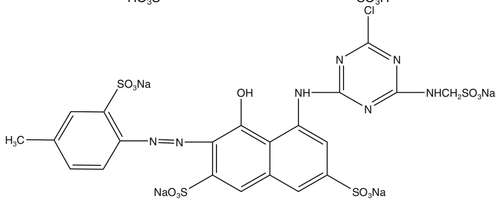
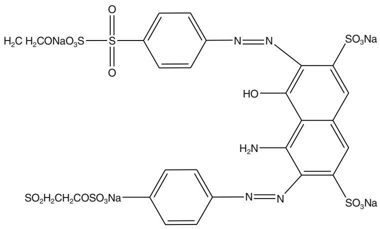
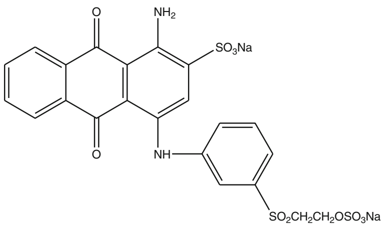
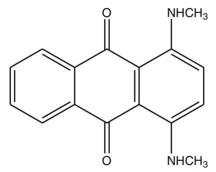
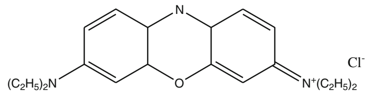
Name	Chemical Structure
Reactive Yellow 2	
Reactive Red 2	
Reactive Red 189	
Reactive Black 5	
Reactive Blue 19	

Fig. 2 Chemical structures of some synthetic dyes

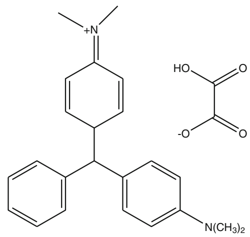
Disperse Blue 14



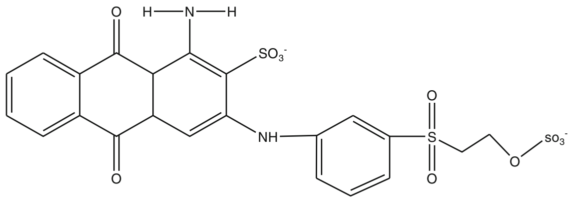
Basic Blue 3



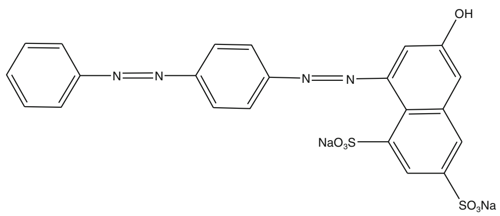
Basic Green 4



Remazol Brilliant Blue R



Acid reactive 73



Acid Reactive 18

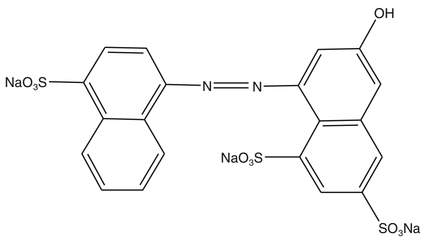
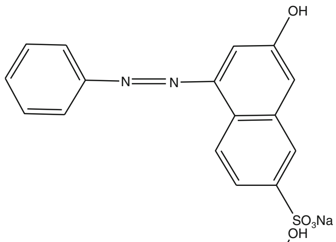
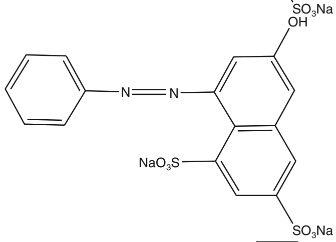


Fig. 2 (continued)

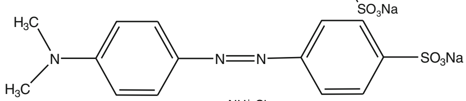
Acid Orange 12



Acid Orange 10



Methyl Orange



Basic Violet

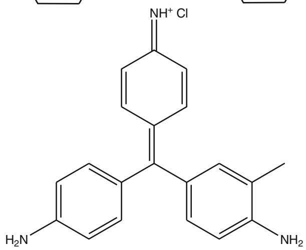


Fig. 2 (continued)

of industrially important derivatives with a broad spectrum of applications. This chapter is aimed at highlighting the recent applications of chitosan composites and derivatives for the removal of dyes from water and wastewaters.

2 Chitosan as an Adsorbent for Dye Removal from Wastewaters

Due to several intrinsic characteristics, mainly low cost compared to commercial activated carbon and outstanding chelation behaviour, chitosan is an effective biomaterial for dye removal and provides increasing interest for researchers working in the field of wastewater treatment. Chitosan is a deacetylated derivative of chitin and is classified as a low-cost adsorbent mainly because of its production from waste products of the seafood processing industry such as from shells of crabs, shrimp, and squid (Fig. 3). The chemical structures of chitin and chitosan are

Fig. 3 Sources of chitosan

depicted in Figs. 4 and 5, respectively. Chitosan contains amino and hydroxyl groups in its chemical structure and has been utilised by many researchers to modify its properties for better adsorption efficiency (Guibal et al. 2005). Chitosan natural polymer has very few functional groups such as hydroxyl and amine groups which make it possible for chitosan to attract synthetic dyes from wastewaters (Annadurai et al. 2002). Juang et al. (1997) successfully removed vinyl sulfone and chlorotriazine reactive dyes from aqueous solutions by chitosan. Wu et al. (2001) studied the adsorption process of three reactive dyes on chitosan in the presence and absence of complexing agents and found that an intraparticle diffusion model best

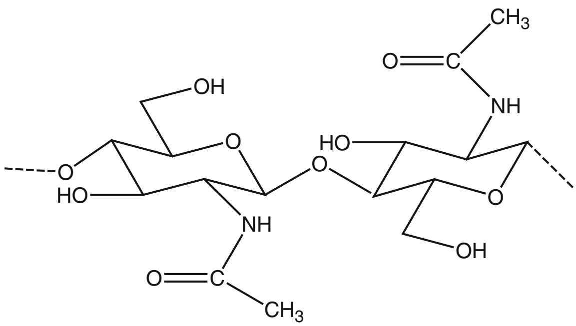


Fig. 4 Chemical structure of chitin

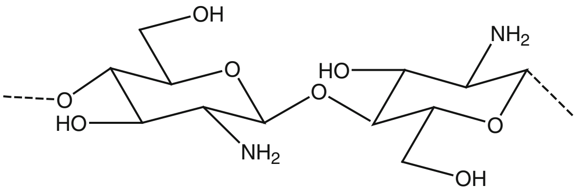


Fig. 5 Chemical structure of chitosan

describes the adsorption process. Cheung et al. (Cheung et al. 2007) found that intraparticle diffusion was mainly responsible for adsorption of Orange 10, Acid Orange 12, Acid Red 18, Acid Red 73, and Acid Green 25, respectively, onto chitosan biopolymer. Chatterjee et al. (Chatterjee et al. 2007) reported a study for the removal of Congo Red, a carcinogenic textile dye using chitosan hydrobeads. Adsorption was found to be dependent on pH. The mechanism proposed by the authors was based on physical forces along with strong ionic interactions arising between anionic sites on the dye molecule with positively charged amine groups on chitosan. To improve the adsorption capacity of chitosan different composites and derivatives with novel properties and mechanisms of action are currently being intensively researched for the removal of dyes from wastewaters. In the following sections, chitosan composites and derivatives are discussed in detail.

3 Recent Advances in Dye Adsorption Using Chitosan Composites

Structurally diverse dyes such as acidic, basic, disperse, azo, diazo, anthraquinone, and metal complex dyes are extensively used by different industries including food, pharmaceuticals, plastics, tanning, and mainly by textiles. Various methods including oxidative degradation, photodegradation, electrocoagulation, and biochemical degradation and adsorption have been extensively studied in recent decades to remove harmful dyes and metals from polluted waters (Khan et al. 2014; Alshehri et al. 2014). Most of these methods have several disadvantages such as high cost, health-related issues, and environmental concerns. Out of all these methods adsorption is particularly attracting scientific attention mainly because of its high efficiency, low cost, ease of handling, and high availability of different adsorbents (Alver and Metin 2012; Bhatnagar and Jain 2005; Wang et al. 2008). Various low-cost and abundantly available natural polymers have been identified as effective adsorbents for the removal of different synthetic dyes from wastewaters and novel methods have been developed to enhance their dye-binding properties (Muzzarelli et al. 2012). Extensive work has been reported for the removal of synthetic dyes from wastewaters employing diverse and efficient chitosan composites (Reddy and Lee 2013; Wan Ngah et al. 2011). Chitosan has formed numerous composites with diverse substances such as montmorillonite, polyurethane, bentonite, activated clay, oil palm ash, and kaolin which have been studied to explore their potential properties towards removal of synthetic dyes (Wan Ngah et al. 2011; Hasan et al. 2008). Zhu et al. (2010) used TEM, SEM, and WAXRD techniques to characterise chitosan/kaolin/nanosized γ-Fe_2O_3 composite synthesised via a microemulsion process. The composite was examined as a low-cost adsorbent for removal of anionic dyes from wastewaters. The adsorption process was quick and most of the dye (about 71 % of Methyl Orange) was adsorbed within 180 min from 20 mg L^{-1} Methyl Orange solution.

Salehi et al. (2010) studied the feasibility of using a novel biocompatible composite, namely chitosan–zinc oxide nanoparticles to remove Direct Blue 78 and Acid Black 26 anionic textile dyes. The pseudo-second–order kinetic model for both dyes fit experimental data well and Langmuir and Tempkin isotherms agreed well with the thermodynamic data. Janaki et al. (2012) used polyaniline/chitosan adsorbent for the removal of Congo Red, Coomassie Brilliant Blue, Remazol Brilliant Blue R, and Methylene Blue from aqueous solutions. Zhu et al. (2011) used a water-in-oil emulsification method for the preparation of γ-Fe_2O_3/SiO_2/chitosan composite to investigate its role in the removal of Methyl Orange from aqueous solutions. Auta and Hameed (2013) reported the use of waste tea-activated carbon/chitosan composites for removal of Methylene Blue dye and Acid Blue 29 from wastewaters. Karim et al. (2014) studied the use of biobased composite membranes involving cellulose nanocrystals as functional entities in the chitosan matrix for the removal of Victoria Blue 2B, Methyl Violet 2B, and Rhodamine 6G dyes from wastewaters. They found that electrostatic interaction arising between negatively charged cellulose nanocrystals and the positively charged dyes is mainly responsible for dye removal. Kannusamy and Sivalingam (2013) observed adsorption of reactive orange 16 dye using chitosan–polyaniline/ZnO hybrid composites. They used FT-IR, BET, SEM, UV-vis spectra, and XRD analysis to characterise the synthesised hybrids and found that Langmuir isotherm agreed well with the experimental data and obtained an adsorption capacity value of 476.2 mg g^{-1}. Nair et al. (2014) reported for the first time preparation and characterisation of a range of chitosan–alkali lignin composites for the removal of anthraquinonic dye, namely Remazol Brilliant Blue R and Cr(VI) ion. The reaction was fast and best described by Langmuir isotherm and followed pseudo-second–order kinetics. The mechanism proposed was based on electrostatic interaction of protonated amino and hydroxyl groups of the composite with anionic SO_3^- and $HCrO_4^-$ groups of dye molecule in addition to chemical interaction between amino and hydroxyl groups of the composite, and carbonyl moiety of the dye. Wang et al. (2015) reported a study for the adsorption of two azo dyes, Methyl Orange and Amido Black 10B, using chitosan aerogels doped with a small amount of graphene oxide. Vanamudan et al. (2015) studied the removal of Rhodamine 6G from wastewaters using a chitosan–clay nanocomposite as dye adsorbent. Peng et al. (2015) reported the synthesis of a chitosan–halloysite nanotube composite using dropping and pH-precipitation method for the removal of Methylene Blue and Malachite Green from aqueous solutions. In their case, the adsorption data were fitted well by Langmuir isotherm and Freundlich isotherm models. Cho et al. (2015) prepared a new composite of nano-magnetite, heulandite, and cross-linked chitosan with chitosan to remove Methylene Blue and Methyl Orange from wastewaters. From the adsorption results, it was found that adsorption on synthesised composite followed pseudo-second–order kinetics with an adsorption capacity of 45.1 and 149.2 mg g^{-1} for Methylene Blue and Methyl Orange, respectively. Methylene Blue was also removed from aqueous solutions by Bulut and Karaer (2014) using a cross-linked chitosan/bentonite composite.

A cross-linked chitosan/bentonite composite has also been used for the removal of Amido Black 10B azo dye by Liu et al. (2015). Zheng et al. (2015) more recently studied adsorption of a novel diatomite/chitosan–Fe (III) composite (Fe (III)/Cs@Dia) for the removal of anionic azo dye. They were able to get a maximal 2 GL dye uptake of 1250 mg g^{-1} at pH 6 and 298 K. They further stated that electrostatic interactions arising are mainly responsible for adsorption of dyes (Fig. 6). Mahmoodian et al. (2015) investigated the use of poly-2-hydroxyethyl methacrylate chitosan nanocomposite for the adsorption of Methyl Orange. They used different isotherms including Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich and found that Langmuir isotherm agreed well with a high correlation coefficient of 0.9991. Zeng et al. (2015) also reported the use of novel chitosan/organic rectorite-Fe_3O_4 intercalated composite microspheres for the removal of Methylene Blue and Methyl Orange. They noted that adsorption of both the dyes on chitosan/organic rectorite-Fe_3O_4 intercalated composite was best described by pseudo-second–order kinetics.

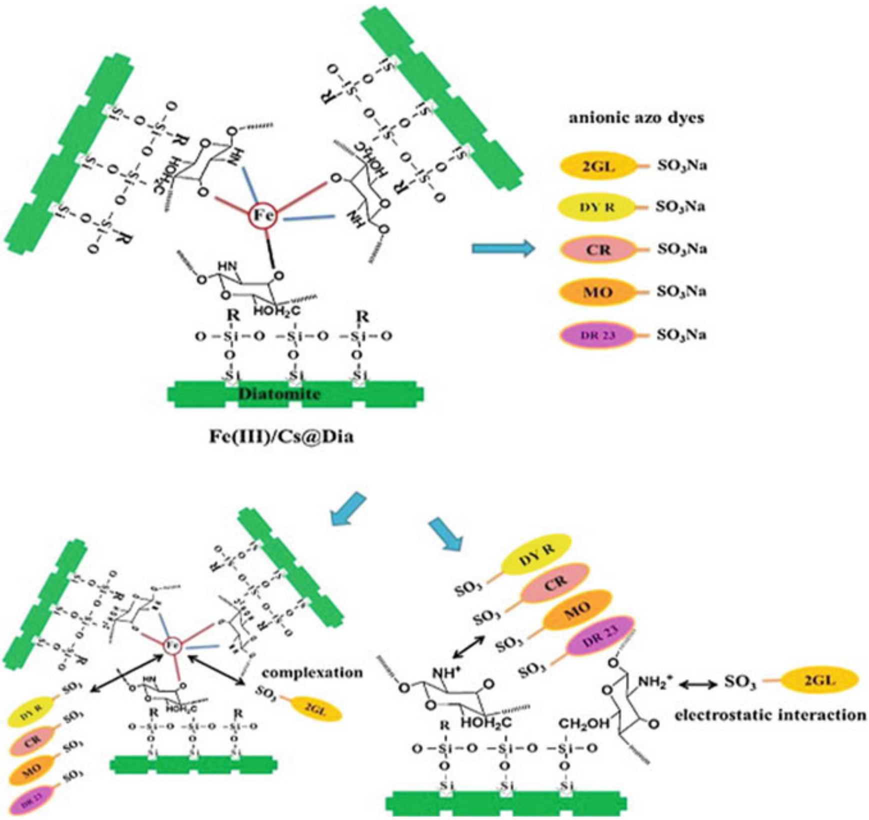


Fig. 6 Mechanism of bioadsorption (Janaki et al. 2012)

4 Chitosan Derivatives for Dye Removal

Adsorption of dyes by using chitosan derivates is particularly attracting scientific attention mainly because of their high efficiency, low cost, high selectivity, environmentally friendly nature, and biodegradability. Over the past few decades, several research investigations have been conducted and are currently underway worldwide for the removal of dyes from wastewaters using chitosan derivatives. Lazaridis et al. (2007) examined the suitability of chitosan derivate produced by grafting and covalent cross-linking for the removal of Remacryl Red dye. It was observed that grafting modification of chitosan especially with acrylic acid showed maximum adsorption capacity of 1.068 mmol/g. Wang and Wang (2008) investigated the adsorption of N, O-carboxymethyl-chitosans with different degrees of substitution for the removal of Congo Red from aqueous solutions. It was found that the adsorption capacity of native chitosan and N, O-carboxymethyl-chitosan with degree of substitution of 0.35 for Congo Red were 78.90 mg/g and 330.62 mg/g, respectively. The adsorption kinetics and isotherms revealed that the adsorption of Congo Red dye on N, O-carboxymethyl-chitosan was best described by pseudo-second–order equation and the Langmuir isotherm. Kyzas et al. (2009) grafted carboxyl and amide groups on chitosan powder or beads to remove a reactive (Remazol Yellow Gelb 3RS) and a basic (Basic Yellow 37) dye from aqueous solutions. For reactive dye, chitosan grafted with amide groups presented maximum adsorption behaviour at pH 2 whereas chitosan grafted with carboxyl groups showed maximum adsorption efficiency at pH 10 for basic dye. Kyzas et al. (2011) also used cross-linking reagents (gluteraldehyde and epichlorohydrin) and grafting reagents (acrylamide and poly(ethyleneimine) to modify chitosan beads chemically for the removal of reactive dyes Remazol Red 3BS, Remazol Blue RN, and Remazol Yellow directly from their dyeing bath. Their study showed that presence of amido and imino groups on chitosan produced because of grafting reactions enhanced their adsorption capacity and cross-linking reactions made them reusable for many cycles. Chitosan grafted with poly (methylmethacrylate), poly (ethyl methacrylate), poly(butyl methacrylate), and poly(hexyl methacrylate) have been reported to be efficient adsorbents for the removal of anionic dyes namely Orange-G, Congo Red, Remazol Brill Blue R, and Methyl Blue (Konaganti et al. 2010). Elwakeel et al. (2012) investigated removal of Brilliant Blue R250 from aqueous media using ammonium chitosan derivatives. Gluteraldehyde was used to chemically cross-link chitosan. Furthermore, ammonium hydroxide, epichlorohydrine, and 3-Amino-1,2,4 triazole, 5-thiol reagents were used to produce modified resins of chitosan/gluteraldehyde. In their study they obtained uptake values of 0.97, 0.79, and 2.505 mmol/g for all three modified resins, respectively. Oliveira and Airoldi (2014) reported the adsorption of reactive yellow GR and blue RN dyes on chitosan modified with a pyridine derivative. They studied the effect of contact time, concentration, and dye structure on adsorption and found maximum adsorption capacity of 2.13 and 1.61 mmol g^{-1} for reactive yellow GR and blue RN dyes, respectively. Furthermore they stated that effective hydrogen bond and van der

Table 1 Adsorption of some dyes using chemically modified chitosan

Chitosan derivative	Dye adsorbed	Kinetic model	Isotherm	References
Chitosan grafted with acrylic acid	Remacryl red	Pseudo-second–order	Langmuir–Freundlich	Karim et al. (2014)
N,O-carboxymethyl-chitosans	Congo red	Pseudo-second–order	Langmuir adsorption	Kannusamy and Sivalingam (2013)
Chitosan grafted with amide groups and carboxylic groups	Remazol yellow Gelb 3RS and basic yellow	Pseudo-second–order	Langmuir–Freundlich	Nair et al. (2014)
Chitosan grafted with polyacrylates	Orange-G, congo red, remazol brill blue R, and methyl blue	Pseudo-second–order	Langmuir	Vanamudan and Pamidimukkala (2015)
Chitosan/gluteraldehyde derivative	Brilliant blue R250	Pseudo-second–order	Langmuir adsorption	Oliveira and Airoldi (2014)
Chitosan/pyridine derivative	Yellow GR and blue RN dyes	Pseudo-second–order	Fickian diffusion low and Elovich model	Peng et al. (2015)
Succinyl-grafted chitosan	Remarcyl red TGL	Pseudo-second–order	Langmuir–Freundlich	Cho et al. (2015)

Waals forces are mainly responsible for the adsorption mechanism of dyes on modified chitosan. More recently, Kyzas et al. (2015) reported synthesis of succinyl-grafted chitosan as an efficient and multifunctional adsorbent for the removal of basic dye (Remarcyl Red TGL) and a heavy metal (Zn). They used various techniques such as SEM, XRD, and TGA to characterise the synthesised chitosan derivative. Results from their study indicated that succinyl-grafted chitosan could be reused as an adsorbent for up to 40 cycles. Table 1 summarises the models and isotherms well fit with the experimental conditions for the removal of dyes.

5 Conclusion and Perspectives

Chitosan has witnessed huge scientific interest over the last few decades in removal of synthetic dyes from waste waters mainly because of its biocompatibility, biodegradability, nontoxicity, and outstanding chelation property. To overcome the limitations with native chitosan such as poor mechanical strength, low specific gravity, easy agglomeration or gel formation, and insufficient solubility in dilute acids, it has been modified in several ways to improve its properties for adsorption applications. Chitosan has formed diverse composites with different substances such as montmorillonite, polyurethane, bentonite, activated clay, oil palm ash, and kaolin to improve its adsorption capacity. Various modification approaches have also been used including grafting and cross-linking to make chitosan a particularly attractive choice for removal of acidic, basic, disperse, azo, diazo, anthraquinone, and metal complex dyes from aqueous solutions. Through chitosan composites and derivatives, it has been possible to remove dyes through various adsorption mechanisms including electrostatic interaction and chelation as well as alter their properties in such a way as to maximise their adsorption benefits even in acidic conditions. This chapter clearly shows that there is a promising future for chitosan derivatives as efficient biomaterials for adsorption applications.

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Polyester Recycling—Technologies, Characterisation, and Applications

Thilak Vadicherla, D. Saravanan and Subramanian Senthil Kannan Muthu

Abstract Polyester, a synthetic fibre made from petroleum, a nonrenewable resource, is widely known for its environmental impacts during its extraction and manufacturing processes. Various environmental problems surrounded with the production of virgin polyester production, namely depletion of nonrenewable resource (petroleum, as a raw material for polyester production), and requirement of large amounts of energy during the production process combined with the environmental issues caused by the disposal of polyester at the end of life, makes the recycling of polyester an important and inevitable option. Recycled polyester produced by post-consumer waste such as PET bottles are found to be very environmentally beneficial compared to virgin polyester. Many studies have revealed the same. Applications of recycled polyester fibres in the production of apparel are becoming familiar these days. This chapter is dedicated to deal with the aspects pertaining to recycled polyester textiles and it includes discussions on various recycling technologies for polyester, the process of recycling polyester (mechanical and chemical recycling), and the latest developments in the characterisation of recycled yarns and fabrics produced from recycled polyester-blended yarns. This chapter also highlights the roadmap ahead for polyester in terms of sustainability.

Keywords Polyester · Recycling · Mechanical and chemical recycling · LCA · Characterisation · Fabric properties

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1 Introduction

Environmental concerns have created awareness of the promotion of eco-friendly industries and eco-friendly industrial practices (Kim 2012). The classical and most popular 3R concept comprises reuse, reduce, and recycle for the benefit of the environment (www.plasticsindustry.org). As everyone knows, recycling is not something new; it has a long history. Of late, increased awareness and concern over waste management, environmental protection, and sustainability have brought recycling of polyester into the limelight. Plastic waste poses huge problems to humanity, the first being that crude oil (raw material for plastic production) is nonrenewable and the second being that most plastics are not biodegradable because the long polymer molecule chains of plastics are too large and too tightly bonded together to be broken apart and assimilated by decomposer organisms. Considering the above problems, it would be wise to recycle plastics and the benefits or motivations of plastic recycling would be decreased or lower landfill expenses, recycled plastics are cheaper than the virgin plastics, recovery of stored energy in the plastic through incineration, and legislation and government regulations of waste recycling policies. Plastic waste can be collected from a wide variety of sources including industrial waste; agricultural waste (containers, pipes, sheets); hotel, restaurant, and shop waste; municipal waste (plastic litter collected from streets, parks, beaches); and household waste.

1. The typical sequences of processes adopted in the development of products from recycled polyester are shown as a roadmap in Table 1. All the steps involved in the roadmap are elaborated at the appropriate places in this chapter.

2 Recycling Technologies

Textile waste materials are broadly classified into three categories (http://www.recycling.about.com; Muthu 2014), namely (i) pre-consumer textile wastes (PrCTW), (ii) post-industrial textile wastes (PITW), and (iii) post-consumer textile wastes (PtCTW).

Pre-consumer textile wastes are those wastes which never make it to the consumers and which come directly from the original manufacturers. Examples include: ginning wastes, opening wastes, carding wastes, comber noils, combed waste yarns, roving wastes, ring spinning waste fibres, ring spun waste yarns, open end spinning waste fibres, open end spinning yarn wastes, knitting waste yarns, weaving waste yarns, fabric cutting wastes, fabric wet processing wastes, apparel manufacturing wastes, and so on. Post-industrial textile wastes are generated during the manufacturing process of upstream products and typically they are from the virgin fibre producers, tyre cord manufacturers, polymerisation plants, and other plastic products. Post-consumer textile wastes are the wastes that are recovered from the consumer supply chain and these are generally the clothes that are ready

Table 1 Sustainability route through polyester recycling

Type of waste	Type of material(s)	Pre-processing steps	Processing	Possible sequence	Final or intermediate products	Demonstration of sustainability
Post-consumer waste	Post-consumer PET bottles	Collect, sort, fibre extraction, pelletising, products or yarn preparation, conversion into product and finishing	Downcycling/upcycling	Mechanical	Extrusion/flakes/pellets Recycled PET bottles Recycled fibres/reclaimed yarns and fabrics/accessories/garments and make-up	Labelling of products
				Chemical	Monomer/Oligomer/Polymer Recycled PET Bottles Recycled fibres/Reclaimed yarns and fabrics/Accessories/Garments and Make-up	

Table 2 Approaches for recycling

Approaches	Raw material for recycling
Primary	Industrial scraps
Secondary	Mechanical processing of post-consumer products
Tertiary	Pyrolysis/hydrolysis of polymeric wastes to get monomers or fuels
Quaternary	Burning the fibrous solid wastes and utilising the heat generated

for disposal or landfill. Popular examples include recycling of the accessories and beverage bottles to make recycled polyester.

Waste is inadvertent in any process and for the betterment of the environment it has to be used again. One of the solutions to the reduction of the carbon footprint in the textile/apparel supply chain would be the use of recycling (Muthu et al. 2012). Conversion of pre-/post-consumer textile wastes into final products consists of the following stages which include collection and sorting, fibre extraction, yarn preparation, conversion into fabrics, and finishing. Recovery from the waste stream is widely known for reuse of a product in its original form and recycling to convert the waste into a product of a lesser value in the case of downcycling and of a higher value in the case of upcycling.

Recycling technologies are typically divided into primary, secondary, tertiary, and quaternary approaches (Table 2).

Primary recycling involves recycling a product into its original form, an example being industrial scraps; secondary recycling involves mechanical (melt) processing of post-consumer plastic products into a new product that has a lower level of physical, mechanical, and/or chemical properties. The tertiary approach involves processes such as pyrolysis and hydrolysis, which convert the plastic wastes into basic chemicals or monomers or fuels. Quaternary recycling refers to burning the fibrous solid waste and utilising the heat generated. Fibres and fabrics are recycled using all four approaches (Scheirs 1998; Wang 2006).

3 PET Recycling Process

3.1 Collection and Sorting

Prior to processing of plastic, waste is washed and sorted according to the coding system. Recycling polyester from polyethylene terephthalate (PET) bottles is achieved either by mechanical recycling or chemical recycling processes. However, collection and sorting of the PET bottles are the initial steps for both processes. PET bottles are initially sorted and separated from other materials such as glass, cartons, metals, PVC, HDPE, LDPE, polypropylene, drink cartons, and the like. The second sorting is done per the colour fractions including transparent or uncoloured polyester, blue and green coloured, and the remainder into mixed colour fractions.

In many places, crushed bottles are sold in bales of various sizes after sorting, commercially.

3.2 Secondary Recycling—Mechanical Recycling

Mechanical recycling of plastic waste is considered the simplest and relatively cheapest recycling method. Mechanical recycling is basically a melt extrusion process and typical process steps of mechanical recycling of PET bottles are: cutting, shredding, contaminants separation, floating, washing, drying, extrusion, and pelletising.

The first step is cutting, where large plastic parts are cut into smaller parts either by saw or shears followed by shredding in which cut plastics are chopped into small flakes. Contaminants such as paper and so on are separated out from plastic in cyclon separators. Various kinds of plastics are separated according to their density in a floating tank. Flakes are washed with detergents or solvents and thoroughly dried for the prevention of any deterioration of hydrolytic degradation. Flakes are heated to melting state in an extruder and ejected through a die which converts into a continuous polymer strand. Sometimes these flakes are also cross-linked to improve the mechanical properties. The strands are cooled by water and cut into pellets, which may be used for new polymer products manufacturing.

Recycled PET flakes or pellets are used as the raw material for a wide range of products that would otherwise be made of virgin polyester fibres, to yarns and other kinds of products. A wide variety of examples includes polyester clothing, infills for pillows, carpets, and the like, polyester sheets, strapping, or back into PET bottles and containers. The disadvantage of mechanical recycling is that the impurities such as polyvinyl chloride (PVC), sodium hydroxide (NaOH), and alkaline detergents present in the post-consumer PET result in flake segregation, degradation, and poor mechanical properties.

3.3 Tertiary Recycling

This is also called feedstock recycling. Tertiary recycling involves chemical recycling (chemolysis) and thermolysis. The objective of chemical recycling is to reduce the polymers into various levels such as oligomers or monomers by reaction with certain chemical agents. Produced oligomers or monomers can find different applications including polymerisation to get the same polymers and fibres again (Gupta and Kothari 1997). The advantage of this process is that the monomers produced through chemical recycling are identical to the monomers used in the preparation of virgin polymers and it is the most suitable process for treatment of clean mono-resin plastic waste. Another advantage of this process is that the contaminants such as PVC, NaOH, alkaline detergent, acidic glues, acetaldehyde, and so on are removed during the course of the depolymerisation. The disadvantage of this chemical recycling is these processes require high temperatures and pressures, and take a long time for the treatment. A wide variety of decomposition routes is available depending upon the type of chemical agent used for the breakdown of polymer.

Chemical agent	Name of the process
Water	Hydrolysis
Glycol	Glycolysis
Methanol	Methanolysis

3.3.1 Glycolysis

Glycolysis is considered the simplest and oldest method of depolymerisation. This reaction occurs at a temperature of 180–240 °C with ethylene glycol and under the catalytic conditions of zinc or lithium acetate in which PET is partially depolymerised into oligomers. This process produces BHET [bis (hydroxyethyl) terephthalate], which in turn can be polymerised into PET again. The disadvantage of this process is, colours, if any are present in the PET wastes, are generally not removed.

3.3.2 Methanolysis

Methanol depolymerises polyethylene terephthalate to dimethyl terephthalate (DMT) and ethylene glycol (EG) under the process conditions of 20–40 atmospheric pressure and a temperature of 180–280 °C. Zn or Mg or Co acetate or lead acetate act as catalysts in this process. The disadvantages of this process include batch process and lack of complete removal of organic impurities. The latest developments in this methanolysis include the use of super-critical methanol under the process conditions of pressure more than 80 atmosphere and a temperature of 300 °C. The advantage of this system is the reduction of process time (depends upon the temperature and reaction temperature), which can be a minimum of 10 min compared to the conventional treatment of 5 h.

3.3.3 Hydrolysis

In this process, water reacts with polyethylene terephthalate, which depolymerises PET into terephthalic acid (TPA) and ethylene glycol (EG) in acid, alkaline, or neutral environments. The disadvantages of this process are severe process conditions and long reaction times.

3.3.4 Thermolysis or Thermal Depolymerisation

The chemical decomposition of condensed organic substances is achieved under thermal (heating) conditions. In pyrolysis, chemical decomposition of polymers is induced by heat at elevated temperatures in the absence of oxygen or at low oxygen temperature. Typical process conditions include atmospheric pressure and operating temperatures of 400–1000 °C. The output of this process is typically basic chemicals and fuels including gasoline, diesel, and heavy oil. The advantages of pyrolysis include its feasibility and economic viability, freedom from air pollution, and smaller space requirements. In gasification, conversion of polymers into a mixture of carbon monoxide (CO) and hydrogen occurs through partial oxidation or incomplete combustion. Typical reaction process conditions are a high temperature of 700–1600 °C and high pressure (10–90 atm). In hydrogenation or hydrocracking, a chemical reaction of plastics with hydrogen (H_2) takes place, usually in the presence of a catalyst, that produces saturated liquid and gaseous hydrocarbons.

3.4 Quaternary Recycling

Quaternary recycling is basically called an 'energy recovery' process. The energy stored in the plastics is reused as the energy source to produce products such as steam and/or electricity. An example is the municipal incineration in energy-from-waste incinerators (combustion). The heat of plastic waste burnt at high temperature is used for the production of electricity or steam. Production of alternative fuels from plastic waste (pyrolysis and gasification) leads to the fuel used in various manufacturing processes and in power stations. Sustainability in the plastic supply chain has brought mechanical recycling, chemical recycling, bio-based PET, and mixed plastics on to the forefront of recycling.

3.5 Bio-Based PET

The American Society for Testing and Materials (ASTM) defines a bio-based material as "an organic material in which carbon is derived from a renewable resource via biological processes (http://www.astm.org)". To put it simply, bioplastic is nothing but plastic in which all carbon is derived from biological (renewable) feed stocks. Bio-based materials can include many articles such as plant and animal mass derived from CO_2 fixed via the photosynthesis mechanism. Bio-based plastics may or may not be biodegradable, which depends upon the bio-based ingredients and the conditions under which bio-based products are going to be biodegraded. The market consists of a wide variety of natural feedstocks including starch (potatoes, corn, wheat, etc.), rice, tapioca, palm fibre, wood cellulose, and bagasse, among others. The advantage of starch is that the molecular structure of starch can be easily broken down by microorganisms and hence starch-based natural raw materials are being extensively used in bioplastics. Because starch is soluble in water, it's first converted into lactic acid and the polymer polylactide is used in bioplastics. Bioplastic products include utensils (cups, plates, bottles, cutlery, etc.), textiles (bedding, home furnishings, bags, carpets, etc.), film, and packaging materials (http://www.sustainableplastics.org/about). In the United States, the percentage of bio-based ingredients required for a product to be referred to as bio-based, is defined by the USDA on a product-by-product basis. The ILSR has recommended that the USDA set a minimum threshold of 50 % bio-based content for products to be considered bio-based.

The typical advantages of bio-based plastics include that a wide variety of renewable (biological) resources can be utilised, can be partially or fully biodegradable depending upon the climactic conditions in which this plastic is loaded, and have the additional advantage of the ability to compost locally with suitable amendments/modifications and ultimately contribute to healthier environmental and societal benefits. The disadvantage of bio-based plastics is on the economic front, in which a typical biodegradable plastic price is 2–10 times more expensive than virgin PET and so not lucrative under the present circumstances, which also poses challenges in the sustainable future.

4 Characterisation of Recycled Polyester

Numerous studies have taken place on the investigation of recycled PET fibres and yarns, fabrics, and garments. Recycled PET is characterised by molecular weight, intrinsic viscosity, carboxyl end-group content, colour readings, thermal stability, and so on. A literature survey shows that molecular weight converges to the fact that there is a decrease with increase in percentage of recycled PET, intrinsic viscosity drops due to thermal degradation, and recycled polymer viscosity decreases with the increase of COOH groups. Upasani et al. (2012), Pawlak et al. (2000), Lee et al. (2013), and Koo et al. (2013) have studied the blending of recycled PET flakes with virgin PET chips.

The effect of reprocessing of polyethylene terephthalate was investigated by Frounchi et al. (1997), and the findings include reduction of mechanical properties of recycled PET with the increase of the recycled PET content and mechanical blending of 20 w/w % recycled PET with virgin PET shows practically the same mechanical properties with its weight-average molecular weight slightly lower than virgin PET.

Lee et al. (2012) have investigated the physical properties of virgin polyester drawn texturised yarn (DTY), material-recycled (MR) polyester DTY, and chemical-recycled (CR) polyester DTY. The findings of the study are: CR PET yarn had better crimp, more stable structure, slightly higher intensity of the crystallisation peak and breaking elongation higher than that of MR PET yarn, and Tm and tensile strength of the MR PET yarns are higher than that of CR PET yarn.

Abbasi et al. (2007) have studied the effect of spinning speed on the structure and physical properties of filament yarns produced from used PET bottles and the results show that increasing the take-up speed resulted in an increase in the optical birefringence, crystallinity, tenacity, and initial modulus, and a reduction in the breaking elongation of both virgin and recycled samples. Recycled fibres are often supplemented with the addition of virgin polyester fibres, organic cotton, flax, and elastomeric fibres in order to achieve enhanced properties, aesthetics, and functional values.

4.1 Yarn Preparation and Characteristics

Yarn, a fibrous structure, is a building block in a wide variety of textile applications which include fabric (woven/knitted), home furnishings, apparel, technical textiles, and so on. Fibre is primarily characterised by mean length, length uniformity, fineness, tenacity, elongation at break, contamination, and colour/shade, among others. The process of making the yarn from fibres is called 'spinning'. Yarn quality is primarily characterised by linear density, tenacity, elongation at break, unevenness, thin places, thick places, neps, and hairiness. Yarn quality fundamentally depends upon the fibre quality and the spinning process. To put it in simple terms, 'a good fiber produces a good yarn'. The basic concept of spinning is that the longer fibres produce stronger yarns, as the scope for a fibre to twist around another fibre increases with the longer fibre. Unfortunately, the process of recycling is such that it can produce fibres with short length, nonuniformity of fibre lengths, unopened/partially opened, and more imperfections. The inherent properties of the recycled fibres allow the production of coarser yarn counts only and it becomes difficult to produce medium and fine count yarns. However, ring, rotor, and friction spinning have been successfully employed for the production of recycled PET yarns.

Rotor spinning is another widely used spinning technique for the production of recycled yarns. The opening roller of the OE rotor spinning systems is one of the three most important parameters (raw material and type) that influence both yarn quality and spinning performance. An attempt has been made in this study to find optimum opening roller speed and other process parameters for the production of recycled PET yarns (Duru and Babaarslan 2003). Polyester staple fibres 32 mm long, 1.2 denier fineness, 7.17 g/denier strength, and 16.7 % breaking extension and waste fibres (cotton noil, recycled fibres, flat waste, etc.) were blended (polyester/waste blend ratio of 60/40) and processed on the traditional short-staple (carding) system to produce Ne 20/1 polyester/waste OE rotor yarns on a laboratory-type spinning machine. Seven different polyester/waste (cotton noil, recycled fibres, flat waste, etc.) rotor yams were produced at seven different opening roller speeds (6000, 6500, 7000, 7500, 8000, 8500, and 9000 rpm). The results indicate that an increase in the opening roller speed negatively affects yarn strength and positively affects unevenness and hairiness values. This study also concludes

Table 3 Yarn Components and Their Constitution %

Yarn samples	Yarn linear density, tex	Yarn components		
		Virgin cotton fibres in sheath, %	RF in core or middle layer, %	Polyester filament in core, %
C	30, 40, 50, 60, 70	100	0	0
R	30, 40, 50, 60, 70	0	100	0
C-R	30, 40, 50, 60, 70	51	49	0
C-R-core	30	41.7	39.8	18.5
C-R-core	40	44	42.1	13.9
C-R-core	50	45.5	43.4	11.1
C-R-core	60	46.4	44.3	9.3
C-R-core	70	47.1	45	7.9

[a]C = 100 % cotton yarns, R = 100 % RF yarns, C-R = cotton/RF two-component yarns, C-R-core = three-component core yarns

that the optimum opening roller speed is 7000 rpm for polyester/waste blends with reference to both yam properties and cleaning effects. However, this study also throws light on the importance of determining the optimum opening roller speed according to the raw material used for spinning OE rotor spun yarns in practice.

Medium count yams of acceptable appearance and tensile properties were successfully produced with friction spinning (Merati and Okamura 2004). In this work, an attempt has been made to produce middle count two-component and three-component yams from recycled fibres (RF) in which RFs in the yarn core are completely covered by virgin cotton fibres, on a modified friction spinning machine. Yarn components and their constitution are shown in Table 3.

The results indicate that the 51/49 cotton/RF two-component appearance is similar to that of 100 % cotton yarn; RF sliver imperfections have no significant effect on yarn appearance; and the strength of a two-component yarn is greater than that of a 100 % RF yarn. The 30-tex three-component core yarn produced in this study possesses higher tensile properties (strength and elongation) than that of equivalent 100 % cotton yarn, a cotton/RF yarn, and a 100 % RF yarn, and less irregularity than that of cotton/RF and RF yams.

Abdurrahman et al. (Telli and Özdil 2013) have made an attempt to produce Ne 20/1 yarns using a ring spinning system (carded). Fibre properties used in this work and the yarn count along with various blend ratios are given in Tables 4 and 5, respectively.

Table 5 refers to the six recycled blended yarns of Ne 20: αe = 3.6 and T/m = 634 were produced under various blend proportions (cotton, r-PET of 70:30, 50:50, 30:70, and PET and r-PET of 70:30, 50:50, 30:70). In addition to 100 % cotton, 100 % r-PET, and 100 % PET yarns on a Rieter G30 ring spinning frame with 10,000 rpm spindle speed, 42 mm ring diameter, ISO 90 travellers, 5.5 mm light grey clips, and 1.18 breaking draft and 20 total draft are used. Tensile strength, elongation

Table 4 Fibre properties

Fibre properties	Cotton	Polyester	Recycled PET bottle (r-PET)
Fineness (dtex)	1.78	1.57	1.85
Mean length (mm)	26.51	28.77	32.62
Tenacity (cN/tex)	27.30	50.66	26.92
Elongation at break (%)	7.0	25.74	39.13

Table 5 Quality characteristics of yarns with r-PET, PET, and CO contents and their blends

Material	Tenacity (cN/tex)	Elongation at Break (%)	Evenness (%CVm)	Thin Places (–40 %)	Thick Places (+50 %)	Neps (+140 %)	Hairiness (H)
100 % Co	12.77	9.68	13.65	56.9	65.9	500.6	5.59
70 % CO 30 % r-PET	13.57	12.75	13.35	32.6	73.1	425.7	5.4
50 % CO 50 % r-PET	13.42	15.14	13.44	47.9	90.7	493.2	5.45
30 % CO 70 % r-PET	12.28	13.19	12.68	24.5	60.1	397.8	5.64
100 % r-PET	14.91	22.08	12.45	32.7	54.6	346.8	5.8
100 % PET	28.66	21.28	10.78	3.1	11.2	23.1	4.77
70 % PET 30 % r-PET	23.3	20.6	11.46	9.6	16.4	112.6	5.09
50 % PET 50 % r-PET	21.08	21.92	11.32	9.1	23.9	154	5.18
30 % PET 70 % r-PET	18.6	20.35	11.8	13.3	27.4	209	5.49

at break, thin places, thick places, neps, evenness, and hairiness results of the yarns produced under the study are shown in Table 5.

The findings of the study are: increase of r-PET content causes decrease in tensile strength for PET/r-PET blended yarns and increase in tenacity for r-PET/cotton blends. Evenness, number of IPI faults (thin places, thick places, and neps), and hairiness values of 100 % r-PET yarns are worse than 100 % PET yarns, however, no significant difference is observed for these properties between r-PET fibre blends with cotton and PET. The important finding of this study is that the required performance of the r-PET yarns can be achieved only by blending of fibres with r-pET and not by 100 % pure r-PET yarns.

Other studies conducted on the comparison of yarns produced from recycled fibres and virgin fibres (El Nouby and Kamel 2007) reflects that tenacity and elongation values of yarns obtained from recycled fibres differ marginally; however, such processes appear to be economically advantageous in the long run (Omar et al. 2004).

4.2 Fabric Characteristics

Choi and Kim (2015) have characterised the knit fabrics produced from virgin PET, recycled PET, and recycled PET–nylon6 blends. Specifications of the double jersey fabrics produced from virgin and recycled PET are shown in Table 6.

Findings of this study are: tensile strength values and compressional properties of both mechanically and chemically recycled PET knit fabrics were similar to that of virgin knit fabrics whereas elongation and drape ratio of recycled PET knit fabric were the best. Recycled PET–nylon6 blend knit fabric possesses good moisture regain, moisture permeability, smoothest appearance, and coolest feeling. Wickability of mechanically recycled PET knit fabric was better than other recycled PET knit fabrics. Virgin and recycled PET knit fabrics possess excellent pilling resistance.

Inoue and Yamamoto (2004) have carried out a study to examine the performance and durability of woven fabrics manufactured from recycled polyester fibres, extruded from PET bottle wastes. Forty-eight commercial fabrics, with varying fibre content and structure were studied for mechanical, surface, thermal/moisture/air transport properties, hand values, and durability values by repeated washing. The samples included 18 polyester/cotton blended, eight 100 % polyester, and 22 polyester/wool fabrics in which the rate of recycled polyester of each fabric group was 25–65, 40–60, and 0–70 %, respectively. The study revealed that with an increase in the recycled polyester fibre content, bending rigidity and shear stiffness values increased. However, durability tests revealed that the bending rigidity and shear stiffness values decreased on repeated washing and the fatigue measures such as higher hysteresis and lower resilience values were not clear. Another interesting feature of this work is that the values of the wool-blended recycled polyester are within +3σ which is very much within the limits of the common summer suiting group.

The authors are currently working a lot with recycled polyester and will report the work once the results are open to the public. A systematic approach has been put in place for the production and characterisation of recycled blended ring spun yarns, manufacturing of woven and knit fabrics, characterisation of fabric properties (aesthetics, utility, durability, low-stress, mechanical, comfort, etc.),

Table 6 Specifications of virgin and recycled PET double jersey knitted fabrics

Sample Code	Sample	Fineness (Denier)	Strength (g/d)	Strain (%)	Weight (mg/cm2)	Thickness (mm)
Virgin	Virgin 75/72 DTY	72.7	4.2	15.0	9.88	0.541
MR	Mechanically recycled 75/72 DTY	78.8	4.14	18.0	11.14	0.584
CR	Chemically recycled 75/36 DTY	756	4.03	30.0	14.11	0.522
Blend	Chemically recycled PET–nylon6 blend 80/20 75/24 SDY	78.	2.83	42.3	12.96	0.378

[a]*DTY* Draw Textured Yarn; *SDY* Spin Draw Yarn

chemical/mechanical finishing processes and their optimisation to enhance the fabric properties, fabric response to the consumer-use phase (washing and ironing), recommendations on care instructions, garment preparation, consumer behaviour, and acceptance of garments prepared from recycled yarns.

5 Applications

History shows that the first PET bottle was recycled in 1997 and since then many companies have started recycling plastic. Recycled plastic has been in use for home furnishings, technical textiles, and apparel since then. Many reputable companies and brands including Patagonia, Adidas, Nike, H&M, Levi's, Puma, Esprit, and others (http://www.patagonia.com; http://www.adidas-group.com/en/sustainability/welcome.aspx; http://www.nikeresponsibility.com/report/content/chapter/our-sustainability-strategy; http://www.hm.com; www.levistrauss.com/sustainability/; www.puma.com/; http://www.esprit.com/; http://www.recycling.about.com; Muthu 2014; http://www.ykkfastening.com/products; http://www.gucci.com; http://www.asics.com/en/; http://www.hanesbrandscsr.com; http://cosmos.ucdavis.edu/archives/2007/cluster8/chong_kim_ppt.pdf; http://www.patagonia.com) are in the forefront of usage of recycled PET plastic in their products. Table 7 gives an overview of the some of the products/brands developed from recycled polyethylene terephthalate and their blends.

Patagonia was widely known as the first apparel manufacturing company which initiated sustainable efforts, as early as the 1990s (http://www.patagonia.com). One

Table 7 Some of the applications of recycled poly(ethylene terephthalate)

Fibre and Blend	Product(s)	Brand/Collection/Company	Ref.
Recycled poly (ethylene terephthalate)	Zippers, sliders, chains	*Natulon/YKK*	30
	Fashion garments	*Conscious Collection/* H&M	24
	Khaki trousers	*Dockers/Levi's*	25
	Sports jerseys and shoe uppers	*Nike*	23
	Sportswear	*Adidas*	22
	Track jacket	*InCycle/Puma*	26
	Inner soles of shoes	*Sustainable Soles/Gucci*	31
	Bumper	*Ford*	34
	Fleece fabrics	*Patagoina*	35
Poly (ethylene terephthalate) and bamboo fibres	Low-cut socks	*Asics*	32
Cotton and poly (ethylene terephthalate)	Sportswear	*EcoSmart/Hanes*	33

popular product from Patagonia is its fleece fabric which is made from post-consumer recycled plastic soda bottles. Adidas (http://www.adidas-group.com/en/sustainability/welcome.aspx) created the same impact across the globe with its London Olympics–2012 as the world's first truly sustainable Olympics initiatives. Nike, with its sports jerseys for the 2010 FIFA World Cup that were made from recycled plastic bottles, has created an awareness of sustainability across the globe in a positive manner (http://www.nikeresponsibility.com/report/content/chapter/our-sustainability-strategy). Some of the examples from H&M which include recycled polyester (http://www.hm.com), are their party wear (second 'conscious' collection), men's brick lane bikes, and standard plastic consumer bags made up of 50 % post-consumer and 50 % pre-consumer recycled polyester. Levi's *WasteLess™ Jeans* (www.levistrauss.com/sustainability/) consist of at least 29 % post-consumer recycled plastics made from eight plastic bottles. Puma's InCycle is a sustainable collection (www.puma.com/) that includes shoes, apparel, accessories, and home insulation materials made up of either biodegradable polymers, or recycled polyester and organic cotton. The recyclable Puma track jacket is made up of 98 % recycled polyester and 2 % elastane. The Esprit (http://www.esprit.com/) clothing range includes garments made up of 100 % recycled polyester. Hera Bamboo low-cut socks (http://www.asics.com/en/) by Asics are made up of a blend of recycled polyester fibres and bamboo fibres. It is interesting to note that the bumpers produced by Ford Motor Company (http://cosmos.ucdavis.edu/archives/2007/cluster8/chong_kim_ppt.pdf) are manufactured from millions of pounds of PET plastic.

Recycled fibre-reinforced composites using various fibres are on the rise and the fibres are not limited to cotton, flax, kenaf, carbon, and PET (www.innovativecompositesinc.com/); and cement concrete using natural and HDPE has been developed. Imperial Chemical Industries (ICI), United Kingdom, has two distinct recycled product lines, namely (www.innovativecompositesinc.com/) Structure-Lite and EcoScape. Structure-Lite composite panels, made up of recycled polyester, are being recommended in the transportation industry as cargo containers, truck body containers, and highway sound barrier panels because these panels offer unmatched durability and strength compared to similar lightweight panels made from other materials. An additional advantage of Structure-Lite composites is that they can be formed into different shapes, making them ideal for the transportation and marine industries. EcoScape-based houses, designed with the adaptation of Structure-Lite panels offer enhanced features such as easy and fast assembling, high strength, and durability, making them ideal for natural disaster situations and relief camps.

Poole Company, South Carolina offers EcoSure®, recycled fibres that are manufactured using recycled polyethylene terephthalate, with a linear density range of 1.2 denier to 500 denier (http://www.poolecompany.com), and are highly suitable for outdoor furniture, roof vents, wipes, industrial scrub pads, and also apparel. Nonwoven fabrics can also be produced through either spun lace or thermal or adhesive bonding methods, as well as needle-punching processes. The company recommends 1.2 and 500 denier for the production of hygiene-grade technical nonwovens and industrial scrub pads, respectively.

Another application of recycled polyethylene terephthalate is disposable and hygienic pillows (http://disposable-linen.co.uk/bed-sheet-towelling-bedding/contents/en-uk/p84.html) developed with the filling made from 100 % recycled, expandable polyester and covered with nonallergenic nonwoven fabrics, which are further recyclable. Marks & Spencer also supplies pillows with washable (machine washable at 50 °C), soft touch, and medium support characteristics (http://www.marksandspencer.com/Supremely-Washable-Medium-Support-Pillow/dp/B002OXKYYS) with nonallergenic fillings made from recycled plastic bottles. Guru Athletics, Ontario produces finished yoga towels (http://www.samaritanmag.com/) which are manufactured with 80 % recycled polyester and 20 % natural cotton fibres. Shaw Floors, Georgia's ClearTouch Carpet (http://shawfloors.com/tips-trends/luxurious-carpet/cleartouch-carpet), comprises ClearTouch® BCF polyethylene terephthalate filament with a significant recycled component and offers exceptional performance characteristics such as excellent appearance retention and long-term wear in addition to the inherent attributes of polyester. An additional feature of this patented process of Shaw Floors, R2x, offers twin resistance against stains and soils for protection against spills and tracked-in dirt. Pottery Barn, San Francisco, offers unique senna antique kilim rugs (http://www.potterybarn.com/products/senna-outdoor-kilim-rug/), consisting of recycled polyester yarns, and woven on a handloom which have a soft and smooth texture and durability. CLASS, Creativity, Lifestyle and Sustainable Synergy (http://www.swicofil.com/products.html) claims that Newlife™, the continuous polyester yarns from 100 % recycled post-consumption PET bottles is the source of the prestigious red carpets of the world, endorsed by divas and celebrities. *Natulon* (http://www.ykkfastening.com/products) is the popular brand name of YKK of Japan that offers zippers made from recycled polyethyelene terephthalate. Varieties include an open metal part made up of recycled PET; the chain and slider of zippers are also made of recycled PET. Another advantage is that these products are easily recyclable as these products have no metal components. Velcro, a hook and loop structure, of *Natulon* is made of recycled polyester (58 %).

6 Conclusions

Recycling of polyester is evolving to match the requirements of the needs. Mechanical and chemical recycling of polyester are the two major technologies currently available. The inherent demerits of mechanical recycling limit the end uses/applications to some extent, but chemically recycled polyester is finding its applications in a wide variety of products. Of late, many different uses are being manufactured from recycled polyester. Beverage bottles produced from recycled PET are on the rise. Consumer acceptance will be a major criterion in making polyester recycling a true sustainable.

7 Future Recommendations

Research on the sustainable use of materials has achieved some concrete results but still can be explored further to make living on Earth truly sustainable. Challenges remain in the sorting of PET bottles, polyester extraction processes from a blend of materials, improving the fibre properties of mechanical recycled fibre, improvements in the spinning process to produce medium and finer count yarns, energy-efficient processes in chemical recycling, and bio-based plastics, and making them affordable to a large section of humanity. A systematic approach to products produced from recycled polyester and their acceptability among consumers can be explored further.

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Recycled Fibrous and Nonfibrous Biomass for Value-Added Textile and Nontextile Applications

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Abstract Waste is a substance that is considered by all as unwanted or additional material arising out of any industrial or agricultural operation process, product, by-product, or any other item at the end of their requisite service life. In a country such as the United Kingdom, about 4–5 % of municipal solid waste is composed of clothes/textiles, 25 % of which is recycled. A large amount of unutilised/processed material is generated in the agricultural, food processing, paper–pulp, and textile industries as waste or residue, such as lignin, sericin, dyes, sizing paste, leather fibre, banana pseudostem sap, cellulosic and ligno-cellulosic short to long biofibres, corncob, tomato seed and peel, and many others. The disposal of such waste or residue creates serious environmental pollution, either during their natural degradation, through the microbial pathway, or through incineration. As many of the agro, food, textile, and paper–pulp processing wastes or residues have high technical potential to be used for many diversified end-applications, they have been seriously considered through R&D efforts and application for the production of nanocellulose, microcrystalline cellulose, bacterial cellulose, recovery of dyes, water purification, biodegradable hard and flexible composites, substrates for tissue engineering, recycled textiles, UV protective and antimicrobial agents, binder and biodegradable pots for transplanting of plants, and so on. Life-cycle assessment has also been explored to analyse the environmental performances of different shopping bags.

Keywords Fibrous biomass · Nonfibrous biomass · Nanocellulose · Recycling · Textile recycling · LCA

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1 Introduction

'Waste' is any substance constituting a scrap or an effluent or any other unwanted surplus substance arising from the application of a process. In textile industries the fibre waste forms the basis of the raw material that can be recycled to get various value-added and day-to-day usable products. Recovery from waste includes reuse of a product in its original form, or in a variation that is commonly followed for clothes and recycling to convert the waste into a product. Typically, recycling technologies can be divided into four categories according to their approaches, namely primary, secondary, tertiary, and quaternary. The primary approach involves recycling of industrial scrap; secondary includes mechanical processing of a post-consumer product; tertiary recycling involves processes such as pyrolysis and hydrolysis that convert the plastic wastes into basic chemicals, monomers, or fuel; and finally, the quaternary recycling approach refers to the burning of the fibrous solid waste for generation of heat (Youjiang 2010; Scheirs 1998; Wang 2006). All four approaches exist for fibre recycling. The 'closed-loop' approach of recycling is to recover the raw material that was used to produce a polymer product and successively reprocess it into the same product of equivalent quality as could be obtained from the virgin material. It may be noted that manufacturing of recycled polymer products not only requires raw material (e.g., petroleum), but also energy for the production process. The recycling process itself involves pollution and energy, which are becoming quite significant in the context of a single polymer. The situation is more complex and challenging for textile and clothing, as different fibres with various intrinsic physical–chemical–mechanical properties are intimately mixed with each other during carding, drawing, or spinning, thus causing difficulty in recycling subsequently by the 'closed-loop recycling' approach (Youjiang 2010).

Due to the enormous increase in world population and overall improvement in human living standards, global textile fibre consumption has increased phenomenally in the past few decades, creating a large quantity of post-industrial as well as post-consumer fibre waste. World fibre production has been steadily increasing in the past few decades, now exceeding 64 million tonnes per year. This includes consumption of both natural and synthetic fibres for making apparel, home furnishings, and technical textiles. The service life of such products could be grouped into (i) short-term, such as baby diapers, sanitary napkins, and other disposables; (ii) medium-term such as shirting and suiting, including apparel textiles, carpet, and automotive interiors; and (iii) long-term, such as those used in composite and reinforcement, for example, textiles for construction. The agro–food industries and paper–textile manufacturing companies also produce a huge amount of wastes and by-products of lower importance in terms of environmental concern and industrial sustainability, because of the associated high cost of handling of such products. In Europe, the agro–food processing industries produce about 250 million tonnes of by-products and wastes per year, whereas Italian paper and textile industries alone produce about 37 million tonnes of wastes each year (Schettinia et al. 2013).

Among the different waste-producing industries, such as agro, food, and textile, the fibres represent a sizeable and functional component. In the United States alone, about 11.9 million tonnes of textile wastes, which is equivalent to almost 4.7 wt % of the total municipal solid waste (MSW) were generated; 15.9 % of textile waste was recovered in 2007 (Youjiang 2010). The outlets of the recovered textile waste include reuse, material recycling, and energy recovery. Overall, 54 % of the MSW were landfilled, 13 % incinerated in waste-to-energy facilities, and 33 % recovered for recycling or composting. Natural fibrous materials, such as jute, kenaf, flax, and hemp, and agricultural residue, including stalks of most cereal crops, coconut fibres, peanut shells, tomato seeds and peels, are becoming popular as reinforcing materials in thermoplastic, thermosetting, and green/biocomposite applications. The natural fibres derived from the agro–food and paper–textile industries offer technoeconomic and environmental advantages for composite preparation, because of their higher strength and stiffness compared to existing materials.

With a better understanding of the recycled products, technological advancement in recycling technologies, and also the societal pressure to reduce the environmental pollution load, many types of wastes and agro-residues have been recycled/reused for making valued processes/products. For example, waste flowers have been used for textile colouration and functionalisation, cotton and leather fibres have been recovered from waste fabric for textile/composite/film application, waste jute fibre used for mushroom cultivation, dyes recovered for recolouration of textiles, and biowaste such as pineapple leaf fibres for vermi-composting. Cellulose, the most important, abundant, renewable, and biodegradable natural polymers exists in several plant biomasses, such as wood, cotton, hemp, straws, sugarcane bagasse, and other plant-based materials. Cellulose has a wide range of application in the form of fibre, paper, films, and polymer. In the literature, a number of approaches have been attempted for the production of highly purified nanocellulose from the various cellulosic to lignocellulosic biomasses, such as cotton-linter, cotton fibre, sugarcane bagasses, pineapple leaf, soy hulls, and corncob as described in detail in Sect. 5 of this chapter. An intensive study has also been conducted to utilise the various agro-bioresidues to produce value-added products, including microcrystalline cellulose, nanocellulose (CN), and bacterial cellulose that can be used as model filler in various polymer matrixes. Similarly sericin, which until recently was considered a waste product of the silk process houses, has now been poised to be one of the important industrial materials for the food, pharma, cosmetic, and textile industries for its excellent moisture absorption and release properties, UV resistance, cell-protection, wound-healing, anticancer, anticoagulant, and antioxidant activities. Similarly lignin, a by-product of the pulp and paper industry with an annual world estimated production of 50 million tonnes, is finding some additional high-end applications with recent improvement in quality. It is being used as antioxidant, antimicrobial, antivirus, biocides, biostabilisers in the paper industry, flame retardant, and in cosmetics for UV protection. One most important biowaste is banana pseudostem sap (BPS), which is generally produced as a waste material during extraction of banana fibres from the banana stem. It has been found that the liquid sap being rich in phosphate, silicate, chloride, and other mineral salts can be used as a green flame-retardant formulation, UV-protective, and an antimicrobial finishing agent for textile substrates. It can also be used as an effective biofertiliser for agricultural production.

In many practical circumstances, processing of such wastes by mechanical, chemical, and/or biological means involves recycling of waste into products, requiring the consumption of a certain amount of energy, additional raw materials, and causing emission of waste into the air, water, and soil. There are some environmental accounting tools required to be employed to evaluate the actual relative benefits of various disposal and recycling options, for example, life-cycle assessment (LCA) (Youjiang 2010). It should also be noted that although a given recycling technique may not offer significant environmental benefits at present, the situation may change as further research and development proceeds towards the development of better and cleaner technologies at a lower cost and with a higher efficiency.

The present chapter mainly discusses the recycling of fibrous and nonfibrous agricultural biomass for textile and nontextile applications. Initially, recycling of waste flowers for textile dyeing and finishing, followed by recovery of sizing materials and dye molecules for re-colouration of textiles and reduction of the effluent load have been discussed. It was noted that good quality textile, mushroom, cellulose acetate film, and activated carbon were possible to produce from the recycled cellulosic, ligno-cellulosic, and protein fibres. Special emphasis has also been given to the synthesis and application of micron- to nanosized cellulose and lignin particles from several of the low-valued agro-residues for their use in packaging, functional textiles, and biomedical uses. The recent technological advancement made in the field of green or biocomposites for development of alternative materials from the waste agricultural residues, such as stalks of most of the cereal crops, rice husks, and coconut fibres, as wood and plastic replacements has also been summarised. The multiple end-applications of banana pseudostem for textiles, paper, fertiliser, dyes, mordant, and antimicrobial agents, as established by recent studies, fostered new research which has been described in detail. All these developments are expected to create increased awareness of recycling of important biodegradable materials through appropriate value addition, while adequately addressing the environmental issues.

2 Recycling of Colouring Compounds and Auxiliaries for Textile Application

2.1 Recycling of Flowers for Textile Dyeing and Finishing

It has been observed that in a country such as India, a large number of flowers are thrown out once the idol worship is over into the river as waste from the temples that successively causes serious water pollution. The disposal of such flower waste itself is an issue and also, a potential source of recycling after collection from the local temples for textile colouration. Recycling or application of natural dyes is important in the context of toxicity, allergic reactions, and possible health risks associated with synthetic dyes during their manufacture and application, as they involve the usage of petrochemical-based raw materials. India has a rich biodiversity and a wealth of useful natural resources. Hence, it is quite likely that the plant kingdom can be successfully utilised as a potential source of diverse natural colourants for dyeing of textiles. Teli et al. reported the environmentally friendly way of dyeing and antimicrobial finishing of soyabean protein fabric (SPF) using recycled marigold flowers obtained from the ISCON temple, Mumbai. They used three natural mordants extracted from harda (*myrobalan*), tamarind seed coat (TSC, *tamarindus indica L.*), and amla (*Indian gooseberry*) (Teli et al. 2013a). As in the dyeing of textiles using natural colours (dyes), metallic mordants are essentially applied, which cause environmental pollution, use of mordants extracted from a nature-based source in place of metallic mordant is an important development. In the reported study, in terms of fabric colour, it was observed that amla and harda showed better results compared to tamarind seed coat, and K/S was found to increase from 2.8 to 4.2 with increasing mordant concentration from 5–20 %. The fabric colour was also found better compared to metal-based mordant such as alum. In all these dyed samples, the fastness to washing and rubbing were very good to excellent grade (4–5) and light fastness was found to be quite satisfactory. Tannins are astringent and antimicrobial in nature; the antimicrobial efficacy of mordant, dye, and the dye–mordant combination was also evaluated quantitatively according to the AATCC-100(2004) method. It was observed that only mordanted or dyed samples possess a low antibacterial efficacy, but, when dyed and mordanted with natural extracts, the sample showed almost 90 % antimicrobial efficiency, against both *S. aureus* and *E. coli* bacteria. After washing for 30 washing cycles as per ISO 105-CO6-1 M standard, the same was found to decrease to about 65 %.

The same research group has also studied the application of temple marigold flower waste for dyeing and antimicrobial finishing of bamboo rayon textiles using the above four mordants (Teli et al. 2014). Generally, the bamboo pulp fibre loses the inherent antibacterial property during processing with alkali. The 1 % stock solution of the marigold dye was prepared by boiling 10 g of dry marigold flowers in 1000 ml water for 1 h. The extract was then filtred and made 1000 ml prior to dyeing. Alum showed the least effect on colour values with increasing concentration of 5–20 %. Among the tannin mordants, harda tannin showed the highest increase in K/S, followed by amla and tamarind seed coat. It was observed that K/S values were much higher in the bamboo rayon fabrics compared to soybean protein fibres. Similarly, the dyed samples exhibited a very good washing and rubbing fastness, while ensuring a reasonable good light fastness rating of 5. The 20 % mordant and 20 % dyed sample could ensure 81–83 % antimicrobial activity against *S. aureus* and *E. coli* bacteria.

A similar line of research was also conducted on cotton and cotton/silk blended textiles (Teli et al. 2013b). Natural dyes from hibiscus, white and pink in colour, and marigold were applied in the above fabrics in three forms: fresh, dry, and pulverised. The dyes were supplied by Adiv natural, Mumbai. It was seen that the dry marigold could impart much better colour in cotton fabric compared to fresh and pulverised dyes in the samples without a mordant, and when mordanted with alum, harada, and Fe_2SO_4. The fresh flower showed the least improvement in colour parameters and the pulverised flowers showed an intermediate result. Similar trends were also observed when the dyeing was carried out on cotton/silk blended fabric. Different mordants were used for getting the proper depth of shades with marigold. The best suited mordant for marigold was found to be alum. It gave bright yellow hues with very high b* values as compared to the other mordants. The Fe_2SO_4 mordant gave a grayish shade with marigold with the highest K/S values and the least L*, a*, and b* values, indicating the dependence of shade on grayish hue. In cotton and cotton/silk blended fabrics, hibiscus flowers exhibited a light-orange colour without a mordant, a light-yellow colour in the presence of alum, and greenish shades in the harda and Fe_2SO_4 mordants. Similarly, *Tagetus erecta* (marigold) flower was also explored in industrial scale for colouration of cotton, wool, and silk (Vankar et al. 2009). Table 1 summarises comparative colour parameters on different fabrics dyed with marigold flowers with two different mordants.

2.2 *Recycling of Textile Dyes and Auxiliaries*

Many a time, the effluents generated from the textile, paper, plastic, leather, food, and mineral processing industries are discharged into the water stream and also, grounded in a land without appropriate post-treatment, leading to environmental pollution and health problems (Dhanapal and Subramanian 2014). The textile dyeing process generates a large quantity of toxic effluents that contain unabsorbed residual dyes, acid, alkali, salts, and other auxiliaries. It has a negative impact on the environment due to their low biological oxygen demand (BOD) and high chemical oxygen demand (COD). Many synthetic organic dyes present in the effluent are

Table 1 K/S and other parameters in marigold-treated fabrics (concentration of mordant: 20 %) (Teli et al. 2013a, b, 2014; Vankar et al. 2009)

Parameters	Cotton fabric		Bamboo fabric		Soybean fabric	
	Harda	Alum	Harda	Alum	Harda	Alum
K/S	1.36	1.43	0.86	0.18	3.80	1.46
L*	87.3	86.3	81.3	86.5	63.7	73.4
a*	–0.73	–0.47	–0.87	–0.42	2.94	4.09
b*	9.61	9.09	10.5	7.23	20.2	23.2
Washing fastness	3	3–4	4	4	4	4–5
Rubbing fastness	–	–	4–5	4–5	4–5	4–5
Light fastness	5	5	5	5	5	5

toxic in nature and endanger aquatic life and the environment. The reactive dyes may be mutagenic and carcinogenic and can cause severe damage to the liver, digestive, and central nervous system of human beings, in addition to affecting agricultural cultivation and underground water (Dhanapal and Subramanian 2014; Rajeswari et al. 2001). Hence, there is an urgent need for removal of dyes from the effluent before being discharged into the water stream using appropriate physical–chemical techniques. For the recycling/separation, some of the well-known adsorption technologies, such as activated carbon, natural clays, modified clays, fly ash, and other adsorbents are generally considered to be a cost-effective method to bring down the concentration of unabsorbed dyes in the dye effluent. In this context, superabsorbent polymers (SAPs) are increasingly being used to remove the colours, toxic and heavy metals, and other pollutants from the wastewater through the adsorption mechanism. Dhanapal et al. photosynthesised the double network polymers (DNP) of different compositions using sodium alginate (NaAlg) and superabsorbent polymer. The different physical–mechanical properties were evaluated for the reactive blue 4 dye (RB 4; molecular weight 637.4) using adsorption–desorption characteristics via adsorption isotherms at different temperature and pH values. Nearly identical visible absorption spectra of the fabrics dyed with virgin and recovered dyes indicated that the recovered dye could maintain its structural integrity during column recovery, and the dyed fabrics possessed good colour fastness properties (Dhanapal and Subramanian 2014). It was observed that the initial adsorption capacity of DNP-16 for RB 4 was 439 mg/g. The adsorption capacity remains fairly constant until the five adsorption–desorption cycles, exhibiting its chances for commercial acceptability in repeatable use.

Similar to recycling of natural dyes from flower waste and reactive dyes from textile effluent, the textile printing chemicals, such as polysaccharide thickeners, namely sodium alginate (A), carboxy methylated guar gum (CMG), and carboxy methylated cellulose (CMC) were also recycled and recovered by Fijan et al. (2009). This kind of polysaccharide is widely used as a thickener in textile printing to ensure the desired viscosity of the print paste. The above thickeners were recycled by ultrafiltration technique from the printing paste residues and from the wastewater concentrates after the screen printing of cotton with reactive dyes. The moderate changes produced by the thickener recycled on the shear-thinning and viscoelastic behaviour of polymers were due to their direct changes in molecular weight averages (MWA) and molecular weight distribution (MWD). In general, a more marked increase in the viscosity and viscoelastic properties of CMG and CMC recycled thickeners were exhibited compared to sodium alginate recycled thickeners that showed only slight changes in rheological properties. Recently, Teli et al. studied the textile printing ability of germinated maize starch, generally discarded as a waste product, and the results were compared with the starch from nongerminated maize (Teli et al. 2009). They analysed the fabric for print quality in terms of colour parameters (K/S, L*, a*, and b* values) and physicomechanical properties, such as bending length and fastness to washing and crocking. They postulated that the germinated maize starch, obtained from the nonedible maize, acted as a full or partial substitute for the nongerminated or sound maize starch.

For over 100 years, starch has been extensively used as a sizing material to protect warp yarns from abrasion during the fabric manufacturing process (Porter 1998). The starch is normally formulated with other chemicals, but it is the principal component in the sizing paste. Once the fabric is woven, it is washed out of the fabric by the desizing process and discharged into the waste stream, thus adding pollution load to the textile wastewater. Polyvinyl alcohol (PVA), another sizing chemical, was also introduced to the textile industry for sizing polyester/cotton blended yarns around 30 years ago to circumvent the above problem, at least partially. Unlike the starch, PVA has a very low BOD with high stability and can be recovered by an ultrafiltration method. The uses of membranes to recover water, chemicals, and dyes are known and practised in the textile industry (Porter 1998). Over a period of time, waste treatment and the associated energy cost have escalated, but the membrane cost has decreased; now, a membrane system has a typical payback period of 2 ± 0.5 years.

2.3 Textile Finishing Using Bio-Waste

Due to more awareness of textile ecoprocessing in the last two decades, several biopolymers, biomaterials, biofibres, and biomolecules are getting constant attention. Chitosan biopolymer has been explored widely for various functional finishings of textile substrates (Teli et al. 2013c). A large amount of crab and shrimp shells being discarded worldwide by seafood companies is now being given considerable scientific and technological attention for extracting chitin and chitosan from these renewable wastes. Chitosan is a linear polymer that can be derived by partial deacetylation of chitin, which is the most abundant natural polysaccharide on the earth after cellulose. It can be obtained from the exoskeleton of marine crustaceans, such as crabs, lobsters, shrimp, and krill. Chitosan is comprised of copolymers of glucosamine and N-acetyl glucosamine. It has many unique properties, such as nontoxicity, biocompatibility, biodegradability, and antimicrobial that make it suitable for applications in foods, agriculture, medicines, pharmaceuticals, and textiles (Gao and Cranston 2008). Chitosan is a natural cationic polysaccharide and is known to suppress the metabolism of bacteria when attached to the bacterial cell wall (Jou et al. 2007). Teli et al. achieved a multifunctional cotton textile using chitosan extracted from bio-waste. Shrimp shell waste was obtained from the local fish market and chitosan was extracted. The thermogravimetric analysis (TGA) data showed that the chitosan-treated sample was more thermally stable with a limiting oxygen index value of 27, compared to 18 in the untreated sample (Teli et al. 2013c). The wrinkle-free recipe using DMDHEU was taken as a standard and it was found that the crease recovery angle of cotton was increased from 105 to 235°exhibiting cross-linking of hydroxyl groups of cotton. The samples treated with 5–20 gpl chitosan concentration showed an almost 73–80 % antimicrobial efficacy (except for one sample) against both *S. aureus* and *E. coli* bacteria.

3 Recycling of Fibres from Waste Textiles and Their Applications

3.1 Recycling of Cellulosic Fibres from Waste Textiles/Paper

It has been reported that the annual production of global fibre for textiles and nontextile applications exceeded 70.5 million tonnes in 2009, in which the share of cotton and polyester fibres was about 40 and 45.2 %, respectively. The leftover textiles after their service life as apparel or home textiles are discarded to be landfilled or incinerated to take care of the environmental pollution problems. However, these can be valuable resources if the constituent fibres from the blended textiles are separated out or recycled. The recycling technologies for processing of textile industrial wastes are very important nowadays. Often, textile materials are manufactured keeping certain blend proportions of synthetic and natural fibres, so as to achieve improvement in properties, such as abrasion resistance, durability, strength, and crease-recovery, in addition to reducing the cost of the product. If the fabric is made with only cotton, or polyester or viscose or acrylic, it is quite easy to recycle those using different available techniques. However, in practice, blended fabrics manufactured the world over in a large quantity exploit the advantages of individual component fibres in the blended products. But, separating the individual fibre from the blended textile is a complex process, and still a challenging operation. For example, separating polyester and cotton fibres from a blended fabric into their individual pure components is too difficult and nearly impossible by mechanical means, as polyester (PET) and cotton fibres are intimately mixed during production of the spun yarn (Sun et al. 2013). In addition to it, PET as well as cotton fibres are not soluble in most of the common organic liquids. In addition, the solvents available for dissolving PET are not environmentally friendly, and toxic in nature. Wang in 2010 reported an overview on fibre and textile recycling with reference to carpets, which account for the generation of a large part of present textile waste. There are several technologies available for recycling of textile-grade fibres and these are listed below (Youjiang 2010).

(i) *Fibre Identification and Sorting*: A waste stream of a single type of polymer is easier to recycle into products with better quality compared to waste streams containing a mixture of different materials/fibres.

(ii) *Size Reduction*: Where the large pieces of carpet and textiles are cut down into smaller sizes by mechanical actions often called shredding or grinding.

(iii) *Mechanical Separation of Carpet Components*: Mechanical methods have been utilised to separate carpet components. One or more segregated components are then recycled into products that generally compete with products produced from virgin polymers.

(iv) *Dissolution/Reprecipitation Technique*: The dissolution/precipitation technique has been used to separate high-value nylon from carpet waste, and cotton from polyester/cotton blended textiles.

(v) *Melt Processing*: Melt processing by extrusion converts the thermoplastic polymers into resin pellets. If more than one type of polymer is blended together, the process is referred to as compounding.

(vi) *Depolymerisation*: The depolymerisation process converts polymeric waste into its monomers or oligomers that may be repolymerised to produce virgin quality, as a means for closed-loop recycling.

In order to recycle and reuse good fibres from textile waste and to address the problems of environmental pollution, in the past a number of methods have attempted to dissolve the cellulosic part of the waste. Some of the solvents used for dissolving cellulose including ionic liquids (ILs) and N-methylmorpholine-N-oxide (NMMO) were developed in order to separate synthetic fibres from waste-blended fabric (Hong et al. 2012). However, these solvent systems have the disadvantages of low dissolution efficiency and large consumption of chemicals and energy, resulting in their limited applications. Similarly, strong alkali such as NaOH and concentrated inorganic acids (70–75 % aqueous sulphuric acid, H_2SO_4, and 85 % phosphoric acid to hydrolyze cellulose) have been studied for separation of blended textiles. Recently, a polyester recovery technique has been developed by employing strong acid (10 N H_2SO_4) degradation of cellulose, followed by mechanical treatment (Sun et al. 2013). All these methods have the limitation of being ecologically unsafe and causing considerable corrosion to the equipment. A more ecofriendly enzymatic method has also been attempted in separation of the cellulosic part of the textiles, but its commercialisation is still an issue due to harsh conditions of enzyme reaction, the prohibitive cost of the currently available enzyme preparations, and the difficulty associated with the enzyme separation. Sun et al. reported a new separation method for acetylation of cellulose to produce acetone-soluble cellulose acetate (CA) so as to separate the cellulose and polyester part from the waste-blended fibres (WBFs) using Bronsted acidic ionic liquid (N-methyl-imidazolium bisulfate) as an efficient and environmentally gentle catalyst rather than a solvent for it (Sun et al. 2013).

The CA is one of the most important cellulose derivatives with a wide application in the fields of coating, film, membrane separation, textile, and cigarette industries for its low cost, toughness, gloss, high transparency, and biodegradability. Acetone-soluble CA is industrially more important due to its low toxicity and lower price of acetone. In the process, a small amount of IL [0.1–0.6 molar equivalents of IL per molar of anhydroglucose units (AGU)] was used and it showed an excellent catalytic activity for the conversion of cellulose into CA (Sun et al. 2013). The study anticipates that recovery of WBFs could be efficiently applied on a large scale in an environmentally friendly manner. The extraction yield of acetone-soluble cellulose acetate (CA) was 49.3 %, which corresponded to a conversion of 84.5 % of the cellulose in the original WBFs. Similarly, it was possible to recover as much as 96.2 % of the original poly(ethylene terephthalate).

The FTIR spectra of regenerated PET and pure PET depicted peaks at the wave-numbers of 1714, 1250, 1120, 1046, and 726 cm^{-1} and postulated the fact that no chemical reaction occurred during the regeneration processes of PET; also CA was not present in the regenerated PET. Differential scanning calorimetry (DSC) curves of the CA and recycled CA showed the same Tg of 187 °C and indeed, the pure and the recycled polyester also showed a melting temperature of 250 °C, indicating the regenerated PET and CA were similar in quality. Sankauskaite et al. reported the separation/recycling of the cotton part of the polyester/cotton blended textile (Sankauskaitė et al. 2014). The waste was pre-treated with aqueous solutions of reagents: $MgCl_2$, $Al_2(SO_4)_3$, $MgCl_2$ and $Al_2(SO_4)_3$ mixture, and $MgCl_2$ citric acid mixture at 20, 50, 90, and 130 °C for blended knitting yarn (50 % cotton/50 % polyester) waste. After the pre-treatment, all the samples were dried at 102 °C and heat-treated at different temperatures: 150, 160, and 180 °C. The experimental data showed that the highest degradation rate (95.5 %) of cotton component from 50 % cotton/50 % polyester blended knitting yarn waste was achieved by using the pre-treatment at 20 °C temperature by aqueous solution of 20 g/l $MgCl_2$ and 4 g/l of $Al_2(SO_4)_3$ mixture, followed by heat treatment of the dry samples at 180 °C temperature. Similarly Lv et al. developed a simple process of separating cotton cellulose and nylon 6 from their waste-blended fabrics, as was necessary for recycling (Fangbing et al. 2015). An efficient procedure of dissolution of the fabrics in an ionic liquid 1-allyl-3-methylimidazolium chloride [(AMIM)Cl)] and subsequent filtration-separation has been demonstrated, and the effects of treatment temperature, time, and the waste fabric ratio of the recovery rates were investigated in detail. With increasing temperature, the cotton component gets dissolved more rapidly and dissolving at 120 °C caused serious degradation of the cellulose. An SEM image of the untreated sample showed cotton fibres in the yarn blended with nylon fibres, but after treatment with ([AMIM]Cl) at 90 °C, the cotton fibres were found totally dissolved, with a regenerated film produced on the top of the nylon fibres (Fangbing et al. 2015). The FTIR spectrum of the regenerated cellulose (RC) was similar to that of the virgin cotton fibres, confirming the absence of any other chemical reaction, apart from the breakage of hydrogen bonds during the processes of dissolution and separation.

Keutennius et al. reported a novel technique of recovery of fibres from the nontextile substrates using the principle of static charge (Keutenius et al. 2013). A range of natural and manmade fibres was used on a number of substrates, including weapons, paper, and plastic bags using polystyrene rods that had a static charge. The average recovery rate from all the substrates was 99.1 %. It was found that the presence of humidity reduced the ability of the rods to recover fibre. Different fibres, such as cotton, wool, cashmere, viscose, polyester, nylon, and many others were also recovered. The waste produced in a cotton mill is an important factor in determining the operating cost and product profitability (Halimi et al. 2008). Similar to other studies an attempt was made at recovery of such fibres. In this context, Halimi and associates examined the waste percentage and the good fibre fraction from two cleaning machines and a card. The quality of recovered fibres was discussed and compared to the virgin cotton. The study showed that the generated waste contained about 50 % good fibre. This secondary raw material showed a good cleanability and fibre characteristics, except the fibre mean-length of the waste fibres that was slightly lower than the initial cotton fibres. It was possible to blend such regenerated fibres in a proportion of 15 and 25 % and process without any noticeable hurdle on the rotor machine for production of quality yarn.

In the last six decades, several technological advances have taken place in the textile sector in order to economise the cost of production, improve product quality, and take care of the environmental impact, such as the application of enzymes, natural dyes, digital printing, low material to liquid processing, spray and foam finishing, infrared dyeing and drying, RF drying, ultrasound dyeing and dispersion, and water-free plasma processing. Plasma, a partially ionised gas composed of both positive and negative ions, electrons, neutrals, excited molecules, photons, and UV light, can be used for nanoscale surface engineering of textile substrates, without altering the inherent bulk properties of the material. Plasma technology can be used to improve the aesthetics and functional values of apparel, home, and technical textiles such as improvement in water absorbency, water repellency, oil absorbency, oil repellency, UV protection, antimicrobial, flame retardant, dyeing, desizing, antistatic, adhesion, and antifelting of wool (Samanta et al. 2009, 2010, 2012). Low-temperature plasma, also known as nonthermal plasma with the bulk temperature of 50–250 °C can be used for such surface modification of textiles. Gaiolas et al. for the first time investigated the effect of cold plasma treatment in paper recycling. The surface of a commercial paper was modified using cold plasma in order to increase its hydrophilic character, thus minimising the disintegration time and/or the energy consumption needed to recycle cellulose fibres and to obtain a homogeneous suspension (Gaiolas et al. 2013). Plasma treatment was applied for different time periods of 5, 10, 15, 30, 60, 120, 180, and 300 s and the plasma treatment power and pressure were kept at 200 W and 700 mTorr, respectively. The effect of plasma treatment on the quality of recycling was evaluated measuring the first-order entropy of the sheet formation and the results showed that for similar entropy values, disintegration time in the reference samples was longer than the treated samples. After plasma treatment, the surface shifted from hydrophobic with a water contact angle of 110° to hydrophilic character with water contact angle of 28° (Gaiolas et al. 2013).

3.2 Recycling of Jute Waste and Its Application

India ranks first in the world's production of jute with 2968.5 thousand tonnes of jute, kenaf, and allied fibres. The fibre is extracted by conventional retting of the jute plant stem in store or running water, whereas the plant leaves and stick are considered agro-waste biomass. Ligno-cellulosic jute waste products, such as jute leaves, stick, and caddies generated in a large quantity during the cultivation of jute and industrial process were used as separate materials and in combination with rice straw in 1:1 ratio for the production of the edible mushroom *Pleurotus sajor-caju* production by Basak et al. (1996). In the industrial mechanical processing of jute fibre, jute caddies (i.e., very short fibres) are dropped in a large quantity, almost 4 % as a loom waste. This material is mostly used as fuel for a boiler to generate heat. The large quantity of such lignocellulosic agro-biomass generated during retting and industrial processing were recycled for mushroom cultivation. This is a low-cost, easily available renewable biomass, having the potential for production of edible mushrooms due to its protein supplement nutritional value to solve protein–calorie malnutrition in developing countries. It was interesting to observe that the production efficiency *P. sajor-caju* in the substrate such as jute was much better than the other lignocellulosic biomass such as sugarcane bagasse and paper waste. However, a more or less similar result was found on sorghum stalk and cotton wastes. The average yield of mushroom production was more than 273 g in the substrates such as jute caddies, rice straw-jute stick (1:1), and rice straw-jute caddies (1:1), which is slightly better than pure rice straw (269 g). Production was reasonably lower in the case of jute leaves, either alone or in 1:1 ratio with rice straw. The rapid decomposition of the jute leaves might be the reason for hindering the growth of mushroom mycelia, either pure or in mixture with rice straw. The presence of protein, fat, and other minerals in the *P. sajor-caju* produced on different substrates was also investigated. Table 2 shows the chemical composition of different lignocellulosic biomass.

In another study by the same research group, pineapple leaf agro-waste was utilised for the extraction of fibre, followed by utilisation of residual biomass for vermin-composting (Banik et al. 2011). In a country like India, ~600 thousand tonnes of pineapple leaf fibre can be extracted from the recycled agro-biomass after harvesting the fruit. The extraction of such fibre alone will not be technoeconomically viable to the farming community, as the leaf is not suitable for cattle feed, and the disposal of such leaf in a large quantity is a serious imposition on the environment. Pineapple leaf fibre is a good quality textile-grade commercial fibre generally extracted by the water retting process. The leaf contains only 2.5–3.5 % of fibres, which are covered by a hydrophobic waxy layer. The fibre quality can be compared with the highly cellulosic and lignocellulosic fibres, which fall between either jute and cotton or jute and ramie fibres. Vermin-composting is a simple biotechnological process of composting using certain efficient species of earthworm, and it is faster than common composting methods. It was found that

Table 2 Chemical composition of different lignocellulosic biomass (Basak et al. 1996)

Constituents	Jute biomass			Rice biomass
	Jute leaf	Jute stick	Jute caddies	Rice straw
Ash	8.8	1.3	2.4	10.9
Fat and wax	3.4	1.8	3.1	2.9
Nitrogen	2.4	2.0	1.4	0.6
Lignin	20.9	22.9	14.0	13.9
Pentosan	11.5	24.7	16.2	25.6
A-Cellulose	20.5	40.8	54.2	42.3

pineapple fibre is finer than average-grade jute fibre, without the meshy structure commonly found in jute fibres (Banik et al. 2011). Flexural and torsional rigidity of the fibre is similar to jute and fibre breaking extension doubles that found with jute fibre. The prepared vermin-compost from the leftover leaf biomass residue was found to contain 1.05–1.2 % nitrogen (N), 0.3–0.4 % phosphorus (P), and 0.4–0.5 % potassium (K), indicating that pineapple leaf debris vermin-compost is rich in NPK, essential for crop production.

Powdered activated carbon (PAC) and granular activated carbon (GAC) are commonly used for the treatment of wastewaters or to make water potable, especially by removing low-molecular weight compounds (Phan et al. 2006). The PAC provides faster adsorption velocities, but limits its industrial acceptability due to difficulty in handling. Phan et al. prepared different fibrous activated carbons from jute and coconut fibres as natural precursors by physical and chemical activation with the aim of reusing the industrial wastewater after the treatment. The adsorption properties of the activated carbons were tested towards pollutants representative of the industrial effluents: phenol, the dye Acid Red 27, and Cu^{2+} ions. Physical activation consisted of the thermal treatment of raw fibres at 950 °C in an inert atmosphere, followed by an activation step with CO_2 at the same temperature. In chemical activation, the raw fibres were first impregnated with a phosphoric acid solution and then, heated at 900 °C in an inert atmosphere. The characteristics of the fibrous-activated carbons were determined in terms of elemental analysis, pore characteristics, SEM micrograph of porous surface, and surface chemistry. Chemical activation by phosphoric acid seems to be the most suitable process to produce fibrous-activated carbon from the cellulosic fibre (Phan et al. 2006). There was a sharp increase in BET specific surface area after carbonisation of both fibres (from <2 $m^2\ g^{-1}$ to 500–650 $m^2\ g^{-1}$), which may be explained by the oxygen contained in the raw fibre (44.1 and 45.9 wt % for jute and coconut fibres, respectively). The specific surface areas obtained after the activation steps in jute and coconut fibre were similar to the commercially available activated carbons, and in the range of 900–1300 $m^2\ g^{-1}$.

3.3 Recycling (Utilisation) of Leather Fibre Waste

Similar to textile-grade fibre waste, nonutilisation of finished and used leather wastes also causes environmental pollution. Conversion of these solid wastes into energy- and resource-efficient products proves to be challenging. Although they contribute significantly towards economic growth, pressure from the pollution control authorities and increased environmental awareness in the masses has forced them to adopt various sustainable strategies including cleaner production and processing methods by using ecofriendly enzymes and waste minimisation technologies. In this regard, a novel attempt was made to utilise the waste leather fibre along with natural and synthetic fibres in a suitable blend proportion for textile application, which has been found to be energy efficient, ecofriendly, and cost effective. This is because in India about 20–30 % of leather is discarded as waste during footwear and leather goods production. An earlier study has shown that solid and liquid leather tanning wastes can be efficiently utilised as a fertiliser and soil agents for acidity correction (Nogueira et al. 2011). The alternative technological solution to the problem of waste shavings utilisation is the production of secondary or artificial leathers designed for footwear, fancy goods, or nonwoven fabrics as substrates for leatherlike materials. Leather fibres (LFs) produced from finished leather wastes are a relatively new and novel material that can be used in the production of textile materials due to their advantages of light weight, low cost, and abundant availability. Similar to the commercially available blended textiles, such as cotton–polyester, cotton–acrylic, cotton–nylon, kenaf–cotton, polyester–viscose, and wool–polyester, an attempt was made to explore the possibility of development of leather–cotton and leather–polyester blended textiles (Senthil et al. 2014).

Leather fibres (LFs) were extracted from these solid wastes and mixed with cotton (CF) and polyester fibres (PF). The fibre size ranged between 1.0 and 2.0 cm in length and 0.3 and 0.7 mm in diameter. These products were ultimately further processed and finally converted into leather blended yarn (LBYs) with the blend proportion of LF:CF/PF (50:50) and fabric (LBFs) as shown in Fig. 1. It was found

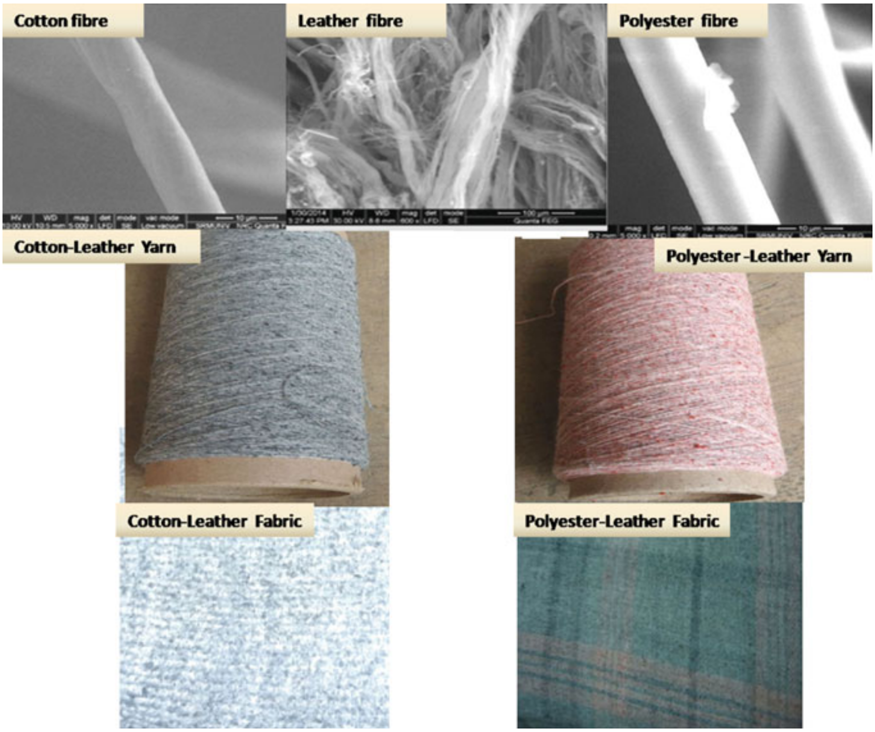

Fig. 1 Leather, cotton, and polyester fibres, yarn, and fabric from blended fibres (Senthil et al. 2014)

that the fabric made of LF:CF and LF:PF were of good quality with a smooth finish. It was also observed that collagen is the major constituent of LF, whereas cellulose is the major constituent of cotton fibres. Tensile strength (MPa) of leather fibre is slightly more than cotton, but lower than the polyester fibres.

4 Recovery of Fibrous Material from Textile and Agro-Biomass and Its Application in Composite

4.1 Application of Biodegradable Fibrous Waste in Composite

Recycling of any waste, as such, is a worldwide phenomenon. Textile fabric waste was collected from various sources and these waste materials were garneted, so as to produce loose fibrous material. Subsequently, this fibrous material was converted into a nonwoven fibrous mat and also twisted for making yarn to be used in manufacturing 3D woven preforms for use in composites (Mishra et al. 2014). In the case of the nonwoven preforms, the webs were produced by combining polypropylene (PP) with cotton in different proportions. Composites of various specifications were produced and the different physical and mechanical properties were determined. The results were compared with similar pure cotton fibre-based products. It was found that as the percentage of PP fibre was increased in the web, the mechanical performance of the composite material also increased. It is interesting to observe that 3D woven fabric reinforced composite produced using recycled fibre yarn and virgin cotton open-end yarn did not exhibit any significant difference in the mechanical and thermal behaviour of composites. The glass transition temperature (Tg) of various samples confirmed that the textile waste material could be safely used as reinforcing material in composite manufacturing, adding value to them, and addressing environmental pollution problems. In another study, three possible routes for use of discarded 50/50 cotton/polyester bed linen as a raw material for heat-induced compression moulded composites were evaluated (Mishra et al. 2014). The fabric (cotton along with PET) acted as the reinforcement in two different composites that gave better mechanical strength to the composites than the reported work of the other group. Further investigation of textile-based composites with enhanced properties may lead to encouragement for the use of recycled textiles for composite preparation and their suitable end applications.

Leaf fibres are the fibres that run lengthwise through the leaves of most monocotyledonous plants, such as pineapple and banana (Leao et al. 2010). Pineapple (*Ananas comosus*) and banana (*Musa indica*) are the two emerging fibres with high potential to be used for composite materials due to their high strength values. As per a rough estimation, over 150,000 ha of pineapple and over 100,000 ha of banana plantations are cultivated in Brazil for fruit production and produce enormous quantities of agricultural biomass as a waste material that is also the single largest source of cellulosic fibres, with almost no cost. The potential consumers for these fibres are pulp and paper, chemical feedstock, textiles, and composites for the automotive, furniture, and civil construction industries (Leao et al. 2010). Composite materials have been developed by the combination of native fibres with different plastics, such as polyvinylchloride (PVC), polypropylene (PP), and polyethylene (PE) for widening their application range in order to reduce the demand for tropical hardwood used for housing, furniture, pellets, and plastics. Recently, green composites have been fabricated using pineapple leaf fibre and soy-based plastic (Liu et al. 2005). In another interesting study on biocomposites, the effect of alkali treatment on the thermal properties of Indian grass fibre reinforced soy protein by the same research group has also been reported (Gao and Cranston 2008). Pineapple fibre has also proven to be a potential reinforcement ingredient with natural rubber (Jou et al. 2007). In addition, the whole of the banana plant has become important in today's context for different end uses, including fibres, sap, food, fruits, mordant, functional material, fertiliser, and for making paper and pulp. Banana plants generate rachis, which is a part of the plant, where the fruits are linked to the pseudostem and the fibre leaves that also come from the pseudostem. Both materials have industrial applications. For example, in DaimlerChrysler's composites the spare-tyre carrier on the Mercedes-Benz A-Class mini car, banana fibre has replaced glass fibre as the reinforcing element in the polypropylene matrix (Leao et al. 2010). Leao et al. reported the utilisation of banana and pineapple leaf fibres (PLAF) to make nonwoven mats (needle-punched) for the production of a thermoplastic composite using polypropylene as a matrix by the extrusion process. It was observed that with increasing PLAF content from 50 to 80 %, the tensile strength was found to reduce from 42 MPa to 19 MPa. A similar trend was also found in the case of flexural strength (MPa) and flexural modulus (GPa). Indeed, the use of natural materials, more specifically the natural fibres, is becoming more common globally, so as to reduce the quantum of synthetic fibre consumption. In Brazil, for example, car manufacturers such as Volkswagen, Ford, Honda, and General Motors are already using natural fibres in car seats, dashboard coverings, roofs, and trunk lids (Alves et al. 2010). Alves et al. analyse the advantages of replacing glass fibres by natural fibre such as jute to produce structural frontal bonnets for a type of off-road vehicle 'buggy' (Luz et al. 2010). In this study, it was found that the natural fibre reinforced bonnet improved the environmental performance of the whole vehicle, mainly because of its lighter weight compared to the bonnet made from glass fibres. Similar to the application of cellulosic and lignocellulosic natural fibres for making a fibre-reinforced composite/green composite/biocomposite, Kimura et al. reported the application of industrial waste-protein fibre, such as silk for the development of composite (Kimura et al. 2014). The cut waste of silk textile was pre-treated in an opener and on a carding machine, and mixed with polypropylene (PP) fibre. The sliver-type silk/PP mixture was fed into the injection-moulding machine directly and silk fibre reinforced PP composites were produced. The result attested that the silk waste was a good reinforcing material for composite application.

Agro-based biofibres have the structural composition and physical–mechanical properties that make them suitable for application in composite, textile, and pulp and paper industries. Biofibres can also be used to produce fuel, chemicals, enzymes, and food (Reddy and Yang 2005). By-products produced from the cultivation of corn, wheat, rice, sorghum, barley, sugarcane, pineapple, banana, and coconut are the major sources of agro-based biofibres. It has been reported that the majority of the agricultural biomass-based fibres, such as cornhusk, PALF, coir, bagasse, banana, rice straw, and such have a fibre cell length of 0.4–9 mm, and width of 4–450 μm depending on their origin. They possess good tensile strength and breaking elongation percentage. Among the various lignocellulosic biomasses, it is worth mentioning that corn stover, PALF, coir, and banana leaves are suitable for textile and composite applications. On the other hand, rice, wheat straw, and also corn stover are suitable for pulp and paper (Reddy and Yang 2005).

The performance of a sound-absorbing material is governed by both acoustic and nonacoustic properties. Plant-based biofibres have good potential in such applications, as they are fully natural, biodegradable, and widely available compared to glass fibre, synthetic fibres, foams, and mineral fibres such as rock wool. They have been widely explored as reinforcement in the preparation of different thermosetting and thermoplastic resin composites in the form of fibres, chips, and dusts due to their relative cheapness and recyclability. It has been reported in the literature that like composite, natural fibres are also the preferred materials for sound absorption/insulation (Chen et al. 2010; Yuhazri et al. 2010; Ersoy and Kucuk 2009). The final properties of such materials strongly depend on the blend proportion, formation methods, and ingredients. An altogether different natural fibre, luffa cylindrical fibres from its fruits, stems, or bark were used in the production of composites and filters. In an another study by Karademir et al. a number of thin biocomposites were prepared by wet lying methods from the old corrugated boards in blend with luffa fibres (LF) and yarn waste (YW) with 15 and 30 % content (Karademir et al. 2011). Mechanical, optical, printability, and sound absorption properties of manufactured biocomposites were determined in detail. Sound absorption values were found to be improved by both LF and YW parallel with the increase in air permeability. Measurements on the foam, the glued foam, and the foam with samples stuck on the surface showed that the glue on the backing foam slightly increased the sound absorption coefficient between 500 to 1500 Hz frequencies. It was found that the addition of both luffa fibre and yarn waste improved the sound absorption value of control sheets. The sample with the addition of 30 % luffa fibre exhibited the highest increase in sound absorption coefficient between 3400 to 4750 Hz. The increase in sound wave absorption in the fibrous mat was possibly due to the porous structures of sheets that provided a barrier for sound wave propagation.

With consumer-enhanced awareness of ecoproducts and organic materials, there has been an increasing demand for sustainable and environmentally friendly materials. In recent years, considerable attention has been given to products produced from nonfood crops for use in various industries, preferably in the textile industry (Islam et al. 2013). Their inherent properties, such as biocompatibility, biodegradability, and nontoxicity, in addition to functional properties such as insect repellent, deodorising, flame retardant, UV protection, and antimicrobial activity are gaining attention across the globe for producing fashionable textiles with functional attributes. Isla et al. highlighted the application of important plant-based products, such as fibres, polysaccharides, dyes and pigments, polyphenols, and oils in textile processing and finishing in an environmentally friendly manner.

4.2 Application of Biodegradable Nonfibrous Waste in Composite and Agriculture

Due to the increasing awareness of the environment and sustainability of process and product in the last decade, significant progress has been made in the field of green or biocomposites in the development of wood and plastic replacing alternate materials using waste agricultural residues, such as the stalks of most cereal crops, rice husks, and coconut fibres (Prithivirajan et al. 2015). These abundantly available agro-wastes from renewable sources are low cost and lighter in weight than most widely used glass fibres, in addition to being economical, less energy intensive with low CO_2 emission, and fully biodegradable compared to their counterpart thermoplastic polymer composites with glass or inorganic fibre reinforcing material. It has been reported that the effective utilisation of corn straw, soy stalk, wheat straw, and other fibres with a biodegradable resin enhances the strength of such agricultural residues. Prithivirajan et al. reported the development of coir pith-epoxy reinforced composite and rice husk hybrid particulates with 10–50 % concentration to produce value-added products due to the attractive physical and mechanical properties of bioparticulates. Waste agricultural residue particulates, namely coir pith and rice husk, were collected from the coir mounds and rice industry, respectively. Coir pith was then sun dried for 2 days and then larger particulates were removed by hand sorting followed by separation using 50-μm sieves. The rice husk of 50-μm size was dried using an air dryer-oven at 100 °C for 2 h. The composite samples were prepared in (300 × 300 × 3) mm^3 mould. The coir pith reinforced composite showed a lower tensile strength value compared to the unreinforced epoxy with a tensile strength of 10 MPa. On the other hand, the tensile strength of all the rice husk composite samples showed a profound increase in tensile strength, irrespective of the loading of the reinforcing material. It was found to be as high as 18 MPa with 30 % loading. The low value of the tensile strength for coir pith–epoxy composites were possibly due to weaker bonding and low compatibility between the particulate and the polymer matrix. On the other hand, the higher value in the rice husk composites was attributed to the crystalline structure of the rice husk that enriches the load-carrying capacity of the composites. The coir–pith–rice husk epoxy also showed encouraging results. The flexural strength also showed a similar trend, where the maximum strength was observed with 40 % loading. Luz et al. substituted sugarcane bagasse fibres for talc as the reinforcing agent in polypropylene composites for making automotive components (Luz et al. 2010). The beneficial aspect of the sugarcane composite is that it absorbs carbon during its cultivation that reduces global warming, has cleaner production processes, lowers the product weight, and recovers bagasse-PP economically (50 % incineration plus 50 % recycling scenario) at the end of life.

For agricultural and nursery transplantation of plants, most of the containers used are made of petroleum-based material, such as polystyrene, polyethylene, and polypropylene due to their superior advantages in mechanical properties, chemical and microbial degradation resistance, durability, light weight, and economy (Schettinia et al. 2013). However, after the transplantation, they are found to contaminate soil, organic matter, and agro-chemicals. The cost of post-use plastic pots in their collection, disposition, and recycling is also higher. The disposals pose difficulty in terms of biodegradation and also cause serious environmental pollution due to their uncontrolled combustion that subsequently emits toxic gases. In this regard, there is a need for development of suitable alternative biodegradable pots, while addressing some or all the above issues. Once buried, the biodegradable pots are subjected to follow the biodegradation pathway process, from forming them into biomass and inorganic products, such as carbon dioxide and water. Biodegradable pots are already available worldwide by the William Sinclair Horticulture Ltd, Fertil SA, and Jiffy Products International AS, that are made of plant fibre, rice, starch, grasses, and vegetable oils, with a service period ranging from a few months to two years. In spite of several merits of the biodegradable pots, they suffer from the lack of adequate mechanical performance hindering the roots from passing throughout, adding odd-smell emissions from them, and cost effectiveness in comparison to the plastic pots. The cost of such pots has been partially reduced by using biocomposites made of a polysaccharide biopolymer matrix along with natural fillers and fibres of wastes of agro-food, and textile-processing wastes in the dispersing or reinforcing phase. Similarly, wastes and by-products of agro-food, paper, and textile industries, such as tomato peels and seeds, and hemp were utilised to produce biodegradable pots for plant transplantation in agriculture. This ensures value addition to the waste products while ensuring minimal usage of petroleum-based nonbiodegradable plastic pots for plant nursery application. Important properties such as mechanical, water vapour permeability, water uptake, and morphological analysis were performed in laboratory conditions on polysaccharide films and biocomposites to understand the chemical–physical correlations between resin, ionic cross-linking agent, reinforcing fibres, and water (Schettinia et al. 2013). The pots were prepared from short flexible tomato seeds and peels, and longer, stiffer, rigid hemp fibres in the presence of sodium alginate as a matrix. Tomato fibres were on an average 80 μm long, 10 μm wide, and 10 μm thick. Both sets of the uncross-linked and cross-linked samples showed a general increase of the mechanical parameters when hemp fibres were added to the tomato peels. It was observed that with increasing hemp fibre content, the tensile strength increased. But, if the samples were cross-linked the strength was found to decrease. The increase in strength was due to the presence of hemp fibre compared to nonfibrous filler, and the reduction in strength in the cross-linked polymer was due to the active engagement of carboxylated and hydroxyl groups of alginate with calcium ions. There was a strong physical interaction between sodium alginate and calcium ions in the development of a three-dimensional network. In biodegradability tests, it was observed that in the initial 60 days of testing in soil, the 100 % tomato-fibre cross-linked samples degraded faster (by 20 %) than the cross-linked sample (15 %) with 70 % tomato fibre and 30 % hemp fibre. The first sample consisted of 100 % tomato fibres that were short and contained pectin, starch, and cellulose, which were easily available to the microbial population and provided a large surface. In contrast, hemp fibres are microcrystalline longer cellulosic fibres, and the hydrophilic macromolecular chains are not easily susceptible to microorganism attack. In order to assess the agronomic performance of the novel biodegradable pots in seedling and transplanting activity, the pots were tested in field conditions during 2009 at the experimental farm of the University of Bari, Italy. Young plants were transplanted in the field and it was inferred that the biodegradable containers had enhanced root development. The plants were growing, avoiding transplant shock, and root deformation. After the requisite time, the pot was found to degrade completely into the soil within 2 weeks.

5 Microcrystalline, Nano, and Bacterial Cellulose from Fibrous Biomass

5.1 Synthesis of Nanocellulose from Agro-Biomass and Nanocomposite

Cellulose is one of the most important, abundant, renewable, and biodegradable natural polymers, and exists in the several plant biomasses, such as wood, cotton, hemp, straws, sugarcane bagasse, and other plant-based materials. It has a wide range of application in the form of fibre, paper, films, and polymers. The utilisation of this natural biomass for processing of novel material applications has recently attracted global interest due to its ecological and renewable characteristics (Li et al. 2012). What is important with nanocellulose are its superior functionalities, such as an extremely large active surface area. In the literature, a number of approaches have been reported for the production of highly purified nanocellulose from the various cellulosic to lignocellulosic biomasses, such as cotton linter, cotton fibre, sugarcane bagasses, pineapple leaf, soy hulls, and corncob (Li et al. 2012). The methods included steam explosion treatment, acid or alkaline hydrolysis, enzyme-assisted hydrolysis, microbial process, and high pressure homogenisation, as well as a combination of two or several of the aforementioned methods. Corncob is an agro-industrial waste available in large quantities in several countries, including Brazil, which deserves to be better and/or properly utilised (Silverio et al. 2013). Maize is an important agricultural product and Brazil is the third largest corn producer, accounting for 7 % of the world production. Although ears of maize are used primarily as food and in the generation of a wide variety of important industrial products, such as ethanol, starch, vegetable oil, and animal feed, however, some parts of the plant do not have any direct use, and thus remained underutilised. The corncob, that is, the central part of the ear of maize in which the grains are stuck, is normally considered waste after the grains are removed. Corncob is mainly utilised for animal feed, and for the production of fertiliser (Silverio et al. 2013). However, in industry it is used for the production of furfural and other chemicals, such as xylose, due to its hardness property. It has also been reported to be used as abrasives and polishers in cleaning products, and in the manufacture of bricks and pottery. For every 100 kg of ears of maize, about 18 kg corncob are generated. The production of corncob in Brazil is estimated to be 10.4 million tonnes.

Intensive study has been conducted on cellulose, microcrystalline cellulose, and nanocellulose to be used as model filler in various polymer matrixes. Nanocellulose-based nanocomposites generally exhibit a significant improvement in thermal, mechanical, and barrier properties compared to virgin polymer or conventional composites. Cellulose nanocrystals are needle-shaped particles, with at least one dimension equal to or less than 100 nm and are found to be highly crystalline (Silverio et al. 2013). In addition to the conventional industrial application of linter as discussed earlier, it can also be used as a viable high-value, low-volume product, once converted into cellulose nanocrystals. In general, nanocrystals of cellulose with diameters ranging from 2 to 20 nm and length ranging from 100 nm to 2.1 μm (more precisely $<$100 nm for defect-free crystal) are referred to in different nomenclatures in the literature, such as cellulose nanowhiskers, cellulose whiskers, whiskers, nanowhiskers, nanofibrils, nanofibres, cellulose crystallites, cellulose crystals, cellulose nanocrystals, nanocrystalline cellulose, cellulose monocrystals, and cellulose microcrystals that are possible to produce from cotton linters as well as from many of the other natural fibres or agro-biomass (Morais et al. 2013; Cherian et al. 2011; Neto et al. 2013). Over the years cellulose fibre or microcrystalline cellulose or nanocellulose has become an alternative choice as a reinforcing material for nanocomposite application due to its unique advantages of superior physical properties and environmental benefits, such as large specific surface area (estimated to be several hundreds of $m^2\ g^{-1}$), very high modulus of elasticity (≈150 GPa), high aspect ratio, ensuring high strength with low filler loading, low density (≈1.56 g/cm^3), nonabrasive nature, nontoxic, biocompatibility, and biodegradability produced from renewable natural agro-biomasses at a lower cost (Neto et al. 2013). It allows the production of composite films with excellent visible light transmittance, with the ease of surface engineering by carrying out suitable grafting reaction with side –OH groups of cellulose.

Biocomposites or green composite is the future potential market for such kinds of product that would unlock the potential of those underutilised renewable materials and will provide a nonfood-based market for the agricultural industry (Cherian et al. 2011). In this context, the use of biomass residues as feedstock for the production of energy and materials has been the interest of academic and industrial research (Santos et al. 2013). The utilisation of these crop residues in industrial processes for the generation of high value-added products could be an additional source of revenue generation for the farmers, and will also help in agro-industry diversification by providing a nonfood-based market for the various agro-wastes. Nanocrystals of cellulose can be used as filler in composite and packaging applications because of their inherent mechanical, stiffness, and low-gas permeability properties. They can also be used as reinforcements for adhesives, components of electronic devices, biomaterials, foams, aerogels, and textiles (Morais et al. 2013). Cotton fibre is a traditional source of cellulose nanostructures, but its chemical compositions are influenced by genotype and the environment where it was produced. Linter is one of the important by-products of the textile industry. In the cotton ginning process, after the separation of good quality textile grade fibre, the linters remain attached to the cotton seed. Linters due to their shorter fibre length cannot be used in the manufacture of apparel textiles and clothing, hence, they are mostly used for the production of absorbent cotton, special papers, cellulose nitrate, and acetate. The fuzzy seeds need to be subjected to an additional process that will mechanically remove the linter. The amount of linter available worldwide is around 2.5 million metric tonnes, considering the production of about 42 million metric tonnes of cotton lint in 2010 (Morais et al. 2013). Sometimes the linter is not extracted, but kept with the seed (for oil extraction) or chemically dissolved (for planting the seed). Generally, cellulose-based biofibres, namely pineapple leaf fibre, banana, cotton, flax, hemp, jute, coconut, and sisal, and also wood fibres are used as a reinforcing material in the plastics due to their relatively high strength, high stiffness, and low density.

Morais et al. studied the production of cellulose nanocrystal from cotton linters by an acid hydrolysis technique. The cotton linter was chosen for the production of nanowhiskers because of its availability in large quantity from textile industrial wastes and its high content of cellulose of 81 % compared to other natural fibrous biomass, such as sisal (67–78 %), banana (54–64.4 %), sugarcane bagasse (44.9–45 %), bamboo (41.8–54.0 %), pineapple leaf fibres (81.2 %), and coconut husk (32.5–45.9 %) (Morais et al. 2013; Cherian et al. 2011). The diffractograms of linter and nanocellulose had peaks related to the crystallographic plans of cellulose with intensity at 17.4, 19.2, and 26.5° as indicated by the International Centre for Diffraction Data (ICDD). The higher crystallinity of about 90.4 % was noted in the case of nanocellulose as confirmed by the crystallinity index (ICr) compared to only 64.4 % in the cotton linter. Nanocellulose exhibited better hydrophilic property in terms of measurement of contact angle compared to raw linters. Cherian et al. studied the production of nanocellulose for medical implants from the pineapple leaf fibre (PALF), an important natural fibre with inherent high specific strength and stiffness. PALF is of fine quality, and its structure without mesh can be extracted into nanofibres thinner than fibres produced from bacterial cellulose (BC). Similar to other natural fibres, it is also very much hygroscopic, relatively inexpensive, and abundantly available. The well-known interfacial adhesion strength problem associated with natural fibre, fibrillated cellulosic fibre, nanocellulose, or wood polymer as reinforcement in composites with synthetic matrix are due to their hydrophilic characteristic, whereas the matrices are hydrophobic in nature. The problem was possible to overcome by use of a hydrophilic polyurethane polymer matrix. The nanofibril nonwoven mat was prepared by filtering the water–nanocellulose slurry and polyurethane (PU) by the solvent casting method. Finally, the nanocomposite was prepared by the film-stacking method with a nanocellulose percentage loading of 2 [PU-NC(2 %)], 5 [PU-NC(5 %)], and 10 [PU-NC(10 %)] at an optimised condition of 175 °C temperature, 10,000 kPa pressure and time of 0.5 to 1 min. The particle size was estimated by atomic force microscopy (AFM) in the range of 5–15 nm. It was interesting to observe under the environmental scanning electron microscope (ESEM) that cellulose nanofibrils are well dispersed in the polyurethane matrix. Absence of any large aggregates ensures a homogeneous distribution of the nanofibres in the PU matrix implying good adhesion between fillers and matrix, hydrogen bonding between the filler to filler and filler to matrix. The nanocellulose characterised in X-ray diffraction (XRD) spectra was similar to Cellulose I due to the presence of peak at 22.7° that is similar to Cellulose I in the original material. With the addition of 2 % nanocellulose, the tensile strength was found to increase to 28.2 MPa from 17.5 MPa in the pure PU sample. It further increased linearly to 51.3 MPa (almost 300 %) in the 10 % loaded sample. Application of nanocomposites in medical uses such as in prosthetic heart valve design and techniques for their implantation has improved the survival time and life for the patients. In an ongoing effort to develop more durable and compatible heart valve prostheses, researchers have used a variety of techniques to determine the suitability of a given valve material for a given implant application, preferably known as 'biocompatibility'. PALF-derived nanocellulose embedded polyurethane has been utilised in an attractive and readily available range of materials for the fabrication of vascular prostheses. The produced nanocellulose and its composites confirmed them as very versatile material having the wide range of medical applications, including cardiovascular implants, scaffolds for tissue engineering, repair of articular cartilage, vascular grafts, urethral catheters, mammary prostheses, penile prostheses, adhesion barriers, and artificial skin. The developed material can also be utilised for construction of nonlatex condoms, breathable wound dressings, surgical gloves, surgical gowns or drapes, medical bags, organ retrieval bags, and medical disposables. In a similar line of work, Santo et al. utilised pineapple leaf in the production of cellulose nanocrystals (Santos et al. 2013). Pineapple is one of the most popular tropical fruits in the world and their crop occupies a prominent position in the Brazilian agricultural sector. Brazil is one of the main producers of the crop with approximately 10.9 % of the world share of production. Currently, the main focus of the pineapple industry is the fruits and related foodstuffs, hence, the other parts of the plant, including stems, roots, and especially leaves, are considered agricultural residues. The post-harvest residue comprises mainly pineapple leaves, which are mostly burned in order to eliminate fungi and other parasites and composted or just crammed to rot. This is mainly due to the lack of adequate techno–economic solution of such left-over biomass as well as the ignorance of the farmers about the existence of commercial uses for leaves. The production of CN from this underutilised agro-waste has the commercial potential that can add value to pineapple cultivation, generate extra income for farmers, and also help in agribusiness diversification. In addition, the reuse of these residues allows a significant reduction in both the volume of waste accumulated in the environment and in the extraction of raw materials. Among the several methods for preparing nanocellulose (CN), acid hydrolysis is the most well-known and commonly practiced. In a study by the Santo et al. nanocellulose was prepared by sulphuric acid (H_2SO_4) that broke the disordered and amorphous parts of the cellulose, releasing the single well-defined crystals. Thus, this process is based on the quicker hydrolysis kinetics presented by the amorphous regions, as compared to crystalline ones (Santos et al. 2013). The X-ray diffraction patterns of the untreated and the treated pineapple fibres from the produced nanoparticles at different times showed a typical diffractogram of semi-crystalline materials with an amorphous broad hump and crystalline peaks, similar to Cellulose I, as confirmed by the presence of peaks at 2ϕ value of 15° (plane 1 0 1), 17° (plan 1 0 $\bar{1}$), 21° (0 2 1), 23° (plane 0 0 2), and 34° (0 0 4). The crystallinity was found to be 69–73 % in the different samples. Under AFM, the nanoparticles were found to be needle-shaped, 160–300 nm in length, and 4 nm in diameter. Similar to the production of nanocellulose from the cotton linters and pineapple leaf fibres, soy hulls, an agro-industrial residue available in huge quantities throughout the world, were also used for the synthesis of cellulose nanocrystals instead of their conventional use as cattle feed. Neto et al. reported the cellulose nanocrystal production by acid hydrolysis of soy hulls at 40 °C for 30 or 40 min using 64 % H_2SO_4 (Neto et al. 2013). From the FTIR spectra, the observed peak at 1742 cm^{-1} in the spectrum of soy hulls was attributed to the acetyl and uronic ester groups of hemicellulose or the ester linkage of carboxylic group of ferulic and p-coumaric acids of lignin and/or hemicelluloses. This peak was found to decrease in the treated soy hulls due to the significant removal of hemicelluloses and lignin, and finally, almost disappear in the spectra of nanocellulose, because of acid extraction and removal of such materials. Similarly, the broad peak at 1520 cm^{-1} in the spectra of soy hull and the treated soy hulls confirmed the presence of lignin, attributed to the C=C vibration. This peak disappeared in the nanocrystal, which is also an additional indication of removal of corresponding groups from lignin. All these samples under XRD showed a pattern of semi-crystalline materials with crystallinity index (CrI) of 64–73 % in the different samples, as determined by the Segal method (Neto et al. 2013). All the diffractogram patterns showed the mixture of Cellulose I and II, with predominance of type I cellulose, as indicated by the presence of peaks at 2ϕ = 15° (plane 1 0 1), 17°(plan 1 0 $\bar{1}$) , 21° (plane 0 2 1), 23° (plane 0 0 2), and 34° (plane 0 0 4), although the diffraction patterns of nanocrystal displayed a mixture of polymorphs of Cellulose I and Cellulose II. The presence of cellulose type II could be identified by the peaks at 2ϕ= 12° (plane 1 0 1), 20° (plan 1 0 $\bar{1}$) , and 22° (plane 0 0 2). The needle-like nanocrystals were detected in the transmission electron microscope, with particle sizes of 94–160 nm in length and around 4 nm in diameter.

Cherian et al. reported the production of nanocellulose from the sugarcane bagasse, an agro-waste biomass by the high-pressure homogenisation technique coupled with an ionic liquid pre-treatment (Li et al. 2012). In recent years, room-temperature ionic liquids (ILs) have received much attention because of their excellent dissolution ability of cellulose. It is reported that the $[Bmim]^+$ cations of 1-butyl-3-methylimidazolium chloride ([Bmim]Cl) in ILs can attack the oxygen atoms of H–O–H bonds, and Cl^-associated with the hydroxyl proton of H–O–H bonds. These two interactions can destroy the strong intra- and intercellular hydrogen bonding network existing in the cellulose chains, resulting in the dissolution of cellulose. Therefore, it was considered to be an appropriate homogeneous medium for cellulose because of its nonvolatility, thermal stability, and recyclability. FTIR spectra of the original cellulose, IL-treated cellulose, and nanocellulose showed similar peak position, and the peaks of the OH-stretching and CH-stretching at approximately 3400 and 2800 cm^{-1}. Other peaks, such as at 1371 and 897 cm^{-1}were attributed to the O–H bending vibration and C–H deformation vibration of cellulose. Unlike the other method of nanocellulose preparation, this method yielded circular shape nanoparticles with 10–20 nm diameters as observed under TEM. Similarly, original cellulose showed a typical feature of Cellulose I with a wide peak position between 22.5 and 18°. However, after dissolving in ionic liquid and subjecting them to high-pressure homogenisation, both regenerated celluloses depicted with typical Cellulose II structural peaks at 12, 20, and 22°. However, the crystallinity index of nanocellulose was seemed to slightly lower by 36 %, as measured by Segal's empirical method.

Silverio el al. reported the production of nanocellulose from the corncob biomass, an industrial waste material by an acid hydrolysis technique (Silverio et al. 2013). From the FTIR analysis, the band in the spectrum near 1736 cm^{-1} was mainly due to C=O stretching vibration of the carbonyl and acetyl groups in the xylan component of hemicelluloses and in the lignin, and the band near to 1250 cm^{-1} corresponds to the axial asymmetric strain of =C–O–C, which is commonly observed in ether, ester, and phenol groups. They almost disappeared in the spectra of nanocellulose due to elimination of hemicelluloses and lignin. The crystallinity index was measured to be 78–83.7 % of the different CN samples. XRD diffraction patterns of the raw material, treated material, and nanocellulose showed typical features of a semi-crystalline material with an amorphous broad hump and crystalline peaks and with predominance type I cellulose. The NC was found to be needle-shaped. The nanocomposite was prepared with 1 % (w/v) of polyvinyl alcohol with NC by the casting method. The weight of NC (synthesis time 60 min): PVA was kept at 3:97, 6:94, and 9:91, respectively. It was observed that compared to control PVA film, all the NC-treated samples showed much higher tensile strength (MPa). There was 49.5, 95.6, and 140.2 % increase in tensile strength in 3, 6, and 9 % NC loaded samples, respectively.

Coconut fibre is a lignocellulosic material, characterised by its high toughness and durability due to high lignin content compared to other natural fibres such as jute, flax, and ramie (Rosa et al. 2010). Similar to cellulose and hemicelluloses, lignin is a major component of plant materials and the most abundant form of aromatic carbon in the biosphere. Recently research has reported a positive effect on thermal stability and on mechanical properties of blends and composites with lignin. In addition to polymer composites, lignin can play an important role as dispersant, improving the dispersion of cellulose whiskers. Rosa et al. synthesised nanowhiskers from coconut husk fibre by an acid hydrolysis technique and the average particle size measured by different techniques was estimated to be in the range of 177 ± 80 to 218 ± 99 nm with diameter 5.5–6.6 nm. X-ray diffraction patterns of cellulose nanowhiskers were compared with treated and untreated coconut fibres, commercial cellulose, and Kraft lignin. As expected, in the untreated coconut fibres a large amorphous portion is present due to their high lignin content (37 % lignin). Treated and untreated coconut fibres exhibited three main reflection peaks at $2\phi = 15.6$, 22.7, and 34.6° relative to the cellulose crystalline structure. After removal of lignin in bleaching treatment, narrower and more intense crystalline peaks were observed. Different conditions resulted in different degrees of crystallinity and the peaks at 16.5 and 22.7° were attributed to the typical pattern of Cellulose I. Unlike production of nanocellulose by mainly acid hydrolysis, Vigneshwaran et al. reported an alternative method of preparation of cellulose nanowhiskers by controlled microbial hydrolysis (Satyamurthy et al. 2011). The cellulolytic fungus *Trichoderma reesei* was used to prepare cellulose nanowhiskers (CNW) from microcrystalline cellulose (MCC) and the data were compared to the acid hydrolysis synthesis. The zeta potential of fungal hydrolyzed CNW was similar to that of native MCC, whereas the CNW prepared by acid hydrolysis had five times higher zeta potential due to its surface sulfation. Preparation of CNW by a concentrated sulfuric acid process is an energy-intensive and environmentally hazardous process in addition to sulfated surface modification. On the other hand, fungal hydrolysis resulted in CNW without any surface modification and such nanostructures showed promising applications in ecofriendly composites and pharmaceuticals. It was seen that after one day, the majority of the particles were >150 nm, and after 3 days it showed in the range approximately 100–150 nm, and after 5 days of synthesis they were ≈25–40 nm. Particle size was measured to be 36.5 ± 1.9 nm by DLS particle size analyser, and length 120 ± 36 nm and thickness of 41 ± 7.6 nm by AFM technique. Some AFM and TEM microscopic images of the nanocellulose are shown in Figs. 2 and 3.

Haafiz et al. reported the production of cellulose nanowhiskers from the microcrystalline cellulose (MCC) obtained from oil palm biomass (Haafiz et al. 2014). The FTIR with spectroscopy absorption around 3400, 2900, 1430, 1370, and 890 cm^{-1} wavenumbers, were exhibited in all the spectra associated with the characteristics of native Cellulose I. The TEM micrograph showed that MCC might have agglomerated to form large MCC particles through the micron range, whereas after the acid treatment, individual rodlike whiskers (crystals) were obtained. The length of the CN was estimated to be more than 100 nm, with diameter 10–20 nm. The XRD patterns were the same for both MCC and CN samples, typically, Cellulose I with no traces of Cellulose II. In essence, this indicates that the MCC structure was not significantly changed by the chemical swelling treatment and most of the crystalline regions were preserved (Haafiz et al. 2014). A new peak also appeared at 21° for MCC after acid hydrolysis, suggesting the coexistence of Cellulose I and Cellulose II allomorphs. A similar finding was reported in the literature during the isolation of nanocellulose from waste sugarcane baggase (Mandal and Chakrabarty 2011). Pineapple leaf fibres can also be utilised for the

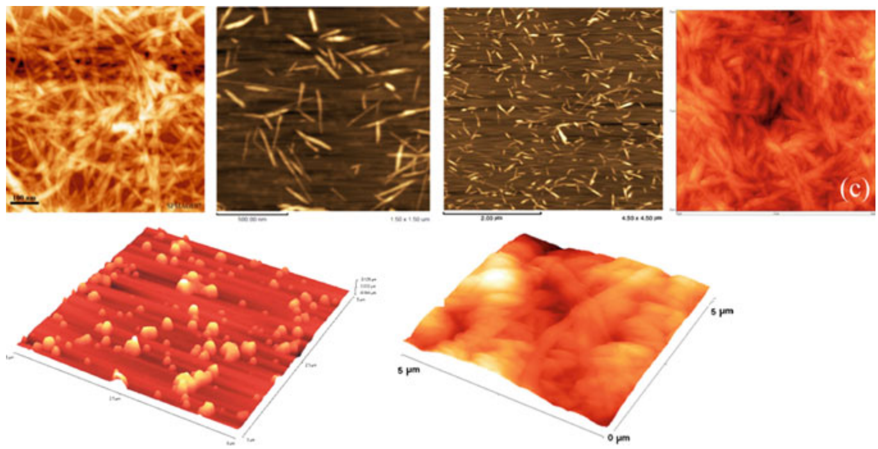

Fig. 2 AFM micrograph of nanocellulose and cotton nanofibrils obtained by various methods from the different raw materials (Silverio et al. 2013; Cherian et al. 2011; Santos et al. 2013; Satyamurthy et al. 2011; Satyamurthy and Vigneshwaran 2013; Karande et al. 2013)

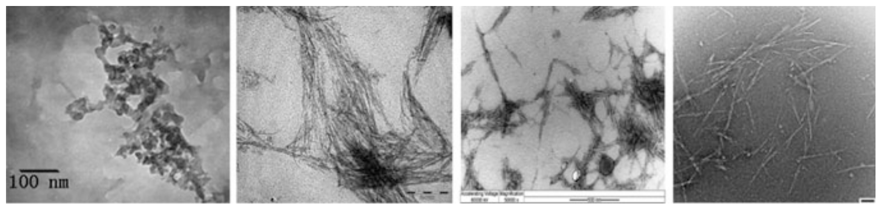

Fig. 3 TEM micrograph of nanocellulose obtained by various methods from the different raw materials (Li et al. 2012; Morais et al. 2013; Neto et al. 2013; Rosa et al. 2010)

production of cellulose nanofibrils. The nanocellulose embedded in the pineapple leaf was successfully extracted using a high-pressure steaming coupled with acid treatment (Leao et al. 2010). The production of nanocellulose from the different starting biomass/materials and synthesis techniques with end applications are summarised in Table 3.

5.2 *Production of Microcrystalline Cellulose*

Any vegetable material rich in cellulose can act as a potential source for the production of microcrystalline cellulose. Several agricultural waste materials including cotton stalk, sawdust, newsprint waste, hosiery waste, fast-growing plants, and cereal straw are used as material for the production of microcrystalline cellulose. The microcrystalline cellulose obtained from cotton waste had better flow

Table 3 Properties of the nanocellulose derived from the various agro-biomasses using different techniques

Sl. no.	Raw material	Particle size, shape, and measuring equipment	Method of preparation	Potential end application, if any	Reference
1	Raw cotton linters	Nanocrystals of 177 nm long and 12 nm wide by TEM 0.9 % of 9.2 nm, 88.6 % of 179.3 nm, and 10.6 % of 2.2 nm by particle size analyser	Acid hydrolysis	–	Morais et al. 2013
2	Pineapple leaf fibre	Diameter 5–15 nm by AFM	Acid hydrolysis and pressure	Composite and medical	Cherian et al. 2011
3	Pineapple leaf	Average length of 249.7 ± 51.5 nm and diameter of 4.45 ± 1.41 nm by AFM Needle-shaped	Acid hydrolysis	Reinforcement in nanocomposites	Santos et al. 2013
4	Soy hulls	Average length of 122 ± 39 nm and diameter of 2.7 ± 0.7 nm by TEM	Acid hydrolysis	Reinforcement in nanocomposite	Neto et al. 2013
5	Sugarcane bagasse	10–20 nm by TEM Circular	High-pressure homogenisation	–	Li et al. 2012
6	Corncob	Average length of 211 ± 44 nm and diameter of 4.1 ± 1.1 by AFM Needle-shaped	Acid hydrolysis	As reinforcing agent in nanocomposites	Silverio et al. 2013
7	Coconut husk fibre	Length 177 ± 80 to 218 ± 99 nm with	Acid hydrolysis	–	Rosa et al. 2010

(continued)

Table 3 (continued)

Sl. no.	Raw material	Particle size, shape, and measuring equipment	Method of preparation	Potential end application, if any	Reference
		diameter 5.5–6.6 nm by TEM			
8	Microcrystalline cellulose (MCC)	36.5 ± 1.9 nm by particle size analysis Length 120 ± 36 nm and thickness 41 ± 7.6 nm by AFM	Microbial hydrolysis	Composite and pharmaceutical applications	Satyamurthy et al. 2011
9	Oil palm biomass based microcrystalline cellulose	100 nm length and diameter 10–20 nm by TEM Rod-like structure	Acid hydrolysis	Green biodegradable nanocomposites	Haafiz et al. 2014
10	Microcrystalline cellulose derived from cotton fibres	Bimodal size distribution (43 ± 13 and 119 ± 9 nm) by AFM Spherical shape	Anaerobic microbial consortium	Drug delivery and biomedical applications	Satyamurthy and Vigneshwaran 2013
11	Short staple cotton fibres	112 ± 49 nm by SEM Fibrilar shape	Disc refiner followed by High-pressure homogeniser	Fillers in composites	Karande et al. 2013

properties than that of the commercial microcrystalline cellulose. This can also be used as a tablet binder, an excipient and suspending agent in pharmaceuticals, and in the food industry it acts as a noncaloric ingredient. It can be adopted in cottage units of the small-scale sector to recycle cotton fibre waste. The annual production of cotton fabrics for textiles and other end applications exceeded 28 million tonnes in 2009, which is almost two fifths of the global market of textile fibres. After their service life as apparel, home and technical textiles, these waste materials are usually used in landfills or incinerated (Sun et al. 2014). Such crude processes create environmental pollution. Therefore, recycling of waste cotton fabric and its conversion into value-added products is an important area of research and product development. In recent years, a number of methods have been pursued for recycling waste cotton fabric (WCFs) to value-added products, such as preparing cellulose derivatives and energy production. Sun et al. reported the usage of microcrystalline cellulose as a reinforcing material in PVA composite that was prepared from waste cotton fabric (WCF). Recently, biodegradable polymer, poly(vinyl alcohol) (PVA), has attracted considerable attention for developing ecofriendly composites, as it could be manufactured from nonpetroleum resources. PVA has a large number of hydroxyl groups in the polymer chains, as most of the hydroxyl groups could form either inter- or intramolecular hydrogen bonds. Therefore, PVA is well suited for preparing composites with cellulose fibre as both of them are highly hydrophilic in nature, and the presence of large amounts of hydroxyl groups on these two materials facilitates the formation of interfacial interactions through hydrogen bonding, leading to better adhesion strength in the composite (Sun et al. 2014). The MCC was prepared by the well-known acid hydrolysis technique. With increasing MCC content from 0 to 25 parts per hundred, the Young's modulus was found to increase linearly from 200 to 800 MPa in the composite material. As described earlier, this outstanding improvement in properties is due to the formation of a networked structure and strong interactions because of hydrogen bonding (Sun et al. 2014). Cellulose from cotton fibres may be hydrolysed using enzymes to produce glucose, which can be used for the production of ethanol, organic acids, and other chemicals (Satyamurthy et al. 2011). Because of zero toxicity, good hygroscopic nature, and chemical inactivity, the high-quality microcrystalline cellulose produced from cotton cellulose is used as an excipient for tablets, gentle filler in cosmetic creams, and as an additive for dietary food. Filamentous fungi, such as *Trichoderma reesei* are one of the efficient producers of extracellular cellulase enzyme. Cellulases are produced as multicomponent enzyme systems comprised usually of three components that act synergistically in the hydrolysis of cellulose, endoglucanases, cellobiohydrolase, and cellobiase (β-glucosidase).

5.3 *Production of Bacterial Cellulose from Textile and Agro Wastes*

Cellulose is composed of the homopolymer of β 1-4-linked D-glucose. The degree of polymerisation of cellulose varies from 100–15,000 to form microfibrils of a single crystalline entity. In reality, pure cellulose is produced by the bacteria *Acetobacter xylinum* and has been explored for more than 100 years. Unlike the cellulose from wood pulp, the bacterial cellulose is free from the other contaminating polysaccharides, such as lignin and hemi-cellulose, and its isolation and purification are relatively simple, not requiring energy or chemical-intensive processes (Kongruang 2008). Although the process of formation of cellulose by *A. xylinum* has been investigated extensively in the past, most of the work has dealt with the elucidation of cellulose biosynthesis. Polysaccharide-producing microorganisms are simple and capable of constructing a polymer from available primary and secondary raw materials, including beets (molasses, sugar), corn, potatoes, wood, dextran production wastes, petrochemical waste products, and such are often also suitable. Coconut juice, mostly discarded as waste is rich in carbohydrates, proteins, and other trace elements, and can be used as a starting substrate for the production of food-grade bacterial cellulose. Kongruang reported the production of bacterial cellulose, a biopolysaccharide produced from the bacteria *Acetobacter xylinum* (Kongruang 2008). Static batch fermentations for bacterial cellulose production were reported in coconut and pineapple juices at 30 °C in 5-l fermenters by using three *Acetobacter* strains: *A. xylinum* TISTR 998, *A. xylinum* TISTR 975, and *A. xylinum* TISTR 893. Results showed that *A. xylinum* TISTR 998 produced a bacterial cellulose yield of 553 g/l, whereas *A. xylinum* TISTR 893 produced 453 g/l and A. *xylinum* TISTR 975 produced 243 g/l. The yields in pineapple juice were more for *A. xylinum* TISTR 893 and 975, which were 576 and 546 g/l, respectively. The strain TISTR 998 showed the highest productivity using coconut juice. The strengths of the resulting dried sheets were tested by applying mechanical compression forces to determine the relative effects of the bacterial strains. Both coconut and pineapple juices yielded the same strength rating. Hong et al. reported the production of bacterial cellulose (BC) from cotton-based textile waste by enzymatic saccharification, enhanced by ionic liquid pre-treatment with *Gluconacetobacter xylinus* (Hong et al. 2012). The cotton fabrics were treated with the ionic liquid 1-allyl-3-methylimidazolium chloride ([AMIM]Cl). The [AMIM]Cl caused 25 % inactivation of cellulase activity at a concentration as low as 0.02 g/mL, and decreased the BC production during fermentation when present in concentrations higher than 0.0005 g/mL. It was found that the removal of the residual IL by hot water washing would be beneficial to enzymatic saccharification as well as BC production. IL-treated cotton fabrics exhibited a five- to sevenfold higher enzymatic hydrolysis rate and gave a seven times higher yield of fermentable sugars than the untreated fabrics. BC from the cotton cloth hydrolysate was obtained in a yield of 10.8 g/L, which was 83 % higher than that of the culture grown on glucose-based medium and possessed 79 % higher tensile strength than BC from glucose-based culture medium.

6 Recovery of Silk Sericin and Its Value-Added Applications

Silk derived from the silkworm *Bombyx Mori* is composed of two major proteins: fibroin and sericin. Fibroin is fibrous in nature and sericin is globular in nature. Silk fibroin has been used for a long time for the manufacturing of apparel and home silk textiles and is now being investigated as a biomedical product for specialised applications. Sericin or silk glue is a globular protein, which has around 25–30 % of silk proteins that have to be removed from silk in order to improve the lustre, softness, smoothness, whiteness, and dyeability of silk fibre (Gupta et al. 2013). It consists of 18 amino acids, and the majority of these have strong polar side-chains consisting of hydroxyl, carboxyl, and amino groups. Its high hydrophilic characteristic originates from the high content of serine and aspartic acid, approximately in the proportions of 33.4 and 16.7 % of the sericin present in silk (Aramwit et al. 2012). Sericin, which until recently, was considered to be a waste product of the silk processing industry, has now been attested to as one of the important industrial materials for food, pharma, cosmetics, and textiles for its excellent moisture absorption and release properties, UV resistance, cell protection, wound healing, anticancer, anticoagulant, antioxidant activities, and inhibitory action of tyrosinase (Aramwit et al. 2012; Gulrajani 2008; Gupta et al. 2014). Sericin can be removed from fibroin by various methods, such as boiling, by enzymatic methods, with the use of alkali, soap, detergents, organic solvents such as tartaric and citric acid, or a high temperature and high pressure (HTHP) process. The conventional process of removal of sericin is soap- and alkali-based, and the process discharges large volumes of sericin and chemicals as effluent. In the process, sericin is hydrolysed or solubilised with the help of soap, alkali, and temperature that causes about 20–25 % weight loss in silk. In a rough estimate, about 1 million tonnes of cocoons are produced worldwide that could produce approximately 50,000 tonnes of sericin discharge into water bodies annually that has a high BOD (4840 mg/L), COD (8870 mg/L), and nitrogen content (11 %), causing huge environmental pollution. Therefore, recycling and reuse of such silk sericin is an important area of research and industrial activity due to its high biomedical value, simultaneously addressing the environmental issue. The recovery of sericin from the soap alkali bath has been attempted using micro-, ultra-, and nanofiltration methods (Gupta et al. 2013). The other process is the high-temperature, high-pressure (HTHP) process that is energy intensive and degrades sericin considerably. Recently, a novel infrared (IR)-based process has been proposed by Gupta et al. to minimise waste in the wet processing of silk (Gupta et al. 2013). Process conditions for extraction of sericin from silk waste using the machine have been developed. Complete extraction of sericin from silk waste could be obtained using a lower temperature, time, and water consumption as compared to the conventional high-temperature, high-pressure (HTHP) process. Total recovery of nondegraded sericin was possible in a later stage to achieve by a simple spray-drying method as compared to multiple filtration and precipitation processes that are used in soap- and alkali-based degumming processes. Additionally, the present innovation reduces the pollution load considerably by not allowing any sericin to go into the effluent.

Silk sericin has also been explored for UV-protective finishing of various fibrous materials. The sericin generated in the degumming process of silk and discharged as an effluent, is a by-product that can be tailored for application in improving the moisture content, UV absorption, and antimicrobial properties of textile substrates (Gulrajani 2008). The polyester fabric, after washing with Lissapol N, was treated on both sides under an excimer lamp for 1, 3, 5, 7, 10, 12, and 15 min at a distance of 5 mm in atmospheric conditions, and was then functionalised with the sericin. The UPF value was found to increase to 125 ± 6 in the treated sample from 55 ± 5 in the untreated sample (Gupta et al. 2014). The sericin acts as a UV absorber thus converting the electronic excitation energy into thermal energy. The high-energy, short-wavelength UV rays excite the UV absorber to a higher energy state and then the absorbed energy possibly gets dissipated in the longer wavelength, thus avoiding skin damage. In addition to UV protection, the sericin-treated sample also exhibited very good hydrophilic properties, where the moisture regain value was found to improve from 0.6 to 2.3 % in the polyester sample. In antioxidant property evaluation, the radical scavenging activity was found to increase by 56 % over the control sample. The antistatic property was measured qualitatively, in which less ash was found to form in the treated sample.

Sericin is soluble in hot water and as the time proceeds, it converts itself into gel due to the transformation of α-random coil to β-sheet structure. At room temperature, 1 % aqueous sericin solution produces a gel at pH 6–7, and the gelation speed increases with increasing concentration of sericin. Blends of polyvinyl alcohol and sericin are cross-linked to give hydrogels (Padamwar and Pawar 2004). The sericin protein is also used as a horizontal alignment film for the liquid crystal to achieve uniform optical properties and to increase the stability of the product (Yasushi 1994). Sericin has been found to possess wound-healing properties and can be used as a wound-covering material in the form of film. Sericin-based membranes are considered good bandage materials and the film has adequate flexibility and tensile strength. Also, its flexibility and water absorption properties promote the smooth cure of defects in the skin and do not cause any peeling of skin under regeneration when detached from the skin (Tsubouchi 1999). In addition to the above-mentioned medical and pharmaceutical applications of sericin, it has also been used as a component of cosmetics. Sericin alone or in combination with silk fibroin has been used in skin, hair, and nail cosmetics. Sericin when used in the form of lotion, cream, and ointment shows increases in skin elasticity, and anti-wrinkle and anti-ageing effects (Padamwar and Pawar 2004).

7 Production, Recycling, and Application Lignin and Nanolignin

Lignin, a complex aromatic heteropolymer, is a major constituent of the secondary cell walls of all vascular plants. It plays essential roles in strengthening and impermeabilisation of the cell walls, and constitutes mechanical and chemical barriers against pathogens. It is primarily synthesised and deposited in the secondary cell walls of xylem vessels, tracheary elements, phloem fibres, and periderm (Verma and Dwivedi 2014). All the natural fibre-based biomasses mostly consist of cellulose, hemicellulose, and lignin. The lignin content varies from 0.6 to 30 % in natural fibres such as flax, hemp, jute, banana, coir, pineapple, and so on. The term ‘lignin’ is a collective name referring to a group of highly polymerised compounds with a similar character and chemical properties of aromatic compounds containing methoxyl –OCH_3, carbonyl –CO, and hydroxyl –OH groups (Verma and Dwivedi 2014). It is a polymer synthesised from three monomers p-coumaryl, coniferyl, and sinapyl alcohol. Lignin is the second important component of plant biomass after cellulose that makes it the second most common organic compound found in nature.

It is a cross-linked macromolecular material based on a phenylpropanoid monomer structure. The molecular masses of isolated lignin are in the range 1000–20,000 g/mol, however, the degree of polymerisation is difficult to measure, and also lignin is invariably fragmented during extraction and consists of several types of substructures, which repeat in an apparently haphazard manner (Doherty et al. 2011). It is a by-product of the pulp and paper industry and estimated to be 50 million tonnes worldwide per year. It can be divided into two categories: sulphur-bearing lignins, lignosulphonates and kraft lignin; and sulphur-free lignins, organosolv lignin, alkaline, and hydrolysis lignin. Usually, these compounds are burnt to produce energy and also used for production of vanillin, bonding agents, tanning agents, dispersing agents, plasticisers, and as fillers in the rubber industry. Recently, with the improvement in quality, they have had some additional high-end applications as antioxidants, antimicrobials, antivirus, cosmetics for UV protection, nutraceuticals, biocides, bio-stabilisers in the paper industry, and as a flame retardant.

Lignin is a natural polymer characterised by its ability to absorb ultraviolet rays and antibacterial properties (Zimniewska et al. 2012). It was interesting to observe that even after application of lignin in nanoform on the fabric surface, its colour did not change from the original dark colour of lignin. Zimniewska et al. obtained a nanostructure lignin from kraft lignin by ultrasound treatment, and the particle size was measured to be in the range of 5–170 nm. However, the majority of the particles were below 40 nm in size (Zimniewska and Batog 2012). The nanolignin was applied by the padding technique several times with silicone emulsion (5–25 g/l) at a temperature of 18–20 °C for 2–5 min, followed by drying at 40–60 °C. The coated fabric could maintain a very good UV protective characteristic even after washing. There was no significant change in the fabric stiffness and air permeability due to such application. The highest achievable UPF was 25 in the treated linen sample compared to 5 in the untreated sample. The presence of silicone emulsion with lignin helped in better UV protection (UPF > 45), by the improved fixation of particles in the fabric structure. However, the improvement was not so promising in the case of fabric made from hemp. It was observed that a plasma treatment with a power of 2000 W for 5 min in an oxygen atmosphere was useful for surface activation, prior to application of nanolignin in the linen fabric (Zimniewska et al. 2008, 2012). In the case of a flax nonwoven fabric, the lignin-treated sample showed almost double the UPF value (50) compared to the unmodified sample (Zimniewska et al. 2012; Kozłowski et al. 2012). An antibacterial test was conducted in the nanolignin-treated linen fabrics against eight bacteria cultures, which are mostly found in the environment. To improve the fixation of particles in the fabrics, different polymeric binder dispersions, such as acrylic, polyurethane, vinyl acetate, and dimethylol dihydroxy ethylene urea have also been used (Zimniewska et al. 2012). As lignin is produced from a renewable source, it is quite cost effective and can be used for sustainable UV protective finishing of textiles.

There is a wide range of lignin sources available in nature, including: jute, hemp, cotton, and wood pulp, hence its physical and chemical behaviour is expected to be different with respect to their source and the extraction method followed. Watkins et al. extracted the lignin from nonwood cellulosic biomass such as wheat straw, pine straw, alfalfa, kenaf, and flax fibre by formic acid treatment followed by peroxy-formic acid treatment for the potential use as a partial replacement for the phenol precursor in resole phenolic systems (Watkins et al. 2015). It was found that lignin obtained from alfalfa provided the greatest yield among the various sources. Enthalpy measurements were higher for lignin from flax fibre and alfalfa at 190.57 and 160.90 J/g, respectively. Overall, lignin extracted from wheat straw had the better thermal stability followed very closely by that obtained from flax fibre. In spite of many potentials of lignin, it is still a waste by-product of paper industries and biorefineries. Nair et al. for the first time reported a facile preparation and characterisation of a range of chitosan–alkali lignin composites for the removal of harmful effluents present in wastewater (Nair et al. 2014). Batch adsorption studies showed that chitosan–alkali lignin (50:50) composite exhibited maximum percentage removal of anthraquinonic dye, Remazol Brilliant Blue R (RBBR), and Cr (VI) compared to other composites. Adsorption of RBBR on the composite followed Langmuir isotherm, and the adsorption of both RBBR and Cr(VI) followed by pseudo-second–order kinetics. The good adsorption was possibly obtained due to the (i) electrostatic interaction of protonated amino and hydroxyl groups of the composite with anionic $SO3^-$ and $HCrO_4^-$ groups of dye and Cr(VI), respectively, and (ii) chemical interaction between amino and hydroxyl groups of the composite, and carbonyl moiety of the dye. Quraishi et al. described a novel approach towards the production of hybrid alginate–lignin aerogels, as a scaffold for tissue engineering (Quraishi et al. 2015). Exposure of alginate and lignin aqueous alkali solution containing calcium carbonate to CO_2 at 4.5 MPa resulted in a hydrogel formation. Stable hydrogels could be formed up to 2:1 (w/w) alginate-to-lignin ratio (1.5 wt % overall biopolymer concentration). Aerogels with bulk density in the range of 0.03–0.07 g/cm^3, surface area up to 564 m^2/g, and pore volume up to 7.2 cm^3/g were obtained. Cell culture studies revealed that alginate–lignin aerogels are noncytotoxic and featured a good cell adhesion, making them attractive for a wide range of applications, including tissue engineering and regenerative medicine.

The coir fibre is composed of at least one third Klason lignin, whereas the lower molecular weight phenolics can be found as extracts in considerable amounts, especially in younger nuts. The thermal behaviour of the original (chemically unmodified) lignin in plant tissues at temperatures above 140 °C, where it melts shows thermosetting properties that have been investigated in detail by Dam et al. (2004). Coconut husk lignin was explored for application as an intrinsic resin in board production, utilising whole fresh husks. Based on this concept, a simple and efficient technology has also been developed to produce high strength–high density panels, without the addition of chemical binders. The effect of lignin as a compatibiliser on mechanical properties of coconut fibre–polypropylene composite has been studied by Rozman et al. (Rozman et al. 2000). The result demonstrates that composites with lignin as a compatibiliser possess higher flexural properties as compared to those without the lignin sample. Lignin is shown to reduce water absorption and thickness swelling of the composite material.

8 Research on Banana Pseudostem Sap

After India and Ecuador, Brazil is the third largest producer of bananas. The country has studied the fibre extensively on various standpoints. The total cultivated area of banana is about 65 million hectares, with an average production of 1500 kg/ha. But only 2 % is exported; the rest is used for internal consumption. These values represent an immense potential for biomass and natural fibre production. It was interesting to note that like the banana fibre, banana pseudostem sap (BPS), a green material, could also be used to improve thermal stability and UV protective performance of textile substrates (Basak et al. 2015a, b, c). It is an agricultural waste material available in large quantity in India and other countries. It was found that in cotton and jute woven fabrics, the LOI was found to increase to over 30 from the value of 18 and 21 in the untreated cotton and jute samples, respectively. The BPS-treated cotton fabric burns with flame only for 4 s, followed by burning with afterglow (after flame stopped) for 900 s. Hence, the total burning time of a 250 × 20 mm fabric sample becomes 904 s, whereas the untreated sample of the same size burnt completely within 60 s with high flame propagation speed (Basak et al. 2015a, b, c). From the various characterisations, it was postulated that the presence of phosphate, silicate, chloride, and other mineral salts in the BPS might have increased the thermal stability of the cellulosic and lignocellulosic textiles by forming more char, while ensuring production of less flammable volatiles. It was observed that the plain woven bleached cotton fabric showed a poor UPF value of 10 and after mordanting with tannic acid and alum, the UPF value did not improve much. However, when the mordanted fabric was treated with the alkaline banana pseudostem sap (BPS), the UPF value was found to improve to over 100 (excellent rating). Subsequently, the UVA and the UVB transmittance percentages were reduced drastically from 9.5 and 7.2 % in the untreated samples to 1.2 and 1 % in the BPS-treated samples, respectively. The UV protection of the BPS-treated sample possibly arises due to the presence of N, N alkyl benzeneamine as confirmed by a GC–MS analysis of the BPS (Sayed et al. 2001; Katarzyna and Prezewozna 2009). Salah et al. reported the utilisation of banana peel saps, an agro-waste for improving UV protection, antimicrobial property, and natural dyeing of cotton fabric (Salah 2011). Cotton fabric made of Egyptian fibre showed a UPF of around 19.8, whereas the same fabrics after mercerisation and sap dyeing, exhibited a UPF of around 60 possibly due to the reduction in fabric porosity because of alkaline swelling after mercerisation, mordant–fabric complex formation, and the presence of luteolin in the banana peel saps. The bleached cotton fabric after mordanting and banana peel sap treatment showed more than 90 % bacterial reduction against both gram-positive and gram-negative bacteria. Recently, researchers have reported the potential of banana pseudostem sap (BPS) as a dye for the Adinkra industry in Ghana. The results revealed that a combination of banana sap and B. micratha dye ensures a high levelness on fabrics. It showed that in addition to the dyeing agent, banana sap could also serve as a good mordant (Dzomeku and Boateng 2013). Researchers have also prepared novel bioresin from banana sap (BPS) for low-end applications such as the interior components of motor vehicles (Paul et al. 2014). In this study, the sap from banana plant (*Musa cavendish*), grown in Kwa-Zulu Natal, South Africa, was used as the starting material for the bio-resin. Qualitative analysis of BPS confirmed the presence of carbohydrates and phenols. It was added in varying concentrations (30–65 wt %) to polyester resin and different thermomechanical properties were evaluated. Navsari Agricultural University, Gujarat, India has recently reported the usage of all the parts of banana pseudostem (BP), including pseudostem sap, scutcher, fibre, and the central core. Fibre- and textile-related performance evaluations were conducted at CIRCOT, Mumbai and MANTRA, Surat and it was found that as the banana fibre had low breaking load, extension, and tenacity, and as such it is not suitable in making fabric out of 100 % banana fibres. Therefore, union fabric was prepared using cotton as a wrap yarn and banana as a weft yarn. At CIRCOT, Mumbai, both woven and nonwoven fabrics were also prepared using 100 % banana fibre for the end application as sofa covers, car covers, school bags, and so on. Banana fibre can also be used as a raw material for the paper industry. As far as the bleached pulp of banana pseudostem fibre is concerned, its bulk, burst factor, and tear factor are more than the bamboo, eucalyptus, and prosopis fibre pulps that are normally used in manufacturing paper. Scutcher-based products of the banana pseudostem have been used for vermin-composting (http://nhm.nic.in/Archive/bananafibre.pdf). The same research group also reported the application of sap as an organic fertiliser. More particularly, it was bio-enriched by adding various other ingredients, such as fresh neem leaves, jaggery, cow urine, cow dung, pulse flour, and buttermilk in the BPS, followed by fermentation to make it suitable as an organic fertiliser, which is a very good substitute for conventional synthetic fertiliser (Kolambe et al. 2013).

9 Biodegradation and Life-Cycle Assessment

In the country such as the United Kingdom, approximately 4–5 % of the municipal solid waste is composed of clothes/textiles (Woolridge et al. 2006). Approximately 25 % of these textiles are recycled by companies such as the Salvation Army Trading Company Limited. Textiles can be reused or undergo a processing stage and enter a recycling stream. Systematic research was conducted in order to quantify the energy used by a reuse/recycling operation and whether this resulted in a net energy benefit. The energy footprint was assessed using a streamlined life-cycle assessment (LCA), taking into account extraction of resources, manufacture of materials, electricity generation, clothing collection, processing and distribution, and final disposal of wastes. It was demonstrated that for every kilogram of virgin cotton displaced by second-hand clothing approximately 65 kWh is saved, and for every kilogram of polyester around 90 kWh is saved (Woolridge et al. 2006). Therefore, the reuse and recycling of the donated clothing results in a reduction in the environmental burden compared to purchasing new clothing made from virgin materials. As described above, the disposal of fabric materials also poses a serious problem in waste management. Hence, production of biodegradable fabric needs to be given due attention. Leather-blended fabric with a 50:50 ratio of leather fibre (LF):cotton/polyester (CF/PF), which possessed better mechanical properties was chosen for the biodegradation study (Senthil et al. 2014). Fabric weight loss due to biodegradation with enzymatic (cellulose and collagenase) processes was studied. It was also observed that leather–cotton fabric samples exhibited a weight loss of approximately 45 % after 90 days, whereas under the same conditions, leather–polyester fabrics showed only 15 % degradation.

The carbon footprint (CF) is a measure of the impact of human activities on Earth and the environment. More specifically, it relates to climate change and the total amount of greenhouse gases produced, as measured by carbon dioxide emission. Muthu et al. in 2011, reported an exhaustive carbon footprint analysis of recycled and reused plastic, paper, nonwoven and woven bags sent to landfills in countries including China, Hong Kong, and India (Muthu et al. 2011). The first stage, that is, the baseline study, has shown the impact of different types of shopping bags in the manufacturing phase, without considering their usage and disposal. In the next stage, the study of the carbon footprint of these bags, including their usage and disposal phases (cradle-to-grave stage) was measured. The results showed high CFs of different types of shopping bags, if no usage and disposal options were provided. However, the CF values were lower in the case where a higher percentage of reuse was preferred by recycling and disposing in landfills. It was interesting to note that reuse could significantly scale down the carbon footprint. Once the shopping bags reached the end of their service life, they must be recycled, rather than disposed of in landfills. It has been observed that in India greenhouse gas emission was the least (708 g) in the polypropylene nonwoven bag, and the highest for 3410 g for the paper bag. For the functional unit assumed, nonwoven bags consumed less energy and fewer amounts of materials and also, they emit fewer greenhouse gas in the production phase of the shopping bags in comparison to their counterparts in China, Hong Kong, and India. Reusable bags, such as nonwoven bags made of polypropylene, followed by woven cotton bags seem to be environmentally friendly compared to the conventional plastic and paper bags for the functional unit assumed in the comparative study. In this context, consumers behavior and governmental policies are also important to encourage people to go for reusable bags, and promote more recycling systems to scale down the environmental impacts made by any type of shopping bag. According to the Life Cycle Inventory (LCI) data and the software used for the study, although limited by certain hypotheses and assumptions, plastic bags were found to be a little better in terms of environmental impacts compared to paper bags (Muthu et al. 2009). Another study by the same research group has modelled the results of the carbon footprint of recycling a natural textile material, cotton, and a manmade fibre, polyester. The calculation of the carbon footprint of 1 kg of cotton and polyester fabrics was modelled by the SIMAPRO 7.3 version of LCA software. Relevant data were referred from the IDEMAT database and it was assumed that both materials were 100 % recycled at the end of their lives. The study showed that 1 kg of polyester fabric provided a better carbon footprint compared to 1 kg of cotton fabric, when their whole life cycles were considered (Muthu et al. 2012).

10 Present Status of Recycling in India

India is blessed with enormous biodiversity, resulting in availability of various agricultural and horticultural crops, fruits, vegetables, fibres, and other biomasses. Even after their successful primary utilisation as food and fibre, a large amount of such agro-biomasses are still regularly discarded as wastes, which cause environmental pollution and also, remained unutilised. However, in recent years in India, a significant effort has been made in the recycling of temple flower waste for textile dyeing and finishing. Recovery of silk sericin from the silk degumming process has also been attempted for textile and other biomedical applications. It is worth mentioning that organic nanoparticles, such as nanocellulose, have been successfully produced from the cotton linter, cotton fibre, sugarcane bagasse, pineapple leaf, and such on. However, the majority of such reported studies have only been practiced on a laboratory scale and their successful commercial applications are still to be realised, depending on their cost-economic and market demand. The Central Institute for Research on Cotton Technology, Mumbai, India under the Indian Council of Agricultural Research has already taken a lead role in setting up the nation's first pilot plant for the production of nanocrystalline cellulose and nanofibrillated cellulose from cotton linters and other agro products by chemomechanical and microbial processes with a production capacity of 10 kg/day (Annual institute report 2013–2014; http://nhm.nic.in/Archive/bananafibre.pdf). Muthu et al. in 2011 reported an exhaustive carbon footprint analysis of recycling and reuse of plastic, paper, nonwoven, and woven bags sent for landfilling and as practiced in the leading textile manufacturing countries, such as China and India (Muthu et al. 2011). A comparative study of such wastes, with and without usage and disposal options, and as per existing consumer behavior and individual government policies in China, Hong Kong, and India, has shown that the carbon footprint for the plastic bags is less in India compared to the other countries. On the other hand, for the other categories of shopping bags made of paper, nonwoven and woven materials, the carbon footprint is less in China. The influence of the reuse option for reducing the carbon footprint is very relevant in all the above cited cases.

11 Summary

Waste is any substance that constitutes a scrap material, such as an effluent or other unwanted surplus substance arising from the application of a process. Due to the growth in world population with overall improvement in living standards, consumption of textile fibres (natural and synthetic) globally has increased phenomenally in the past few decades, creating a high amount of post-industrial and post-consumer fibre waste. World fibre production has been steadily increasing in the past few decades, and now exceeds 64 million tonnes per year. In addition to production of fibrous or textile waste, the textile industry during chemical processing also produces waste or residue, such as sizing material, unutilised dye and pigment, functional chemicals and auxiliaries, sericin, and lignin that can be recycled or converted into various high-value low-volume, low-value high-volume or any other day-to-day usable products. The recycling situation is somewhat complex and challenging for the textile and clothing sectors, as a different fibre with various intrinsic physical–chemical–mechanical properties are intimately mixed with each other during carding, drawing, or spinning. A number of organic solvents, ionic liquids, and enzymes have been explored to recycle cellulosic cotton fibre, polyester fibre, or to produce cellulose acetate film. Natural fibrous materials such as jute, kenaf, flax, coconut, and hemp, and agricultural residue, including stalks of most cereal crops, peanut shells, tomato seeds and peels have become popular as suitable reinforcing materials in thermoplastic, thermosetting, and green/biocomposite application. Natural fibres derived from the agro-food and paper–textile industries offer technoeconomic and environmental advantages for composite applications due to their higher strength and stiffness compared to their counterpart synthetic materials.

With the advancement of recycling technology, it has been possible to recycle/reuse or use many important wastes or agro-residues for the same or other valued processes/products, and also reduce the environmental load. For example, waste flowers for textile colouration and functionalisation, cotton and leather fibre recovery from waste fabric for textile/composite/film application, waste jute fibre for mushroom cultivation, dye recovery for textile recolouration, and bio-waste such as pineapple leaf fibres for vermin-composting have been explored in the past. A number of approaches have also been attempted for the production of highly purified nanocellulose, bacteria cellulose, and microcrystalline cellulose from the various cellulosic to lignocellulosic biomasses, such as cotton linter, cotton fibre, sugarcane bagasses, pineapple leaf, soy hulls, and corncob for their application as reinforcing agents, pharmaceuticals, packaging, and biomedicine. Sericin protein, a waste of the silk processing industry, has now become one of the important industrial materials for applications in the food, pharma, cosmetics, and textile industries for moisture absorption and release properties, UV resistance, cell protection, wound healing, anticancer, and anticoagulant properties. Similarly, lignin, a naturally cross-linked biomacromolecule and by-product of pulp and paper and the jute industry, have also been recently utilised for antioxidant, antimicrobial, antivirus properties, cosmetics, and biocide applications. In this regard, banana pseudostem sap has been explored for applications as flame retardant, UV protective, and antimicrobial agent for textiles, besides its utilisation as a fertiliser for agricultural applications. In many practical circumstances, processing of waste mechanically, chemically, and/or biologically to recycle waste into products, required a certain amount of energy, additional raw materials, and emission of waste into the air, water, and soil. The life cycle assessment (LCA) tool was hence introduced in some of the products to evaluate their actual relative benefits during the disposal and/or recycling process. All these developments would create awareness of recycling of important biodegradable materials along with their requisite value addition, while addressing environmental issues.

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Recycling and Reuse of Textile Effluent Sludge

T. Karthik and R. Rathinamoorthy

Abstract In the whole world today there has been a growing awareness of the damage caused to the environment by the haphazard use of chemicals, some of which are very poisonous and carcinogenic. The textile industry has been strongly criticised as being one of the world's worst lawbreakers in terms of pollution because it demands a large amount of water and chemicals. Although air, water, and noise pollution are created at every step of fabric treatment, the most problem-filled is fabric wet processing, in terms of the huge amount of water and goodly number of chemicals used in wet processing and on completion of the process, leftover dyes and chemicals together with water are discharged as effluents. As the amount of sludge created by wastewater treatment increases, effective reuse and safe disposal of sludge becomes most important. This chapter provides comprehensive information about the various methods and techniques in recycling textile effluents and sludge treatment process of textile effluents.

Keywords Textile industry · Effluent treatment · Methods · Sludge management

1 Introduction

The expanding populace and the dynamic reception of a mechanical-based way of life have unavoidably prompted an expanded anthropogenic effect on the biosphere. The term contamination portrays the presentation of a substance at a fixation adequate to be hostile or unsafe to humans, creatures, or vegetation (Mohana et al. 2008). Every industrial process is considered by the utilisation of raw materials,

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water, energy, and so on that continue conversion into products and waste. The wastes produced at every stage of the various categories of human activity depend on consumption patterns and production methods. The main concerns are focused on the impact of these elements on human health and the environment (Walker and Weatherly 1997).

Natural debasement, which is the disintegration of the Earth through exhaustion of assets, for example, air, water, and soil, the pulverisation of biological systems, and the eradication of untamed life have been genuine concerns of preservationists. Ecological debasement may accept the manifestation of compound and organic corruption, oxygen consuming or anaerobic biotransformation, and mineralisation forms. In spite of the fact that industrialisation itself has resulted in rising salaries and levels of material welfare combined with a lessening in shares of the populace beneath destitution lines in any nation, these advantages are generally accomplished to the detriment of the Earth (McMullan et al. 2001; Nigam et al. 2000; Bechtold et al. 2001). Natural insurance exercises can be seen as a step of practices masterminded together against an inclination towards contamination using different strategies, for example, treatment and reutilisation. Treatment of mechanical emanations can be viewed as a method for contamination aversion as industrial effluents remain a wellspring of direct input of toxins into the amphibian biological community.

Water is a critical natural resource for sustaining life and the environment, which is thought to be available in abundance. Today water pollution is one of the major global threats. Many water sources contain harmful substances in concentrations that make the water unsafe to drink or unfit for domestic use. Due to rapid industrialisation and urbanisation many chemicals including dyes, pigments, and aromatic molecular structural compounds were extensively used for several industrial applications such as textiles, printing, pharmaceuticals, food, toys, paper, plastics, and cosmetics manufactured and used in day-to-day life (Walker and Weatherly 1997). Untreated industrial effluent discharged into ecosystems poses a

Fig. 1 Aquatic pollution by industries. *Source* http://www.consumerinstinct.com/

serious problem to aquatic living organisms, plants, and human beings. Almost all of the available industries release their untreated or partially treated wastewaters into municipal sewers or directly into nearby drains, rivers, stagnant, ponds, lagoons, or lakes (McMullan et al. 2001; Nigam et al. 2000; Bechtold et al. 2001). Such wastewater disposal may cause damage to the quality of the receiving water bodies and the environment at large as shown in Fig. 1.

2 Water Pollution by Textile Industry

The textile industry has a major impact not only on the nation's economy but also on the economic and environmental quality of life. Textile industries are one of the major consumers of water and dispose a huge volume of effluent to the environment (Ding et al. 2010; Meyer 1981; Zollinger 1987). The mechanical processes such as spinning and weaving consume less water whereas textile wet processing consumes a huge quantity. Figure 2 shows the various processes involved in the textile chemical processing industry.

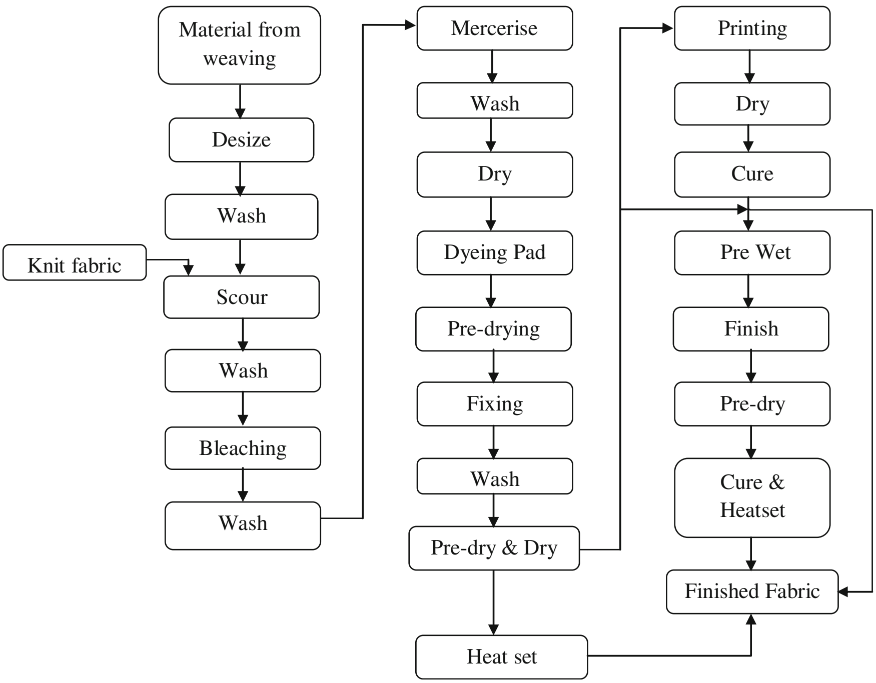

Fig. 2 Sequence for textile wet processing. *Source* Ramesh Babu et al. (2007)

2.1 Water Consumption in Textile Processing

The production of textile goods involves spinning (fibre to yarn), weaving/knitting (yarn to fabric), chemical (wet) processing, and garment manufacturing. The majority of water consumption (72 %) takes place in the chemical (wet) processing of textiles (Mishra and Tripathy 1993; Banat et al. 1996; Juang et al. 1996). The water is required for preparing the fabric for dyeing, printing, and finishing operations; intermediate washing/rinsing operations; and machine cleaning. The quantity of water required for textile wet processing is huge (120–150 l/kg) and varies from industry to industry depending on the type of fabric processed, the quality and quantity of fabric, processing sequence, and the source of water (Ghaly et al. 2014; Atul Kumar et al. 2011). Other major uses of water in the textile industry, as shown in Fig. 3, are:

- Steam generation (heater food water)
- Water treatment plant (reject stream, intermittent cleaning of converse osmosis plant, recovery and washing of demineralisation, conditioner plant, backwash of media channels)
- Cooling (transforming machines, cooling tower)
- Humidification (turning procedure)
- Domestic purposes (watering system of yard and greenhouse, sanitation, cleaning, drinking, and other uses)

The specific water consumption for cellulosic fabric processing ranges from 100 to 120 l/kg of fabric processed, whereas for synthetic fibre, yarn, and fabric it ranges between 25 and 70 l/g of the product processed. Textile industries use a lot of water in their various manufacturing stages (e.g., scouring, bleaching, mercerising, dyeing, printing, and final finishing) and thus they produce a great deal of wastewater

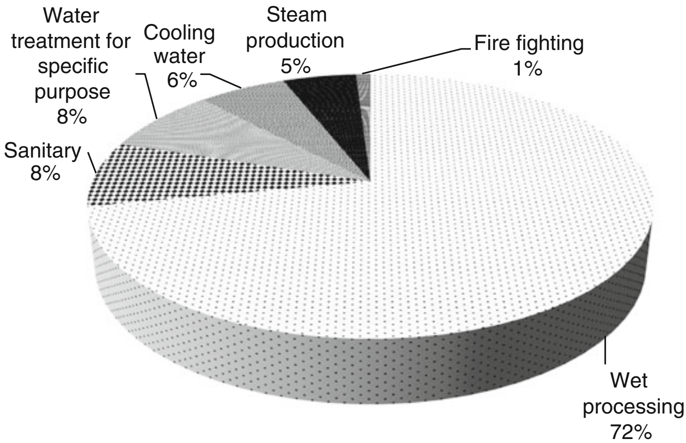

Fig. 3 Water consumption Pattern in Textile Industries. *Source* Kalra et al. (2011)

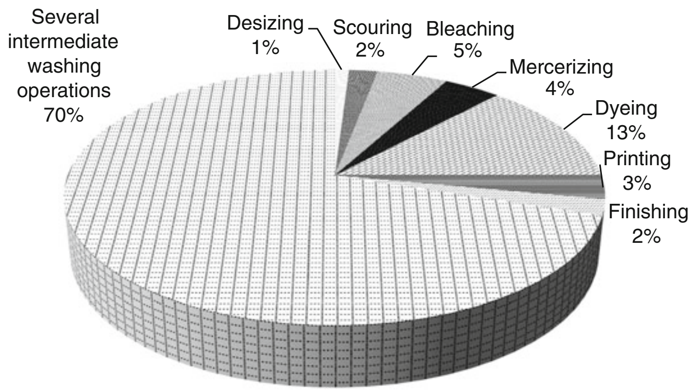

Fig. 4 Water consumption Pattern of Wet Processing of Textiles. *Source* Kalra et al. (2011)

(Ramesh Babu et al. 2007; Correia et al. 1994; O'Neill et al. 1999). Figure 4 shows the water consumption of the individual components of the wet processing stage (Kalra et al. 2011).

Effluents discharged from these operations as a rule contain a lot of contamination load as many colours and auxiliary chemicals are utilised as part of the most complex phases of wet techniques (e.g., colouring and printing) and this is typically released into water bodies half treated or untreated. These dyes and other related chemicals add to significant pollution heaps of the receiving water bodies. The significant constituents of effluent released by dye houses is the colour; it is the first contaminant in wastewater and the vicinity of its sum in wastewater is profoundly visible and undesirable (Gosavi and Sharma 2014; Sultana et al. 2013). Textile effluents have been found to contain a higher measure of metals particularly chromium, copper, lead, and cadmium as these metals are as a rule generally utilised as a part of the production of colour pigments of textile dyes.

3 Characteristics of Textile Wastewater

The quality of water is defined by its chemical, physical, and biological contents, hence preserving a healthy aquatic ecosystem depends on the physicochemical properties and biological diversity, which calls for regular monitoring of water bodies (Adinew 2012; Italia 2007). Industrial activities have been notorious as a major source of pollution for water ecosystems. The production of textiles, cellulose, and various chemicals is usually connected with synthetic dye usage and with other toxic metals and the discharge of their effluents could have a serious hazardous influence on the environment. The textile industry is the fifth significant industry that is a source of ecological issues. On the other hand, in terms of releasing colouring effluent, the textile industry is the biggest business malefactor.

3.1 Characteristics of Dye Effluent

Colour: Colour present in dye effluent not only creates a negative aesthetic effect but also inhibits the self-purification potential of dye effluent by reducing the photochemical synthesis of O_2 and disturbing the aquatic ecosystem.

Dissolved solids: Dissolved solids in dye effluents are likewise critical attributes of textile industry effluents. Common salts are utilised as a part of dyeing methodologies which tremendously increase total dissolved solids (TDS) in dye effluents.

Chlorine: Chlorine salt is used in the textile industry resulting in residual Cl_2 in textile effluent. Chlorine in dye effluent decreases the dissolved oxygen (DO) in a water body and additionally chlorine responds with other compounds and forms complex chlorine salt.

Organic materials: Organic dyes, acid, enzymes, and sizing material are also responsible for organic pollutants in dye effluents. The presence of natural toxins in dye effluents is measured in analysis of biological oxygen request (BOD) and chemical oxygen interest (COD).

Toxic metals: Metals may act as primary or secondary pollutants and are extremely dangerous in nature to aquatic life. Dye effluents containing metals result from textile processing. The majority of the toxic metals in dye effluent are chromium (Cr), cadmium (Cd), nickel (Ni), zinc (Zn), copper (Cu), lead (Pb), and iron (Fe) among others.

Wastewater discharged from the textile industry is characterised by high chemical demand, low biodegradability, and high salt content (Alinsafi et al. 2005; Wu et al. 2004; Karthik and Gopalakrishnan 2012a, b, c, d). Some of the dyes such as azo dye are carcinogenic and cause serious health problems such as cancer (Karthik and Gopalakrishnan 2013a, b; Rita Kant 2012; Joshi et al 2004). This means the treatment of dye before release is imperative to ensure sustainable development. The typical characteristics of untreated textile effluent are shown in Table 1. The possible pollutants from textile wet processing are shown in Table 2 and the typical characteristics of effluent from various textile processing operations are given in Table 3 (Ghaly et al. 2014).

3.2 Dyes

Colour removal is a momentous problem for all kinds of textile effluents due to the variety of chemicals used in dyeing and printing of fibre, yarn, and fabrics. The colour of dye is a combination of the effects of chromophores and auxochrome. Some of the important chromophores are –N=N–, –C=O, $-NO_2$, and quinoid groups and important auxochromes are $-NH_3$, –OH, $-SO_3H$, and $-CO_2H$. Both chromophore and auxochrome increase the bath chromic effect on a conjugated system of dye. In addition to enhancing the chromophore in the production of

Table 1 Characteristics of typical untreated textile wastewater

Parameter	Range
pH	6–10
Temperature (°C)	35–45
Total dissolved solids (mg/L)	8000–12,000
BOD (mg/L)	80–6000
COD (mg/L)	150–12,000
Total suspended solids (mg/L)	15–8000
Total dissolved solids (mg/L)	2900–3100
Chlorine (mg/L)	1000–6000
Free chlorine (mg/L)	<10
Sodium (mg/L)	70 %
Trace elements (mg/L)	
Fe	<10
Zn	<10
Cu	<10
As	<10
Ni	<10
B	<10
F	<10
Mn	<10
Hg	<10
PO_4	<10
Cn	<10
Oil and grease (mg/L)	10–30
TNK (mg/L)	10–30
NO_3–N (mg/L)	<5
Free ammonia (mg/L)	<10
SO_4 (mg/L)	600–1000
Silica (mg/L)	<15
Total Nitrogen (mg/L)	70–80
Colour (Pt–Co)	50–2500

Source Ghaly et al. (2014)

colour, auxochromes are also responsible for the solubility of dye and increase its reactivity towards fibres (Turhan et al. 2009).

Dyes may be classified in numerous ways, according to their chemical structure, application class, or end use. The primary categorisation of dyes is based on the fibres to which they can be applied and the chemical structure of the dye. Textile dyes are classified under the classes of anionic, cationic, and nonionic types. Anionic dyes mostly incorporate the direct, acid, and reactive dyes. Basic dyes are the main class of cationic dyes used in the textile industry. Nonionic dyes refer to disperse dyes, which do not ionise in a watery medium. During dyeing, the vast

Table 2 Pollutants from textile wet processing operations

Process	Compounds
Desizing	Sizes, enzymes, starch, waxes, ammonia
Scouring	Disinfectants and insecticide residues, NaOH, surfactants
Bleaching	H_2O_2, AOX, sodium silicate or organic stabiliser, high pH.
Mercerising	High pH, NaOH
Dyeing	Colour, metals, salts, surfactants, organic processing assistants, sulphide, acidity/alkalinity, formaldehyde
Printing	Urea, solvents, colour, metals
Finishing	Resins, waxes, chlorinated compounds, acetate

Source Eswaramoorthi et al. (2008)

Table 3 Characteristics of the effluent from various wet textile processing operations

Source of effluent generation	Parameters		
	pH	COD (mg/L)	BOD (mg/L)
Process effluent			
Desizing	5.83–6.50	10,000–15,000	1700–5200
Scouring	10–13	1200–3300	260–400
Bleaching	8.5–9.6	150–500	50–100
Mercerising	8–10	100–200	20–50
Dyeing	7–10	1000–3000	400–1200
Wash effluent			
After beaching	8–9	50–100	10–20
After acid rinsing	6.5–7.6	120–250	25–50
After dyeing (hot wash)	7.5–8.5	300–500	100–200
After dyeing (acid and soap wash)	7.5–8.64	50–100	25–50
After dyeing (final wash)	7–7.8	25–50	–
Printing washing	8–9	250–450	115–150
Blanket washing of rotary printer	7–8	100–150	25–50

Source Ghaly et al. (2014)

majority of the dye is exhausted on the fibre and the unfixed dyes are discharged into wastewater (Turhan et al. 2012; Santos et al. 2007; Vijayaraghavan and Karthik 2004). Textile industries consume a huge quantity of water and produce a considerable amount of wastewater which has unconsumed dyes and their components. The wastewater is extremely variable in composition due to the large number of dyes and other chemicals used in processing.

The utilisation of different dyes relies on the attributes of the fibre, the particular colour to be applied, and the desired finish needed on the fibre. The textile processing industries have demonstrated a noteworthy increment in the utilisation of

Table 4 Typical pollutants generated by synthetic dyes

Dye class	Typical pollutants associated with the dyes
Acid	Colour, organic acids, and unfixed dyes
Basic	N/A
Direct	Colour, salt, unfixed dye, cationic, fixing agents, surfactant, levelling, retarding agents, finish, diluents
Disperse	Colour, organic acids, carriers, levelling agents, phosphates, lubricants, and dispersants
Reactive	Colour, alkali, oxidising agent, reducing agent, and unfixed dye
Sulfur	Colour, alkali, oxidising agent, reducing agent, and unfixed dye
Vat	Colour, alkali, oxidising agents, and reducing agents

Source Adinew (2012)

synthetic complex organic dyes as the colouring material. The global consumption of textiles is currently around 30 million tonnes with expected growth at 3 % per annum (Kalra et al. 2011; Gopalakrishnan & Karthik 2012). The dyeing of these materials requires approximately 8×10^5 tonnes of dyes and it is estimated that 10,000 different types of dyes and pigments are produced worldwide annually, out of which a large number of dyes are azo compounds (–N=N–). Synthetic textile dyes utilised every year are lost amid production and processing operations and 20 % of these dyes enter the earth through effluents that come from the treatment of residual industrial waters. Typical pollutants generated by synthetic dyes are given in Table 4.

3.3 *Environmental Impact of Wastewater*

Wastewater is both a resource as well as a problem. To the extent wastewater and its nutrient content can be used for irrigation and other ecosystem services, wastewater reuse can deliver positive benefits to the farming community, society, and municipalities. However, wastewater reuse also imposes negative externality effects on humans and ecological systems. Thus, from an economic perspective, both the benefits and costs of wastewater reuse should be evaluated.

3.3.1 Effects on Public Health

Wastewater contains pathogenic microorganisms, for example, bacteria, viruses, and parasites which can possibly bring about infection. Specifically, human parasites, for example, protozoa and helminth eggs, are of exceptional importance in such manner as they turn out to be hardest to eliminate by treatment processes and have been involved in various resistant gastrointestinal diseases in both developed and developing nations (Ray 1986).

3.3.2 Effects on Crops

Generally, treated wastewater can be utilised for production without undesirable effects on crops. The treated wastewater can give (1) dampness required for crop growth, an alternative for traditional irrigation systems; and (2) plant sustenance supplements, therefore a substitute for costly chemical fertilisers. Along these lines, from an economic angle both the water and nutrient content of wastewater are imperative.

In general, wastewater is a rich resource of fundamental plant nourishment supplements and can, hence, be utilised as a substitute for chemical fertilisers. Nonetheless, if the aggregate nitrogen delivered to the crop by means of a wastewater watering system surpasses the suggested nitrogen rest for ideal yields, it may encourage vegetative development, postpone maturing and development, and in extreme circumstances cause yield loss. Then again, supplement insufficiency might likewise lead to lower than potential product harvests and resulting monetary misfortune. In this way, for ideal usage of wastewater supplements, careful agronomic management is key.

3.3.3 Effects on Aquaculture

Wastewater is a rich resource of supplements for fish production; on the other hand, general well-being concerns remain a key factor restricting the utilisation of wastewater for aquaculture. As fish and other aquaculture items are regularly expended straightforwardly after harvest, the heavy metals and pathogens present in fish tissues are liable to be ingested by individuals with potential health effects. On the other hand, these potential health impacts can be evaded if enough treated wastewater is utilised for aquaculture. Actually, low-cost frameworks could be intended to use on farm and residential effluents for yield generation, dairy farming, and aquaculture in an incorporated way to attain water use efficiency and optimal resource utilisation.

3.3.4 Effects on Soil Resources

Wastewater is a rich resource of supplements, disintegrated salts, and other trace components and heavy metals. Subsequently, effluent irrigation systems may include many salts and heavy metals and nutrients to the soil after some time. Some of these salts may aggregate in the root zone with conceivable unsafe effects on soil well-being and crop yields and the leaching of these salts underneath the root zone may bring about soil and groundwater contamination. The real effect of the high saline substance of wastewater on soil is the danger of soil saltiness which thus brings the twin evil of water-logging. When the soil becomes saline and water-logged, its capacity to support ordinary crop production is extremely affected.

Wastewater, moreover, contains high concentrations of sodium particles which may interact with saline salts to make insoluble mixes and increase the exchangeable sodium percentage in the soil which thus might break down the soil structure. A drawn-out utilisation of saline- and sodium-rich wastewater is a potential health peril for soil as it may erode the soil structure, and thus efficiency, for all time thereby rendering the land nonsustainable over the long run. In spite of the fact that the issue of soil saltiness and sodicity can be determined by the use of natural or artificial soil amendments, soil recovery measures have costs in addition to crop productivity loss. Also, it may not be conceivable to restore full health, and consequently profitability, of the soil utilising these soil amendments. Wastewater-actuated saltiness may diminish crop productivity because of general development concealment at the pre-early seedling stage, development concealment because of nutritional imbalance, and development concealment because of toxic particles. The net impact on development effects is a loss in crop yields and potential income for the farmers.

3.3.5 Effects on Groundwater Resources

Wastewater contains nitrogen, phosphorous, and other plant nourishment supplements in abundance of the crop requirements, consequently a wastewater irrigation system may bring about nutrition loading to the soil. The abundance of nutrients and salts may leach beneath the plant root zone and henceforth cause groundwater contamination. The filtering of saline salts and nitrates can possibly influence the nature of groundwater resources over the long run. Nonetheless, the actual effect relies on upon a large group of variables including depth of the water table, nature of groundwater, soil drainage, size of the wastewater irrigation system, and so on.

3.4 Environmental Impacts of Textile Effluent

The features of textile effluents vary and rely upon the type of textile manufactured and the chemicals used. Textile wastewater effluent contains high measures of agents that cause harm to nature and human well-being including suspended and dissolved solids, biological oxygen request, chemical oxygen interest, chemicals, odour, and colour (Solozhenko et al 1995).

Dyeing industry effluent modifies the colour and nature of the water which is perilous to the oceanic biological system and it reduces the sunlight diffusion which is key for photosynthesis. The vicinity of colours in water will bring about human well-being issues, for example, nausea, haemorrhage, and ulceration of the skin and mucous membranes. The vicinity of such lethal compounds additionally resulted in extreme harm to kidney, reproductive system, liver, brain, and central nervous system (Pala and Tokay 2002; Chavan 2001). Numerous dyes were known as cancer-causing agents, for example, benzidine and aromatic components, all of which may be developed as a consequence of the microbial digestion system. The highest rates of toxicity were noted for basic, diazo, and direct dyes (Karthik and Gopalakrishnan 2013a, b, c). Some algae and higher plants presented to effluent rich in disperse dyes at higher concentration tend to bio-aggregate the heavy metal particles from textile effluents (Karthik and Gopalakrishnan 2013b).

The chromophores in anionic and nonionic colours are basically azo group or anthraquinone kinds. The responsive cleavage of azo linkage is accountable for the development of harmful amines in the effluent. Anthraquinone-based colours are more impervious to degradation because of their fused aromatic structures and in this way, stay coloured for a more extended period of time in the wastewater (Turhan et al. 2009; Santos et al. 2007). The azo colour and pigment production plants deliver a waste which has low pH, high colour, high organic content, and low risk to biological degradation and can be characterised as a typical dye waste. The alkaline-reducing systems based on Na_2S in some dyeing recipes cause release of the effluent containing sulfur, which gives off a foul smell, and pollute ocean water/river water with their toxicity and devastate marine life.

The ecological effect of metals in wastewater effluents is additionally a vital issue confronted by the dye manufacturing and application industries today. The textile effluents contain trace metals including Cr, As, Cu, and Zn, which can harm the environment (Bello et al. 2013; Vautier et al 2001). The suspended solid concentrations in the effluents assume an imperative part in influencing nature as they consolidate with oily scum and meddle with the oxygen transfer mechanism of the air–water interface (Robinson et al. 1997). Inorganic substances in the textile wastewater make the water unacceptable because of the vicinity of a larger concentration of soluble salts. Inorganic chemicals, for example, hydrochloric acid, sodium hypochlorite, sodium hydroxide, sodium sulfide, and reactive dyes, are harmful to marine life. The organic compounds are found to experience chemical and biological changes that result in the expulsion of oxygen from water (Turhan et al. 2012; Ranganathan et al 2007).

The impact of wastewater from textile industries on fish, plants, and other water-living beings in the exposed water has been explored at different levels. Studies have also been extended to the plants and vegetables developed in the region presented to effluents from textile industries. The levels of metals, in particular, lead (Pb), cadmium (Cd), and chromium (Cr) in soil from the industrial territory and the plants grown on the soil were observed to be higher than in nonindustrial zones (Robinson et al. 2001). The outcomes acquired further affirmed the increased risk of growing vegetables around these industries. Consequently, the primary challenge for the textile chemical processing industry is to adapt suitable production strategies so they are all more environmentally friendly at an economical price, by utilising safer dyes and chemicals, and by decreasing the cost of effluent treatment.

4 Recycling of Textile Wastewater

Recycling has become an essential component in textile effluent treatment because of the need to control pollution. There are three approaches to diminish water contamination: (1) utilisation of modified/new/less polluting technologies; (2) effective treatment of textile effluent with the goal that it adjusts to determined release necessities; and (3) reusing textile waste a few times over before release (Sule and Bardhan 2001), which is considered the most practical solution. The treatment of textile effluent involves four or five different processes:

- *Segregation*. This should occur at the source of generation.
- *Preliminary treatment*. It includes various unit procedures to dispose of undesirable attributes of wastewater. Techniques incorporate utilisation of screen, grit chambers for removal of sand and substantial particles, communitors for pounding of coarse solids, pre-aeration for odour control, and removal of oil and grease.
- *Primary treatment*. It entails removal of settable solids prior to biological treatment. The general treatment units include: flash mixer plus flocculator plus sedimentation.
- *Secondary treatment*. It includes cleansing of wastewater basically with dissolved organic matter by microbial activity. Various methods are accessible yet the ones that are predominantly utilised are anaerobic and/or aerobic treatment techniques.
- *Tertiary treatment*. This mainly includes physical and chemical treatment processes that can be used after the biological treatment to meet the treatment objectives.

4.1 Preliminary Treatment

Conventional treatment systems have processes such as physicochemical treatment followed by biological treatment that are installed in the majority of textile industries. The preliminary treatment process flow is shown in Fig. 5.

The initial phase in wastewater treatment is to blend and equalise the wastewater streams that are released at distinctive times and diverse interims from distinctive stages in processes. Equalisation guarantees that the effluent will have uniform characteristics in terms of pollution load, pH, and temperature (Ajibola 2001; Slokar & Majcen 1997). Preparatory treatment techniques are mainly physical. The simple grit chambers use gravity to remove coarseness and dirt, which comprise to a great extent mineral particles that need to be removed before biological treatment. Coarse screens, commonly bars or woven wire, strain out large solids. Where organic material enters as vast particles, comminutors may be utilised to diminish particle size to upgrade treatment in later stages.

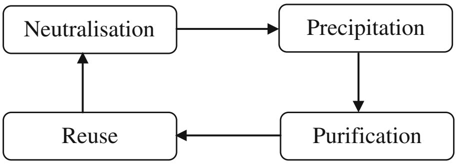

Fig. 5 Preliminary treatment process. *Source* Atul Kumar et al. (2011)

Equalisation basins blend influent wastewater to decrease the variations in concentrations of wastewater constituents and are likewise utilised with possibly toxic wastewaters to: (1) release effluent to treatment processes at a uniform rate, levelling out the impact of peak and minimum streams, (2) mix smaller volumes of concentrated squanders with larger volumes at lower concentrations, and (3) control pH to avert variances that could disturb the effectiveness of treatment system units by blending acid and alkaline wastes (Atul Kumar et al. 2011). Pre-aeration or pre-chlorination may be necessary to control odours if wastewater gets to be oxygen-deficient while going through the sewer collection system or to assist grease removal during primary elucidation. The gathered garbage is normally discarded in a landfill.

5 Primary Treatment

The second step in textile wastewater treatment is the removal of suspended solids, and excessive amounts of grease and oil and abrasive materials. The primary treatment includes screening, sedimentation, equalisation, and neutralisation, however, after the treatment of effluents by the above procedures some fine or suspended and colloidal particles cannot be productively removed. In such cases mechanical flocculation or chemical coagulation is utilised.

- *Screening*: Coarse suspended matter, for example, bits of fabric, filaments, yarns, and lint are uprooted. Bar screens and mechanically cleaned fine screens remove the majority of the strands. The suspended fibres must be removed preceding secondary biological treatment; else they may influence the secondary treatment system. They are accounted for to obstruct trickling filters, seals, or carbon beads.
- *Sedimentation*: The suspended matter in textile effluent can be uprooted productively and economically by sedimentation. This methodology is especially helpful for treatment of wastes containing a high percentage of settable solids or when the waste is subjected to combined treatment with sewage. The sedimentation tanks are intended to enable smaller and lighter particles to settle under gravity. The most widely recognised equipment utilised incorporates horizontal flow sedimentation tanks and centre-feed circular clarifiers. The

settled sludge is expelled from the sedimentation tanks by mechanical scrapping into containers and pumping it out along these lines.

- *Equalisation*: Effluent streams are gathered into a 'sump pit'. In some cases blended effluents are mixed by rotating agitators or by blowing compressed air from underneath. The pit has a tapered base for improving the settling of strong particles.
- *Neutralisation*: Typically, pH estimations of cotton-finishing effluents are on the alkaline side. Therefore, pH estimation of equalised effluent ought to be balanced. Utilisation of dilute sulphuric acid and boiler flue gas rich in carbon dioxide is not uncommon. Because the majority of the secondary biological treatments are successful in the pH 5–9, the neutralisation step is a critical procedure to facilitate.
- *Chemical coagulation and mechanical flocculation*: Finely separated suspended solids and colloidal particles cannot be productively removed by simple sedimentation by gravity. In such cases, mechanical flocculation or chemical coagulation is utilised.

Nearly 25–50 % of the incoming biochemical oxygen demand, 50–70 % of the suspended solids (SS), and 65 % of the oil and grease are uprooted during primary treatment. Some organic nitrogen, organic phosphorus, and heavy metals coupled with solids are likewise removed during primary sedimentation, however, colloidal and dissolved constituents are not influenced.

5.1 Secondary Treatment

In secondary treatment, the dissolved and colloidal organic compounds and colour present in wastewater are uprooted or reused to settle the organic matter. It is primarily done to reduce the BOD, phenol, and oil substances in the wastewater and to control its colour. This can be biologically done with the assistance of microorganisms under aerobic or anaerobic conditions. In aerobic techniques, bacteria and different microorganisms consume organic matter as food. They bring about the following sequential changes.

(i) Coagulation and flocculation of colloidal matter
(ii) Oxidation of dissolved organic matter to carbon dioxide
(iii) Degradation of nitrogenous organic matter to ammonia, which is then converted into nitrite and eventually to nitrate

Anaerobic treatment is principally employed for the absorption of sludge. The efficiency of this methodology relies on pH, temperature, waste loading, and the absence of oxygen and toxic materials. However, aerobic treatment of azo dye waste has been demonstrated to be inadequate by and large, yet it is regularly the commonplace technique for treatment utilised today (Smith et al. 2007; Asia et al

2006). Aerated lagoons, activated sludge systems, and biological filters are among the aerobic systems used in secondary treatment. Anaerobic treatment is primarily used to balance out the generated sludge.

5.2 *Tertiary Treatment*

Textile waste contains considerable amounts of nonbiodegradable chemical polymers. Primary and secondary treatment removes the greater part of BOD and suspended solids found in wastewater. However, it is inadequate to secure the receiving waters for industrial and/or domestic recycling. In this way, advanced wastewater treatment is utilised for additional organic and suspended solids removal, removal of nitrogenous oxygen demand (NOD), nutrient removal, and removal of toxic materials (Santos et al. 2007; Alinsafi et al. 2005; Correia et al. 1994). Advanced wastewater treatment could be classified into three major categories by the type of process flow scheme utilised:

1. Tertiary treatment
2. Physicochemical treatment
3. Combined biological–physical treatment

Tertiary treatment may be characterised as any treatment process in which unit operations are added to the stream plan following conventional secondary treatment. Physicochemical treatment is characterised as a treatment process in which biological and physical–chemical processes are mixed to realise the desired effluent. Combined biological–physical–chemical treatment is separate from tertiary treatment in that in tertiary treatment any unit methodologies are added after conventional biological treatment, whereas in combined treatment, biological and physicochemical treatments are blended.

5.2.1 Chemical Oxidation

This is the most utilised system for decolourisation by chemical means. This is accepted mainly due to its ease of application. The principal oxidising agents are ozone (O_3), hydrogen peroxide (H_2O_2), and UV irradiation. Combination of these oxidising agents demonstrated the maximum promise to treat textile wastewater (Kalra et al. 2011). Chemical oxidation removes the colour-containing effluent by oxidation in the aromatic ring cleavage of the dye molecules.

5.2.2 Ozonation

Ozone is an intense and fast oxidising agent that can respond with most species containing multiple bonds (e.g., C=C, C=N, N=N, etc.) and with simple oxidisable ions, for example, S-2, to form oxyanions, for example, SO_3-2 and SO_4-2. Oxidation by ozone is capable of degrading chlorinated hydrocarbons, phenols, pesticides, and aromatic hydrocarbons (Zhang et al. 2007; Gaehr et al. 1994).

5.2.3 Photochemical Process

This process degrades dye molecules into carbon dioxide and water by UV treatment. Degradation is brought on by the creation of high concentrations of hydroxyl radicals. UV light may be utilised to enact chemicals, for example, H_2O_2 and the rate of removal is influenced by the intensity of the UV radiation, pH, dye structure, and the dye bath composition (Ghosh and Gangopadhyay 2000).

5.2.4 Ion Exchange Process

The ion exchange process is utilised for the removal of inorganic salts and some particular organic anionic components such as phenol. All salts are made out of a positive ion of a base and a negative ion of an acid. Ion exchange materials are able to exchange soluble ions and cations with electrolyte solutions. Wastewater is passed over the ion exchange resin until the accessible exchange sites are saturated. Both cationic and anionic dyes can be expelled from dye-containing effluent in this way (Gaehr et al. 1994).

5.2.5 Electrochemical Process

The electrochemical processes are utilised as a part of the pulverisation of toxic and nonbiodegradable organic matter by direct or indirect oxidation/reduction. They have a lower temperature prerequisite than those of other equivalent nonelectrochemical treatments and there is no requirement for extra substance (Lin and Peng 1996).

5.2.6 Membrane Filtration

The rising cost of water and its debauched utilisation require a treatment process that is integrated with in-plant water circuits as opposed to as a consequent treatment (Machenbach 1998). From this point of view, membrane filtration offers potential applications. The benefits of membrane filtration are its ability to clarify, concentrate, and above all to separate dye continuously from effluent; it is a quick process with low spatial necessity and the saturate can be reused (Xu and Lebrun 1999).

Reverse Osmosis

Reverse osmosis is a familiar method which makes use of membranes that can remove a completely dissolved solid substance alongside ions and larger species from the effluents. Reverse osmosis membranes have a withholding rate of 90 % or more for most sorts of ionic compounds and produce a high quality of penetrate (Treffry-Goatley et al. 1983; Tinghui et al. 1983). Decolouration and elimination of chemical auxiliaries in dye house wastewater can be completed in a solitary step by reverse osmosis. Reverse osmosis allows the removal of all mineral salts, hydrolyzed reactive dyes, and chemical auxiliaries (You et al. 2008).

Ultrafiltration

This method is similar to reverse osmosis. The distinction between reverse osmosis and ultrafiltration is basically the holding properties of the membranes. Reverse osmosis membranes hold all solutes including salts, whereas ultrafiltration membranes hold macro-molecules and suspended solids yet the removal of polluting substances, for example, dye, is just somewhere around 31 and 76 %. Consequently salts, solvents, and low molecular weight organic solutes go through ultrafiltration membranes with the permeating water (Marcucci et al. 2002; Watters et al. 1991).

Nanofiltration

Nanofiltration can be situated between reverse osmosis and ultrafiltration. Nanofiltration is basically a lower pressure membrane where the immaculateness of permeated water is less imperative. This procedure is utilised where the high salt rejection of reverse osmosis is not necessary. Nanofiltration is favored when permeated with TDS yet without colour, COD, and hardness is adequate (Tang and Chen 2002).

Microfiltration

Microfiltration is suitable for treating dye baths containing pigment dyes (Mehta and Soham 2003), and for resulting rinsing baths. The chemicals utilised as part of a dye bath, which are not separated by microfiltration, will stay in the bath. Microfiltration can likewise be utilised as a pre-treatment for nanofiltration or reverse osmosis. The filtration spectrum indicating size and weight of molecules, operating pressure, and so on, with respect to reverse osmosis, ultrafiltration, and nanofiltration, is shown in Table 5.

Table 5 Filtration efficiency of different membrane systems

Process	Pore size (Micron)	Molecular weight	Application
Microfiltration	0.007–2.00	>100,000	Bacteria, pigments, oil, etc.
Ultrafiltration	0.002–0.10	1000–200,000	Colloids, virus, protein, etc.
Nanofiltration	0.001–0.07	180–15,000	Dyes, pesticides, divalent ions, etc.
Reverse osmosis	<0.001	<200	Salts and ions

Source Mehta and Soham (2003)

5.2.7 Adsorption

Adsorption is the method by which ions or molecules in one stage have a tendency to amass and concentrate on the surface of another stage (Alfons and Myung 2003). Physical adsorption happens when frail molecule bonds exist between the adsorbate and adsorbent. Examples of such bonds are Van der Waals interactions, hydrogen bonding, and dipole–dipole associations. Chemical adsorption happens when strong interspecies bonds are available between the adsorbate and adsorbent because of exchange of electrons. Adsorption can give good quality water (Walker and Weatherly 1997). The most utilised adsorbent for treatment is activated carbon.

5.2.8 Photocatalytic Degradation

Photocatalytic degradation is yet another process by which an extensive variety of dyes can be decolourised relying upon their molecular structures. Photocatalytic methods are picking up significance in the region of wastewater treatment because these methods bring about complete mineralisation with operation at mild states of temperature and pressure (Kiriakidou et al. 1999; Fu et al 2001).

5.3 Choice of Treatment Technologies

In light of the textile effluent attributes, suitable technologies could be distinguished to land at the likely mix of treatment technologies in a treatment plan. The advantages and disadvantages of various textile effluent treatment methods and guidelines for the selection of suitable processes are given in Tables 6 and 7, respectively.

Table 6 Advantages and disadvantages of some of the physicochemical and biological methods of textile effluent treatment

Processes	Advantages	Disadvantages
Coagulation–flocculation	Elimination of insoluble dyes	Production of sludge blocking filter
Adsorption on activated carbon	Suspended solids and organic substances well reduced	Cost of activated carbon
Electrochemical processes	Capacity of adaptation to different volumes and pollution loads	Iron hydroxide sludge
Reverse osmosis	Removal of all mineral salts, hydrolyzes reactive dyes and chemical auxiliaries	High pressure
Nanofiltration	Separation of organic compounds of low molecular weight and divalent ions from monovalent salts. Treatment of high concentrations	
Ultrafiltration–microfiltration	Low pressure	Insufficient quality of the treated wastewater
Fenton's reagent	Effective decolourisation of both soluble and insoluble dyes	Sludge production
Ozonation	Applied in gaseous state: no alteration of volume	Short half-life (20 min) of O_3
Photochemical	No sludge production	Formation of by-products
NaOCl	Initiates and accelerates azo bond cleavage	Release of aromatic amines
Bacteria (Aerobic)	• Decolourise both azo and anthraquinone dyes • Production of biogas	• Low decolourisation rates • Requires specific oxygen catalyzed enzymes • Requires additional carbon and energy sources
Bacteria (Anaerobic)	• Suitable for large-scale application • Takes place at neutral Ph for sludge treatment system • Allows obligate and facultative bacteria to reduce azo dyes	• Generation of toxic substance • Requires post-treatment • Immobilisation and recovery of redox mediator presents a challenge
Fungi	Decolourise anthraquinone and indigo-based dyes at higher rates	• Decolourisation rate is very low for azo dyes • Requires special bioreactor and external carbon source • Needs acidic pH (4.5–5) • Inhibition by mixture of dyes and chemical in textile effluents

Source Adinew (2012)

Table 7 Specific treatment options for textile effluents

Combination	Quality of effluent	Treatment options
High TDS, high COD, and equivalently high BOD	Waste is not easily biodegradable but toxic	• Thermal decomposition (based on calorific value) • Chemical oxidation by hydrogen peroxide, ozone, etc. • Evaporation plus secured landfill
High TDS, High COD, and high difference between COD and BOD	May be toxic; not suitable for biological treatment; mostly inorganic salts	• Chemical treatment (recovery, precipitation, etc.) • Evaporation plus secured landfill of evaporated residue
High TDS, high BOD, and low difference between COD and BOD	Highly organic effluent fully biodegradable	• Anaerobic plus aerobic treatment • If quantity is less, incineration (based on calorific value) plus secure landfill of incineration ash
High TDS, low BOD, and low BOD and COD difference	Only inorganic salts, no need for biological treatment	• Solar evaporation • Forced evaporation (after separation of volatile organic matter) • Membrane technologies
Low TDS, high COD, and equivalently high BOD	Highly organic effluent, may not be easily biodegradable	• Thermal decomposition • Chemical oxidation by hydrogen peroxide or ozone or sodium hypochlorite etc.
Low TDS, High COD, and high difference between COD and BOD	Highly inorganic effluent, not suitable for biological treatment	• Chemical recovery • Chemical oxidation and biological treatment
Low TDS, high BOD, and low difference between COD and BOD	Organic effluent, fully biodegradable	• Anaerobic and aerobic treatment
Low TDS, low BOD, and low BOD and COD difference	Low organic and low inorganic effluent	• Recycle and reuse (after preliminary treatment)

Source Chougule and Sonaje (2012)

5.4 *Economics of Textile Effluent Treatment Plant*

The capital cost, power consumption, and recurring cost of primary treatment, ultrafiltration, and RO treatment units are presented in Table 8. The basic establishment expense of the treatment and recycling plant including primary, ultrafiltration, and RO is Rs. 145 Iakh which is proportionate to Rs. 25,217 for every KLD of effluent. The operation and maintenance expense of primary treatment is Rs. 5.85 lakh every month, that is, Rs. 34.08/every KL. For the primary and ultrafiltration system together, the recurring expense comes to 9.04 lakh every month which works out to Rs. 52.40 every KL. The recurring expense of the whole system

Table 8 Capital and operation costs of treatment scheme for recovery of water

Treatment unit	Capital cost (Rs. Lakh)	Recurring cost (Rs. Lakh/m)
Primary treatment	30.0	5.88
Ultrafiltration	60.64	4.03
RO Plant	54.36	2.72
Total	145	12.63

Source www.cpcb@nic.in

Table 9 Economics of treatment scheme for recovery of water

Particulars	Primary treatment system	Primary and ultrafiltration system	Primary, ultrafiltration, and reverse osmosis
Capital cost (Rs. Lakhs)	30.0	90.64	145
Annualised capital cost [@15 % p.a. interest and depreciation, plant life 10 years] (Rs. Lakh)]	5.79	18.06	29.69
Operation and maintenance cost (Rs. Lakh/annum)	5.88	7.04	12.63
Annual burden (Annualised cost plus O&M cost) Rs. Lakh	11.85	27.1	42.5
Treatment cost Rs./Kl (without interest and depreciation)	34.08	52.40	73.22

Source www.cpcb@nic.in

accounts for 12.63 lakh every month. When calculated in terms of Rs./KL it comes out to be Rs. 73.22. The economics analysis of the treatment and recycling plant is given in Table 9.

6 Sludge Management in the Textile Industry

Sludge is the biggest by-item from wastewater treatment plants and its transfer is a standout amongst the most difficult natural issues in wastewater treating methodologies. Sludge from organic treatment operations is sometimes alluded to as wastewater biosolids. Before sludge can be arranged, it needs to be dealt with to a certain degree. The kind of treatment required relies upon the transfer strategy proposed. There are principally three final disposal strategies for wastewater sludge and sludge components and even though there are many 'grey zones', between these are clear-cut alternatives. Sludge and sludge components may be deposited on land (in landfills or special sludge deposits), in the sea (ocean disposal), or to a certain extent in the air (mainly as a consequence of incineration).

The textile sector uses amounts of water as high as 3,000 m^3/day and employs toxic products in their industrial processes such as metals, solvents, surfactants, and dyes. These processes produce large volumes of effluents that need to be adequately treated before their release into the environment (Sharma et al. 2007; Mathur et al. 2007). Biological treatment such as activated sludge has been the choice of the majority of the facilities (Kunz et al. 2002). However, this process generates a great quantity of sludge (Kunz et al. 2002) that is basically formed by the excess of biomass and substances that were not degraded during the biological treatment. An industry that consumes 50 m^3 of water per hour can generate 1–10 tonnes of sludge per day in wet basis (Balan and Monteiro 2001). The dewatered sludge in the effluent treatment plants is currently stored in the treatment unit premises.

It creates leachate with toxic metals and organic impurities and causes pollution of groundwater and land. It is very essential to manage the sludge generated from the treatment. Due to the disposal of sludge in the nonengineered landfills the groundwater as well as the soil was found to be polluted. So, disposal of sludge on Earth is a major problem existing today (Thomson et al. 1999). Presently enormous amounts of sludge are dumped in secured zones within the treatment plant premises and anticipate a suitable transfer technique. As the measure of sludge created by wastewater treatment plants expands, powerful reuse and safe transfer of sludge get to be more critical. The customary transfer routines such as landfilling and incineration may not be suitable on the grounds that the leachate from the landfilling destinations and the buildups from the incinerators lead to optional contamination. Moreover, such transfer choices are not financially practical. The sludge cannot be connected to ripe terrains in view of its synthetic substance.

6.1 Classification of Sludge

Biologically degradable and nondegradable organics and inorganic pollutants existing in the wastewater in soluble, colloidal, or suspended form are removed by a number of methods in wastewater treatment plants. The suspended solids and some of the dissolved solids that are present in the wastewater as well as those added or cultured by wastewater processes, are separated in the form of settleable solids (Bhalerao et al. 1997). Thus, sludges are the solid, liquid, or semisolid residuals (concentrated contaminants) generated as a by-product of wastewater treatment. Usually sludge contains 0.25–12 % solids by weight, depending upon the operations and the processes used (Metcalf Eddy Inc. et al. 2001). Sludge treatment/disposal represents 50 % of the capital and operational costs of a wastewater treatment plant (Aksu and Yener 1998; Isaacs et al. 1995). The various types of sludge with examples are given in Fig. 6 (Bhalerao et al. 1997).

Sludge can become a problem if improperly managed or disposed of. It can induce three impacts on the environment distinguishing the gaseous, liquid, and solid phases (Wett et al. 2002).

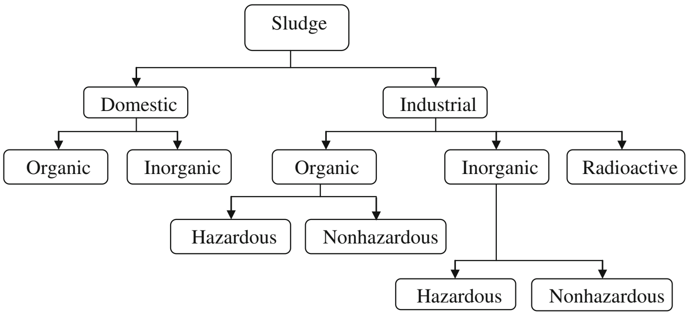

Fig. 6 Classification of common sludge. *Source* Bhalerao et al. (1997)

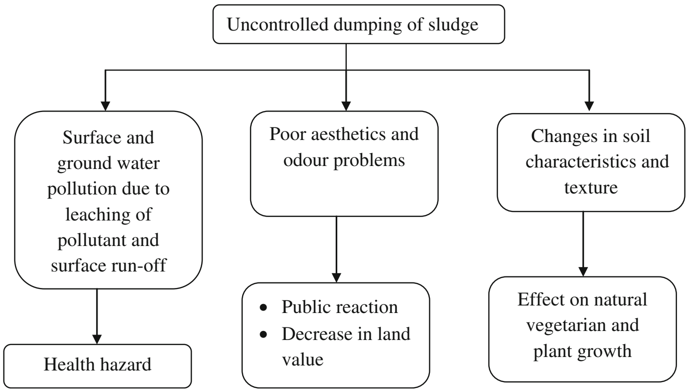

Fig. 7 Environmental impacts due to uncontrolled dumping of sludge. *Source* Wett et al. (2002)

- Impact on soil composition by the input of compounds enriched in the sludge (potentially toxic elements and compounds, pathogens, and parasites).
- Impact on the percolating water and consequently on the groundwater quality by the immobilisation of the compounds accumulated in the soil.
- Impact on the neighbouring environment by eventual problems of odour nuisance. The impact identification network due to uncontrolled dumping of sludge is given in Fig. 7.

6.2 Characteristics of Sludge

The sludge generated by effluent treatment needs to be further processed and disposed of safely. It is the by-product of the effluent treatment process, produced in the form of solid waste. In fact the production of sludge is a good indicator as to whether the ETP is running continuously. Sludge can be generated at different stages of treatment, including screening, primary settling, chemical precipitation, and the activated sludge or tricking filter stage, but most will come from the physicochemical stage of treatment. The sludge collected from different stages has different characteristics and compositions. It may contain breakdown products of the original factory waste or compounds created from the waste products and chemicals added to aid the treatment process. For example, nitrogen or phosphorous compounds from chemicals are added to the activated sludge process or sulphur compounds resulting from the large quantities of sodium sulphate used in dyeing. Despite the differences in the nature of the sludge from each process stage, all the sludge is usually combined and handled together.

Some knowledge of the sludge characteristics is required to select the best appropriate means of sludge handling and processing. The textile sludge characteristics are shown in Table 10.

Numerous researchers have described the chemical sludge from textile wastewater treatment plants. Semi-dried sludge tests produced by physico-concoction treatment of textile effluent from drying beds of an effluent treatment plant of a neighbourhood textile unit occupied with the development of faded and coloured/printed, cotton, polyester cotton, and thick fabrics were dissected by Ansari et al. (2001). Electrical conductivity values were also high (1.15–1.16 S/m). The sludge pH was found to be alkaline due to the addition of lime during the primary treatment (chemical coagulation) of the textile effluent. The total solid content was 20–25 % out of which 30–40 % was volatile solids. The calorific value

Table 10 Characteristics of textile sludge

Property	Value	Unit
Water content	26.22	Percentage
Specific gravity	2.66	–
pH	8.5	–
Cadmium	4.89	mg/kg
Copper	30	mg/kg
Total Chromium	88.66	mg/kg
Zinc	343.4	mg/kg
Nickel	51.48	mg/kg
Lead	59.1	mg/kg
Ferrous (Fe ++)	43100	mg/kg
Bi-Sulphates	0.0565	Percentage
Calcium	2317.92	mg/L
Magnesium	600.32	mg/L
Chlorides	0.036	Percentage
Total volatile solids	15.30	Percentage

Source Lara et al. (2007)

was very low (496.6 kcal/kg) and the specific gravity in the range of 1.11–1.12. The sludge also contained heavy metals including cadmium, chromium, cobalt, copper, lead, nickel, and zinc, reported by same researchers. Heavy metals such as arsenic and mercury were rarely present. Findings of these creators edified the way that the chemical sludge was rich in supplements components needed for plant development. Potassium was available in follow sum; whereas nitrogen and phosphorus were available in noteworthy sum in sludge. The sludge likewise contained a critical measure of minor components such as calcium, magnesium, and sulfur, and follow components such as copper and zinc. Balasubramanian et al. (2005) observed that the specific gravity of sludge was 2.4 and the volatile substance was 32 % which brought about high ash substance as an aftereffect of incineration and in this way it was not suggested as a sludge transfer alternative. They likewise examined the heavy metal fixations, for example, Cd, Cu, Total Cr, Zn, Ni, and Pb. Baskar et al. (2006) acquired dewatered and outside-dried sludge tests from the textile industry in Tamilnadu, India. They performed physico-substance portrayal of oven-dried sludge at 105 °C. They dissected diverse oxides, for example, CaO, Fe_2O_3, SiO_2, and Al_2O_3. Calcium oxide (28.4 %) was discovered to be the real constituent because of the expansion of an overabundance of lime amid the treatment transform and is additionally in charge of the high pH (10.5). The heavy metals such as Cd, Cu, Cr, and Zn were also analysed and the concentrations were found to be Cd (5.6 mg/kg), Cu (119 mg/kg), Cr (358 mg/kg), and Zn (190 mg/kg).

6.3 *Sludge Management Systems*

In later times, endeavours have been equipped towards the treatment of residential and industrial wastewaters whereas the sludges connected with them are only dumped untreated into the environment. Steps taken to treat wastewaters brought about the amassing of toxins into sludge. Sludge therefore becomes unstable, putrescible, and pathogenic. Sludge must therefore be treated before disposal or reuse in order to remediate our environment. The various sludge treatment processes are shown in Fig. 8.

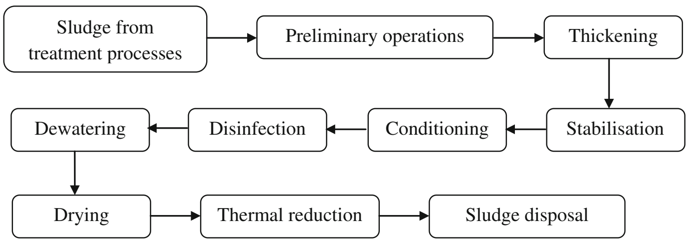

Fig. 8 Different processes of sludge treatment. *Source* Garg (2009)

6.3.1 Preliminary Operation

Sludge is produced in essential, auxiliary, and propelled wastewater-treatment processes. Primary sludge comprises settleable solids conveyed in the crude wastewater. Auxiliary sludge comprises organic solids and in addition extra settleable solids. Sludge created in the propelled wastewater may comprise natural and chemical solids. Sludge is mixed to deliver a uniform blend to downstream operations and methodology. Uniform blends are most essential in short-detainment time frameworks, for example, sludge dewatering, heat treatment, and incineration.

6.3.2 Thickening

Thickening is the act of expanding the solid substance of sludge by the evacuation of a segment of its fluid substance. Thickeners in wastewater treatment are utilised most effectively in uniting essential sludge independently or in blend with streaming channels. Water treatment squanders from both sedimentation and channel discharging can be compacted successfully by gravity partition.

6.3.3 Stabilisation

Sludge is balanced out to decrease its pathogens, remove hostile smells, and lessen or kill the potential for festering. Advances utilised for adjustment incorporate lime adjustment, heat treatment, high-impact absorption, anaerobic assimilation, and fertilising the soil.

6.3.4 Composting

The goal of sludge treating the soil is organically to balance out putrescible organics, demolish pathogenic life forms, and diminish the volume of waste. During treatment of the soil natural material experiences biological degradation, bringing about a 20–30 % lessening of volatile solids.

6.3.5 Conditioning

Conditioning includes the synthetic or physical treatment of sludge to upgrade its dewatering qualities. The two most connected conditioning systems are the expansion of chemicals and warmth treatment. Other conditioning methodologies incorporate solidifying, light, and elutriation.

6.3.6 Dewatering

Dewatering is a physical unit operation for diminishing the dampness substance of sludge. Sludge is not burned but land connected with it must be dewatered or dried. This can be attained by applying sand beds or by utilising mechanical dewatering equipment.

6.3.7 Drying

The reason for ooze drying is to diminish the water substance to under 10 % by evaporation, making sludge suitable for incineration or handling into compost. Economically drying is performed mechanically by the utilisation of auxiliary heat.

6.4 Sludge Treatment Process

6.4.1 Anaerobic Digestion

An anaerobic biological treatment process makes use of anaerobic bacteria to decompose the organic matter in anaerobic conditions. The procedure includes the anaerobic lessening of natural matter in the sludge by organic action. Anaerobic absorption comprises two stages that happen during sludge processing. The first comprises hydrolysis of the high atomic weight natural mixes and transformation of natural acids by corrosive framing microbes. The second stage is gasification of the natural acids to methane and carbon dioxide by the corrosive part of the methane framing microbes.

As of now, the anaerobic processing procedure (Fig. 9) is a crucial measure in the organic treatment of material colouring wastewater. Furthermore, there are

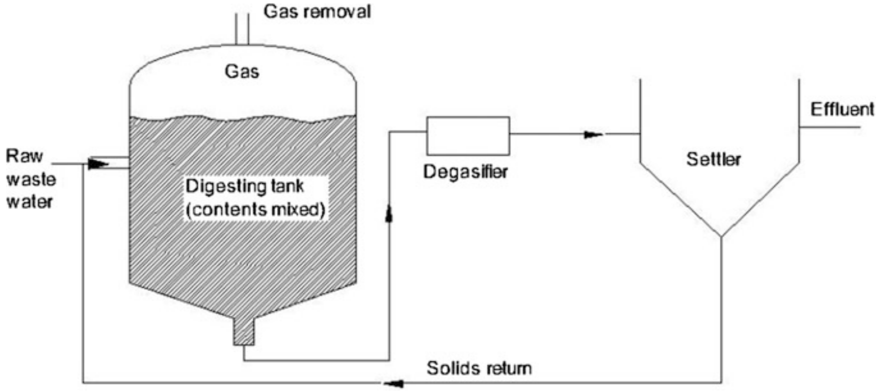

Fig. 9 Anaerobic digestion process. *Source* Bortone et al. (1995)

numerous different procedures utilised as a part of material colouring wastewater treatment, for example, upflow anaerobic sludge bed (UASB), upflow anaerobic fluidised bed (UABF), anaerobic confounded reactor (ABR), and anaerobic organic channel among others. Anaerobic absorption treatment of sludge will diminish the unstable organics by 40–50 % and decrease the quantities of pathogenic organics in sludge. The upsides of anaerobic absorption incorporate the generation of usable energy as methane gas (Kapdan and Kargi 2002; Sultana et al 2013). Advantages of this process are low solid production and very low energy input. Disadvantages include very high capital expenses, vulnerability to upsets from shock loads or toxics, and complex operation requiring skilled operators.

6.4.2 Aerobic Digestion

Oxygen-consuming processing sludge methodology is like the enacted sludge process. The capacity of high-impact absorption is to balance out waste sludge solids by long-haul air circulation, in this manner diminishing BOD and crushing volatile solids. It includes the immediate oxidation of biodegradable matter and microbial cell material in open tanks for an augmented period of time. In vigorous treatment the sludge is circulated through air for a stretched-out time, commonly 12–20 days. During this measure of time the organic material is decreased to about a large portion of its unique sum. Air circulation appears to be either regular or by method for mechanical aerators and diffusers. Long-haul air circulation of waste sludge makes a building material that opposes gravity thickening (Neeraj Kumar Garg 2009).

Advantages of Aerobic Digestion

- Volatile solids reduction approximately the same as anaerobic digestion
- Supernatant liquor with lower BOD concentrations
- Production of an odourless, biologically stable end product
- Recovery of most of the basic fertiliser values in the sludge
- Operation relatively easier
- Lower capital cost

Disadvantages of Aerobic Digestion

- Higher power cost associated with supplying oxygen
- Production of a digested sludge with poor mechanical dewatering characteristics
- Process significantly affected by temperature, location, and type of tank
- High operating cost

6.4.3 Solidification/Stabilisation Method of Sludge Reduction

Solidification/stabilisation (S/S) was utilised extensively in the 1950s to treat atomic wastes and after that was generally sought for the treatment of hazardous wastes in the mid-1970s (Barth 1990). The technology is being connected to:

(1) Treatment of industrial wastes
(2) Treatment of wastes preceding landfill transfer
(3) Treatment of contaminated land containing substantial amounts of soil containing contaminants (US EPA 1989)

The US EPA has distinguished the S/S as the best demonstrated available technology (BDAT) for 57 directed hazardous wastes (Shi and Spence 2004) and it is a standout amongst the most applied technologies at Superfund locales in the United States, being utilised at 24 % of the destinations around 1982 and 2002. Solidification is a procedure in which adequate amounts of hardening material are added to the perilous materials to result in a hardened mass of material (Cote et al. 1987). This increases the quality, diminishes the compressibility, and reduces the penetrability of waste.

Stabilisation is a process that changes the waste and its dangerous constituents into a frame that minimises the rate of contaminant relocation into nature or decreases the harmfulness, hence lessening the perilous nature of waste by utilising added substances. The S/S can be arranged into six noteworthy classes (Weitzman 1990):

(1) Cement-based binders
    - Portland cement
    - Cement kiln dust
    - Fly ash mixtures
(2) Lime-based binders
    - Lime
    - Lime kiln dust
    - Mixtures of fly ash and lime
(3) Absorbents
    - Hydro- and organophillic clays
    - Wood chips, sawdust, rice hulls
(4) Thermoplastic materials
    - Asphalt bitumen
    - Thermoplastic polymers
(5) Thermosetting polymers
(6) Vitrification

Cement-based fasteners have been most normally utilised for the treatment of numerous sorts of squanders, basically inorganic sludges containing substantial metals. Portland cement is most broadly utilised for S/S as a cover material. It is not utilised alone but rather as a significant fixing as part of various S/S forms. Numerous formulations have been created for the S/S procedure as per diverse sorts of squanders. This shows that Portland cement can be adjusted for suitable S/S procedures utilising fly ash, lime, slag, dissolvable silicates, and mud.

6.5 Environmental Impact of Sludge Disposal

The negative impact of different sludge disposal routes such as ocean disposal, incineration, sanitary landfill, landfarming, and beneficial land application are discussed below.

6.5.1 Ocean Disposal

Sea transfer is a restricted practice in many nations inasmuch as it can conceivably create negative effects on the marine environment. The sludge may contain pathogens, harmful natural mixes, and metals. Some of these may settle to the base of the ocean, adding to modify the benthic group, prompting passing of delicate species, or bio-amassing metals and harmful mixes in the trophic chain, at last coming to individuals through ingestion of defiled fish and mussels. Moreover, plankton growth and the resulting increase in dissolved oxygen consumption are furthered by nutrients in sludge (Lara et al. 2007).

6.5.2 Incineration

It is not considered as a last transfer strategy because it produces ashes as deposit, which must be satisfactorily disposed of. Contingent upon the sludge attributes, 10–30 % of the aggregate dry solids are changed into ashes, which are usually landfilled. Ashes landfilling is an extra effect identified with incineration, inasmuch as mixes not wiped out by thermal annihilation, such as metals, are gathered in the ashes (Al-Rekabi et al. 2007).

6.5.3 Landfill

As with any other form of wastewater sludge disposal, sludge monofills or codisposed of with municipal solid wastes require adequate site selection. The fundamental effect of landfills is on surface or groundwater that may be polluted by filtering fluids conveying nitrates, metals, natural mixes, and pathogenic microorganisms. As an after-effect of the anaerobic adjustment process as in landfills, gasses are created which need to be depleted and controlled. Ecological effects from landfilling wastewater slops may diminish if the site is found and secured all around, leachate treatment is given, gasses are legitimately taken care of, and the landfill is productively overseen and worked.

6.5.4 Landfarming

Landfarming is an aerobic treatment of the biodegradable organic matter that takes place on the upper soil layer. Sludge, site, soil, climate, and biological activity interact in a complex dynamic system in which the component properties modify with time. Because it is an open system, the wrong planning and management may cause contamination of water sources, food, and the soil itself.

6.5.5 Beneficial Land Application

Land utilisation of sludge may adjust the physical, substance, and natural soil qualities. A few progressions are useful, whereas others may be undesirable. Positive effects are identified with natural matter and supplements added to soil, cultivating its physical and compound properties and microbial action (Al-Rekabi et al. 2007; Heukelekian 1941). The negative effects are results of (a) aggregation of lethal components, predominantly metals, organics, and pathogens, on soil; (b) filtering of constituents coming about because of sludge disintegration, basically nitrates; (c) stream runoff, defiling adjacent regions and water bodies; (d) volatilisation of exacerbates that, albeit less huge, may prompt foul smells and vector fascination.

6.6 Reuse Potential of Textile Sludge

6.6.1 Sludge in Construction Material

Patel and Pandey (2009) concentrated on the conceivable outcomes of utilising textile industry sludge as a halfway substitution in development material. They described the sludge for different physicocompound parameters and heavy metals utilising standard routines, for example, BIS, APHA strategies and CPCB. The scientists dried the sludge and powdered it in a ball mill and after that they were made into blocks. They examined the viability of the blocks regarding solidifying time, unconfined compressive quality (UCS), and toxicity characteristic leaching procedure. They affirmed in their outcomes that the compressive quality estimation of the created square had lessened as the rate of sludge in cement was expanded.

Then again, the specialists cited different sorts of blocks utilised as a part of construction and specified that this likewise can be utilised. They specified that by contrasting the outcomes and models for distinctive sorts of development materials; that is, if there should arise an occurrence of block accessible in the scope of 3.5–35

Nmm-2, the quality of the cemented sludge–concrete blocks was discovered to be in the scope of 6.5–25 Nmm-2 complying with nine classes of brick. There are additional building materials such as empty and strong solid pieces having obliging quality 5 and 4 Nmm-2 and empty and strong lightweight solid blocks having quality 10.8 and 7.0 Nmm-2, dirt-based pieces with compressive quality of 2 Nmm-2, and lime–pozzolona solid pieces for clearing with a compressive quality of 3.5 Nmm-2. Accordingly considering the quality necessary for these development materials, the bond sludge pieces satisfy the prerequisites. The authors also identified that there is no significant leaching of heavy metals from the cement–sludge blocks. The heavy metal concentrations in the leachate were compared with US EPA regulatory limits and were found to be negligible compared to the stipulated limits.

Brick is a standout amongst the most widely recognised stonework units as a building material because of its properties. It has the vastest scope of items, with its boundless collection of examples, compositions, and hues. Numerous endeavours were made to join squanders into the production of bricks for samples, plaster of paris, fly ash, and sludge. Reusing such squanders by consolidating them into building materials is a functional answer for the contamination issue. Blocks made from dried sludge gathered from material wastewater treatment plants were examined by Lissy et al. (2014). Their test results indicated that the sludge proportion and the firing temperature were the two key factors influencing brick quality. They concluded that the brick weight loss on ignition was mainly attributed to the organic matter content in the sludge being burnt off during the firing process. With up to 6.66 % sludge added to the bricks, the strength measured at temperatures 5000 °C met the National Standards requirements. The control bricks and sludge bricks were cast with same condition for comparison. Because the test results showed more than the minimum compressive strength of an ordinary brick, they suggested the bricks made of sludge for the use of construction purposes.

6.6.2 Sludge in Concrete

The utilisation of sludge as development and building material changes the waste into helpful items as well as obviating the transfer issues. Characteristic assets such as clay are saved. Advantages of utilising sludge as an added substance to brick incorporate immobilising substantial metal in the terminated lattice, oxidising natural matter, and destroying any pathogens amid the terminating process and decreasing frost damage. The sludge from the textile chemical processing industry is used in concrete mixtures as an alternative disposal method by Kulkarni et al. (2012) Research conducted with the concrete mix M:20 was prepared with OPC of 43 grade cement. The twelve number 150 mm × 150 mm × 150 mm concrete cubes for M:20 grade are cast as per standard practice.. The textile industry sludge was utilised as fine total as a part of the scope of 4–36 % by weight at an addition of 4 %. The outcomes were examined regarding slump variation for M20 evaluation of concrete for distinctive sludge percentage. Their findings express that workability of cement (measured regarding slump qualities and compaction factor) continues decreasing as the rate of sludge increments. Material sludge up to 32 % can be effectively utilised as building material by including it in the M20 evaluation of cement.

Sludge from hosiery knitwear dyeing wastewater treatment plants was analysed and reported by Chandrasekaran (2001) showing bricks made from 10 % sludge and 90 % clay soil are suitable for use in construction of load-bearing walls. The bricks with 30 % sludge and 70 % clay soil as well as 20 % sludge and 80 % clay soil, having a strength of 2.8 N/mm and 4.5 N/mm, respectively, are ideal for construction of partition walls. Further burning of bricks also reduces the leaching of colour from them. The option of mixing small quantities of sludge, up to 15 % for load-bearing bricks and up to 30 % for partition bricks, is also a promising technoeconomic alternative.

Rajkumar and Hema (2011) investigated the potentials for incorporating the sludge during the casting of cement concrete cube specimens, mortar cube specimens, hollow blocks, pavement blocks, and mortar bricks with 4, 8, and 12 % of textile ETP sludge along with it. Their outcomes showed that the material ETP sludge was discovered to be better when utilised as a part of the nonstructural components. Especially, the 4 % sludge blended examples after 28 days curing were found to have great quality when contrasted with other blend rates. Despite the fact that the 8 and 12 % sludge-blended cement and concrete examples were found to take great loads, when contrasted with the reference specimen the load-conveying limits were extensively less. This study uncovers that textile ETP sludge can be blended with plain concrete solid specimens. This may be one of the routes for the safe transfer of sludge. The utilisation of textile ETP sludge in strengthened concrete solids will erode fortifications because of its destructive properties. Thus, sludge must be utilised as part of plain cement concrete specimens. The sludge-blended building specimens such as mortar bricks and hollow blocks can be utilised as a part of development of partition walls and compound walls. The textile ETP sludge-mixed pavement blocks can be utilised as part of pathways where the normal load is less. These systems for utilising sludge as a part of building materials is not merely another building material inasmuch as it additionally decreases environmental degradation because of inappropriate transfer of sludge.

6.6.3 Sludge in Clay Bricks

Sundaram et al. (2006) reported that addition of textile CETP with clay up to 30 % by weight in increments of 3 % and mixed well to form a homogeneous mixture, led to results indicating that the compressive strength is greatly dependent on the amount of waste in the brick and the firing temperature. The compressive strength of bricks decreases with the increase of waste mix in the bricks and increases with the increase of firing temperature. Baskar et al. (2006) studied the usage of waste sludge from a textile industry common effluent treatment plant as a clay substitute to produce quality bricks. All the bricks made with mix proportion (0–30 % waste) were found to satisfy the norms for shrinkage and weight-loss properties of quality bricks. The results indicate that the compressive strength is greatly dependent on the amount of waste in the brick and the firing temperature.

Sundaram et al. (2006) reported the estimated physicochemical properties of the waste-dried sludge. The addition of excess lime during the treatment process made the material brown in colour due to the contribution of a significant quantity of iron oxide (9.1 %) present in it. The addition of excess lime during the treatment process makes calcium oxide (28.4 %) one of major constituents in the sludge and is also responsible for its pH value (10.5). The average particle size determined based on the sieve analysis is 0.285 mm. The estimated physicochemical properties of the waste-dried sludge are given in Table 11.

The heavy metal concentrations in the leachate were compared with US EPA regulatory limits and were found to be negligible as compared to the stipulated limits. Therefore there is no significant leaching of heavy metals from the cement–sludge blocks.

Jahagirdar et al. (2013) discussed the reuse of textile mill sludge in fired clay bricks. The textile mill sludge was mixed together in different proportions (5–35 %) as the raw material in this study. The brick was fired at 600–800 °C for 8, 16, and 24 h. Based on the results, textile sludge can be added up to 15 % as it gives compressive strength above 3.5 MPa and the water absorption ratio is also less than 20 %.

The study demonstrated that textile mill sludge can be used as partial replacement for clays in burnt clay bricks. Textile mill sludge can be used up to 15 % without compromising on the compressive strength of 3.5 N/mm^2 and water absorption of 20 % as per the code requirements. This makes bricks porous resulting in lesser compressive strength and greater water absorption capacity. Tg-dta analysis showed there is a decrease in the weight of sludge with an increase in temperature because of the burning of organic matter present in the sludge, due to which a large number of voids are created in the body of the bricks. This results in a

Table 11 Physicochemical properties of the waste-dried sludge

Property	Value
Colour	Brown
Appearance	Agglomerated fine solids
Specific gravity	2.32
Average particle size	0.295 mm
Cadmium	5.6 mg/kg
Copper	119 mg/kg
Chromium	358 mg/kg
Zinc	190 mg/kg
Calcium (as CaO)	28.4 %
Iron (as Fe_2O_3)	9.1 %
Silicon (as SiO_2)	7.1 %
Aluminium (as Al_2O_3)	0.698 %

Source Balasubramanian et al. (2005)

porous brick structure and lesser compressive strength and increased water absorption. Firing temperature of 8000 °C and a firing period of 24 h gives good results in terms of compressive strength with the same percentage of sludge. Use of 15 % textile mill sludge in making burnt clay bricks is recommended and it will increase the bulk usage of sludge in building bricks, thus eliminating the problem of ultimate disposal.

Other researchers (Gobinath et al. 2013) investigated the effect of textile sludge addition in bricks based on the sludge obtained from a specific textile processing industry in Tirupur. The goal of their study was to distinguish the potential outcomes of utilising the sludge from the textile industry as a brick material. They found that augmentation in the rate of sludge by 50 %, water necessity, and additionally water assimilation of the blocks expanded by 19 %. Be that as it may, in the meantime, the compressive quality of the block diminished. On expansion of concrete, crusher sand, the compressive quality expanded by 30 % and the properties of the blocks made strides. The analysts presumed that the block began to get more fit on ignition, which was basically credited to the natural matter substance in the sludge being blazed off amid the terminating procedure. So they said that the sludge alone cannot be utilised for block fabrication yet the properties can be enhanced if utilised alongside the expansion of stabilisers such as concrete.

Raghunathan et al. (2010) developed a composite material that was a combination of ordinary Portland cement and dyeing industry effluent treatment plant sludge (DIETPS). They have made different compositions of mixtures and the test results of different mixtures were analysed. The economical composite (1:1.7) was directly used for brick manufacturing. The compressive strength of the bricks was similar to that of second-class bricks as per BIS. Researchers also developed aggregates by breaking down the bricks and using them as a replacement for sand in various percentages in M20, M30, and M40 concrete. The compressive strength of all the concrete mixes showed a decline in strength with an increase in the percentage of sludge. This may be due to the chloride and sulphates present. The findings of the result show only 5 % aggregates are advisable to use as a replacement for sand in concrete.

Jayakumar et al. (2013) utilised textile sludge in cement and steel slag as a partial replacement of coarse aggregate in the production of sludge-based paver blocks. Paver blocks were cast with sludge as cement replacement material at 0, 10, 20, 30, and 40 % and steel slag at 0, 10, 20, 30, and 40 % as coarse aggregate replacement for the above combinations. Tests for compressive strength at 7 days were conducted. Compressive strength on 28 days, flexural strength, rapid chloride permeability test (RCPT), and water absorption at 28 days are to be conducted on the paver blocks.

They concluded from their results that the use of textile sludge up to a maximum of 30 % substitution for cement may be possible in the manufacture of nonstructural building materials. Steel slag up to a maximum of 60 % substitution for aggregate may be possible in the manufacture of nonstructural building materials. The use of textile sludge and steel slag in these applications could serve as an alternative solution to disposal.

6.6.4 Sludge as Fertiliser

The motivation behind utilising sludge as part of agribusiness is incompletely to use supplements, for example, phosphorus and nitrogen, and mostly to use natural substances for soil change on a fundamental level. A wide range of sludge can be spread on farmland on the off chance that it satisfies the quality necessities (overwhelming metals, pathogens, pre-treatment) set around the rules of the particular nation. Regularly, the measures of sludge permitted to be spread are restricted by the measure of supplements needed by the plants and the aggregate sum of dry solids. All Western European nations and the United States have acts or bills on the utilisation of sludge on farmland. (Albert et al. 2006).

In some countries the regulations are so strict that only a minor part of the sludge can fulfil the conditions. The following requirements are common to these regulations:

- Pre-treatment (reduction of the water content in sludge, reduction of organic substances, reduction of pathogens)
- Restriction on the amount of heavy metals contained in sludge
- Restriction on the amount of dry solids and heavy metals spread per unit of land and time
- Restriction on the content of heavy metals in the soil on which sludge is spread, and requirements for the pH of the soil
- Restriction on the amount of nutrients added to the soil (nitrogen and phosphorus)
- Restriction on the choice of crops
- Restricted access conditions to farmland on which sludge is spread
- Legislative compliance control

Spreading of sludge on farmland offers these advantages (Albert et al. 2006):

- Utilisation of nutrients contained in the sludge, for example, phosphorus and nitrogen
- Utilisation of organic substances contained in the sludge for improvement of the humus layer of the soil (i.e., soil improvement)
- Known regulations on its application

Often the cheapest disposal route, sludge spread on farmland may have these disadvantages (Albert et al. 2006):

- Major investments in storage facilities as sludge can only be spread on farmland a few times a year
- Dependency on the individual farmers and considerable administration of agreements
- Lack of knowledge as to the content of organic micropollutants and pathogenic organisms in sludge and their impact on the food chain

Kakati et al. (2013) studied the potential reuse of textile effluent treatment plant sludge on the growth of green gram (*Vigna radiata* L) as a fertiliser. The textile sludge treated seedlings were subjected to analysis of various biochemical constituents in the leaves. The results showed that biochemical analysis coincided with the results of biometric analysis. All the biochemical parameters were found to be increased in the leaves treated with 10 % sludge along with 90 % of farmyard manure, followed by 100 % farmyard manure and 25 % sludge plus 75 % of farmyard manure. The untreated control treatment showed a moderate response in biochemical analysis such as in seed germination. Similarly, biochemical parameters were increased when the concentration of the textile sludge was decreased. It might be due to the toxic effect of the sludge. The reduction in protein content might be due to blockage of protein synthesis by heavy metals of the sludge during plant growth. Sugars are phenolics and the depletion of sugars in treated plants would result in the depletion of phenolic compounds.

They have concluded that above a 75 % sludge and 25 % farmyard manure combination an inhibitory effect of plant growth showed, and 100 % sludge as fertiliser showed adverse effects on plant growth. A combination of 10 % sludge plus 90 % farmyard manure enhanced plant metabolism by increasing all the biometric parameters and enzyme activities. The sludge material may be used as a fertiliser at low concentration to enhance plant growth considerably. Accumulation of toxic materials if any in the plant system after treatment should be studied in detail.

Umadevi et al. (2014) conducted a pot culture experiment to study and compare the effect of terry towel textile sludge application on enzyme activity of fast-growing pulp wood tree species raised under sandy loam and clay loam soils. They used three fast-growing pulp wood tree species, the she oak (*Casuarina junghuhniana* Miq.), forest red gum (*Eucalyptus tereticornis* Sm.), and white lead tree (*Leucaena leucocephala* Lam. de Wit), and six treatments having various dosages of terry towel textile sludge and farmyard manure. The research findings showed that the activities of plant enzymes such as catalase and peroxidase were analysed at 60 and 120 days after planting. The comparisons among three species revealed that *Eucalyptus tereticornis* responded well in sludge-treated soils and recorded significantly higher catalase activity; whereas *Casuarina junghuhniana* exhibited higher peroxidase activity. However, the wide variety of substances such as heavy metals and other potential pollutants in textile solid waste limits the use of these residues as organic amendments. They suggested further long-term studies in this area.

Maddumapatabandi et al. (2014) developed a slow-releasing organic fertiliser from the textile sludge. As textile sludge is a rich source of macro- and micronutrients, the researchers analysed it to assess its possibilities for development into a slow-releasing organic fertiliser. Their results revealed that textile sludge was the best source of primary plant nutrients, namely nitrogen, phosphorous, and potassium. More important, they experimentally found the average nitrogen content in textile sludge (1.758 %) was significant compared to nitrogen content present in commonly used manure. The average phosphorus (0.26 %) and potassium (0.34 %) content were approximately similar to the amount of phosphorus (0.3–0.6 %) and potassium (0.5 %) concentrations found in common manure. In addition the results revealed the presence of a range of micronutrients specifically Ca, Mg, Fe, Cu, and Ni which are essential requirements for plant growth.

A series of studies conducted by Garg et al. revealed that textile mill sludge can be used as a vermicompost for the growth of plants. In their first attempt they used the sludge mixed with cow dung for the growth of *Eisenia foetida* in different ratios in a 90-day composting experiment. In their study the developed vermicomposting resulted in a significant reduction in C:N ratio and increase in total Kjeldhal nitrogen (TKN). Total K and Ca were lower in the final cast than the initial feed mixture. Microbial activity measured as dehydrogenase activity increased up to 75 days and decreased on further incubation. Total P was higher in the final product than the initial feed mixture. Total heavy metal contents were lower in the final product than the initial feed mixture. They have suggested that solid textile mill sludge can be potentially useful as a raw substrate in vermicomposting if mixed with up to 30 % cow dung (on a dry weight basis). The results also indicated that the cast quality is only slightly affected, but a higher percentage of sludge in the feed mixture retards the growth and sexual maturity of the worms used and also affects the quality of the compost. (Priya Kaushik and Garg 2003).

The authors also analysed the growth and fecundity of *Eisenia foetida* in textile mill sludge mixed with cow dung and/or agricultural residues as well as assessed the physical and chemical changes in different substrates. They monitored the growth, maturation, mortality, cocoon production, hatching success, and the number of hatchlings in a range of different feed mixtures for 11 weeks in the laboratory under controlled environmental conditions. They found that the maximum growth and reproduction were obtained in 100 % cow dung, but worms grew and reproduced favorably in 80 % cow dung plus 20 % solid textile mill sludge and 70 % cow dung plus 30 % solid textile mill sludge also. Addition of agricultural residues had adverse effects on growth and reproduction of worms. They have also mentioned that the final product obtained in this study had a lower C:N ratio, rich in TKN, TP, TK, and TCa than initial feed mixtures. The pH of the final product was lower than initial feeds, which may be attributed to evolution of CO_2 and accumulation of organic acids. (Priya Kaushik and Garg 2004).

Priya Kaushik and Garg (2005) extended their work with the aim of assessing the growth and fecundity of *E. foetida* in solid textile mill sludge spiked with poultry droppings as well as to assess the physical and chemical changes in different substrate mixtures. The growth and reproduction of *E. foetida* was monitored in a range of different feed mixtures for 77 days in the laboratory under controlled experimental conditions. The maximum growth was recorded in 100 % cow dung. Replacement of poultry droppings by cow dung in feed mixtures and vice versa had little or no effect on worm growth rate and reproduction potential. Their results mentioned that the vermicomposting resulted in significant reduction in the C:N ratio and an increase in nitrogen and phosphorus contents. Total potassium, total calcium, and heavy metals (Fe, Zn, Pb, and Cd) contents were lower in the final product than initial feed mixtures. The pH of the final product was lower than initial feeds, which may be attributed to evolution of CO_2 and accumulation of organic acids. The final product was more stabilised as demonstrated by a significant decrease in the C:N ratio.

A study conducted by other researchers showed the potential of *Eisenia foetida* in composting the different types of organic substrates (i.e., textile sludge, textile fibre, institutional waste, kitchen waste, agro-residues) and quality of vermicompost thus produced. Their results indicated that the efficiency of the vermicomposting process using *E. foetida* (epigeic species) on the basis of nutrient content (N, P) of the compost was found maximum for industrial waste followed by institutional waste, agro-residues, and kitchen waste. Experimental data provide a sound basis that vermicomposting is a suitable technology for conversion of different types of organic wastes (domestic as well as industrial) into value-added material (Payal Garg et al. 2006). Araujo et al. (2007) studied the effect of composted textile sludge on growth, nodulation, and nitrogen fixation of soybean and cowpea in a greenhouse experiment. Their study verified that the composted textile sludge was not harmful to growth, nodulation, and nitrogen fixation of soybean and cowpea; however, the researchers suggested that proper consideration should be given to the metal content of textile wastes. In contradiction to earlier findings, the researchers showed that none of the parameters examined were negatively affected by the heavy metals in composted textile sludge. This study provided insights to the possibilities of using textile mill sludge for plan growth.

Priya Kaushik et al. (2008) reported the possibilities of mixing textile mill waste with the range of 20–30 % with cow dung to develop a vermicompost mix. They analysed the effect of inoculation, of nitrogen fixing *Azotobacter chroococcum* strain, *Azospirillum brasilense* strain, and phosphate solubilising *Pseudomonas maltophila*, on nitrogen and phosphorus content of vermicomposts prepared from cow dung and cow dung spiked textile mill sludge. Their research findings were more supportive and provided an alternative strategy to dispose of textile mill sludge. It is evident from their results that *A. chroococcum*, *A. brasilense*, and *P. maltophila* bacterial strains proliferated rapidly, fixed nitrogen, and solubilised MRP during the incubation period. *A. chroococcum* and *A. brasilense* helped to increase the nitrogen content by activating the nitrification bacteria and reducing denitrification of the substrate. *P. maltophila* increased TAP content by conversion of insoluble MRP to solubilised phosphate during the inoculation period.

6.6.5 Other Methods Used in Sludge Management

Sludge has likewise been utilised as a part of cement manufacturing. This industry is profoundly energy concentrated; however, the substantial energy expenses of making clinker at 15,000 °C can be balanced by using biosolids as an easy and promptly accessible supplemental energy source. Besides, biosolids can be infused into the fumes' gas load to kill NOx outflows utilising the thermal energy of the hot fumes' gasses consolidated with ammonia contained in the biosolids to change over NOx to nitrogen gas (Kahn and Hill 1998). A technique called 'sludge-to-fuel' (STF) involves a process that converts sludge organic matter into an incinerable oil using a solvent, atmospheric pressures, and temperatures in the range of 200–300 ° C (Millot et al. 1989) or, alternatively, high pressures in the range of 10 MPa combined with high temperatures (Itoh et al. 1994). One framework utilises an aqueous reactor to change over mechanically dewatered sludge to oil, char, carbon dioxide, and wastewater. The char, making up 10 % of the item, is sent to a landfill, and the vaporous emanations are dealt with and discharged to the air. The delivered oil has give or take 90 % of the warming estimation of diesel fuel and can be sold to off-site clients or refineries (Hun 1998).

Jahagirdar et al. (2015) used the incinerated textile mill sludge as an absorbent for dye removal from wastewater. In their study they incinerated sludge at 800 °C and examined the ash structure. The scanning electron microscopic study uncovered that the sludge ash was made permeable in nature and they identified that it can be utilised for dye-absorbing applications as a retentive. They attempted the examination with Remazol Blue in the acidic pH range. The outcomes demonstrated that the sludge fiery debris indicated higher shading evacuation effectiveness.

7 Conclusions

Supportable development is based on three essential premises: financial development, natural parity, and social progress. Financial development accomplished in a manner that does not consider environmental concerns will not be manageable over the long run. Subsequently, sustainable development needs careful integration of ecological, financial, and social needs keeping in mind the end goal to accomplish both an increased standard of living in the short term, and a net gain or equilibrium among human, natural, and monetary assets to support future eras in the long run. Waste minimisation is of huge significance in diminishing pollution load and production costs. This chapter discussed the different systems to treat cotton textile effluents and to minimise pollution load. The best treatment process for satisfactory recycling and reuse of textile effluent water includes the accompanying steps. At first, refractory organic compounds and dyes may be electrochemically oxidised to biodegradable constituents before the wastewater is subjected to biological treatment under aerobic conditions. Colour and odour removal may be accomplished by a second electro-oxidation process.

Pollution prevention routines are those measures that dispose of or diminish contamination before off-site recycling or treatment. The control technology to minimise the effect because of the process rejects/wastes varies with quantity and qualities, desired control efficiency, and financial matters. Therefore, the best alternative is to avoid pollution. This preventive approach refers to a ladder that involves (i) prevention and reduction, (ii) recycling and reuse, (iii) treatment, and (iv) disposal, respectively. In source reduction, production methods are analysed to uncover conceivable outcomes for decreasing the amount of discharged air, water, and land pollutants. This can be accomplished by conservation\optimisation of chemical utilisation, substitution of chemicals, process changes, equipment modification, raw material control, and improved maintenance and housekeeping. Reusing and recycling water and chemicals can likewise reduce the measure of toxins discharged.

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Recycled Paper from Wastes: Calculation of Ecological Footprint of an Energy-Intensive Industrial Unit in Orissa, India

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Abstract Various reports and scientific literature relating to sustainable development suggest that producers and consumers are adopting alternative performance evaluation indicators for monitoring business activities in addition to traditional economic performance indicators. In this chapter one such new index, the ecological footprint (EF) has been used for assessing the sustainability of an industrial unit manufacturing paper from wastepaper in India. EF has been chosen as it is a transparent approach that provides comprehensive footprint information. This was deemed to be a more appropriate approach as it can be used by the company as a communication tool thereby helping to identify the environmental benefits of implementing improvement scenarios. Recycling paper is a very efficient way to reduce environmental impacts. Putting wastepaper to its best possible use can lower emissions and thereby lower the level of consumption of natural resources. Using recycled paper has been considered to be an attribute for making the environment more sustainable both in the paper and other industries. Recycling paper is an integral part of any solid waste management plan. In this work EF of paper produced by a paper production unit in Balasore, Orissa, India, manufacturing 'newsprint' and 'printing & writing paper' has been calculated for the year 2011–2012. The manufacturing unit of the case study manufactures 1,25,414 MT tonnes of paper per annum, primarily from wastepaper. Results reveal that the total ecological footprint of the case study unit in 2011–2012 ranged between 60,852–62,751 ha and the ecological footprint per tonne of production varies between 0.48–0.50 ha for the year 2011–2012. This low EF per ton of production is because the unit is using recycled paper for production of its final output. The hotspots or factors affecting the size of the unit's footprint are namely: energy (generation of electricity in captive plant through coal fired steam turbine), materials (i.e., wastepaper, pulp, and chemicals required for the manufacturing of papers produced), and wastes such as fly ash, paper, plastic, sludge, and the like generated in the process of production. An effort has been made to assess scopes for interventions to help reduce the EF for the

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production unit under study. Alternative scenarios are identified and based on interaction with the unit the barriers were identified towards implementation of solutions for reducing EF under alternative scenarios.

Keywords Ecological footprint · Wastepaper/recycled paper · Indian industrial unit

1 Introduction

Managing rapid industrialisation and economic growth without causing environmental degradation is a major challenge towards sustainable development. Recycling paper is an efficient way to reduce environmental impacts. Putting wastepaper to its best possible use can lower emissions and lower the level of consumption of natural resources. Using recycled paper has been considered to be an attribute for making the environment sustainable both in paper and other industries. Recycling paper is an integral part of any solid waste management plan. It is one of the three Rs familiarly used: reduce, reuse, and recycle. The example in Table 1 shows how the use of recycled paper (instead of virgin paper) can help to reduce environmental impacts or generate environmental benefits.

Here an effort has been made to make an assessment of the environmental impact of producing paper from wastepaper/recycled paper by using the new environmental index, the ecological footprint (EF).

A literature review suggests that the ecological footprint is one of the measures to assess environmental performance (Wiedmann and Barrett 2010). The EF measures in hectares(ha) the use of available bioproductive space, and is a measure of how much productive land and water an economic agent requires using prevailing technology to produce the consumption level and to absorb all the waste generated. It acts as a resource accounting tool to keep track of the effect of humanity's consumption of

Table 1 Virgin paper versus recycled paper

	1 Tonne Virgin Fibre Paper	1 Tonne 100 % Recycled Paper	Environmental Savings from Recycled Contents (%)
Trees	24 trees	0 Trees	100
Energy	33 million BTUs	22 million BTUs	33
Greenhouse gas Released—CO_2 Equivalent	5601 pounds	3533 pounds	37
Wastewater	22853 gallons	11635 gallons	49
Solid waste	1922 pounds	1171 pounds	39

Source Kinsell, Susan., (2012):Paperwork: Comparing Recycled to Virgin Paper, Re Paper Project natural resources and generation of wastes. A number of studies have estimated the ecological footprint to measure the dependence of a given population on the natural environment and assess ecological deficits (Wackernagel and Rees in 1996; Wackernagel et al. 1999b). This approach has been used in the calculation of the ecological footprint and biocapacity for more than 200 countries, including Australia (Lenzen et al. 2001); New Zealand (McDonald et al. 2004); Austria, the Philippines, South Korea (Wackernagel et al. 2004), and China (Chen et al. 2007) to name a few along with other nations and the world (Ewing et al. 2010) at the local and regional level (Simmons and Chambers 1998; Simmons et al. 2000; BFF 2002), and Stockholm Environment Institute (SEI; Barrett et al. 2002), for the university campus (Li et al. 2008), for businesses (Chambers & Kevin (2001) ;Barret and Scott 2001; Lenzen 2003; Loone et al. 2008), life-cycle assessment of products (Huijbregts et al. 2008), ecological footprint of products and the influence of nutrients and non-CO_2 greenhouse gas emissions (Hanafiah et al. 2010), and the biodiversity footprint of products compared to the ecological footprint of the products (Hanafiah et al. 2012). Applications of the footprint method to assess industrial systems are not too many. Ecological footprint estimation for paper pulp production was analysed with the help of this component-based approach by Kissinger et al. (2007). In India ecological footprint analysis has been used for estimating the impact of tourism on the sustainability of different states (Cole and Sinclaier 2002; Sonak 2004), the expansion of city limits over natural landscapes (Arabindo 2006; Burte and Krishnankutty 2006), and for a university campus (Thattai et al. 2007), and transport for the city (Munshi 2007) among other applications.

The industrial sector plays an important role with 27.3 % GDP share (in 2012–2013) in the fast economic growth of India (http://indiabudget.nic.in/es2013-14/echap-01.pdf). The paper industry makes a variety of products, namely printing and writing papers, tissue products, newsprint, and paperboard packaging to name a few. At present in India there are 759 pulp and paper mills with an installed capacity of 12.7 million tonnes producing around 10.11 million tonnes/annum of paper/paperboard and newsprint out of the total world production of around 402 million tonnes (Kulkarni 2013). The Indian paper industry structure consists of small-, medium-, and large-sized paper mills having production capacities ranging from 10 to 1150 tonnes per day (Kulkarni 2013). The industries employ wood, agro residues, and recycled/wastepaper as the major raw material for manufacturing different varieties of paper, paperboard, and newsprint. Paper mills in India continue to face challenges with forest (wood)-based raw materials. The projected demand for paper by 2025 is 24 million tonnes leading to an estimated shortfall of 12 million tonnes of wood (Kulkarni 2013). This is because agro-based industries are closing down due to pollution-related problems and wastepaper quality and price putting pressure on the paper industry (Kulkarni 2013). In 2011 the share in production of paper from recycled/waste, wood-based raw materials, and agro residues (such as bagasse, wheat, rice straw) had been 47, 31, and 22 %, respectively (Kulkarni 2013).

It is important to know the impact on ecological resources and nonrenewable energy consumed by the industries in their production process. A literature survey in the Indian context reveals that a considerable gap in knowledge exists in the performance evaluation of the industries through resource use assessments. In this chapter an attempt is made towards estimation of the ecological footprint for one paper production unit located in the Balasore District of Orissa, India. It was established in 1983 as an agro-based unit for manufacturing 'newsprint' and 'writing and printing' paper. The plant is an ecofriendly 100 % wastepaper (recycled)-based manufacturing company with a capacity of 114,000 tonnes per annum (TPA) of newsprint and 16,000 TPA of writing and printing grade of paper. The present sales turnover is 3800 million Indian Rupees (INR). The unit is ISO 9001, ISO 14001, 18001 excellence and consistency certified and exports writing and printing paper to Sri Lanka, Nepal, Bangladesh, and Myanmar. The study site covers a total area of 69 acres [i.e., 27.923 hectres (ha)] which includes 48 acres of built-up area of the mill, road area of 14 acres, and parking area of 7 acres. The unit produced 125,414 MT of 'newsprint' and 'writing and printing' paper in the year under consideration, 2011–2012, using 77 % of local wastepaper and 23 % of imported raw material (information collected from face-to-face interview). The EF of paper manufactured from wastepaper has been calculated for the year 2011–2012 and has been described in different subsections of Sect. 2.1.

The case study unit chosen for the present study is a representation of an important segment of Indian paper manufacturing units and belongs to a company which produces paper from wastepaper to meet the sustainable demand in the market.

This chapter also demonstrates the ways in which the ecological footprint can be estimated using unit-level data collected through the face-to-face interview method. The final choice of study unit was mainly determined by the willingness of the unit to cooperate in data sharing and time commitment for face-to-face interviews.

The remaining part of the chapter is structured as follows. Section 2 provides a detailed description of the research methodology adopted, and Sect. 3 presents results, analysis, and limitations of the study, and some possible policy interventions for the paper production unit are suggested. The chapter concludes with Sect. 4.

2 Methodology for Estimating Ecological Footprint

In this study the Eco-Index™ methodology developed by Best Foot Forward (Chambers et al. 2000) utilising a 'component' or bottom-up approach to perform ecological footprint analysis has been adopted. The component-based approach of footprinting is applied to measure the footprint of individuals and organisations. This approach divides the organisation's activities into different categories of consumption (energy, materials, etc.), then adds up the values to calculate the total footprint of activities (Chambers et al. 2000). Separating the EF of each individual component demonstrates how each one of these components contributes to the total demand or total EF. The reason behind selecting this EF index is that it considers various components of resource use and waste production by an entity. Also this new index is suitable for calculating the EF values of certain activities using data appropriate to the region under consideration (Simmons et al. 2000). Another advantage of this adopted new index is that it is informative and is easier to communicate. The break-up of each individual activity and its resultant impacts has a well-defined beneficial appeal to those concerned with policy making and education. The literature suggests the use of a component-based approach for a university campus (Li et al. 2008) or for businesses (Barret and Scott 2001; Lenzen 2003; Loone et al. 2008) using a standard equation (Lyndhurst 2003).

However, EF as an index is not free from disadvantages. The availability of reliable and detailed data poses a serious challenge to make comparative studies at the national and international level. Being a very data-intensive methodology, small assumptions made in the absence of required data can lead to different results. It is true that the method is not currently used by ISO standards and there are alternative methods also suggested in the literature (Wiedmann and Barrett 2010), still estimating this one single index provides interesting information to identify the relative resource behaviour of a production unit as well as to identify hotspots.

For calculating the ecological footprint of the industrial unit the following equation is used (Lyndhurst 2003):

$$\begin{aligned} EF_{BUS} = {} & EF_{L(km^2)} \times CF + EF_{EN(GWh)} \times CF + EF_{FT(tonne\ km)} \times CF \\ & + EF_{ET(passenger\ km)} \times CF + EF_{WT(m^3)} \times CF + EF_{M(tonnes)} \times CF \\ & + EF_{W(tonnes)} \times CF\ ) \end{aligned} \tag{1}$$

Let

EF_{BUS} Total ecological footprint of business unit
EF_L Ecological footprint of land use in km^2 sq km
EF_{EN} Ecological footprint of energy use in GWh
EF_{FT} Ecological footprint of freight transportation in tonne-km*
EF_{ET} Ecological footprint of employee transportation in passenger-km*
EF_{WT} Ecological footprint of water consumption in m^3 cubic metres
EF_M Ecological footprint of material use in tonnes
EF_W Ecological footprint of waste in tonnes
CF Conversion factors in ha/year (hectare/year)

(*EF of freight and employee transportation were excluded due to nonavailability of adequate data.)

2.1 Process Description

Ecological footprint analysis of the selected paperboard and paper production unit was studied on the basis of the primary data collected from a factory located in the state of Orissa, India. The paper manufacturing process is a continuous process.

A brief description of the technological process, major equipment, and facilities of the production unit are given.

2.1.1 Paper Manufacturing Process

The paper is manufactured in the 'Fourdrinier machine' having different subsections. The Fourdrinier machines are modern-day continuous paper machines comprising four sections from beginning to end; first the wet end, then the press section, then the drier section, and finally the calendar section. These machines were first put to commercial use in 1804 in England by the Fourdrinier brothers and have since been known as the Fourdrinier paper machines (http://www.thepapermillstore.com/paper-machine-fourdrinier). The necessary amount of fibre, fillers, and other substances are supplied to the said machine in the form of fluid suspension to a moving woven wire screen for making paper.

2.1.2 Sheet-Forming Section

The stock is discharged on the moving wire and stock is deposited on the wire. This wire section consists of elements including rolls and foils for drainage of water and finally a vacuum is applied to improve dryness up to 20 %.

2.1.3 Press Section

At the end of the Fourdrinier table the free water contained in the wet sheet is removed so as to improve the sheet compactness.

2.1.4 Drying

The sheet is passed through the drying cylinder by means of a drying screen. Steam is supplied to heat the cylinder.

2.1.5 Calendaring

The function of the calendar is to produce the desired finish and thickness of the sheet.

2.1.6 Reeling

Finally the paper is reeled on a moving drum for conversion.

2.2 Study of Boundary and Data Collection

For calculating the ecological footprint of this case study production unit under consideration, the consumption resulting from the activities relating to the production of finished goods has been included. Data relating to the period 2011–2012 have been gathered from the production unit using a preset questionnaire (enclosed as Appendix 1). To be able to implement Eq. (1) the data relating to these components have been collected:

- Land use
- Energy use
- Water use
- Wastepaper and forest land use (material use)
- Wastes generated in the production process

  Data relating to freight movement and transportation of employees were not available.

  Primary data based on the personal interviews of environmental managers of the selected unit (during the time period 2011–2012) are the source of information. The formula given in Eq. (1) has been used to calculate the total EF of the unit. Primary data relating to each component (e.g., land, energy, water, wastepaper, wastes, etc.) have been multiplied by their corresponding conversion factors (CF). The conversion factors have been gathered from Chambers et al. (2000), Barrett et al. (2002), and Burgess and Lai (2006). Table 2 shows the dataset collected from the production unit, their corresponding conversion factors, and the sources from which such factors have been adopted for the purpose of calculation.

In this analysis *built-up land* constitutes the built-up area, total parking area, and road length of the production unit. *Grid electricity* includes the electricity purchased from the state grid and also electricity consumed for treating wastewater plants. The unit has two captive steam turbines generating 20 MW of electricity. The footprint area per unit of *water consumption* includes water consumed in process, cooling, and water supplied for domestic use. However, the same footprint conversion rate has been applied for water used for processing and cooling. The footprint area per unit of *material use* (wastepaper mainly and a small quantity of *purchased pulp* in the case of this study) has been calculated. The EF of wastepaper material used has been calculated by using the conversion factor of recycled paper (Burgess and Lai 2006). The wood required (in m^3) for making one tonne of pulp and not paper has been calculated. The reason is that the wood requirement and the weight of the pulp are related. One such rough estimate shows that 4.73 m^3 of green wood (assuming that the purchased pulp is derived from green wood in this case) is required to make a tonne of pulp (http://www.ruraltech.org/projects/conversions/briggs_conversions/briggs_ch08.chapter08_combined.pdf). The wood required to make the purchased pulp (in m^3) is converted into tonnes of wood [1 tonne of wood = 1.4 m^3 of wood (http://bioenergy.ornl.gov/paper/misc/energy_conv.html)] and the wood required

Table 2 Data, sources, and conversion factors for estimating ecological footprint of the paper production unit (2011–2012)

Information needed	Source and units of measurement	Unit and conversion factor	Reference
Land—use			
(i) Built-up area of the unit (ii) Parking area (iii) Road length of the mill unit	Paper production unit Sq ft	ha yrs 2.83	(Chambers et al. 2000, p. 73)
Direct Energy Use			
Grid electricity	Paper production unit KWh/yr	ha yrs/GWh 150	(Barrett et al. 2002, p. 47)
Coal	Paper production unit MT/yr	ha yrs/GWh 103	(Barrett et al. 2002, p. 47)
Water Consumption			
Mains (process)	Paper production unit m^3/day	m^2 yrs/100 liters ha/m^3 low—0.0002 high—0.0009	(Chambers et al. 2000, p. 155)
(Cooling)	Paper production unit m^3/day	ha/m^3 low—0.0002 high—0.0009	(Chambers et al. 2000, p. 155)
(Domestic)	Paper production unit m^3/day	ha/m^3 0.00197	(Chambers et al. 2000, p. 138)
Materials Use			
Purchased pulp	Paper production unit MT/yr	ha yrs/tonne (4.73 m^3 of wood is required to make 1 tonne of pulp and global average yield kg/ha for wood pulp {t} in RWE is 198)** 1.0–5.7 (timber, lower end for softwood and higher end for hardwood)	(Chambers et al. 2000, p. 95)
Wastepaper	Paper production unit MT/yr	0.273 ha yrs/tonne of wastepaper	Burgess and Lai (2006) Ecological footprint analysis and review
Wastes			
Waste (assumed to have been recycled and used for the making of bricks, road filling, and construction)	Paper production unit MT/yr	ha yrs/tonne Brick—0.08	(Chambers et al. 2000, p. 138)
Waste (assumed to be have been recycled)	Paper production unit MT/yr	ha yrs/tonne	

(continued)

Table 2 (continued)

Information needed	Source and units of measurement	Unit and conversion factor	Reference
Paper	Paper production unit MT/yr	ha yrs/tonne 2	(Chambers et al. 2000, p. 138)
Plastic	Paper production unit MT/yr	ha yrs/tonne 2	(Barrett et al. 2002, p. 138)

(in tonnes) is converted into hectares by using the timber conversion factor (Chambers et al. 2000). Calculation of EF of materials is based only on the quantity of wastepaper along with a very small quantity of pulp and auxiliary materials used in the production process.

The study unit generates three types of wastes—sludge, fly ash, plastics and paper.

Sludge (about 75 tonnes/day) is recycled and used as fuel in the boiler. Out of the total fly ash generated in the production process (150 tonnes/day), 40 % is used in the making of bricks and the other 60 % of wastes are sold off for recycling outside the production unit's boundary. This portion is used in the construction of roads and filling up of nearby low-lying areas. For calculating the footprint of the sold-off wastes, the conversion factors for the recycled wastes have also been used depending on the nature and amount of such sold-off wastes. The details of the nature and amount of wastes sold off were obtained from the environmental report of the paper plant. A working note in Appendix 2 shows the dataset collected from the production unit, their corresponding conversion factors, and the sources from which such factors have been adopted for the purpose of calculation. The ecological footprint of the case study unit is calculated on a 330 working-day basis (after providing for 10 % of the total number of days as days of maintenance).

2.3 Scope and Limitation of the Study

The study helps the case study unit and its stakeholders to understand the extent to which the use of recycled/waste paper and recycling of generated wastes can help towards generating a low EF per tonne of production. Also the factors affecting the size of EF could be identified. However, the lack of data or information relating to freight and employee transportation may have resulted in underestimation of the resultant EF of the case study production unit. Again, for most of the components internationally standardised conversion factors have been used in this study. Country-specific conversion factors (conversion factors relating to Indian industry) could have helped to provide more accurate or authentic EF numbers or results.

3 Results and Discussions

The total ecological footprint of the case study unit in 2011–2012 was 60,852–62,751. The conversion factors of various footprint items (Table 2 and Working Note in Appendix 2) reveal that for water and materials (pulp) there are two types of conversion factors, one being the lower-end conversion factors and the other being the higher-end conversion factors. This variability in the footprint conversion factors occurs in the case of raw materials because the lower-end conversion factor is used when pulp is derived from softwood and higher-end ones in cases when pulp is derived from hardwood. Because the unit under study uses imported pulp only, it is difficult to know what kind of wood has gone into it. So both factors have been used to arrive at the range of values. For water the variations in the conversion factors occur as conversion values for water depending on things such as efficiency of treatment and distribution. The results of the final ecological footprint figure have been calculated by taking into consideration both these conversion factors thereby giving a range of values.

Table 3 shows the final ecological footprint for the case study paper production unit taking both the lower- and higher-end conversion factors for water and materials.

The total ecological footprint for the production and allied activities of the case study unit is found to vary between 60,852–62,751 ha, and ecological footprint per tonne of production varies between 0.48–0.50 ha for the year 2011–2012. This is based on 125,414 MT of production and the variation occurs due to higher and lower conversion factors for materials and water. The component with the greatest contribution to the total ecological footprint is the ecological footprint of materials, 43,490 ha (69.31 %), when the higher-end conversion factor for material and water is considered. The second and third largest contributors to the unit's ecological footprint are those of energy (21.55 %) followed by waste (7.42 %). The footprint of water comes fourth (1.00 %) and that of built-up land occupies the fifth and last position.

Table 3 Ecological footprint of the paper production unit (2011–2012) with lower end and higher end conversion factor for materials and waste

Component	Total ecological footprint (ha)	% of Total EF in ha	Footprint per tonne of production in ha (125,414 MT)
Energy	13,522.00	22.22–21.55	0.10
Transport (freight)	Data not available	Data not available	Data not available
Transport (employee)	Data not available	Data not available	Data not available
Materials	42,451–43,490	69.77–69.31	0.33–0.34
Wastes	4660.00	7.65–7.42	0.037
Water	140–630	0.23–1.00	0.0000–0.0050
Built-up land	79.0	0.11–0.112	0.00056
Total	**60,852–62,751**	**100**	**0.48–0.50**

When the lower-end conversion factor for material and water are considered, there also the materials component has the highest percentage (69.77 %) in the total ecological footprint of the unit, followed by the ecological footprint of energy (22.22 %) and that of waste (7.65 %). The lower conversion factor for materials indicates that the pulp purchased from international markets has been derived from softwood timber. Water with a 0.23 % contribution towards the total EF and built-up land (0.11–0.112 %) takes the last two positions, respectively, in the total footprint contribution.

Wastepaper constitutes the largest portion (99 %) of the raw material purchased by the company, followed by pulp (1 %) along with fillers, white and coloured pigments.

Direct energy consumed by the company is from grid electricity and coal used in the captive plant for the generation of electricity through a steam turbine. The ecological footprint of direct energy from two of the above sources taken together amounted to 13,522.00 ha for the year 2011–2012. The generation of electricity through the steam turbine in the captive plant of the production unit resulted in a higher ecological energy footprint. The ecological footprint resulting from electricity generation at the captive plant alone amounts to 13,415 ha, that is, accounting for 99.2 % of the total ecological footprint from direct energy, whereas the EF of energy resulting from electricity purchased from grid amounted to 107.00 ha accounting for only 0.79 % of the total EF of direct energy consumed.

Out of the total waste (74,580 tonnes) generated by the unit a large portion of it —49,500 tonnes—consists of fly ash. Of this fly ash 40 % is recycled inside the boundary of the production unit for making bricks and the remaining 60 % is used for road construction and filling up of low-lying areas in the nearby locality. The unit owns two brick manufacturing units with three machines which are used for making two types of bricks which are double the strength of conventional bricks. There are no landfill wastes. The ecological footprint of recycled wastes in the form of brick making, road construction, and filling up of low-lying areas amounts to 3960 ha (96.35 %). The EF of the remaining amount of wastes in the form of paper and plastics amounts to 700 ha (3.65 %). The sludge (waste) generated in the production process is burned in the boiler for generating energy, thereby helping to reduce the energy consumption of the said unit. Sludge is used as a substitute for coal and has helped the unit towards reduction in coal consumption from 1.99 tonne/tonne of paper in 2007–2008 to 1.45 tonne/tonne of paper in 2011–2012. So the EF of the waste generated in the form of sludge has been considered to be nil.

Water used in the process, as well as for cooling and domestic use, has been taken into account here for footprint calculation. Two conversion factors, high and low, have been used for the calculation. Taking the higher conversion factor, the ecological footprint of water is found to be 630 ha and taking the lower end, the observed result is 140 ha. The ecological footprint numbers help in identifying the hotspots or factors affecting the size of the unit's footprint. The hotspots are, namely materials (i.e., wastepaper pulp and chemicals required for the manufacturing of papers produced) and energy (generation of electricity in captive plant through the coal-fired steam turbine) and wastes.

Table 4 Possible policy interventions to reduce ecological footprint for paper production unit

Ecological footprint				
Factors affecting company's footprint	Possible alternative scenarios	Likelihood of changing them by company's short- and medium-term efforts	Barriers for change	Solutions/breaking the barriers
1. Generating electricity in captive plant through steam turbine.	(i) Increasing use of grid electricity. (ii) Reduction in energy component of ecological footprint can reduce total carbon footprint.	i) Low ii) Medium	(ia) Increasing unreliability in grid power supply. (ib) Purchase of total electricity requirement from the regional/national power grid will increase the monetary cost. (ii) Steam is an integral part of paper manufacturing process and this steam is obtained from generating electricity through steam turbine.	(ia) Centralised low carbon generation capacity enhancement and power contracts to provide reliable power supply. (ib) National policy correcting coal price by making it sensitive to carbon content. (ii) Solar power generation can be used to supplement the coal used towards generating steam. Solar photovoltaic panels can be used as substitute for day-to-day electrical energy use. (iii) Heat of the flue gas can be extracted at an economiser. (iv) Policy incentives to fuel switch from coal to low carbon fossil fuel gas or low carbon alternative sources of energy such as solar.
2. Pulp used as raw material.	(i) By increasing the use of substitutes for raw materials to reduce material component of ecological footprint. (ii) By increasing afforestation or plantation of trees and saplings can help	i) Low ii) High	(i) Currently no policy incentives are in force for encouraging such actions (ii) No government incentives currently in force.	(i) Policy incentives for development of cost-competitive substitutes, infrastructure, and supply chain to make the required pulp available locally at cheaper rate. (ii) Government incentives in this regard can reduce the carbon footprint.

(continued)

Table 4 (continued)

Ecological footprint				
	towards CO_2 sequestration.			
3. Wastes not recycled.	(i) If 100 % of the generated fly ash is used in the making of bricks and clay (instead of 40 % under the present situation), then together it can decrease the waste footprint. (ii) Self-help group can be employed for manually bringing the wastepapers to the production sites thereby helping towards reduction in the fuels used for transportation and reducing the resultant carbon footprint.	i) Medium ii) Low	(i) Management decision to be taken in this matter. (ii) Lack of professionalism at the initial stage.	(i) Innovations for waste recovery/regulations for waste disposal. (ii) Proper training of self-help groups by the management.

Footprint estimates are a useful guide for adopting environmentally responsible actions. An effort has been made to assess the scope for interventions to help reduce the EF for the production unit under study. Alternative scenarios are identified and based on our interaction with the unit we could identify the barriers towards implementation of solutions for reducing the EF under alternative scenarios. Also we recommend intervention points for breaking the barriers. These possible policy interventions for reducing EF for the paper production unit are presented in Table 4. The alternative scenarios for each of the three hotspots or factors affecting the size of EF have been taken into consideration. For example, for generation of electricity in the captive plant by coal-fired turbine, an alternative scenario such as increasing the use of grid electricity has been suggested. However, the uncertainty or barrier of implementing this considered alternative scenario along with the possible ways of breaking such a barrier has also been recommended. In a similar way the alternative scenarios, uncertainty of implementation, and possible ways of breaking such uncertainty are also provided for the other two factors affecting the size of the EF or hotspots, materials used, and wastes generated in the production process.

4 Conclusion

The ecological footprint of a paper production unit in India is estimated and analysed. The dominating components are on-site coal-based power production, use of imported raw materials (though in small quantity), and waste disposal, both on-site and off-site. The current study shows that industrial units in India do maintain data although in a scattered way but for preparation of various official reports to the State Level Pollution Control Board. Full implementation of the methodology was not possible due to nonavailability of data relating to freight movement and employee movement. It was realised that these can be developed but need more targeted research. Despite limitations the derived footprint numbers can be used by the company and by policy makers as well. From the point of view of the company it can now formulate strategies to adopt socially responsible sustainable development steps and make approaches for dissemination of the information to shareholders. It can also enhance the image of the company to earn goodwill in the marketplace. The first action may be to switch over to a cleaner fuel for power generation; the second may be to create dependence on locally produced raw materials and better waste recycling within the system boundary. For national-level policy makers it can provide a clear idea of wherein lies new investment opportunity through expansion of new production processes and scopes for using renewable sources of energy such as generating solar power. Also it can provide an insight to what might be the new incentive designs to encourage adoption of cleaner power production by industrial units. For example, the case study unit is burning the sludge (generated waste) in the boiler which in turn has helped the unit to reduce its energy consumption. This type of innovative initiative should be incentivised by the government. However, these numbers by themselves cannot be expected to drive investment decisions as there may be other barriers towards technology choice. Still, these numbers are useful indicators of intervention for making possible efficient use of a nation's resources. The existing method of data compilation by the production unit is found to be considerably satisfactory to arrive at total estimation of the ecological footprint of the manufacturing unit. The results obtained by using these new performance footprint indicator also provide an assessment of the production unit's environmental impacts over time and in developing an assessment of sustainable limits for the case study units.

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Appendix 1

Ecological Footprint of Paper Production Unit in Orissa, India

Questionnaire

General Information

1. Name of the plant and company:

2. Address:

3. Name of the person answering the questionnaire:

4. (a) Total area of the unit:

   (b) Built-up area:

   (c) Total parking area (for bikes and other vehicles):

   (d) Road length of the unit area:

5. Scale of operation:

   i) Large Scale (Above 100 tpd)

   ii) Medium Scale (30–100 tpd)

   iii) Small Scale (5–30 tpd)

[* tpd – tons per day]

6. Total production (in units)

7. Total sales/turnover (net):

   a) In units

   ii) In (Rs.)

8. Details of Inputs and output of the plant:

List of the Inputs Purchased/Consumed :	Quantity of Inputs (in MT)	Categories of Final/End Products : (in MT)

Input–Output Table

9.

Products Manufactured by /Final output of this unit	Inputs of the Unit Raw Materials Purchased	Inputs of the Unit Raw Materials Locally Purchased	Inputs of the Unit R.M. Imported and Local	Inputs of the Unit R.M. Imported

Distribution of Output

10.

	Units
i) Government	

ii) Private	
iii) Household	
iv) Sectors	
v) Exports	

11. How much electricity is:

a) Purchased units (KWh in lacs)

b) Own Generation (KWh in lacs)

i) *Through Diesel Generation*

Units (in kWh)

Units/litre of diesel Oil

Cost/unit (Rs.)

ii) *Through Steam Turbine*

Generator Units (in kWh)

Units/litre of diesel oil

Cost/unit

Units/litre of Petrol

Cost/unit

iii) *Through Wind/Solar/Hydro* (in kWh)

c) Do you transport/supply electricity to the local grid? If yes specify the quantity and price.

d) Production process ranking by energy consumption.

12. a) Details of fuel-based energy consumption

Categories of Fuel-Based Energy	**Process**	**Power**	**Total**
Coal (MT) *Total Cost (Rs. in lacs)* Grade of coal used (C/F)			
Furnace oil (litres) *Total cost (Rs. in lacs)*			
Other/Internal Generation (De oil, bran, sawdust, etc.) Qty (in MT) *Total cost (Rs. in lacs)*			
L.P. Gas (No. of cylinders used) *Total cost (Rs. in lacs)*			

13. How much fuel is used by the vehicles used by your company (bus, cars, trucks, etc.) for transportation of raw materials, products, and wastes and for communication of the employees?

Nature of Vehicles/No. of Vehicles	**Transportation of R.M., Products, Wastes, and Output (in tonne kms)**	**Vehicles: Owned or Hired**	**Fuel Used for Running the Vehicles (Petrol/Diesel)**
Air			
Rail			
Ship			
Road			

14. How much fuel is used in business travel by employees of the company?

Nature of Vehicle	**No. of Days Each Vehicles Is Operated During the Year**	**Distance Each Vehicle Runs per Day (in kms)**	**Average Mileage (km/litre) of Each Vehicle**	**Fuel Used for Running the Vehicles (Petrol/Diesel)**	**Vehicles: Owned or Hired**
Bikes and scooters					
Bus/Cars					
Bicycles					
Train					
Air					

15.Fugitive Emission: (i) Air-conditioning, (ii) refrigeration leaks, (iii) leaks from pipelines, (iv) CH_4 and CO_2 emissions from wastes and landfill CH_4 and CO_2 emissions

16. Details of generated wastes:

Sl. No.	Description of Generated Solid Wastes	Qty (Total in MT)	Qty of Wastes Recycled (in MT)	Landfill Wastes (in MT)	Qty of Wastes Disposed of (in MT)	Qty of Wastes Sold (in MT)
1.						
2.						
3.						

17. Consumption of water from two different sources for three different purposes (i.e., production, cooling process, and domestic use)

	Freshwater Consumption	Polluted Water
Process–m^3/day Cooling–m^3/day Domestic–m^3/day Process water consumption Per unit of output m^3/MT Thus total process water consumption is (m^3/day)		

Appendix 2

Working Note

Detailed Workings of the Footprint Calculations

Ecological Footprint of Paper Production Unit in Orissa, India (2011–2012)

Information needed	Consumption (A)	Unit	Footprint conversion (B)	Footprint (A * B)
Land-use				
Built-up land	27.923 ha	ha yrs	2.83 (Chambers et al. 2000, p. 73)	79.0
Subtotal				79.0
Direct energy				
Grid electricity	0.7122 GWh	ha yrs/gWh	150 (Barrett et al. 2002, p. 47)	107.00
Coal	130.24 GWh	ha yrs/gWh	103 (Barrett et al. 2002, p. 47)	13,415.00
Subtotal				**13,522.00**

Freight Transportation (raw materials, products, wastes, and output) Do not keep an account/record of this information				
Employee Transport Do not keep an account/record of this information				
Water consumption				
Mains (Process)	2000 m^3/day = 700,000 m^3/year	ha yrs/m^3	low—0.0002 high—0.0009 (Chambers et al. 2000, p. 155)	140–630
(Cooling)	m^3/day = m^3/year	ha yrs/m^3	low—0.0002 high—0.0009 (Chambers et al. 2000, p. 155)	
(Domestic)	m^3/day = m^3/year (based on 330 working days)	ha yrs/m^3	0.00197 (Chambers et al. 2000, p. 138)	
Subtotal				**140–630**

Material use				
Wastepaper Purchased pulp	154,690 (t) 221 t = [W.N. 1]	ha yrs/Conversion factor of recycled paper has been taken 4.73 m^3 of wood is required to make 1 tonne of pulp and global average yield kg/ha for wood pulp {t} in RWE is 198)**	0.273 1.0-5.7 (Timber—lower end for softwood and higher end for hardwood) (Chambers et al. 2000, p. 138)	42, 230 221–1260
Subtotal				**42,451–43,490**

Wastes				
Waste—used for the making of bricks and road	49,500 (t)	ha yrs/tonne	Brick and road filling – 0.08 (Chambers et al. 2000, p. 138)	3,960
Waste-		ha yrs/tonne		
Paper (recycled) and plastic	330(t)	ha yrs/tonne	2 (Chambers et al. 2000, p. 95)	700.00
Sludge	24,750 (t)	ha yrs/tonne	Burned in the boiler	–
Subtotal				**4660**
Total				**60,852–62,751**

Workings: (1)
**Purchased pulp – 65 t
1 tonne of oven-dry bleached kraft pulp (kappa 30) pulp requires 4.76 m^3 of green wood = 310 cu m^3 of wood
Again, 1 tonne of wood = 1.4 cu m^3 of wood
Therefore, 310 cu m^3 of wood = 221 tonnes of wood

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