Recycling Of Textile Materials

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Abstract

Throughout history, society has recycled waste and used specific waste fractions as starting points for new goods. Yet, due to a lack of unprocessed virgin materials and worries about the unsustainable use of natural resources, the utilisation and recycling of trash have recently become even more crucial. The rising cost of waste management and the scarcity of landfill space have also raised interest in recycling garbage into useful materials or energy. An expanding range of goods have been created using recycled materials as the primary raw material.

Resources for teaching about recycling textiles cite the mechanical and chemical recycling of textiles and other thermoplastics with a focus on carpet and PET bottle recycling as examples of the recycling of textile materials.

1   INTRODUCTION

In 2007, the world's population consumed between 72 and 75 million tonnes of fibre, with the EU being the greatest user and second-largest producer with 10 million tonnes. The average amount of fibre consumed per person is 11 kg, with Americans consuming the most fiber—over 32 kg—per person. Consumers from Turkey or Mexico weigh 10 kg per head, while those from China and India weigh 3-5 kg per head. Between 2002 and 2007, the consumption of fibre increased globally at a pace of 7–10% per year, and it is still rising, primarily due to fashion, even in industrialised nations. 5.8 million tonnes of textiles are discarded annually by consumers in the European Union. This stream only contains a third municipal garbage. While making up only around 5% of the waste stream, textiles are the fifth-largest category of municipal waste. An large untapped supply of secondary raw materials, some 4.3 million tonnes of municipal waste are either burned in municipal waste incinerators or dumped in landfills. 5% of the landfill's capacity is occupied by textile materials. Less than 1.5 million tonnes of post-consumer textiles are recycled, primarily by businesses and nonprofit organisations.

At the current rate of demographic and economic growth, global fibre consumption will have reached 110 million tons by 2020. Mankind cannot sustain this growth for a range of reasons. Firstly, textiles are at the bottom of the league in terms of recycling. While 80% of steel is recycled, 65% of paper and 30% of plastics, recycling of textiles stands at 15-20%. Secondly, textiles require indirect inputs such as water (200 litres to a kg of synthetic fibres and 8000 litres to a kg of cotton), energy (100 litres of petrol to one kg of fibre) and land. An American or European consumer requires around 600 m^2 of land a head to satisfy their annual fibre needs. Cotton requires irrigation, takes water away from human consumption and with a high use of pesticides, it contributes to the pollution and salinization of soil. More than 60 million tons of textiles annually are sent to landfills or burned. Thirdly, because of the fragmentation of globalization of supply chains, a reduction of the environmental impact of production and disposal is much harder to organize than for the more concentrated steel, plastic or paper industries. Therefore, the transformation of textiles into a sustainable industry is harder to attain through voluntary agreements, collective covenants, levies or regulation. Fourthly, the shortage of materials will lead to increasing fibre prices, possibly from the current level of € 1.60/kg to around € 3.00/kg. Cotton will compete for land with other agricultural crops, mainly food crops that use less water and/or provide higher yields. Higher fibre prices shall create more room for alternative (sometimes more expensive) fibres such as PLA or flax. Higher fibre prices will also provide incentives for more efficient processing methods. Finally, higher prices create incentives for recycling.

Textile recycling industry is able to process 93% of the waste without the production of any new hazardous waste or harmful by-products [1]. Further, at the beginning of the 1990s, disposal costs were €5/t for landfilling, but nowadays it is higher than €170/t for incineration [2]. The statistics of 20 years collection shows that 50,000 t of end-of-life apparel was

collected by Humana, which means 175,000 m^3 of landfill volume and 8 million € of disposal fees for communities have been saved [3].

2 LEGISLATION

Governments are increasingly focusing on commercial waste and producer responsibility in order to meet the increased recycling/reuse/prevention targets. In Europe the Directive 2008/98/EC [4] sets the basic concepts and definitions related to waste management, such as definitions of waste, recycling, and recovery. It explains when waste ceases to be waste and becomes a secondary raw material (so called end-of-waste criteria), and how to distinguish between waste and by-products. The Directive lays down some basic waste management principles: it requires that waste be managed without endangering human health and harming the environment, and in particular without endangering water, air, soil, plants or animals, without causing a nuisance through noise or odours, and without adversely affecting the countryside or places of special interest. Waste legislation and policy of the EU Member States shall apply the following waste management hierarchy (Figure 1):

Figure 1: Waste management hierarchy

The Directive introduces the "polluter pays principle" and the "extended producer responsibility". It incorporates provisions on hazardous waste and waste oils (old Directives on hazardous waste and waste oils being repealed with the effect from 12 December 2010), and includes two new recycling and recovery targets to be achieved by 2020: 50% preparing for re-use and recycling of certain waste materials from households and other origins similar to households, and 70% preparing for re-use, recycling and other recovery of construction and demolition waste. The Directive requires that Member States adopt waste management plans and waste prevention programmes. The revised Waste Framework Directive required that Member States established national waste prevention programmes, by 12 December 2013. These programmes shall be evaluated at least every six years and revised as appropriate. They shall be integrated either into the waste management plans or into other environmental policy programmes, as appropriate, or shall function as separate programmes. If any such programme is integrated into the waste management plan or into other programmes, the waste prevention measures shall be clearly identified.

Best practices

Effective strategies to promote public awareness of waste prevention and to reduce the generation of specific types of waste are already operating in EU Member States and abroad. Practices have been selected to demonstrate excellent examples of informational, promotional and regulatory measures to stimulate the prevention of waste. They were selected in consideration of the following criteria:

Targeted: Practices have a strong waste prevention focus, clearly distinct from other waste management strategies or broad environmental goals.

Innovative: Practices use original or resourceful techniques for waste prevention.

Replicable: Practices can be easily reproduced and are similarly relevant in regions across Europe.

Representative: Practices originate from a wide range of countries, operate at national, regional and local level, and target a variety of waste streams.

Effective: Practices have clearly defined objectives and measurable results.

The Real Nappy Campaign (UK) [5]

Disposable nappies make up half of the household waste produced by families with a new baby. Each infant will have used on average 4,000 to 6,000 nappies by the age of two and a half, contributing over a tonne of waste to landfill. Disposable nappies take 500 years to fully decompose. The associated collection and disposal fees cost taxpayers in the borough of Milton Keynes around £400,000 annually. A guide for parents was created, featuring step by step instructions to simplify the switch to reusable nappies and detailed local information on suppliers as well as laundering services. There are a variety of types of reusable nappies and differences in cost, performance and environmental impact are described in the guide, which also responds to frequently asked questions and dispels common myths.

A central element of the real nappy campaign in Milton Keynes is its cash-back incentive scheme. The cash-back incentive scheme is offering families who invest more than £60 in reusable nappies a payment of £35 to £40. The application form is included in the guide and

payment is made within two weeks of sending receipts. Using reusable nappies saves families up to £500 per infant, or more if they are used for subsequent children. The real nappy programme in Milton Keynes and other local programmes in the UK were supported by WRAP (Waste and Resources Action Programme) between 2004 and 2006, over which time 23,000 nappies were successfully diverted from landfill, awareness among parents of the environmental impact of disposable nappies grew significantly, and many new local incentive schemes were created.

Reusable Shopping Bag "Eco-Sac" [6]

The "Eco-Sac project" has been launched by a public private partnership (PPP) between the Luxembourgish Ministry of Sustainability and Infrastructures, the Luxembourgish Confederation of Commerce (CLC), and VALORLUX a.s.b.l., non-profit association and licensee of the 'Green Dot Luxembourg', as part of the National Waste Prevention Plan. The goal of the project has been consisting in sustainably replacing disposable shopping bags, and thus contributing to the conservation of resources and reducing the emissions of greenhouse gases by sensitising the population to environmental issues and networked ecological thinking. In the course of its introduction in January 2004, the Eco-Sac was distributed along with the participating retailer's proper free disposable shopping bags. In 2007, the distribution of the latter was totally stopped, whereas in 2008 a smaller version of the Eco-Sac has been introduced. In the same year, the PPP was extended to another 5 years. Three different kinds of shopping bags have been part of the "Eco-Sac project":

• a big ECO-Sac (PP; 34 litres capacity);

• a small ECO-Sac (PP; 17 litres capacity);

• a small, so called "emergency bag" (HDPE).

The latter, containing at least 40% recycled material, was conceived to stepwise support the transition from disposable to reusable shopping bags. The big and the small Eco-Sac is sold for 0.70€ and 0.50€, respectively; the price for the "emergency bag", becoming more and more insignificant as anticipated, is 0.03€. Damaged ECO-Sacs get replaced free of charge and subsequently recycled. The durable, highly robust Eco-Sac, at the same time being stylish and freshly designed, is suited for meeting almost all shopping situations of daily life. In cooperation with 85 retailing companies, including the five major supermarket chains in Luxembourg, the "Eco-Sac project" has been nationwide experiencing a resounding success.

As permanent and periodical performance reviewing, initiated and monitored by the tripartite partners, is of paramount importance to the project, it can be stated that the project's objective could be achieved to the greatest possible extent. Since the project's start, the use of some 300 million disposable shopping bags could be prevented; due to the Eco-Sac, the emissions of CO_{2eq}[1], linked to the production of disposable shopping bags, are annually reduced by 1,000 tons; high degree of popularity: as a result of goal oriented public relation campaigns and

according to the conducted consumer survey's, the Eco-Sac has been successfully established as kind of "national brand".

3   INTERNATIONAL TREATIES

Kyoto protocol [7]

The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change. The major feature of the Kyoto Protocol is that it sets binding targets for 37 industrialized countries and the European community (Figure 2) for reducing greenhouse gas (GHG) emissions. The goal is to lower overall emissions of greenhouse gases -carbon dioxide, methane, nitrous oxide and three long-lived industrial gases – hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6)[2].
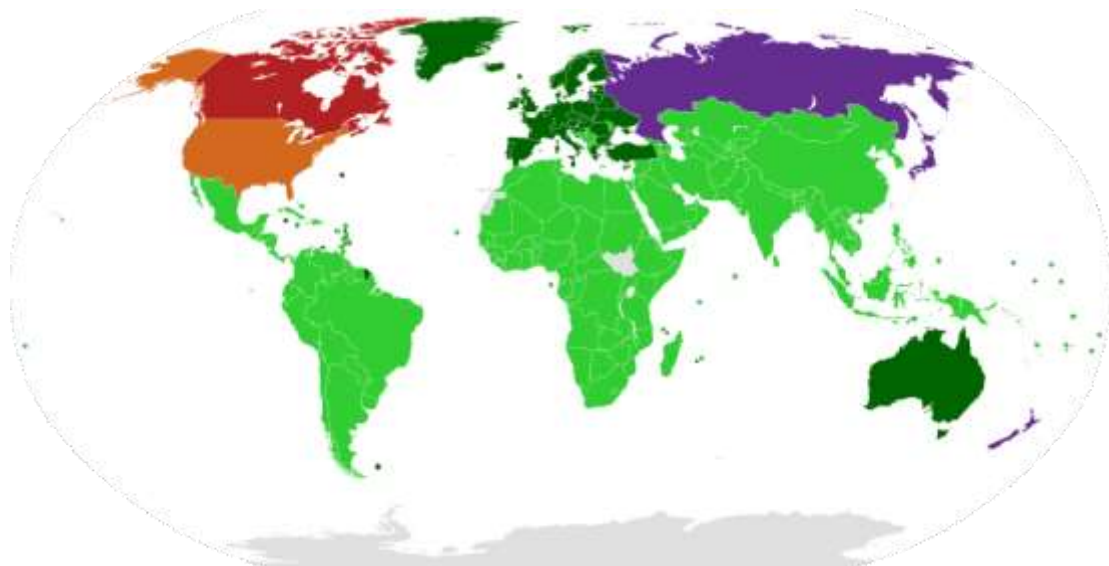

Figure 2: Kyoto Protocol participation map (commitment period: 2013-2020)

Recognizing that developed countries are principally responsible for the current high levels of GHG emissions in the atmosphere as a result of more than 150 years of industrial activity, the Protocol places a heavier burden on developed nations under the principle of "common but differentiated responsibilities." The Kyoto Protocol was adopted in Kyoto, Japan, on 11

[1] A carbon dioxide equivalent, normally expressed in tones.
[2] A major group of industrial gases, chlorofluorocarbons, or CFCs, are dealt with under the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer.

December 1997 and entered into force on 16 February 2005. Under the Treaty, countries must meet their targets primarily through national measures. However, the Kyoto Protocol offers them an additional means of meeting their targets by way of three market-based mechanisms:

- Emissions trading (»carbon market«)
- Clean development mechanism (CDM)
- Joint implementation (JI)

The EU emissions trading system (EU ETS) works on the 'cap and trade' principle. A 'cap', or limit, is set on the total amount of certain greenhouse gases that can be emitted by the factories, power plants and other installations in the system. The cap is reduced over time so that total emissions fall. In 2020, emissions from sectors covered by the EU ETS will be 21% lower than in 2005. By 2030, the Commission proposes, they would be 43% lower. Within the cap, companies receive or buy emission allowances, which they can trade with one another as needed. They can also buy limited amounts of international credits from emission-saving projects around the world. The limit on the total number of allowances available ensures that they have a value. After each year a company must surrender enough allowances to cover all its emissions, otherwise heavy fines are imposed. If a company reduces its emissions, it can keep the spare allowances to cover its future needs or else sell them to another company that is short of allowances. The flexibility that trading brings ensures that cuts in emissions are made, where they are most affordable. By putting a price on carbon and thereby giving a financial value to each tonne of emissions saved, the EU ETS has placed climate change on the agenda of company boards and their financial departments across Europe. A sufficiently high carbon price also promotes investment in clean, low-carbon technologies.

JI and CDM are the two project-based mechanisms, which feed the carbon market. CDM involves investment in sustainable development projects that reduce emissions in developing countries, while the JI enables industrialized countries to carry out joint implementation projects with other developed countries [8].

In general, the three Kyoto mechanisms are:

• Stimulate sustainable development through technology transfer and investment.

• Help countries with Kyoto commitments to meet their targets by reducing emissions or removing carbon from the atmosphere in other countries in a cost-effective way.

• Encourage the private sector and developing countries to contribute to emission reduction efforts.

The Kyoto protocol is to date the only international agreement that calls for action to reduce emissions of CO_2. Yet some Harvard scientists and economists who study climate change

express almost universal criticism of the Kyoto protocol, which they see as economically inefficient, inequitable, and ineffective. They point out that the protocol fails to include the largest future sources of CO_2 emissions [9].

Montreal Protocol

The Montreal Protocol on Substances that deplete the ozone layer is an international treaty designed to protect the ozone layer by phasing out the production of a number of substances believed to be responsible for ozone depletion. The treaty was opened for signature on September, 1987 and entered into force on January, 1989. Since then, it has undergone five revisions, in 1990 (London), 1992 (Copenhagen), 1995 (Vienna), 1997 (Montreal), and 1999 (Beijing). Chlorofluorocarbons (CFCs), along with other chlorine- and bromine-containing compounds, have been implicated in the accelerated depletion of ozone in the Earth's stratosphere. CFCs (also known as freons) are non-toxic, non-flammable and non-carcinogenic [10]. They contain chlorine, fluorine and carbon atoms; the five main CFCs include:

CFC-11 (trichlorofluoromethane - CFCl3),

CFC-12 (dichloro-difluoromethane - CF2Cl2),

CFC-113 (trichloro-trifluoroethane - C2F3Cl3),

CFC-114 (dichloro-tetrfluoroethane - C2F4Cl2), and

CFC-115 (chloropentafluoroethane - C2F5Cl).

In the past, CFCs have been widely used as coolants in refrigeration and air conditioners, as solvents in cleaners, particularly for electronic circuit boards, as a blowing agents in the production of foam (e.g. fire extinguishers), and as propellants in aerosols. Indeed, much of the modern lifestyle of the mid-20th century had been made possible by the use of CFCs. The pie chart below (Figure 3) shows the uses of CFCs in various products before the 1987 Montreal Protocol, which required countries to phase out their usage to protect the ozone layer.
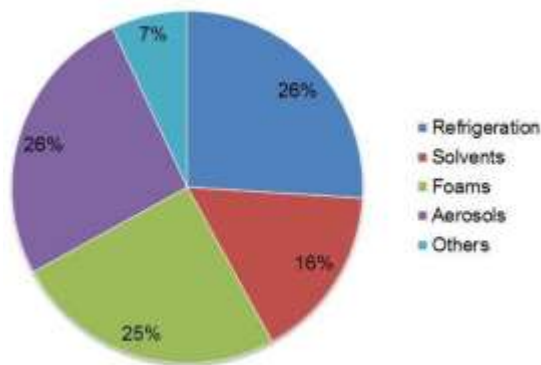
Figure 3: Uses of CFCs in various products before the 1987 Montreal Protocol

In 1973 chlorine was found to be a catalytic agent in ozone destruction. Catalytic destruction of ozone removes oxygen species while leaving chlorine unaffected. A complex interplay of chemistry, dynamics, and radiation lead to conditions conducive to significant ozone loss in the polar regions. Net reaction of ozone degradation is presented in Figure 4.

$$Cl + O_3 \longrightarrow ClO + O_2$$

$$ClO + O \longrightarrow Cl + O_2$$

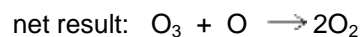$$\text{net result: } O_3 + O \longrightarrow 2O_2$$

Figure 4: Schematically presentation of ozone degradation by catalytic activity of chlorine.

CFC's have half-lives between 50-100 years, so their presence in the atmosphere and reactivity with ozone is long lived. One CFC molecule typically degrades around 10,000 ozone molecules before its removal, but this number can sometimes be in the millions.

No new CFCs have been produced since 1995 in developed nations. Total usage of CFCs has also fallen dramatically, particularly by aerosols [11].

Effective chlorine concentrations (all substances) with the scenario with and without Montreal Protocol and effective chlorine concentrations of chlorofluorocarbons in the atmosphere are presented graphically in Figure 5.
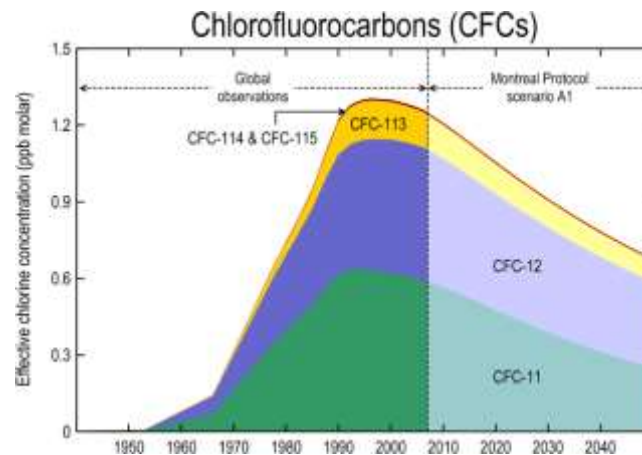
Figure 5: Effective chlorine concentrations of chlorofluorocarbons in the atmosphere with and without Montreal Protocol.

Replacement of CFCs compounds with hydrochlorofluorocarbons (HCFCs) which still contain chlorine atoms, but the presence of hydrogen makes them reactive with chemical species in the troposphere. This greatly reduces the prospects of the chlorine reaching the stratosphere, as chlorine will be removed by chemical processes in the lower atmosphere. Hydrofluorocarbons (HFCs) contain no chlorine and they have been evaluated for potential effects of fluorine compounds on ozone destruction.

Carbon footprint

A **carbon footprint** is a measure of the impact human activities have on the environment in terms of the amount of greenhouse gases produced, measured in units of carbon dioxide. It is "the total set of GHG (greenhouse gas) emissions caused directly and indirectly by an individual, organization, event or product" [12]. An individual, nation or organization's carbon footprint is measured by undertaking a GHG emissions assessment. Once the size of a carbon footprint is known, a strategy can be devised to reduce it.

A **carbon offset** is a financial instrument representing a reduction in greenhouse gas emissions. Although there are six primary categories of greenhouse gases carbon offsets are measured in metric tons of carbon dioxide-equivalent (CO_{2e}). One carbon offset represents the reduction of one metric ton of carbon dioxide, or its equivalent in other greenhouse gases.

The **ecological footprint** is a measure of human demand on the Earth's ecosystems. It compares human demand with planet Earth's ecological capacity to regenerate. It represents the amount of biologically productive land and sea area needed to regenerate the resources a human population consumes and to absorb and render harmless the corresponding waste. Using this assessment, it is possible to estimate how much of the Earth it would take to support humanity if everybody lived a given lifestyle.

Ecological footprint analysis compares human demand on nature with the biosphere's ability to regenerate resources and provide services. It does this by assessing the biologically

productive land and marine area required to produce the resources a population consumes and absorb the corresponding waste, using prevailing technology. Footprint values at the end of a survey are categorized for food, housing, goods and services as well as the total footprint number of Earths needed to sustain the world's population at that level of consumption. This approach is also applied to an activity such as the manufacturing of a product or driving of a car. This resource accounting is similar to life cycle analysis wherein the consumption of energy, biomass (food, fibre), building material, water and other resources are converted into a normalized measure of land area called 'global hectares' (gha).

In 2005, the average biologically productive area per person worldwide was approximately gha per capita. The U.S. footprint per capita was 9.4 gha, and that of Switzerland was 5.0 gha per person, while China's was 2.1 gha per person (Figure 6). The World Wildlife Fund (WWF) claimed that the human footprint has exceeded the bio capacity (the available supply of natural resources) of the planet by 20%.

According to the most recent National Accounts for the year 2009 [13], the total Earth's biocapacity is estimated at 12 billion gha (or 1.8 gha per person) but humanity's Ecological Footprint has reached 17.6 billion gha (or 2.6 gha per person). Correspondingly, the number of planets demanded by all humans has increased to 1.47 planets, which represents an increment of 2.4 times the demand for nature's renewable resources since 1961.
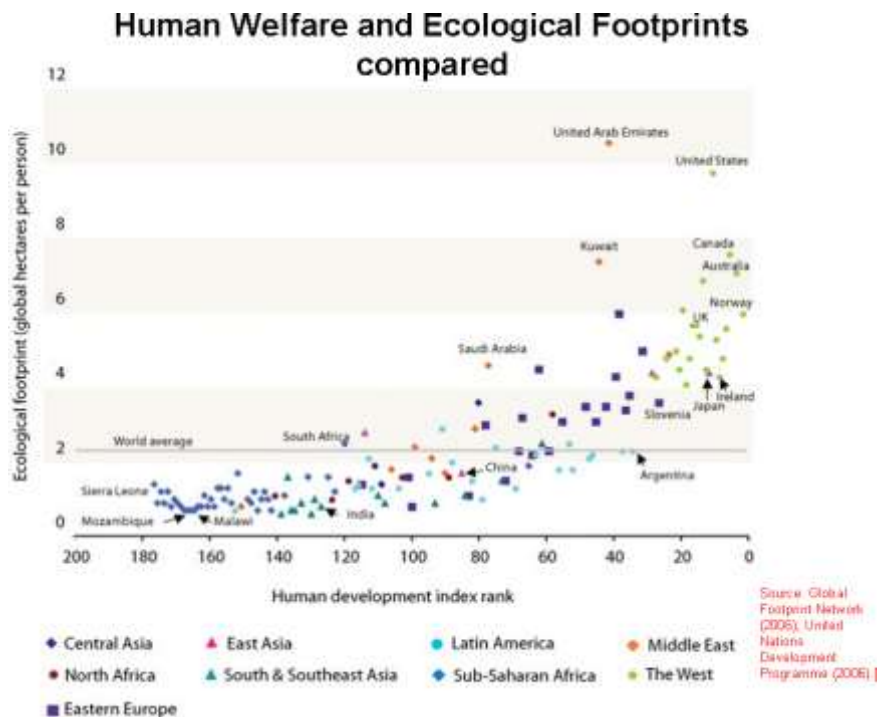

Figure 6: Comparison of human welfare and ecological footprint.

While the term ecological footprint is widely used, methods of measurement vary. However, calculation standards are now emerging to make results more comparable and consistent. A carbon footprint reduction refers to reducing the impact on climate change by reducing

greenhouse gas production. Individuals and businesses produce carbon dioxide from daily activities such as driving, heating, and the consumption of products and services. To reduce the effects of climate change, we could reduce our carbon output by going on a carbon diet. The following outlines the steps of a carbon diet:

- Calculate a carbon footprint to understand the amount of carbon dioxide emissions.
- Measure the carbon footprint against peers (e.g., similar company size or for individuals, a national average).
- Determine the ideal carbon footprint.
- Identify the source of the most significant carbon dioxide emissions.
- Reduce carbon dioxide emissions by starting with the most significant sources first.

The carbon footprint can be efficiently and effectively reduced by applying the following steps:

- Life Cycle Assessment (LCA) to accurately determine the current carbon footprint.
- Identification of hot-spots in terms of energy consumption and associated CO_2 emissions.
- Where possible, switch to buying electricity from renewable sources (from wind turbines, solar panels or hydro electrical plants).
- Optimisation of energy efficiency and, thus, reduction of CO_2 emissions and reduction of other GHG emissions contributed from production processes.
- Identification of solutions to minimise/neutralise the CO_2 emissions that cannot be eliminated by energy saving measures. This last step includes carbon offsetting; investment in projects that aim at the reducing CO_2 emissions, for instance tree planting.

A life cycle assessment (LCA, also known as life cycle analysis, ecobalance, and cradle-to-grave analysis) is the investigation and valuation of the environmental impacts of a given product or service caused or necessitated by its existence. The term 'life cycle' refers to the notion that a fair, holistic assessment requires the assessment of raw material production, manufacture, distribution, use and disposal including all intervening transportation steps necessary or caused by the product's existence. The sum of all those steps - or phases - is the life cycle of the product. The goal of LCA is to compare the full range of environmental and social damages assignable to products and services, to be able to choose the least burdensome one. At present, it is a way to account for the effects of the cascade of technologies responsible for goods and services. Consequently, LCA succeeds in accurately measuring the impacts of the technology used for delivering products, but not the whole impact of making the economic choice of using it.

Cradle-to-grave is the full Life Cycle Assessment from manufacture ('cradle') to use phase and disposal phase ('grave'). For example, trees produce paper, which is recycled into cellulose using low-energy process; this cellulose is then used as insulation material in a home

for 40 years for saving on fossil-fuel energy. After 40 years the cellulose fibres are replaced and the old fibres are disposed of, possibly incinerated. All inputs and outputs must be considered for all the phases of the life cycle.

Cradle-to-gate is an assessment of a partial product life cycle from manufacture ('cradle') to the factory gate (i.e., before it is transported to the consumer). The use phase and disposal phase of the product are usually omitted. Cradle-to-gate assessments are sometimes the basis for environmental product declarations (EPD).

Cradle-to-cradle is a specific kind of cradle-to-grave assessment, where the end-of-life disposal step for the product is a recycling process. Two types of products can emerge from the recycling process: new, identical products (e.g., glass bottles from collected glass bottles), or different products (e.g., glass wool insulation from collected glass bottles).

In the book Cradle to Cradle, Remaking the Way We Make things, by W. McDonough and M. Braungart [14], authors discuss why to lose all the ”nutrients” which should go back into technical or biological cycles by incineration. The cradle to cradle approach is to see waste as food, as nutrition (Figure 8).

Gate-to-Gate is a partial LCA looking at only one value-added process in the entire production chain.

Figure 8: The cradle to cradle approach

Well-to-wheel is the specific LCA of the efficiency of fuels used for road transportation. The analysis is often broken down into stages such as "well-to-station" and "station-to-wheel, or "well-to-tank" and "tank-to-wheel".

 A system or life cycle can begin with extracting raw materials from the ground and generating energy. Materials and energy are then part of manufacturing, transportation, use (wearing and washing the t-shirt, for instance), and eventually recycling, reuse, or disposal. A life cycle approach means we recognize how our choices influence what happens at each of these points so we can balance trade-offs and positively impact the economy, the environment, and society. A life cycle approach is a way of thinking; it helps us recognize how our selections – such as buying electricity or a new t-shirt – are both part of the same system of events.

3.4 The waste hierarchy

The waste hierarchy refers to the 3Rs of reduce, reuse and recycle, which classify waste management strategies according to their desirability. The 3Rs are meant to be seen as a hierarchy and are thus listed in order of importance (Figure 9).

Figure 9: EU Waste hierarchy [15]

Some waste management experts have recently incorporated a 'fourth R': "re-think", with the implied meaning that the present system may have fundamental flaws, and that a thoroughly effective system of waste management may need an entirely new way of looking at waste. Some "re-think" solutions may be counter-intuitive, such as cutting fabric patterns with slightly more "waste material" left - the now larger scraps are then used for cutting small parts of the pattern, resulting in a decrease in net waste. This type of solution is by no means limited to the clothing industry. Source reduction involves efforts to reduce hazardous waste and other materials by modifying industrial production. Source reduction methods involve changes in manufacturing technology, raw material inputs, and product formulation. Waste is traditionally spoken about in the context of the 3Rs: reduce, reuse and recycle, but recently 3 more Rs were introduced to the debate and these are: residual waste management resources and regionalism.

Recycling of thermoplastic waste (mainly all textile synthetic fibres comprise in this group) such as PET, PE, PE, PA etc, can be carried out in many ways, but four main approaches have been proposed.

Primary recycling: reuse of off-grade and scrap materials directly by the recycling plants.

Secondary recycling (mechanical recycling): involves separation, cleaning and then reuse of the product as individual polymers or as a blend. In polymer recycling the mechanical recycling means reprocessing of waste into granules by conventional melt extrusion. In textile mechanical recycling means two processes: melt extrusion and defibrillation of textile products into fibres by carding method. The main disadvantage of these processes is the deterioration of products properties in every cycle.

Tertiary recycling (chemical recycling): process leading in total/partial depolymerisation of polymers to monomers, oligomers and other chemical substances or fuels.

Quaternary recycling/energy recovery: incineration with recovery of energy [16].

Among the above recycling techniques chemical recycling is the only one acceptable according to the principles of sustainable developments because it leads to the formation of the raw materials from which the polymers is made from (monomers). In this way there is no need for extra resources.

4   RECYCLING OF PLASTIC AND TEXTILE MATERIALS

Pre-consumer waste refers to material which comes out of manufacturing as a manufacturing scrap (such as trimmings from textile production, defective aluminium cans, etc.) and do not reach a consumer (Figure 10).

Figure 10: Pre consumer waste

Post-consumer waste refers to material which has been consumed and of which the life cycle (at least the first life cycle) is finished (Figure 11).

Figure 11: Post-consumer waste

Second hand clothing

Whereas charity shops dominated the second hand market from the 1960s to the 1970s, more specialized, profit-oriented shops emerged in the 1980s. These shops catered primarily to the fashionable female demographic and offered women and children designer clothes, and occasionally high-end formal wear for men. Current fashion trends ("up-cycling") are

reflected by a team of young designers who use and customize second-hand clothes for a chain of specialty vintage clothing stores. Its offerings include 'cheap chic and occasional designer surprises' [17], (Figure 12).

Figure 12: Up-cycling

The largest volume of goods is sorted for export to developing countries or disaster relief. It is reported that the used apparel serves as the largest export from the United States based on volume. Western clothing is a highly valued commodity and perhaps serves as the only source of affordable clothing in many developing countries where levels of income are so low that food and clean water are the primary concerns. However, we can argue here that the export of clothing to these nations has threatened the traditional dress for many indigenous cultures and at the same time may threaten the fledgling textile and apparel industries of those countries (Figure 13). While this is certainly an issue that should be taken into consideration, wearable, climate appropriate, and affordable clothing is a valuable commodity for most of the population in less-privileged areas of the world [18].

Figure 13: Second hand market in Kenia

Mechanical recycling of textiles - Defibrillation/thread opening

Defibrillation/thread opening is carried out by breakdown of fabric to fibre through cutting, shredding, carding, and other mechanical processes. The fibre is re-engineered into value-added products. Textile materials which are defibrillated are mainly not thermoplasts (cotton, wool, and aramids lately).

Carding

The main objective of carding is to separate small tufts into individual fibres, to begin the process of parallelization and to deliver the fibres in the form of a web. The principle of carding is the mechanical action in which the fibres are held by one surface while the other surface combs the fibres causing individual fibre separation. At its centre is a large rotating metallic cylinder covered with card clothing. The card clothing is comprised of needles, wires, or fine metallic teeth embedded in a heavy cloth or in a metallic foundation. The cylinder is partly surrounded by an endless belt of a large number of narrow, cast iron flats positioned along the top of the cylinder. The top of the cylinder may be covered by alternating rollers and stripper rolls in a roller-top card.

The fibres are fed by a chute (for fibres up to 60 cm long) or hopper which vibrate (for longer fibres) and condensed into the form of a lap or batting. This is initially opened into small tufts by a licker-in, which feeds the fibres to the cylinder. The needles of the two opposing surfaces of the cylinder and flats or the rollers are inclined in opposite directions and move at different speeds. The main cylinder moves faster than the flats and, due to the opposing needles and difference in speeds, the fibre clumps are pulled and teased apart (Figure 14). In the roller-top card the separation occurs between the worker roller and the cylinder. The stripping roller strips the larger tufts and deposits them back on the cylinder. The fibres are aligned in the machine direction and form a coherent web below the surface of the needles of the main cylinder.
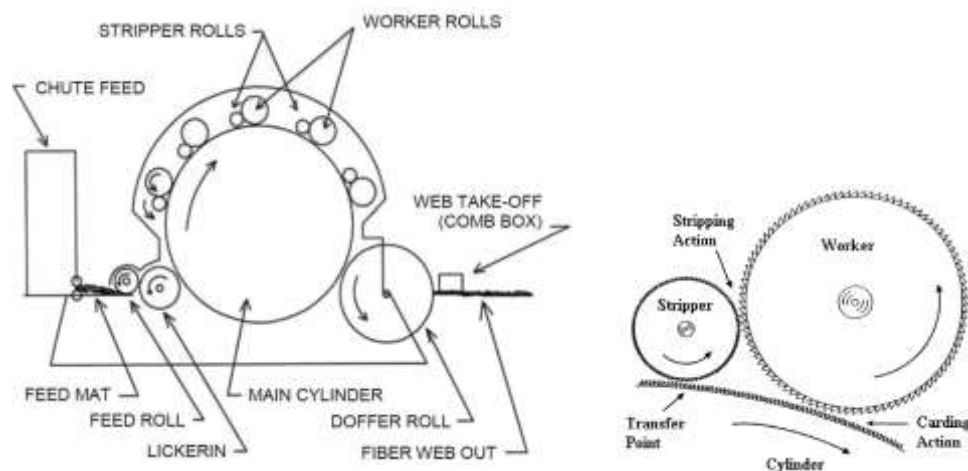

Figure 14: Basic construction of a card and its parts and carding action

The fibre is then re-engineered into value-added products. These value-added products include stuffing, automotive components, and carpet underlays, building materials such as insulation and roofing felt, and low-end blankets. The majority of this category consists of unusable garments - garments that are stained, torn, or otherwise unusable. A vast number of products are made from reprocessed fibres because much of this fibre is re-spun into new yarns or manufactured into woven, knitted, or non-woven fabrications, including garment linings, household items, furniture upholstery, insulation materials, automobile sound absorption materials, automobile carpeting, and toys.

This process represents an economic and environmental saving of valuable fibre that would otherwise be lost to the landfill. Ironically, the most unusable and damaged of post-consumer textiles often have the highest level of specifications forced upon them by the end-use industries (e.g. building, auto, aeronautics, and defence).

Best practise of textile mechanical recycling

A denim recycling segment is big enough to achieve a technical and economical interesting process, if several big denim brands would agree in a mutual concept. Pure cotton denim jeans could be liberated from all metal parts and labels and shredded. The so achieved recycling cotton could be used as is, or be mixed with fresh cotton used again as raw material in the denim production chain. This "real denim recycling" could become attractive for the consumer. Additionally such "R- Jeans" would generate an attractive marketing concept, especially for the growing, environmental-conscious customers [19].

Phoenix Fibres converts over 300 tons of denim and other cotton fabric per month into fibres which is then manufactured into many different products. These products include UltraTouch™ Denim Insulation used in homes and businesses, appliance insulation, insulation (Figure 15) and even prison mattresses [20].

Figure 15: Thermal insulation prepered from denim

Mechanical recycling of plastic and textiles – melt processing (extrusion)

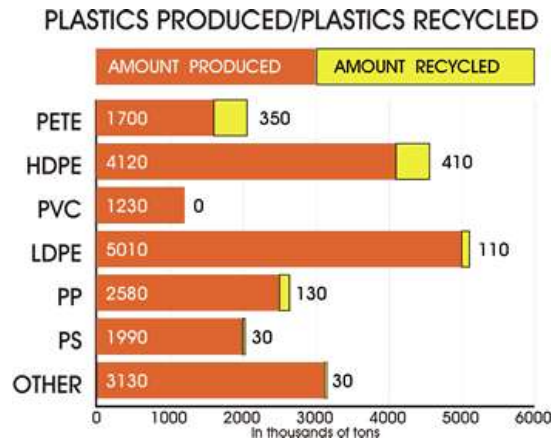Ratio between the produced plastic materials and their recycling is presented in Figure 16.

Figure 16: Ration between produced and recycled plastic

Mechanical recycling of thermoplastic[1] (PO, PES, PAs and others in the form of various plastic products and textile materials) refers to processes which involve the melting, shredding or granulation of thermoplastic waste. The primary criterion for mechanical recycling (melt processing) is the purity of the end product so waste must be sorted prior to recycling. Contamination of the recovered plastic can greatly reduce the value of the recovered plastic. Sorting of plastic is an important part of plastic waste recycling and it can be carried out by hand or machine according to colour and chemical structure of the plastic. Sorting by hand is time consuming and not very accurate, so nowadays mainly automatic sorting is used. Technology is being introduced to sort plastics automatically, using various techniques such as near infrared spectroscopy, X-ray fluorescence, electrostatics and flotation. Sorting of big pieces (bottles) or small pieces (plastic chips) is carried out by various techniques.

Near IR (NIR) spectrophotometry (electromagnetic radiation with wavelength of 14.000-4000 cm^{-1}) is used for big pieces sorting. 8 bottles/s can be separate according to their chemical structures (PO, PS, PVC and PET). The problem arises if plastic pieces are dark colour, then NIR spectrophotometry does not give the spectra.

Further, **X-ray fluorescence** can use for separation of PVC plastic pieces from the rest of the bulk. Reprise Technologies, Govoni Italija (European Vinyls Corporation) introduced the method where by X-ray detector PVC plastic bottles are separated from monolayer of plastic bottles on conveyor. PET and PE are separated later (usually by optical sorting). The error of this method is 1 per 10.000 bottles; 1t of plastic per hour can be sorted.

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[1] Thermoplatic is a polymer that becomes pliable or mouldable above a specific temperature, and returns to a solid state upon cooling.

To avoid problems with the detection and sorting, markers (infrared or fluorescent dyes) can be added during bottles processing.

Detection and separation of small plastic chips relies on flotation technology, according to which the target plastic was separated from waste of different specific densities by grinding the feed material and choosing a liquid of appropriate density to float off the waste and allow the target plastic to sink, or vice versa. However, this method did not produce an end product of sufficient purity. Recently, hydrocyclones, previously used in mineral separation and other industries, have been applied to plastic separation, and these devices have produced a good improvement over the old technology.

Following sorting, the thermoplastic waste is either melted down directly and moulded into a new shape, or melted down after being shredded into flakes and then processed into granules called regranulate.

In the extrusion of plastics, thermoplastic material in the form of small beads (often called resin in the industry) is gravity fed from a top mounted hopper into the barrel of the extruder. During the recycling process, the fed materials are usually in the form of polymer chips. Additives such as colorants and UV inhibitors (in either liquid or pellet form) are often used and can be mixed into the resin prior to arriving at the hopper. The material enters through the feed throat (an opening near the rear of the barrel) and comes into contact with the screw (Figure 17). The rotating screw (normally turning at up to 120 rpm) forces the plastic beads/chips forward into the barrel which is heated to the desired melt temperature of the molten plastic (which can range from 200 °C to 275 °C depending on the polymer). In most processes, a heating profile is set for the barrel in which three or more independent controlled heater zones gradually increase the temperature of the barrel from the rear to the front. This allows the plastic to melt gradually as they are pushed through the barrel and lowers the risk of overheating which may cause degradation of the polymer.
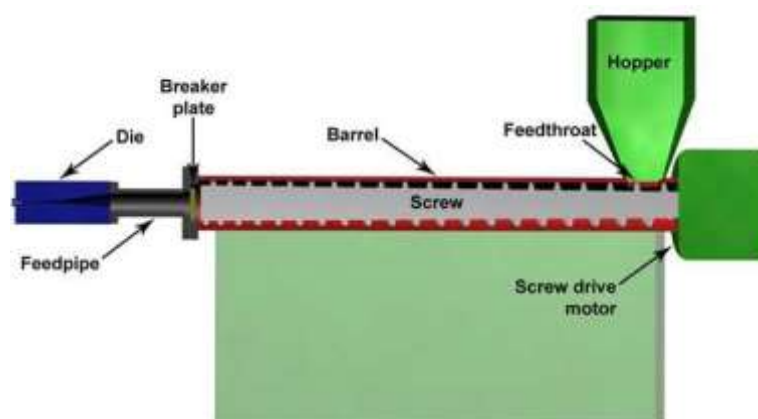

Figure 17: Extrusion

At the front of the barrel, the molten plastic leaves the screw and travels through a screen pack to remove any contaminants in the melt. The screens are reinforced by a breaker plate (a

thick metal puck with many holes drilled through it) since the pressure at this point can exceed 34 MPa. The screen pack/breaker plate assembly also serves to create back pressure in the barrel. Back pressure is required for uniform melting and proper mixing of the polymer, and how much pressure is generated can be 'tweaked' by varying screen pack composition (the number of screens, their wire weave size, and other parameters). After passing through the breaker plate, molten plastic enters the die. The die is what gives the final product its profile and must be designed so that the molten plastic evenly flows from a cylindrical profile, to the product's profile shape. Uneven flow at this stage would produce a product with unwanted stresses at certain points in the profile. Almost any shape imaginable can be created so long as it is a continuous profile [21]. When recycling materials is used the extrusion final product are granulate.

A major handicap in the mechanical recycling (re-melting) of thermoplastic polymers is that reprocessing adds a heat history, change/reduce properties and makes repeat use for the same application difficult. Effects of recycling processes on physical, mechanical and degradation properties of PET yarns were studied. Koo, HJ and co-workers [22] examined the effects of mechanical and chemical recycling processes on yarn properties such as tensile properties, thermal characteristics, prone to hydrolysis and photo-degradation. They found that the virgin and the chemical recycled yarns with sufficient purification show similar processability, physical and mechanical properties, and long-term degradation behaviour.

PET soft drink bottle recycling (general approach)

There are about 50 different groups of plastics, with hundreds of different varieties. All types of plastic are recyclable. To make sorting and thus recycling easier, the American Society of Plastics Industry developed a standard marking code to help consumers identify and sort the main types of plastic. Before recycling, plastics are sorted according to their resin identification code. The type of plastics (as per the resin identification code) and their most common uses are presented in Figure 18.
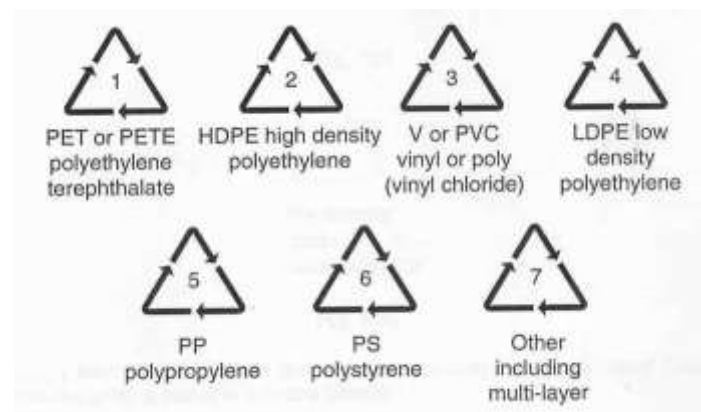
Figure 18: Plastic indication code

Polyethylene terephthalate (PET) bottle production accounts for about 30 percent of the PET produced. Today PET bottles are usually clear or green coloured. Bottles (Figure 19) are baled after collection and send to the recycling plant for processing [23]. The sorted bottles are first broken down into small flakes and compressed into bales, which are easier to transport and are then used to make new bottles or other products such as textile fibres. These small flakes have superior processing properties for the production of new plastic articles. PET is easily recycled and since there is an abundance of post-consumer PET in bottle form it is becoming a preferred source of material in the production of textile materials (carpet fibre).

Figure 19: Baled plastic bottles

Pre-treatment

Bales of PET bottles [24] are moved with a forklift to a conveyor belt. After removal of the wires that hold the bales together, the bales are broken apart in a separator drum and large dirt particles are removed. The bottles are rough cut in two grinders, and then reduced by cutting mills to a uniform pellet size. These processes result in a mixture of chopped PET bottles, labels and bottle caps. The paper and plastic labels are separated from the feedstock with an air separator; intensive washing removes any remnants of labels. The following step is a float-sink process. It separates the light fraction (polyolefin bottle caps) from the heavy fraction (PET). After appropriate drying, the polyolefins are reused in the plastics industry.

Main Process

The PET chips are mixed with sodium carbonate solution in a vat with a mixing screw. This mixture moves slowly through a long rotary kiln; it remains there for several hours. The PET material and the caustic soda react in the front part of the oven, removing the top surface of the PET material and any remaining dirt particles. At a specific temperature and an added airflow migrated foreign material are removed in the end stage of the kiln processing resulting in a mixture of a salt and clean PET material.

Final Treatment

To achieve high levels of purity the main process is followed by more washing. A sifting machine separates salt/PET mixture; still adhering salts are removed by another washing process. After washing, the remaining moisture is evaporated from the material in a mechanical dryer. Any metal particles are removed from the milled material by a metal separator.

Contamination of the recovered plastic (paper, PE, PP, etc.) can greatly reduce the value of the recovered plastic. Researchers study the influence of some contaminants on recycled PET thermal and rheological properties and found that the presence of HDPE (high density PE) in the blend reduces the melt viscosity of the blend indicating good flow ability compared to PET waste [25]. However, incompatibility between HDPE and PET in the "blend" occurs at a content of HDPE higher than 5% resulting in poor mechanical properties compared to pure PET. The results of this work indicated that it is possible to recycle PET waste containing small amount of HDPE (less than 5%).

The effect of the small amounts of PLA on the mechanical and rheological properties of the PET was investigated [26] and results showed that the viscosity of the contaminated PET decrease compare to pure PET, but the blend possessed higher thermal sensitivity compared to pure PET waste (Figure 20). The research further revealed that the small amount of PLA do not affect the tensile properties.
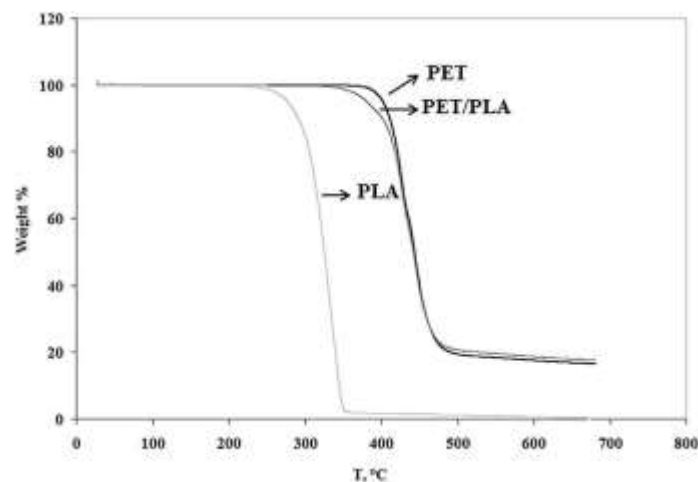

Figure 20: Influence of PLA on thermal stability of recycled PET

Best practices

Ecomax is a textile company that is engaged in manufacturing PET bottle recycled fibre. By way of innovative and eco-friendly technology developed by Ecomax, PET bottles are recovered, cleaned, scraped, melted and then through spinning and texturing transformed to

PETSPUN® yarn. Over the years, they had introduced various kind of PETSPUN® fabric, which satisfied the versatile market demand [27].

The Poole & Company produces a variety of EcoSure polyester staple fibres that are made from 100% post-consumer recycled PET fibre; these fibres are used for apparel and industrial fabric industries. The PET undergoes sorting and rigorous washing process and then it is ground into flakes. During the fibre-making process, the flakes are melted at 290°C and spun into polyester staple fibre using the same process as it is used for production of high-quality staple virgin fibres. The fibre is purchased and used by manufacturers to produce nonwoven fabrics thermally, chemically or mechanically bonded. EcoSure fibres range from 1.2 denier to 500 denier and are made from 100% PCR PET; they are suitable for hygiene, industrial products, geotextiles and all types of textile products [28, 29].

Chemical recycling

Chemical recycling (also called feedstock or tertiary recycling) allows the recovery of more value products from plastic wastes than incineration, and overcomes some of the problems that limit mechanical recycling. By more restrictively definition the chemical recycling may be defined as 'the production of chemical products of value from waste polymeric materials by economically feasible processes'. This definition, which requires the recovery of products of value, excludes from chemical recycling both biodegradation and combustion, and limits chemical recycling to those processes that are also economically feasible. The products of chemical recycling are easily reintroduced into the production cycle, without any problems of market saturation; another benefit is that the crude products resulting from chemical breakdown can be used without further purification.

The easiest to depolymerise are condensation-type resins (polyester (PET), polyamide (PA), polycarbonate (PC), polyurethanes (PU), etc.). The bonding of molecules in these materials is such that, if appropriate heat and pressure are applied in the presence of a reactive chemical agent, they break into shorter chains in relatively controllable ways. Technologies for the breakdown of such polymers, mainly PET (hydrolysis, glycolysis, methanolysis, aminolysis, etc.) have already been proven, and are viewed as relatively cost-effective. The products recovered from these chemical processes can be either monomers, with a degree of purity suitable for repolymerisation, or a mixture of oligomers with reactive end groups. Depolymerisation of addition-type polymers (PO, styrenics, acrylates, etc.) is of great interest for monomer recovery by precisely unzipping the bonds. This requires an appropriate choice of reaction conditions and catalysts. When the unzipping of monomers from the polymer chain occurs at a rate lower than transfer reactions of the active sites, a complex mixture of products, from low to medium molecular weight, are formed. In general, it is not economically viable to derive well-defined chemical products directly from this mixture, which instead can be used either as a fuel or reintroduced into petroleum processing.

Chemical recycling of PET

PET recycling represents one of the most successful and widespread examples of polymer recycling. The overall world consumption of PET in 2004 was about 13 million tons, of which 9.5 million tons were processed for the textile industry [30] and 1.5 to 2.0 million tons were consumed in the manufacturing of various type of packaging (mainly bottles). In Figure 21 it is graphically presented how many (in tons) beverage containers were wasted in year 2006. Data from Container Recycling Institute from 2006 (Figure 22) presents that the trend of bottles wasted in US decreased through the years, which is promising, but the amount of bottles wasted was still enormous.
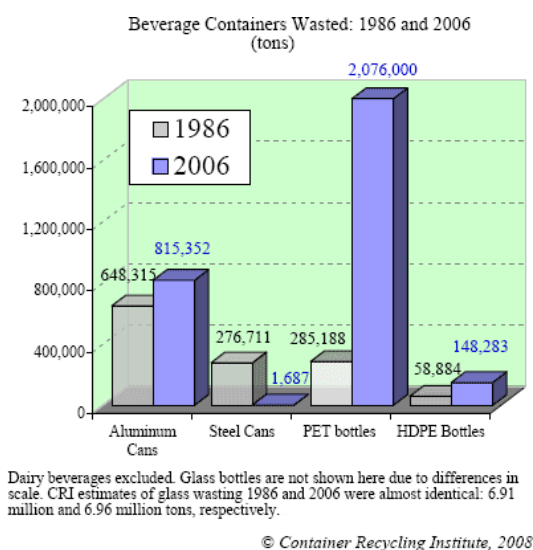
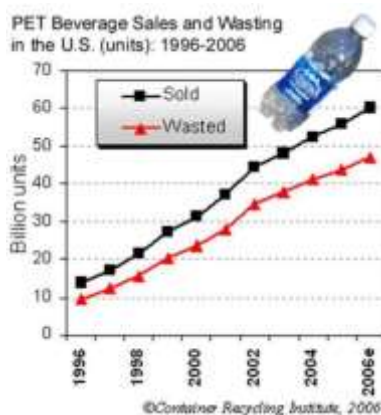Figure 21: Plastic bottles wasted in tons

Figure 22: Trend of sale and wasted plastic bottles units in the USA

The recycled PET is mostly used in the form of fibres, films, foams, sheets, bottles etc. Thus, chemical-recycling processes for PET are divided as follows (Figure 23):

- glycolysis,
- methanolysis
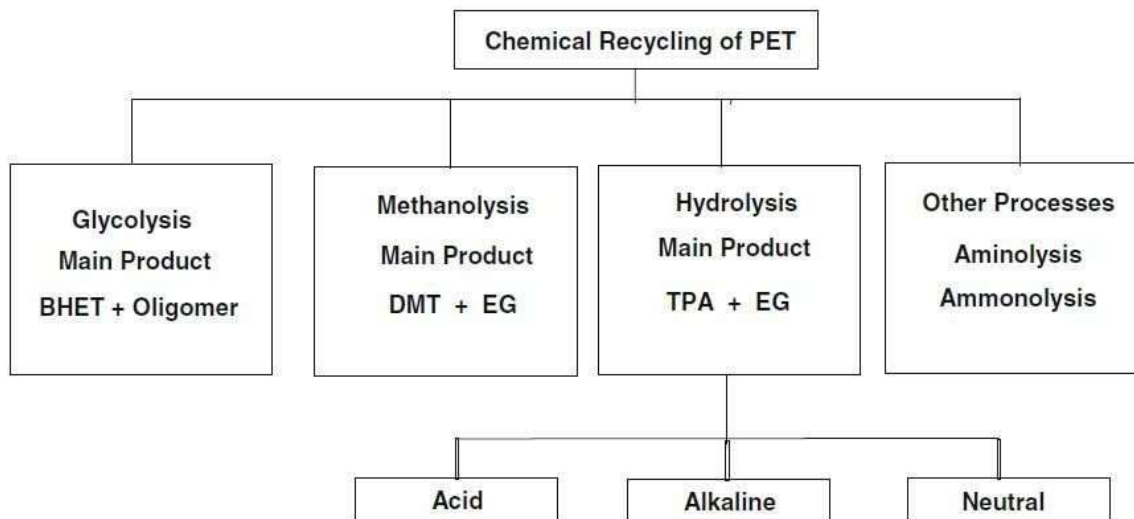- hydrolysis and
- other processes.

Figure 23: Chemical recycling

Glycolysis is used widely on a commercial scale. The glycolysis reaction is the molecular degradation of PET polymer by glycols, in the presence of trans-esterification catalysts, mainly metal acetates, where ester linkages are broken and replaced with hydroxyl terminals. PET waste is converted into bis(hydroxyethyl) terephthalate (BHET) and its oligomers (Figure 24). The extent of depolymerisation of PET depends on the excess of ethylene glycol (EG) taken for glycolysis. Process of glycolysis can be carried out in a wide range of temperatures (180-250°C) during 0.5-8 hours. In the glycolysis of PET below 240°C zinc compounds have catalytic effect. The main advantage of this method is that it can be easily integrated into existed PET production process and that the recovered BHET can be blended with virgin BHET. The main disadvantage is that BHET contains higher oligomers which are very difficult to remove by economically visible procedure.
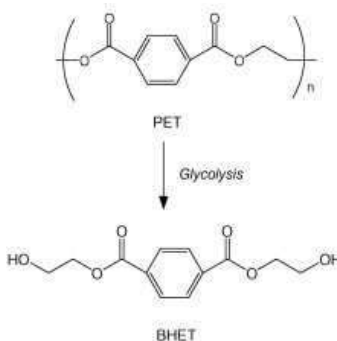
Figure 24: Conversion of PET to BHET [31]

For glycolysis of PET waste, the microwave irradiation in the presence of ethylene glycol (EG) and zinc acetate as catalysts can be used [32]. The yield of the main product BHET is nearly the same as that obtained by conventional electric heating. However, the time taken for completion of reaction is reduced from 8 h to 35 min leading to substantial saving in energy [33]. Various metal salts (zinc acetate, sodium carbonate, sodium bicarbonate, sodium sulfate and potassium sulfate) as depolymerization catalysts in the process of glycolysis influence/control the yield of the reaction, the highest yields of the reaction are obtained with zinc acetate and sodium carbonate at 196°C [34, 35].

Methanolysis is degradation of PET by methanol at high temperatures and high pressures producing two main products: dimethyl terephthalate (DMT) and EG (Figure 25). Methanolysis of PET is usually carried out at temperatures between 180-280°C at pressures of 2-4 MPa. The advantages are that the produced DMT can be purified by destilation and it can be reused as a raw material for PET production, further methanol can be recovered and recycled as well. The disadvantage is the high cost of separation and purification of produced mixture (glycols, alcohols and phthalate derivatives). The main disadvantage is associated with the trend of all new PET production processes where TPA (terephtalic acid) instead of DMT as raw material is use. The hydrolysis of DMT to TPA adds a considerable cost to the methanolysis process [30]. Typical feedstock for methanolysis includes scrap bottles and textile waste.
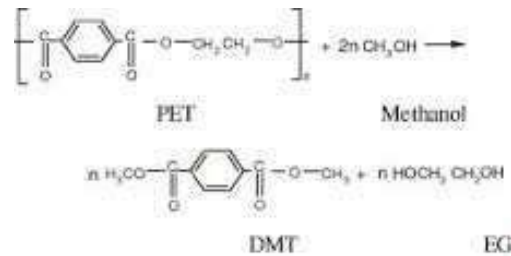

Figure 25: Methanolysis of PET [36]

Hydrolysis became very interesting methods duo to the fact that new processes for PET production use TPA and EG as raw materials. Hydrolysis of PET flakes can be carried out in an acid, alkaline and neutral media.

Acid hydrolysis can be carried out by using concentrated acids such as sulphuric (Figure 26), nitric or phosphoric acid and relative low pressure or by using diluted acids and higher pressure. Acid hydrolysis usually required long reaction times.
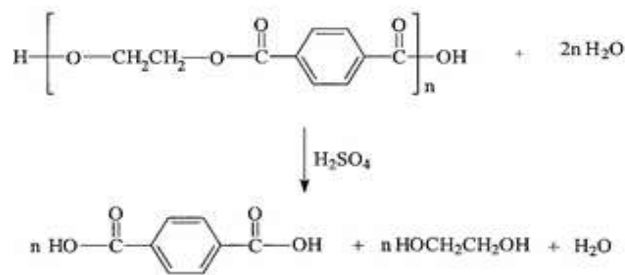
Figure 26: Acid hydrolysis of PET

Alkaline hydrolysis is carried out with the help of 2-20 wt% alkaline solutions of sodium or potassium hydroxide. The reaction time varies according to alkaline solution concentration and pressure and can be from 2-7 hours. The reaction time can be reduced by addition of methanol (40 min). The reaction products are EG and the disodium terephthalate salt. Pure TPA is obtained by neutralisation of the reaction mixture with s strong mineral acid.

Neutral hydrolysis is carried out with the use of hot water or steam. The process runs is ran in high pressure autoclaves (1-4MPa) at 200-300°C with excess of water [37], [38], [39], [40]. The ratio by weight of PET to water is from 1:2 to 1:12. In spite of this, the pH of the post reaction mixture amounts to 3.5–4.0, which according to Michalski [41] is caused by the formation of TPA monoglycol ester during the reaction. Campanelli [42] have described the application of the process in PET recycling. It has been confirmed that PET hydrolysis proceeds significantly faster in the molten state than as a solid; therefore, it is advantageous to carry out neutral hydrolysis at temperatures higher than 245°C.

The catalytic effect of zinc salt as well as sodium salt is attributed to the electrolytic destabilization of the polymer-water interface in the hydrolysis process. During the PET hydrolysis, monoester of glycol and terephthalic acid is formed as a by-product. It dissolves well in water at temperatures of 95–100°C; at these temperatures, TPA is practically insoluble. Owing to this, the separation of TPA from the post reaction mixture does not create any problems [43].

The neutral hydrolysis method is exempt from the primary drawbacks characteristic for acid or alkaline hydrolysis. The formation of substantial quantities of inorganic salts difficult to dispose of is avoided; also, problems connected with the corrosion of apparatus due to the use of concentrated acids and alkalis do not occur. An undoubted advantage of neutral hydrolysis is its high ecological purity, and therefore growing interest in this technology can be expected. Its drawback is that all mechanical impurities present in the polymer are left in the TPA; thus, the product has a considerably worse purity than the product of acid or alkaline hydrolysis. Consequently, a much more sophisticated purification process is necessary. Possible product contaminations are removed by filtration of the solution of TPA dissolved in caprolactam or in an aqueous solution of sodium hydroxide [43]. The crystallization of TPA from caprolactam makes it possible to obtain a product with a purity of at least 99% [44]. During

the hydrolysis of PET a substantial volume of diluted EG is generated, which can be recovered through extraction or by distillation. An effective five-stage process of neutral hydrolysis of PET to EG and TPA of a purity required for the synthesis of the new polymer has been patented by Tustin [45]. PET is hydrolyzed at temperatures of 200–280°C. After cooling the post reaction mixture to 70–100°C, the solid product of the process is filtered and dried at temperatures of 25–199°C. EG is recovered from the filtrate as a result of two stage distillation. The solid product of hydrolysis is heated with water at temperatures of 310–370 °C, and after cooling TPA is obtained. The purity of the recovered TPA and EG allows their application in the production of high quality homo- and copolymers and does not exclude their use in the manufacture of bottles and fibres.

Kamal et al. have presented an efficient process of continuous hydrolysis in which they have used a twin-screw extruder as a reactor [46]. Using this method, it is possible to obtain in an efficient manner PET oligomers containing 2–3 repeating units. Those products with end carboxyl groups have higher melting temperatures in comparison with virgin PET, while those with one carboxyl group and one or two hydroxyl groups have lower melting points. It has been demonstrated that utilization of cold or even hot water in the process does not give a satisfying degree of depolymerization. There is a difference when high-pressure saturated steam of temperatures close to that of molten PET is injected into the reaction zone of the extruder. The maintenance of adequate high pressures requires the application of suitable throttling systems, allowing the control of backleakage of the postreaction mixture from the extruder [47].

The main problems encountered in neutral hydrolysis and glycolysis is either employment of large excess of reactants such as water or glycols, as well as high temperatures and pressures and generation of large amounts of waste salts with acidic and basic conditions. For example, in case of neutral hydrolysis large amounts of water (ratios of 5/1 [48] to 20/1 [49] water/PET (w/w)) are required to depolymerize down to TPA and EG, the latter ratio providing the complete solution of TPA under the reaction conditions. Campanelli et al. [47] found that zinc acetate catalysis caused only a modest increase in hydrolysis rate, since they were applying a very high loading of 5.1 g water/g PET and high temperatures of 250–280∘C. Although from reaction stoichiometry only 0.18 g of water/g PET is sufficient to depolymerize PET to TPA and EG, Campanelli et al. have found that below 2 g of water/g PET, an equilibrium is established and no further reaction occurs. The equilibrium point was also confirmed by approaching it from the initial monomer stage, as well [50]. Guclu and co-workers [51] reported that the presence of inert solvent (such as xylene) in neutral hydrolysis provided grater degrees of depolymerization at lower temperatures and pressures, and allow production of oligomers suitable for polycondensation and more concentrated EG solutions compared to conventional neutral hydrolysis processes.

Amminolysis is a bond cleavage reaction carried out by using an amine. This reaction on PET [52] initially attracted attention for modification of fibres to improve some specific properties.

Currently, amminolysis has been receiving renewed attention due to its possibility to prepare some interesting chemicals or intermediates [53].

Ammonolysis is a solvolitic reaction which gives therephthalamide (TAD) and EG usually by using concentrated ammonia. TAD is not an economically interesting chemical but it can be converted into a more added value products.

Many other **trans-esterification processes** have been developed to prepare added value products from recycled PET. By these processes, PET has been used to prepare alkyd resins and thermosetting polyester resins, polyols for polyurethane manufacture, plasticisers for PVC etc.

Each technology of chemical recycling shows advantages and disadvantages that usually cannot be clearly identified as it is stated in paper of Lorenzetti and co-workers [53]. Until now, only a few processes and plants for PET chemical recycling are actually operative, with some being sustained by government funds in Japan, country that shows high interest in recycling and in the rational use of non-renewable resources. Challenge can be summarised as discontinuity and not sufficient homogeneity of PET supplies, leading to long breaks and continuous process changes to adapt to new feed specifics. Reactor and batch processes are clearly more flexible and capital costs are lower but they could be economically attractive only for higher margin productions such as intermediates for varnishes or polyols for polyurethanes. These applications do not require expensive and time consuming purification steps for TPA or DMT which mandate bigger plant sizes. These processes will become economically competitive only at higher monomers prices on international markets. If we consider also the growing problems of access to petroleum feedstock, and the growing demand of chemical intermediates on the long term, an ''explosion'' of technologies for a more rational use of resources is predictable and among them chemical recycling will play an important role.

Best practice

Developed by Teijin Fibres, ECO CIRCLE is a closed-loop recycling system for used polyester products. The system employs the world's first technology for chemical recycling, which chemically decomposes polyester for conversion into new polyester raw materials that offer purity comparable to those derived from petroleum. Teijin cooperates with over 130 registered apparel and sportswear manufacturers worldwide that share a commitment to promote progressive environmental activities for the development and manufacture of recyclable products, as well as collection and recycling of these products at the end of their useful lives. Compared to developing polyester materials from petroleum, this repeatable recycling system reduces energy consumption and carbon dioxide emissions by approximately 80% each.

5   CARPET RECYCLING

A large amount of fibrous waste is generated each year, consisting of a variety of synthetic and natural polymers. Post-consumer carpet is a complex system and requires extensive processing to convert it into products. Tufted carpet, the most common type (90%) as shown in Figure 27, typically consists of two layers of backing (mostly polypropylene fabrics), joined by calcium carbonate-filled styrene- butadiene latex rubber (SBR), and face fibres (the majority being nylon 6 and nylon 6,6 textured yarns) tufted into the primary backing. The SBR adhesive is a thermoset material, which cannot be re-melted or reshaped. The waste containing the SBR (post-consumer and some industrial waste) has not found suitable uses and it forms the major part of the carpet waste going into the landfills. Figure 28 shows the typical masses of the various components.
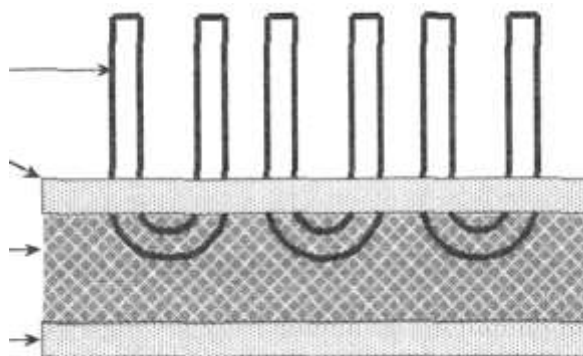

Figure 27: Tufted carpet: face yarn (nylon), primary backing (PP), adhesive ($CaCO_3$/latex), secondary backing (PP)
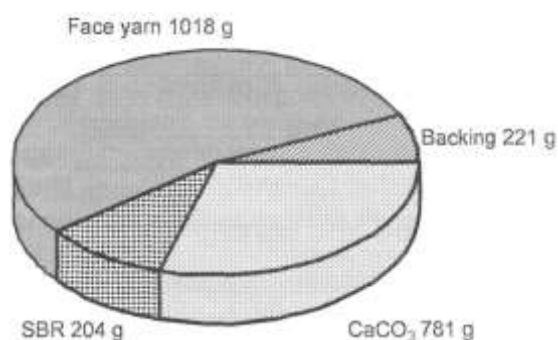

Figure 28: Component mass/area for a typical carpet (glm2). Total mass is 2224 g/m^2

According to the US carpet industry statistics, the total fibre consumption in 2001 was about 1.4 million tons: nylon 60%, olefin 29%, polyester 10%, and wool 0.3%. Among the nylon face fibre, about 40% is nylon 6 and 60% is nylon 6,6. About 70% of the carpet produced is for replacing old carpet, typically after 5-10 years of service. The rate of carpet disposal is

about 2-3 million tons per year in the USA, and about 4-6 million tons per year worldwide. The type of carpet is classified according to the type of face fibres used. Nylon generally performs best among all synthetic fibres as carpet face yarn. However, it is also the most expensive. This provides a perspective on the economics of recycling as well. For example, if it takes the same processing effort to convert the fibre back into recyclate, an operation on nylon would be most profitable. This also explains why most of the recycling effort is on nylon recovery [54].

Depolymerization is the preferred route of carpet recycling, since it converts the carpet fibres (nylon 6 and/or nylon 6,6) into the corresponding monomers. This allows the recovery of the monomers that can be re-polymerized into new nylon products of high quality.

Extraction methods attempt to separate and recover the polyamides from the other carpet components without converting them back to the original monomers. During extraction, the nylon from the fibres is recovered in its polymeric form and can be reused in injection moulding applications. The main problem associated with this approach is the selection of a suitable solvent that selectively dissolves the nylon fibres and does not react with or dissolve any of the other carpet components.

Melt blending of the entire carpet scrap generates a thermoplastic mixture that can be used for the manufacturing of a lower quality plastic material. Such a material can be utilized in lower value products. The method consists of melting the entire carpet waste, without a previous separation into its components, to obtain a blend of different polymeric and inorganic materials. The low quality and lack of homogeneity of the resulting mixture are the main drawbacks of this method, restricting the number of applications in which its product can be used [55].

Sorting

For carpet, the sorting is according to the type of the face fibre. Melting point indicator is an inexpensive instrument that can identify most fibre types, but it is generally slow and cannot distinguish between nylon 6,6 and polyester. Infrared and Raman spectroscopy are much more effective. Carpet collection involves collecting in individual stations, sending the carpet to a regional warehouse, and then to the processing facilities. Sorting can be done either as the carpet is collected or at a central location. A portable infrared spectrometer was designed to identify the common carpet face fibres: nylon 6, nylon 6,6, polypropylene, polyester, and wool. Sorting can also be done in a centralized facility.

Size reduction and separation

Size reduction, the cut of large pieces of carpet into smaller sizes is often needed in the preparation stage of most recycling processes. In a typical process, the carpet waste is cut by a rotary drum fitted with hardened blades against a feeding bed, and the cut material is then moved against a screen with specified openings. Pieces smaller than the screen openings are

allowed to drop off and those that do not fall out are sent back to the cutting chamber for re-cutting. Although a fibre shredder appears similar to those used for cutting other types of waste such as wood, the design for fibrous waste requires sharp cutting edges and a tight gap between the cutting blades and the feeding bed to avoid fibre wrapping. High-torque, low rotational speed for the cutting drum is preferred in order to avoid heating and melting the polymers. Modern shredding machines are low maintenance, efficient and inexpensive to operate.

In a process developed by DuPont, nylon 6,6 carpet is passed through dry processes consisting of a series of size reduction and separation steps. This provides a dry mix of 50-70% nylon, 15-25% polypropylene and 15-20% latex, fillers and dirt. Water is added in the second step, where the shredded fibres are washed and separated using the density differences between fillers, nylon and polypropylene. Two product streams are obtained: one is 98% pure nylon and the other is 98% pure polypropylene. The recycled nylon is compounded with virgin nylon at a ratio of 1:3 for making automotive parts.

A centrifuge system can be used to separate ground nylon carpet into nylon, polypropylene and adhesive. The system employs a drum rotated of a high speed; in the first stage, a liquid with a 1.15 g/cm^3 density is used to separate the fibres (nylon and polypropylene) from the adhesive. The second stage, using a liquid with a l.0 g/cm3 density (e.g. water), further separates the nylon from the polypropylene.

Some processes separate carpet components without first going through a size reduction step. The United Recycling process starts with clipping the face fibres on loop carpet to open the loops. The next step is debonding, in which the carpet is bombarded with a combination of air and steam to loosen the calcium carbonate-filled latex backing. The secondary backing then is peeled off mechanically, exposing the primary polypropylene backing. Next, mechanical picks pluck the face fibres. It is claimed that the cost of this process is low and that it yields a product stream with 93-95% pure face fibres. Other devices employ water jet or dry ice pellets. The dry ice pellets are shot into an abrasive zone as a segment of discarded carpet on a conveyor system is stripped apart and disassembled. The pellets freeze the binder material (usually latex), lowering it to a temperature that makes it brittle and easy to break apart. The dry ice pellets sublimate directly into gas without any liquid residues. This process eliminates the need for a drying operation, which saves energy and avoids potential chemical pollution.

Depolymerisation of nylon

Because of the higher value of nylon in comparison with other polymers used in carpet, nylon carpet has been looked at as raw material for making virgin nylon, via depolymerisation. The depolymerization of nylon 6 is a first-order reaction, which takes place in initiation and de-propagation steps. Water is an initiator for the depolymerization process. This process is endothermic and requires high temperatures. Steam not only acts as a heat source and water supply, but also provides a better agitation for the reaction system. Temperatures above the boiling point of caprolactam (around 267°C) are typically used. Under such conditions a

heterogeneous system is formed (a liquid polymer melt and a gas-phase caprolactam product). The caprolactam monomer is removed from the reactor along with the steam, resulting in a shift of the equilibrium towards further monomer formation. Companies such as BASF, AlliedSignal (Honeywell) and DSM which produce nylon 6, have led the efforts in naylon 6 recycling. DuPont, on the other hand, which manufactures nylon 6,6, has focused its depolymerization efforts on the recovery of hexamethylenediamine (HDM) and adipic acid (the corresponding monomers of nylon 6,6).

Nylon 6 and/or nylon 6,6 can be converted into a mixture of the respective monomers through an ammonolysis process, alkaline (Bayer AG Bayer AG, DuPont, DMS) or acid (Allied Corporation, BASF Corporation) catalysed depolymerisation or depolymerisation with water by using superheated steam (AlliedSignal).

6 CONCLUSION

The repurposing of textile raw materials is represented by textile recycling, which has a long history. Its effectiveness is heavily reliant on the creation of recyclable products. One of the main driving forces has been the scarcity of resources. The demand for textiles is growing, but prices for energy and raw materials are also rising, and raw material reserves are depleting. It is a fact that recycled goods are challenging to sell. The large range of cutting-edge product and process advances that can be used with secondary textile raw materials are still underappreciated. Budgets and the market will always place restrictions on designers, with globalisation adding to economic thinking and environment remaining only one of many potential areas of focus. Nonetheless, textile recycling will advance.

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