TEXTILE RECYCLING: A REVIEW

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Abstract

Textile recycling has a long history in the developing world. The original reasons for textile reclamation were efficient utilization of resources, whereby waste garments could be reconstructed into cheap clothes for disadvantaged societies and other application such as wipes and flock fillings for upholstery. The second reason for textile recycling came into existence due to an increase in industrialization hence pressure on environmental protection. To date the level of textile recycling is determined by the value of the recycled products and the level of wastes generated. There are various reasons for increasing in textile wastes, but the main is the increase in number of fashion affluences. While the number of fashion affluences increase, the cost for waste disposal increases and the source of material for making new fibres decreases. Therefore this paper reviews the global textile recycling technologies from the 17th century to date. This comprehensive review may bring in focus of the available recycling technologies from which innovative recycling ideas can be built in order to save the world from increasing pollution caused by textile.

Key words: recycling, textiles, waste garments, Re-use

1 Introduction

Textile recycling has a long history in the developed world. The original reasons for textile reclamation were efficient utilization of resources, whereby waste garments could be reconstructed into cheap clothes for disadvantaged society and other application such as wipes and flock fillings for upholstery etc. The second reason for textile recycling came into existence due to an increase in industrialization hence pressure on environmental protection. To date the level of textile recycling is determined by the value of the recycled products and the level of wastes generated. There are various reasons for increasing in textile wastes, but the main one is the increase in number of fashion affluences. While the number of fashion affluences increase, the cost for waste disposal increases and the source of material for making new fibres decreases. Therefore this paper reviews a global textile recycling technologies from the 17th century to date. This comprehensive review may bring in focus of the available recycling technology from which innovative recycling ideas can be built in order to save the world from increasing pollution caused by textile waste. The review also contributes to efficient use of textile wastes as a feed stock for making of new fibres and discouraging the second hand clothing business in developing countries. The study considers the development of available recycling technologies which leads into different end products and their limitations

1.1 Developments in textile recycling

The very early recycling/ reuse of second hand clothes was recorded in the UK in the year 1660 when people could sell the casted clothes to the poor (Lemire, 2000, Lambert, 2004). Since the business was not well regulated, it involved a burglary of clothing and selling to hawkers. A more formal recycling of used clothes was in the United Kingdom in 1813 when rags were collected by ragmen and sent to the rag grinding (or pulling) machines where the they were pulled and produced into paper and flock fillings for saddlery and upholstery (Bromley and Dunstan, 1978). Later on recycling was more advanced whereby fibres could be pulled and constructed into shoddy and mungo which could then be used by poor people for clothing. However following the emergence of synthetic fibres, advancement in fibre blending technology, the separation of synthetic fibre components from the fabrics has been difficult and this probably can be considered as a major reason for decline in the use of cotton rags in paper making (Tucker and Tucker, 1951).

2 Sources and Categories of Textile Wastes

Textile wastes are classified by two main categories namely post-consumer wastes and pre-consumer wastes (Bromley and Dunstan, 1978, Hawley, 2006b, Hawley, 2006a). The post-consumer wastes are those which arise from textile products which have served their useful life. The post-consumer wastes are generated either because they are worn out, damaged, outgrown, or have gone out of fashion. The pre-consumer wastes are those which arise from fibre spinning, yarn spinning, fabric construction and garment make. The percentage waste generation from both pre and post consumer sources are presentenced on table 1. The figure indicates that the garment make-up process is the least efficient due to the highest waste production percentage among the arising sources.

Table 1: The textile generated from various sources (Bromley and Dunstan, 1978)

Type of waste	Source	Percentage generation by type of source
Pre-consumer	Spinning process	1
	Staple stage	4
	Garment production	5
	Fabric production	1.5
	Garment make-up	10
Post consumer	All domestic sources	3

However future trends indicate that the wastes generated by the garment manufacturing industry may be reduced due to advancement of garment making technologies which have reduced the trimming processes. For instance, whole garment knitting on the Shimaseki automatic machines requires no panel knitting; whole body garment is knitted directly (Shimaseiki., 2016).

2.1 Textile for re use

This category covers textiles which are recovered for re-use as it is or after value addition by reparing and/or cleaning. This category covers almost 50% of the textiles wastes collected. Literature sussegests that the main fraction of the collected textiles are shipment to developing countires for reuse (DEFRA, 2006).

An Oakdene Hollins report (DEFRA, 2006) refers to the textile recycling industry as ‘secondary textiles industry’ and involves three main stages namely collection, processing and re-use, recovery

& disposal. The stages are presented dramatically in Figure 1 which it notes sorts and distributes used textiles (in mettric tonnes) into some 140 different grades, with four main categories. Further work conducted for the Centre for Re-manufacture and Re-use at Oakdene Hollins (Hussey et al., 2009), developed a diagrammatic representation of the process involved in the "processing" phase (Figure 2)

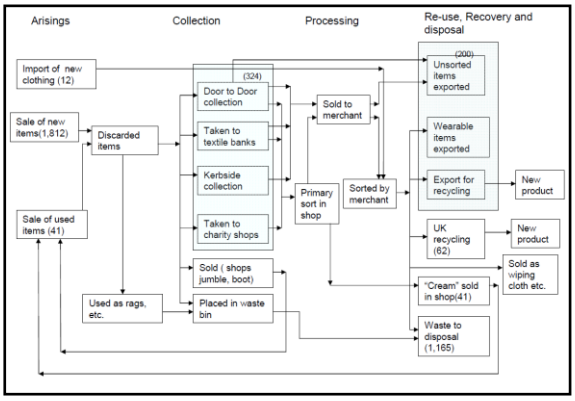


Figure 2: UK Secondary Textile Industry Material Flow Figures in '000 tonnes, year 2003(DEFRA, 2006)

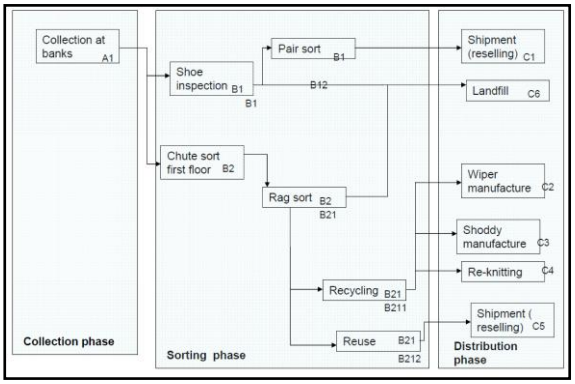


Figure 2: Summary of the textile recycling process at LMB and Co. (Hussey et al., 2009)

The postconsumer wastes reach the recycling centres via , private sales, textile banks, charity shops door to door collection, kerbside recycle and direct disposal on comingled rubbish bin (DEFRA, 2006, Bartlett et al., 2012). However in some countries the collection system is via private waste pickers who collect and sell the used garments to collection shops (Mo et al., 2009). These shops collect the Municipal Solid Wastes (MSW), classify the recyclables, and sell them to collection enterprises. The discard routes include private sales, textile banks, charity shops, door to door collection, kerbside recycle scheme and direct disposal (DEFRA, 2006, Bartlett et al., 2012, DEFRA, 2009).

Private Sales: Textile items are sold through jumble sales or boot fairs or by e-sales such as eBay. Also, some high value clothing is sold through commercial second hand clothes retailers with a proportion of the value of each item being returned to the original owner. Surplus, unsold materials from these ventures are sold to the merchants.

Textile Banks: The wearable items are taken to a local textile 'bring' banks operated by either a charity-linked organisation or by a strictly commercial collector.

Charity Shops: The owners of the garments would take garments which are either out of fit due to size or fashion to the charity shops, in some case they get paid some amount of money but some shops do not provide any pay.

Door-to-door Collections: Collection bags are delivered to the householder's doorstep by a charity or a commercial collector. The house holder will fill the bags with the garments. The deliverer of the bags will visit the houses for collection and delivery of new bags.

Kerbside Recycle Schemes: These schemes are operated on behalf of Local Authorities, either by waste management companies or by resource management consortia which include textile recycling companies. The schemes usually involve collection bags being supplied to every doorstep in the district. When the bag is filled by the householder it is left out for collection, and a replacement bag is issued. The garments collected from this approach as reported to be heavily contaminated especially the coloured garments

Direct Disposal: The items are placed in the household rubbish bin, sometimes after re-use as rags, wipers, etc. Bulky items such as curtains or carpets may be taken to the local civic amenity disposal site. The existing collection system is set to collect re-usable / re-wearable clothes only and not all the textile wastes available in the market (DEFRA, 2006, DEFRA, 2009). In order to keep the transportation costs at a minimum, textile recycling companies are often located in large metropolitan areas (Hawley, 2006b) hence laving the less populated areas unattended.

3 Sorting Technologies

The collected waste garments are either sold direct to merchants for sorting or primary sorted into various categories. The sorting process can be

manual (Chris, 2003) thus labour intensive process or automatic (Editorial Board, 2008, http://www.soex.de, 2009, Wang, 2007). Although manual sorting dominates the sorting process, recently there have been some advances made in sorting technology in Swaziland, where a modern computerized sorting plant has been installed by the TEXAID sorting company, which has increased sorting efficiency as well as lowering labour costs (Editorial Board, 2008). In German the Soex Group also employs advanced sorting technology with an increased sorting and recycling efficiency (http://www.soex.de, 2009). The sorting uses an infrared probe which would detect the garments depending on the fibre composition, thus sorting and grouping becomes easy (Wang, 2007).

The high labour costs in developed countries encourage shipment of unsorted used clothing to developing countries (Editorial Board, 2008, , 2009), in Tanzania a ban has been imposed on second-hand underwear and requirement for fumigation and the decease-free certificates for second-hand clothes (Hawley, 2006b) and this ban has now been extended to all East African Confederation member states (Tanzania., 2010). These restrictions necessitate not only advanced sorting technology but also alternative means of recycling used cloths other than export to developing countries for re-wear.

The sort categories include used clothing market, conversion into new products, wiping and polishing cloths, incineration and high value items (Hawley, 2006b, Hawley, 2006a, DEFRA, 2006, Bartlett et al., 2012). Figure 3 indicates the conceptual frame work of the sorting categories of reclaimed waste textiles with the used clothes covering high percentage, the high value items (diamonds) covers lowest volume percentage. Value-wise, the diamonds are the highest (Hawley, 2006a). A private communication confirmed that a wedding costume sorted form the collected garments can be sold up to £2000 (2009).



Figure 3: Grades of recovered textiles materials (Hawley, 2006a)

In order to ensure marketability of the second hand clothes, the value of the sorted items is further improved by washing prior to selling in the shops (Hawley, 2006b, Hawley, 2006a, DEFRA, 2006). Some research has been done on assessment of the suitability of the washing and drying of the waste garments in order to add value of the wastes garments for re-use. The preliminary results indicated that the washing and drying process could increase the value of the waste garments in the range of 790 to 1220 % depending on the level of contamination of the fabrics. The process is said to be highly resource efficient. The level of contamination of the collected garments varies depending on the type of method used for collecting the waste garments (Beth and Liz, 2012, Bartlett et al., 2012).

After the textiles have been sorted into the main categories, further sorting is carried out to bring more grades and those can be further refined based on women or men's garments, weather applicability, type of material, etc. with sorting potentially resulting in up to 400 grades (Chris, 2003). For instance it has been reported that 95% of the sorted used clothes market grade are in a wearable condition (Bartlett et al., 2012) and those can be further grouped into local- re-use and export for re-use (DEFRA, 2006, DEFRA, 2009). Once the sorting is complete, the clothes for export are packed into bales whose weight depends on the rules and regulations governing second hand clothing at the destination countries (2009). The main export market for used clothing is Africa (DEFRA, 2006, DEFRA, 2009, Baden and Barber, 2005, Hawley, 2006b, Hawley, 2006a), sub-Saharan Africa in particular.

4 Non Garment Market for Recycled Textiles

Due to increased limitations over the second hand clothing overseas (Hawley, 2006a, Hawley, 2006b, Tanzania., 2010), the sorting companies are working with other stake holders to venture for new markets of recycled products (Hawley, 2006b). For instance products developed from recycled wool fibres command higher price in upholstery and protective clothing in European countries. The conversion of waste garments into new products covers 28% of the total textiles collected for recycling. Traditional conversion involves various mechanical processes such as shredding, carding, and other processes to engineer the final product depending on the end use (Hawley, 2006b, Hawley, 2006a, DEFRA, 2006, DEFRA, 2009, Leifeld, 1996). The recycled products includes recycled yarns, nonwoven products, carpet under lays, sound insulators, thermal insulators, phase change materials, geo-textile materials ,odour removal material, filtration material and other many (DEFRA, 2006, DEFRA, 2009), some part of the sorted material are considered for application in the wiping and polishing industry (Bromley and Dunstan, 1978, Hawley, 2006b, Hawley, 2006a, DEFRA, 2006, DEFRA, 2009). The type of material applied for wiping and polishing depends on the specific need of the user. For instance rags from cotton based waste garments suits most as mopping and wiping material when the application involves the removal of polar liquids such as water. In garages where oil spills are obvious, rags from synthetic fibres such as Polyester suits the application due to its ability to absorb oily liquids. In some instances blends of polyester and cotton fibres are used to get a better application in wiping of both water and oil based liquids. Some of the materials which cannot be converted into any other useful products are either directed to the landfill or incinerated as an alternative energy source (Hong et al., 2012, Shen et al., 2013, Jeihanipour et al., 2010, Jeihanipour and Taherzadeh, 2009).

5 Mechanical Shredding of Waste Garments

In order to convert the textiles material into other useful products, size reduction of the textiles into its fibrous form is important and traditionally done using a shredding (pulling) machine (Bromley and Dunstan, 1978, Lambert, 2004)

In principal, each known machine has one or more drums with points. Each of these drums with points rotates in front of a pile of textile wastes which is fed to it and which it shreds into pieces. The materials shredded by the first drum are fed to the following drum which shreds them into pieces again, and does this again until a complete and perfect fibre removal is obtained (Andre, 1984, Arthur R and Hooshang, 1970, Atkinson, 1963, Bacon, 1998, Ball, 1994, Bell, 2004, Campman, 1970, Deem, 2000, Hagguist, 1993, Morel, 1984, Sharer, 1996a). Depending on the nature of the operation the process can be "opening" or "garneted". When the pulling process open up the fabric up to fibre level, the operation is called opening and when the fibre requires further opening then the operation is called garneting (Lambert, 2004). Some designs of the shredding machines are equipped with auxiliary systems to facilitate material cleaning, feeding and collection of the shredded fibres (Leifeld, 1996, Morel, 1984, Ball, 1994). In some cases the machines are designed with recycling system whereby the shredded materials are allowed to recycle until completely opened into its fibrous state. A system which collected the insufficiently shredded material by set of rotating drums drawn by air duct and then separated by cyclone system and subsequently recycled to the feed system by means of belt conveyor was developed (Leifeld, 1996, Morel, 1984, Ball, 1994). There are some design of shredder which uses a pneumatic system to collect the fibres away from the shredding area (Leifeld, 1996). The stock from the shredding apparatus is usually processed through subsequent carding steps so as to align the fibres in order to produce yarn of required linear density. The degree of shredding accomplished in the initial operation substantially affects the cost of maintaining the cards and also affects the quality of the finishing material. It is important that the feed stock is held to the minimum shredded with a minimum of fibre breakage to preserve fibre quality (Campman, 1970, Atkinson, 1963). Some shredding machines use perforated drums which deploy a strong suction power for collection of the shredded fibres (Morel, 1984).

During finishing of textile materials chemicals are applied in order to enhance physical and aesthetic performance of the finished products. Detergents and bleaches are also applied during serviceability of the garment. The residue finishes need to be removed as part of recycling of waste garments in order to keep the performance of the recycled product. The removal of the chemical residue can be either before or after the shredding of the waste garments (Ball, 1994).

A comprehensive waste denim recycling system which integrates sorting, starch and size removal shredding, low tension carding and yarn spinning have been reported (Ball, 1994). The system can accommodate both pre and post consumer wastes. The collected wastes are sorted to remove non denim materials, then according to colours, after which starch and sizes are removed and

subsequently shredded into fibres. In order to reduce fibre breakage during opening and carding, fibres are lubricated and then blended with virgin fibres up to 50%. Fibre blending ensures good fibre length distribution, an important factor affecting the quality of the spun fibres. The blended fibres are then opened cleaned, carded, spun into yarns and subsequently a denim fabric is produced. The properties of the produced denim fabric are within the range acceptable by the consumers.

5.1 Carpets and fibre separation techniques

Mechanical shredding of waste carpets operates in similar manner as shredders for waste garments. Normally a carpet contains at least four types of material, the face fibres, backing fibres and adhesive which contains latex and filler material (Wang, 2010, Wang et al., 2000, Wang et al., 1994). Thus owing to the hard binder in the carpet, unlike the waste garments, shredders for carpets have been designed to overcome the strength of the carpet which is induced by the presence of the adhesives (Rowe, 2000, White, 2000, Costello, 1998, Wolfgang et al., 1997, Hagguist, 1993).

Process for separating pre-shredded carpet materials into as many as three main components of different densities which comprises finely breaking the carpet materials in the liquid phase suspension has been developed. The density of the liquid phase is adjusted to a level between two adjacent densities of the components. Separation of one component from the other components and from the liquid phase in the suspension is effected in a double-cone full-jacketed screw centrifuge. The process is repeated if there are two materials of different densities in the other components fraction. The process is useful for recovering nylon, polyester, or polypropylene from carpet scraps which nylon or polyester can be depolymerised to reusable monomers and which polypropylene can be reprocessed into pellets, non-woven products or fibres (Costello, 1998, Wolfgang et al., 1997).

Other method for recycling carpet is by disintegrating and separating carpet into its base component materials, through a process and apparatus that, through a series of mechanical, hydraulic, fluid, heat and pressure devices, separates and segregates carpet into its principal components, i.e., secondary backing, binder, pile and primary backing (Hagguist, 1993).

Some of the shredding apparatus shred the carpet pieces into substantially even sized small pieces of not more than five square centimetres. These pieces are passed to a granulating apparatus, which slices them into smaller pieces of between one to two centimetres in order to partially separate the fibrous material and backing material. The partially separated materials are delivered in even manner to an elutriator for full separation. More detailed features of such a technology are available in the literature (Sharer, 1996b, Sharer, 1996a).

Process and system for reclaiming polymeric fibres (e.g., nylon) from post-consumer carpeting includes shredding the post-consumer carpeting into strips, dismantling the carpet strips to form a mixture of the fibres to be reclaimed and the backing material to be discarded, and then separating a substantial portion of the fibres from the backing material.

In another technology carpet strips are dismantled by impacting the strips of carpeting against an anvil structure with hammer elements using, e.g., a hammer mill. From the dismantled strips fibres are recovered by separating a mixture of fibres and backing material. The recovered fibres are either pelletized and/or baled as desired (Sferrazza, 1996).

A method of manufacturing composites for used building material from waste carpets is available and includes shredding carpet waste, coating the carpet waste with a binding agent, and subjecting the shredded, coated carpet waste to elevated heat and pressure. As an additional step, the composite material may be actively cooled to prevent deformation of the material (Deem, 2000, Murdock, 2011). In some cases the waste carpets are mechanically reduced into fibrous form and then added as fillers to other material such as polymers in standard latex or PVC carpet back coatings (Keating, 2012, Bell, 2004).

6 Fibre Separation Techniques

Since most of textiles are made up of blends of different types of fibres and the joining of garments uses various types of threads, there is need for separating the fibres into its original types. Items such as carpets which are made up of face, backing and adhesives, also needs to be separated. Mechanical separation is widely applied as a means to separate various fibres depending on their differences in densities.

The process of fibre separation by centrifuge has been reported (fibre and textile waste utilization (Wolfgang et al., 1997). The system was successfully used to separate ground nylon carpet into nylon, polypropylene and adhesive (latex and fillers). The system employs a drum rotating at high speed to generate a centrifugal acceleration 1,000–1,500 times that of the gravitational acceleration. 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 1.0 g/cm^3 density further separates the nylon from the polypropylene (Wang,

2010, Wang et al., 2000). Other separation methods by cyclones have been reported (Rowe, 2000, White, 2000, Merriman, 1993, Costello, 1998).

The sink –float technique was reported to separate fibres based on difference in density characteristics of the material in liquids, however the main challenge was the partial disentanglement of the fibres in order to move freely in the liquid (Bromley and Dunstan, 1978).

Non cellulosic materials are separated from wood pulp by the use of cyclone separators (Merriman, 1993) and have also been used to separate carpet face fibres from other carpet materials (Costello, 1998). With the cyclone separators, the stock of known consistency is allowed to flow in a separating column, in the column the cellulosic material are separated from the non cellulosic material by centrifuge force due to the differences in densities among them. The cellulosic material is directed to accept line whereas the non cellulosic ones are directed to reject line. Own experience on separation of polyester flock fibres from viscose fibres indicated formation of fibre clumps due to electrostatic charge attraction among the fibre thus difficulty in separation. However the fibre clumping issue was fixed by modifying the fibres with 0.1%owf carboxymethyl cellulose (CMC) which made the fibre free in dispersion hence potential to separating. The efficiency of cyclone separator depends on parameters such as the feed pressure, accepts pressure, cleaner diameter and the stock consistency.

The method for fibre separation by electrostatic separator was reported in the late 1970s (Bromley and Dunstan, 1978). In electrostatic separation, the disentangled fibres are made airborne and passed between positive and negative plates. Depending on the charge, fibres will be attracted to the positive or negative plate. Plates take the form of endless belts which carry the separated fibres to the storage bins. The separation efficiency of the electrostatic separator was affected by fibre formation into clumps.

Due to the way the carpet material are constructed to each other and the difference in their properties, waste carpets can be separated into its constituent fibres without the shredding process (Hagguist, 1993, Sferrazza, 1996, Howe, 2001, Bacon, 1998). Direct separation of the fibres involves carpet loop opening by chipping of the face fibres, and then bombarding the carpet with air and steam in order to weaken the bond between the adhesives, fillers and the fibres. The backing material is exposed and subsequently pickers are used to collect the face fibres (Hagguist, 1993). In some cases , the carpets are cut into small pieces which are then impacted on the anvil using hummer mill to de-bond the fibres and then separate by centrifugal methods (Sferrazza, 1996). Spray of high velocity water jet on the face of waste carpet dismantle the carpet components from one another, and thereafter, separating the secondary backing from the yarn and tufting primary. The method requires drying of the fibres after separation (Howe, 2001). A preferred method of abrasion uses dry ice pellets (made of frozen carbon dioxide), which are ejected at high speed from a set of nozzles that shoot the pellets directly into an abrasion zone, as a segment of discarded carpet on a conveyor system is being stripped apart and disassembled. The dry ice pellets "freeze" the binder material (usually latex) by lowering it to a temperature that makes the binder brittle and easy to break apart. This eliminates the need for a drying operation, which saves time and energy and avoids a potential air pollution problem (Bacon, 1998).Other separation methods involves the use of solvents whereby one or more fibre components dissolve in a desired solvent then the unresolved fibres are recovered from the solution (Bromley and Dunstan, 1978, Booij, 1997, Booij, 2003, Sifniades, 1997, Frentzen, 2000, Sarian, 1998, Griffith et al., 1999, Braun et al., 1999, Dahlhoff et al., 2001).

The Polyamide can be recovered from carpet by extracting the polyamide using aliphatic alcohols such as methanol ethanol and propanol. In the process the carpet is cut into smaller pieces, dissolved in the solvent where the nylon dissolves leaving the other solid parts of the carpet. After filtration, the filtrate is precipitated into nylon with a yield of at least 90%. The yield depends on the extraction time, temperature and pressure. The optimum extraction parameters are, temperature of 135-140 °C, pressure of 0.2-2MPa and time 1 hour and the solvent to waste carpet ratio is 5-20(w/w). One advantage of this process is the ability of alcohol to solubilise dyes which after precipitation of the nylon, the dyes are extracted from the solvent by the dissolving the alcohol or use of adsorbent such as active carbon (Booij, 1997, Booij, 2003).

The recovery of nylon from waste carpets is by treating a mixture of shredded waste carpet containing nylon 6 with water at a temperature between about 200° C. and about 400° C. the treatment at high temperature depolymerises the nylon 6 into coprolactam. Insoluble materials are separated and then the coprolactam is extracted from the oligomers using alkyl phenols and subsequently recover the coprolactam from the extracting agent by distillation process (Sifniades, 1997, Frentzen, 2000).

In another process the nylon fibres are recovered from the waste carpet by dissolution with mineral acids such as sulphuric, formic acid and

hydrochloric acid, the insolubilised material are filtered and then the nylon material is precipitated by diluting the solution in water. During the process, pieces of waste carpet which contain nylon face fibres are placed in a known concentration of hydrochloric acid at 40° C. and dissolution times of 2 to 30 minutes. The nylon face fibres dissolve very readily and quickly, leaving the primary backing, the latex with the calcium carbonate filler and the secondary backing intact. Some of the calcium carbonate reacts with the hydrochloric acid to form calcium chloride. The solution is filtered to remove insoluble materials (Sarian, 1998).

The hydrochloric acid solution, with the dissolved nylon, is diluted with water. When the dilution reaches 12% to 13%, the nylon begins to precipitate. Initially, the precipitate is in the form of viscous, pitch like, sticky fluid. Upon further dilution, the precipitate begins to solidify in the form of film and particulate matter. Dilution to about 5% results in near complete precipitation. The other option is the face yarn carpet containing nylon fibres is placed in sulphuric acid at concentrations of 40% to 60%, temperatures of 80° C. to 104° C., and dissolution times of 5-10 minutes. The nylon face fibre dissolves very readily and rapidly, leaving the primary backing, the latex with part of the calcium carbonate and the secondary backing intact. Part of the calcium carbonate reacts with the sulphuric acid to form calcium sulphate. The sulphuric acid solution, with the dissolved nylon, is diluted with water. When the dilution reaches 22% to 27%, the nylon, in both cases, begins to precipitate. Both nylon recovered by hydrochloric and sulphuric acid is filtered, neutralized, washed with water several times and dried. In both options the acid is decanted and concentrated by evaporating the water for re use. The purity and yield of the nylon recovered by mineral acid is at least 92% (Sarian, 1998).

Recovery of nylon polymer from waste carpet is by combination of selective dissolution and superficial fluid anti solvent precipitation. The process involves selective dissolution of nylon by using 88wt. % liquid formic acid at 40C up to 2.31 wt. % from the waste carpet and subsequently the nylon product powder is precipitated with supercritical carbon dioxide at pressures between 84 and 125 bar at 40°C. After precipitation both formic acid and carbon dioxide are recycled. The process is said to yield high quality nylon material (Griffith et al., 1999, Wang, 2010).

The recycling of nylon 6 carpet via depolymerisation provides the potential for an environmentally benign new process to produce world-class caprolactam is by the modification of the methods which have just been described (Sifniades, 1997, Frentzen, 2000). With the modified method, the depolymerisation of nylon 6 carpet in the presence of steam under medium pressure 1500 kPa and temperature of 340 °C for 3 hours could produce a 95% yield of crude caprolactam with 94.4%purity (Braun et al., 1999). The advantage of this the new method over the latter (Sifniades, 1997, Frentzen, 2000) is that it does not use any chemicals catalysts and extracting agents, however the process time is relatively longer (Dahlhoff et al., 2001).

6.1 Recycling by depolymerisation and re-polymerisation

The conversion of polyester based products into its monomers and then use the monomers for productions of other items have been reported (Upasani et al., 2012, Patagonia, 2013, Shukla et al., 2008, Oakley, 1993). Simple recycling process that involves crushing the used bottles to obtain flakes from the bottle walls, washing and cleaning the flakes to remove external contaminants, drying, and then melt extrusion into desired product leads to the loss of molecular weight to from [μ]0.82 to 0.6 dL/g while a typical limiting viscosity for PET fibres is 0.6dL/g. The melt extrusion step can optionally be carried out after blending with virgin PET so as to reduce the negative impact on the quality of the end product. In an alternative approach, the washed, recycled PET flakes can be completely or partially depolymerised by glycolysis with monethylene glycol. The alcoholysis takes place at 180-210 °C and pressure of 150-250psi for 4 to 6hrs and then the mixture is cooled to 150° C (Oakley, 1993). The depolymerisation product can be filtered and then further repolymerised to give desired product quality (Upasani et al., 2012) the recycling of PET wastes into yarns have already been commercialised in Japan by Taijin (Patagonia, 2013). The process involves collection of polyester based waste garments sort and separate, depolymerise into monomers and then reconstitute the monomers into new fibres.

The recovery of polyester from poly-cotton fabrics by glycolysis of the polyester into monomers has also been reported (Shukla et al., 2008). Polyethylene terephthalate (PET) waste fibres are initially depolymerised using a glycolysis route into monomer, bis (2-hydroxyethylene terephthalate). During glycolysis reaction sodium sulphate is included as a catalyst. The purified monomer is converted into different fatty amide derivatives to obtain quaternary ammonium compounds that have a potential for use as softener in the textile finishing process. The products were characterized and evaluated for performance and found to give good results.

It has also been reported that polyester –cellulose waste garments can be recycled into regenerate fibres and recover the monomers of polyester by combination of hydrolysis and the lyocell process (Negulescu et al., 1998). In the first step of the process, the cotton component of a fabric made of 50/50 cotton/polyethylene terephthalate was separated from the polyester by basic hydrolysis of the latter in NaOH solutions. In the second step, the cellulose component from another sample of the same fabric was selectively dissolved in N-methyl morpholine monohydrate to form a 1-2% cellulose solution. The cellulose solution was then concentrated to a spinnable 15-17% solution by dissolving the cotton separated in the first step and subsequent fibre spinning following the standard lyocell process. Lyocell fibres were subsequently spun at 85-90°C using an advanced capillary extrusion rheometer system. however this literature (Negulescu et al., 1998) did not disclose the optimal hydrolysis conditions. Although this process recover spinning solution with low percentage in cellulose concentration, literature suggests that fibres with good mechanical properties can be regenerated even at this low percentage of cellulose by incorporation of additives (Chanzy et al., 1990). Some work carried out on the spinning lyocell fibres using cellulose-wood pulp blend indicated that a blend of up to 20% polyester in the initial feed stock can produce lyocell fibres with acceptable mechanical and dyeing characteristics (Joshi et al., 2010). This implies that the separation of polyester cellulose fibres can be done with up to at most 20% of the polyester remaining in the cellulose and still the cellulose can be regenerated into new fibres via Lyocell process, while the PET monomers are repolymerised back into Polyester fibres by the Taijin technology.

Polyester –cellulose waste garments can be treated to recover the polyester fibres and convert the cellulose into ethanol (Jeihanipour et al., 2010). An environmentally friendly cellulose solvent, N-methylmorpholine-N-oxide (NMMO) was used in this process for separation and pre-treatment of the cellulose. The solvent was mixed with blended-fibres textiles at 120 °C and atmospheric pressure to dissolve the cellulose and separate it from the un-dissolved non-cellulosic fibres. Water was then added to the solution in order to precipitate the cellulose, while both water and NMMO were reused after separation by evaporation. The cellulose was then either hydrolyzed by cellulase enzymes followed by fermentation to ethanol, or digested directly to produce biogas. The process was verified by testing 50/50 polyester/cotton and 40/60 polyester/viscose-blended textiles. The polyesters were purified as fibres after the NMMO treatments, and up to 95% of the cellulose fibres were regenerated and collected on a filter. A 2-day enzymatic hydrolysis and 1-day fermentation of the regenerated cotton and viscose resulted in 48 and 50 g ethanol/g regenerated cellulose, which were 85% and 89% of the theoretical yields, respectively. This process also resulted in a significant increase of the biogas production rate. While untreated cotton and viscose fibres were converted to methane by respectively, 0.02% and 1.91% of their theoretical yields in 3 days of digestion, the identical NMMO-treated fibres resulted into about 30% of yield at the same period of time. direct enzymatic hydrolysis of cellulose fibres from poly –cellulose fabrics blend and recover polyester fibres by filtration have been reported (WrzeÅ›niewska-Tosik et al., 2003). During the process, pre shredded waste fabrics in a stock of 4 wt.% cellulose fibres is treated with a cellulolytic enzyme solution in a 0.05M sodium acetate buffer (pH 4.8) at the temperature of 50°C for 96 hours with continuous agitation/ shaking and subsequently the residual fibres are separated from the enzyme solution by filtration , water washed at (90°C), cold washed and finally dried. Polyester fibres can also be recovered from poly-cotton blends by selective hydrolysis of the cellulose in acid and then recover the fibres after mechanical beating in water (Ouchi et al., 2010). This is a two-step procedure that consists of one minute static acid treatment of the mixed fabrics with aqueous 10 N H2SO4 at 95 °C and successive mechanical beating in room-temperature water. Cellulose was efficiently removed from polyester fabrics as a powder, with high recovery of both cellulose powder and polyester cloth.

A process for recycling polyester/cotton blends by selective reduction of the two polymers into simple compounds has been developed (Oakley, 1993). This novel process to recycle the polyester/cotton blends includes the following steps; (a) subjecting the polyester/cotton blend to a first alcoholysis in a bath containing ethylene glycol and an effective catalyst (basic alkali metal such as sodium carbonate and sodium hydroxide at a suitable temperature until the polyester is depolymerized to a lower molecular weight polyester oligomer; (b) remove the cotton fibres from the alcoholic solution of oligomers and process the recovered cotton fibres by pulping and acetylyzing processes to recover the cellulose acetate; and (c) alcoholyze the low molecular weight polyester oligomers to produce the lower dialkyl ester of terephthalic acid.

The liquor to goods ration ranges 4-3:1 and the catalyst is 0.25% owf. The alcoholysis takes place at 180-210°C and pressure of 150-250psi for 4 to 6hrs and then the mixture is cooled to 150°C and subsequently the cellulose is filtered out of the de-porimerised polyester. The low molecular weight

oligomer is further reduced by reacting with methanol at 0 to 50 psi and temperature of 60-100°C to dimethyl terephtalate. the cellulose fibres are cleaned and then acetylated to cellulose acetate.

7 Physical Reclamation of Fibres

It has been emphasized that in order to ensure high quality of yarn spun from fibres reclaimed from waste garments sorting of materials according to type of fibres prior to shredding is important. Moreover, the size of the pieces of the waste garments fed into the shredder may affect the spinnability of the fibres. Too small pieces accelerated fibre breakage whereas too large pieces make the shredding difficulty and process longer (Cheng and Wong, 1997). Carding and spinning parameters of reclaimed fibres requires a clear understanding of the properties and type of the reclaimed fibres. For instance high carding drum speed is favourable when handling hard salvages whereas high carding drum speed tends to produce yarns with weaker strength and more hairs as it causes considerable breakage of fibres (Cheng and Wong, 1997).

Yarn spun from 100% recovered fibres with acceptable commercial qualities was only produced by pneumatic spinning processes (Lebedev N, 1995), but the process was further improved owing to high breakage rates. Mixtures of virgin fibres and reclaimed fibres to make new yarns could work for DREF II and pneumatic spinning whereby yarn of 80-250 tex has been achieved by using a series of cards. (Lebedev N, 1995). Owing to shorter length of the fibres which are mechanically reclaimed from waste garments it has been difficult to spin the fibres into fine count yarn. However a mixture of reclaimed and virgin fibres can be produced using a modified friction spinning machine (Merati and Okamura, 2004). Two component yarns were successfully spun into 30tex count from reclaimed fibres as a core and covered by virgin cotton fibres and the properties of the yarn was similar to 100%cotton yarn. The tensile properties of recycled yams could further be improved by production of a three-component yarn with a continuous filament in its core, reclaimed fibres in the middle layer, and virgin cotton fibres in the sheath (Merati and Okamura, 2004).

8 Fibre Recycling by Melting

With the melting process the stock of synthetic waste fibres, are heated to melting point and then the melt is extruded through a die to form strands which are then cooled and chopped into pellets (Wang, 2010). Size reduction of the waste textiles material prior to melting process is vital in order to easy the melting process. Fibre separation is also important prior to the melt process especially when the waste textile contains natural fibres. For instance, natural fibres cannot be melt blended with nylon or polyesters because the required high melt temperatures cause extensive degradation.

9 Conclusion

The origin recycling of textiles was to convert the waste garments into non fashion application such as paper making, and others. However, following the emergency of synthetic fibres, the use of fibre blends and lack of technology for fibre separation, waste garments could not be used for paper making. Over years, 50% of the collected waste garments has largely been prepared and supplied to developing countries for reuse. Efforts have been put on adding the value of the second hand clothes supplied to developing countries. However the second hand clothing business is challenged for retarding the growth of local textile and fashion industries at the destination countries. Other recycling technologies involve the shredding of the garments into fibres and reconstitute the fibres into yarns; however the resultant yarns has limited properties. Other recycling approaches involve chemical conversion of the wastes into new fibres, other usable items and production of energy and other chemicals. The future trend of recycling of textiles is in the direction of conversion of the wastes into new products and not recycling for re-use.

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