A large amount of fibrous waste including post consumer carpet is generated each year. Increase the rate of recycling has been one of the goals for resource conservation and environmental protection. It a large industry with appropriate infrastructure is needed if a significant amount of the fibrous waste is to be recycled. The activities of this industry must be economically competitive and environmentally beneficial. It requires diversified commercial operations employing many technologies so as to maximize the use of the fibrous waste collected. Some of the recycling technologies are reviewed in this chapter.

1. Introduction

A large amount of fibrous waste is generated each year, consisting of a variety of synthetic and natural polymers. Frequently different types of polymers and other materials are integrated to form an article, such as blended textiles, carpet, conveyer belts, to name a few. Much of textile waste collected could be reused directly, be used as wipes, or be shredded for filling or nonwoven applications. Post consumer carpet, on the other hand, is a more complex system that often requires extensive processing to convert it into products.

The tufted carpet, the most common type (90%) as shown in Figure 1, typically consists of two layers of backing (mostly polypropylene fabrics), joined by CaCO$_3$ filled styrene-butadiene latex rubber (SBR), and face fibers (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 remelted 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 2 shows the typical masses for the various components [1].

According to the U.S. carpet industry statistics [2], the total fiber consumption in 2001 was about 1.4 million tons: Nylon 60%, Olefin 29%, Polyester 10%, and Wool 0.3%. Among the nylon face fiber, 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 U.S. [3], and about 4-6 million tons per year worldwide.

The type of carpet is classified according to the type of face fibers used. A nylon 6 carpet, for instance, contains not only nylon 6 face fibers but also backing fibers (polypropylene) and adhesive (latex and filler). Nylon generally performs the best among all synthetic fibers as carpet face yarn, but it is also the most expensive. Typical price per kg for the plastic resins are: Nylon $2.50, Polyester $1.20, and Polypropylene $0.75. This price list provides a perspective on the economics of recycling as well. For example, if it takes the same processing effort to convert the fiber into resin, an operation on nylon would be most profitable. This also explains why most of the recycling effort is on nylon recovery.

Post consumer carpet can be collected in large quantities, as demonstrated by a previous national network in the U.S., the Evergreen Nylon Recycling, LLC [4,5] and a collection and sorting demonstration project in Europe, Carpet Recycling Europe (CRE) [6,7]. In order to establish a carpet recycling industry that is capable of processing a sizable amount of the waste discarded, say 20 to 50% of the waste generated each year worldwide, there must exist a collection network to provide sufficient and consistent supply of post consumer carpet at reasonable cost, and a diversity of commercial operations to produce a variety of
marketable products. Diversity is very important for the success of the industry, as it would allow most of the carpet waste collected to be utilized for profitable recycling, without quickly saturating any market of a product. As the past experience has shown, it cannot be economically competitive if only a fraction of the carpet collected can be recycled, while the rest has to be sent back to landfills. Many technologies are available and more are being developed to recycle fibrous waste [3,8,9,10,11]. Figure 3 illustrates the spectrum of technologies in terms of product quality, potential volume, processing steps and cost. They should all play an important role in carpet recycling.

2. Fiber Identification and Sorting

For many recycling processes such as nylon depolymerization and polymer resin recovery, it is desirable or required to sort the feedstock according to the type of face fibers. For carpet, the sorting is according to the type of the face fiber. Melt point indicator is an inexpensive instrument that can identify most fiber types, but it is generally slow and cannot distinguish between nylon 6,6 and polyester. Infrared and Raman spectroscopy is much more effective. Table 1 compares the various carpet identification systems [12].

Carpet collection involves collecting carpet 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 has been developed by Kip et al [13], which is a lightweight, battery operated unit. It is designed to identify the common carpet face fibers: nylon 6, nylon 6,6, polypropylene, polyester, and wool. Unidentifiable fibers, either due to operating conditions or fiber types other than those in the above list, would be shown as “unknown”. Such a low-cost, portable device is suitable for sorting when it is done at each collection point. Sorting can also be done in a centralized facility. A typical instrument employed consists of an A/C powered base unit for data acquisition, analysis and display, and a probe connected to the based unit via a fiber-optical cable. In a manual operation, the probe is moved around to sort carpet pieces. In an automated facility, a carpet piece moving along a rail passes by the fiber identification sensor, and it is sent to different downstream tracks according to the type of face fiber [6].

3. Size Reduction

Size reduction to cut large pieces of carpet into smaller sizes is often needed in the preparation stage of most recycling processes. Size reduction by mechanical actions, often called shredding or grinding, has been reported [14,15,16,17,18,19,20] and many types of equipment are commercially available for processing textile and carpet waste [21,22]. In a typical process, the feedstock 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 opening. Pieces smaller than the screen opening are allowed to drop off and those that do not fall out would be sent back to the cutting chamber for re-cutting. Although a fiber 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 fiber 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.

4. Mechanical Separation of Carpet Components

Mechanical methods have been utilized to separate carpet components. One or more segregated components then are recycled into products that generally compete with products produced from virgin polymers.
In a process developed by DuPont [9,23], nylon 6,6 carpet first 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 fiber is washed and separated using the density differences between the fillers, nylon and polypropylene. Two product streams are obtained: one 98% pure nylon and the other 98% pure polypropylene. The recycled nylon is compounded with virgin nylon at a ratio of 1:3 for making automotive parts.

A centrifuge system has been developed to separate ground nylon carpet into nylon, polypropylene and adhesive (latex and fillers) [24]. The system employs a drum rotated at a speed to generate a centrifugal acceleration 1000 to 1500 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 fibers (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.

Some processes separate carpet components without first going through a size reduction step. The United Recycling process [25,26] starts with clipping the face fibers 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 fibers. It is claimed that the cost of this process is low and that it yields a product stream with 93-95% pure face fibers. Other devices employing water jet [27] or dry ice pellets [28]. 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 dry ice pellets freeze the binder material (usually latex), lowering it to a temperature that makes the binder brittle and easy to break apart. The dry ice pellets sublime directly into gas without any liquid residues. This process eliminates the need for a drying operation, which saves energy and avoids potential chemical pollution.

5. Solvent Extraction of Nylon from Carpet

Solvent extraction has been used to separate the high value nylon from carpet waste. The solvents used include aliphatic alcohol [29], alkyl phenols [30] and hydrochloric acid [31]. In the process developed by Booij, et al. [29], the carpet waste is shredded into 0.5-20 cm$^2$ pieces. Then the carpet pieces are mixed with the extraction agent, such as methanol. The weight ratio of solvent to carpet waste is generally 5 to 20. An extraction time of 60 minutes is found to be sufficient to dissolve nylon 6 at a temperature of 135-140°C and a pressure of 0.2-2 MPa. Solids are filtered out, the solution cooled down and the nylon 6 precipitated. The nylon obtained has at least 90% of the relative viscosity of the nylon present in the carpet waste, indicating that no serious degradation takes place in the extraction process. In addition, the yield of nylon is high (above 90%). The drawbacks of solvent extraction are the chemicals involved, modest temperature and pressures required, and time required. In comparison, the use of hydrochloric acid [31] as a solvent requires lower temperature (20 to 100°C) and shorter dissolution time (2 to 30 minutes). Based on relative viscosity data, no degradation of the recycled nylon is observed. However, hydrochloric acid solvent is not recyclable due to its reaction with the calcium carbonate filler in the carpet waste.

Another approach to separate carpet components is to use a supercritical fluid (SCF) method in a batch process [32,33]. The solubility of the polymer changes with the variation in pressure and temperature of the SCF. Sikorski [32] discloses that the individual polymers in carpet can be extracted sequentially using a SCF such as CO$_2$ by increasing temperature and pressure. However, high temperatures (170-210°C) and pressures (500 to 1000 atm) are required to dissolve the various polymers in the SCF solvent.
Another development enables the separation of carpet waste at close to room temperature and moderate pressure [33]. Up to 2.3 wt% nylon was dissolved in an 88 wt% formic acid solution. Then supercritical CO₂ as an anti-solvent was added to precipitate the nylon out of the solution at a temperature of 40°C and a pressure between 84 and 125 atm. Both the solvent and the anti-solvent can be recycled. The whole process is very controllable and the resultant nylon is of high quality.

6. Depolymerization of Nylon

Because of the higher value of nylon resin in comparison with other polymers used in carpet, nylon carpet has been looked at as raw material for making virgin nylon via depolymerization [5]. The majority of polyamides used commercially are nylon 6,6 and nylon 6. The waste carpets are collected, sorted and then subjected to a mechanical shredding process before depolymerization.

Nylon 6 is made by polymerizing a single monomer, the caprolactam, and the process may be reversed. Chemical recycling of nylon 6 carpet face fibers has been developed into a closed-loop recycling process for waste nylon carpet [4,5,10,34]. The recovered nylon 6 face fibers are sent to a depolymerization reactor and treated with superheated steam in the presence of a catalyst to produce a distillate containing caprolactam. The crude caprolactam is distilled and repolymerized to form nylon 6. The caprolactam obtained is comparable to virgin caprolactam in purity. The repolymerized nylon 6 is converted into yarn and tufted into carpet. The carpets obtained from this process are very similar in physical properties to those obtained from virgin caprolactam.

The “6ix Again” program initiated at BASF and now part of Honeywell Nylon Inc., has been in operation since 1994. Its process involves collection of used nylon 6 carpet, shredding and separation of face fibers, pelletizing face fiber for depolymerization and chemical distillation to obtain a purified caprolactam monomer, and repolymerization of caprolactam into nylon polymer [35].

Evergreen Nylon Recycling LLC, a joint venture between Honeywell International and DSM Chemicals, was in operation from 1999 to 2001. It used a two-stage selective pyrolysis process. The ground nylon carpet, without separation, is dissolved with high-pressure steam and then continuously hydrolyzed with super-heated steam to form caprolactam. With a 100 thousand tons per year capacity, the program has diverted over one hundred thousand tons of post consumer carpet from the landfill to produced virgin-quality caprolactam [4,5].

Polyamid 2000 in Germany was another large commercial carpet recycling facility. With a capacity to recycle 120 thousand tons of unsorted carpet each year, it was in operation from 2001 to 2003. A major source of carpet supply was the Carpet Recycling Europe (CRE). It employed a process similar to the “6ix Again” sequence to depolymerize nylon 6, and produced resin compounds from nylon 6,6 face fibers.

Depolymerization of nylon 6,6 is more complicated than that of nylon 6 because nylon 6,6 is made of two monomers, the adipic acid and hexamethylene diamine (HMDA). Depolymerization of nylon 6,6 to recover adipic acid and HMDA has been demonstrated [23,36,37,38] but has not been implemented in commercial operation.

7. Melt Processing

Melt processing by extrusion converts thermoplastic polymers into resin pellets [21,22]. If more than one type of polymer is blended together, the process is also referred to as compounding (the resulting pellets are called compounds). Carpet or other fibrous waste typically undergoes a size-reduction process. The
shredded material is bulky and requires a separate densification process or be fed to an extruder by a specially designed crammer-densifier feeder. Integrated systems are available with feeding conveyer belt, shredder, feeder and extruder are available to convert bulk carpet, fibers, nonwovens and films into pellets. Such systems require less floor space, are easier and cleaner to run, and incur low cost in terms of energy, labor and maintenance. However, the flexibility in terms of product range is reduced. The extruders may use a single screw, twin-screw co-rotating, or twin-screw counter rotating design depending on the throughput, product range, and mixing intensity desired. The extruder normally has venting ports to remove volatile gas due to fiber finishes, moisture, lubricants and others.

The molten polymer is extruded through a die to form multiple polymer stands, which are cooled and chopped into pellets. There are several types of pelletizers, and the common ones are water ring pelletizer, strand pelletizer, and underwater pelletizer. Selection considerations include: polymer characteristics such as type, melt temperature, and melt flow index, and operational characteristics such as degree of automation and pellet quality [22]. The water ring method uses a water jet and a rotating knife to cool and cut the strands as they emerge, and it is mostly suitable for polymers with a low melt flow index such polyethylene. The strand and underwater pelletizers can process a wider range of polymers including nylon, polyester terephthalate, and polypropylene. In strand palletizing, the strands is cooled in a water tank, dewatered, and chopped into pellets. It occupies a large floor space and requires constant attention of an operator should the strands break often. In underwater palletizing, the exit of the extrusion die is submerged in water and the strands emerging from the die are cut by rotating knives before the polymer solidifies. The process is compact, highly automated and produces pellets that are consistent, smooth, and spherical in shape.

The product properties and its market value of resins from recycled polymers depend on the composition of the material, mostly the purity of the feed stock. Most carpet waste contains two immiscible plastics, nylon and polypropylene. The immiscibility of these two components leads to poor mechanical properties. When carpet is recycled using melt blending, compatibilizers could be used to improve the properties of the blends [39,40,41,42,43,44,45].

United Recycling Inc. (URI), which was in operation from the early 1990s to 1999, introduced two extruded blends (URI 20-001 and URI 10-001) from post consumer carpet waste for injection molding in 1993 [39]. These were the first commercial recycled carpet compounds. The process used both polypropylene and nylon carpet. Their products were described as proprietary blends containing nylon, polypropylene and other polymers and inorganic fillers.

In 1994, Monsanto patented a process to recycle all the components of post consumer nylon 6,6 carpet, without separation, into a filled thermoplastic product suitable for injection molding [40,41]. They used a twin screw extruder to accomplish high intensity mixing of the thermoplastic from carpet samples. The recycled material contained 35-67 wt% nylon, 8-21 wt% polypropylene, 5-29 wt% SBR and 10-40 wt% inorganic filler. In one study, no compatibilizer was used [40]. The properties of the extruded thermoplastic were comparable to those of the virgin polystyrene but lower than those of virgin nylon 6,6 [46]. In their subsequent work [41], a maleic anhydride grafted polypropylene, PolyBond 3150 at 3 wt%, was added to compatibilize the nylon and polypropylene in the carpet waste, which resulted in improved properties. Other studies have been carried out on the addition of maleic anhydride grafted polypropylene, PolyBond and Kraton (Kraton is a trademark of Shell Company) [42,43,44], toughening agent (styrene-ethylene/butylene-styrene block copolymer, SEBS) [43], and poly (ethylene-co-vinyl acetate) (EVA) [44]. Although compatibilized resins show better mechanical properties, the cost is significantly higher even with a low rate of compatibilizer addition.
Polymers from carpet waste by melt processing may be used to make products in a molding process, either used alone or blended with virgin polymers. The recycled polymers may also be used as matrices in glass fiber reinforced composites. For such applications, the properties of the composites are dominated by the reinforcement (glass fibers), and therefore even recycled polymers without compatibilization could provide the composites with satisfactory mechanical properties [47].

8. Use of Waste Fibers as Reinforcement in Polymer Composites

Kotliar et al [48,49,50] have explored the use of carpet face yarn and textiles as reinforcement for a composite or laminate. Because of the fine diameter of the fibers involved, a low viscosity prepolymer in a water base was used to insure complete coverage of the fibers. Adhesives were selected to result in a high modulus and creep resistant material with good weathering characteristics.

The work emphasized shredded carpet selvage to which various amounts of cut waste fibers such as nylon 6, nylon 6,6, polyester and cotton were added. Fabric bits of waste denims and cotton-polyester fabrics were also used. The waste carpet blend was then coated with phenolic or urea formaldehyde resins that were dispersed in a water base. The composites contained various amounts of different fibers or fabrics and 7.5 to 20 wt% adhesive solids with respect to the fiber content. The fibers were spray coated and molded in a heated press at 150 to 200°C and 3.4 MPa. Test results show that one can achieve high flexural moduli of 2.4-2.8 GPa with face yarn, i.e., fibers that bind to the matrix such as nylon, polyester and cotton. These values together with flexural strengths of 34-48 MPa make the products suitable for many outdoor and transportation applications.

Laminates directly from waste carpet pieces were also made by coating the face yarn with a phenol formaldehyde resin and molding the carpet pieces back to back with the face yarn on the outside to achieve a high flexural modulus [49]. Holes were punched into the carpet prior to spray coating the face yarn so that protrusions of the matrix material could flow into the backing during the molding process to avoid shear delamination. The laminates were also made into honeycomb sandwich structures for improved flexural stiffness and lighter weight.

Gowayed, et al. [51] explored the use of edge trim of polypropylene (PP) fabric waste (from the carpet backing) to reinforce a polyethylene (PE) matrix. Four layers of 0.1 mm thick PE film were laid with a single layer of washed PP fabric waste. Then they were molded at a temperature of 150°C and a pressure of 290 kPa. It was found that the resulting PE/PP composite, with 25% PP volume fraction, exhibited a three-time increase in tensile strength and a 60% increase in flexural modulus when compared to the properties of pure PE.

9. Waste to Energy Conversion

The energy content of the waste materials may be recovered, at least in part, by incineration, or burning the waste materials [11,52,53,54,55]. Municipal solid waste (MSW) combustion facilities incinerated about 14% (33 million tons) of the municipal solid waste in the United States in 2003 [56]. Most of these facilitates have a waste to energy conversion process. Waste containing used paper/wood products, contaminated packaging, and discarded tires has been combusted. The volume of these MSW is reduced by about 75% after incineration. The post-combustion ash still needs to be treated separately and then landfilled. Public concerns exist for the incineration of polymer waste. However, with advanced technologies and proper management, waste-to-energy conversion can be a viable alternative to landfilling. It is estimated that, if all the MSW that is currently generated in the United States were incinerated, the resultant carbon dioxide would be only 2% of that produced from the combustion of all
other fossil fuels [53]. The current challenges for the incineration of polymer waste include further improving the incineration efficiency and reducing the harmful end products in the form of ash and noxious gases.

Incineration may be an option for carpet waste that is beyond the capacity of other viable recovery approaches. Incineration may also be desirable for carpet collected but is not suited for recycling, such as carpet with unknown face fibers, or carpet with uncommon compositions.

Solid waste such as tires has been used in cement kilns as fuel supplement for making Portland cement. In an Atlanta, Georgia, plant, the use of tires has decreased the plant’s air emissions by up to 30%, and allow the company to meet tighter nitrogen oxides (NOx) guidelines [57,58]. The use of carpet waste in cement kilns is also quite attractive and an effort is made in this direction [59]. The relatively high fuel value of carpet polymers can reduce the need for fuels, and the calcium carbonate in carpet becomes raw material for cement.

10. Summary

A large amount of fibrous waste is disposed of in landfills each year. This not only poses economical and environmental concerns to the society but also represents a waste of resources. There have been several commercial carpet recycling operations in the U.S., and the products range from virgin-equivalent nylon 6 resin (or fiber), resin for automotive parts, fibrous mats, and vinyl carpet backing, composites, among others. While many of commercial operations are still active, some of the carpet recycling facilities have been closed due to economical reasons. There clearly is a need for further research to develop diversified approaches that can recycle all types of fibrous waste collected. This article reviews some of the recycling technologies. Several other technologies are discussed in separate chapters in this book.

REFERENCES


Table 1 Comparison of fiber identification technologies [12]

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Figure Captions

Figure 1 Typical carpet construction

Figure 2 Component mass/area for a typical carpet (g/m²). Total is 2223 g/m².

Figure 3 Recycling technologies according to product value, processing steps and cost
Figure 1  Typical carpet construction

Figure 2  Component mass/area for a typical carpet (g/m²). Total is 2223 g/m².

Higher value  
Higher cost

• Recovery of “pure” resins (e.g., nylon)
  – High value of products
  – Sort carpet then separate its components by chemical or mechanical means
  – Complicated & costly processes

• Processes to convert entire carpet of a given type into products (e.g., glass fiber reinforced composites)
  – Need to sort carpet, but no need to separate components

• Processes independent of carpet type
  – Converting any type of carpet into products (e.g., wood-like composites, incineration)
  – No sorting & component separation. Lower cost

Figure 3  Recycling technologies according to product value, processing steps and cost