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Poly(lactic acid) fibers (PLA)

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5.1 Introduction

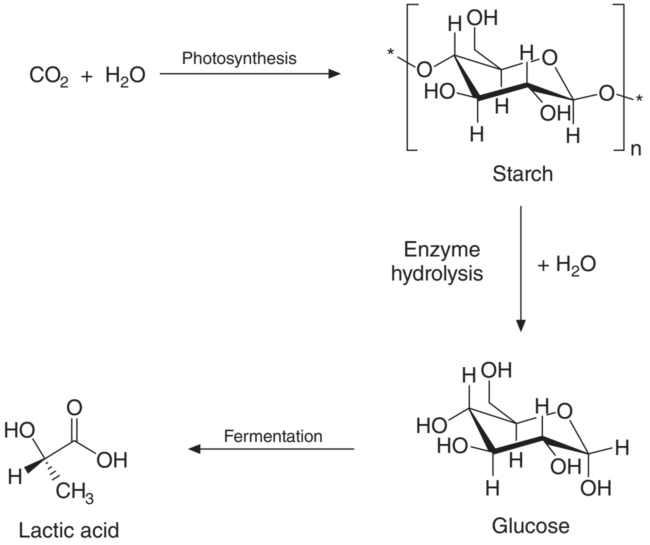
In a world that is becoming increasingly sensitive to the need to protect our environment, the ability to manufacture products from sustainable resources and which are fully compostable at the end of their useful life, is an exciting and attractive proposition. Poly(lactic acid) (PLA) is a linear aliphatic thermoplastic polyester derived from 100% renewable sources such as corn, and the polymer is compostable.[1,2] However, most initial uses were limited to biomedical applications such as sutures[3] and drug delivery systems[4] due to availability and cost of manufacture. Over the past few years, NatureWorks LLC has developed large-scale operations for the economic production of PLA polymer used for packaging and fiber applications. It is important that PLA is used broadly in textile applications for several reasons. Polyesters currently used for apparel and related fiber applications, mainly poly(ethyleneterephthalate) (PET), account for over 40% of world textile consumption (second only to cotton) and their use is constantly increasing. Production of such polyesters consumes fossil fuel resources and disposal of the polymer adds to landfill sites as they are non-biodegradable and are not easily recycled. In contrast, PLA fiber is derived from annually renewable crops, it is 100% compostable and its life cycle potentially reduces the Earth's carbon dioxide level. The recognition by the FTC in the USA and the EU commission that PLA fibers are a completely new generic class of synthetic fibers further reinforces the validity of this new approach to producing performance melt-spinnable fibers.

This chapter will review the chemistry of PLA and will discuss the commercial manufacturing process that confirms its position as a viable material for many applications in both the fibers and the plastics industries. It will review the various properties of the polymer and consider the fiber properties that make it attractive to the commercial sectors into which it is being developed today. Recognizing that this is very much a new polymer with its own characteristics and processing requirements, the current status of the downstream technologies in these sectors will be appraised. The environmental benefits of PLA will be discussed and compared with the current petroleum-based polymers. The potential for further improvements in the environmental impact will be considered as the technologies for this new polymer are advanced.

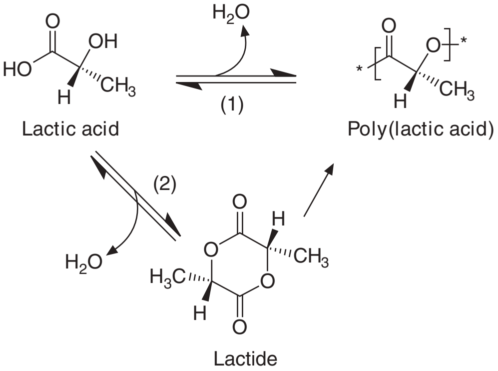
5.2 Chemistry and manufacture of PLA polymer resin

Conventional synthetic polymers rely on reserves of oil and gas for their monomer source and energy to manufacture. These reserves of fossil fuel take millions of years to regenerate and are a declining resource. In contrast, the monomer used to manufacture poly(lactic acid) is obtained from annually renewable crops. Energy from the sun promotes photosynthesis within the plant cells; carbon dioxide and water from the atmosphere are converted into starch. This starch is readily extracted from plant matter and converted to a fermentable sugar (e.g. glucose) by enzymatic hydrolysis. The carbon and other elements in these natural sugars are then converted to lactic acid through fermentation (Fig. 5.1).[5,6]

Presently, the cheapest and most abundant source of sugar is dextrose (glucose) from corn. The land mass necessary for feedstock production is minimal. Producing 500 000 tonnes of PLA requires less than 0.5% of the annual US corn crop;[7] since corn is a cheap dextrose source, the



5.1 Production of lactic acid from renewable resources.



5.2 Polymerization routes to poly(lactic acid).

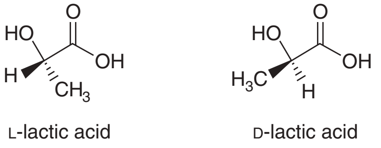
current feedstock supply is more than adequate to meet foreseeable demand. Furthermore, there are many other alternatives for the starch or sugar supply. As fermentation techniques improve, as PLA production improves, and if PLA production extends to other geographies, it is quite likely that other materials such as grass and even biomass could be used; there is no need to be reliant on food crops. PLA takes advantage of a biological system to do chemistry that traditional chemical techniques cannot.

5.2.1 Production of PLA

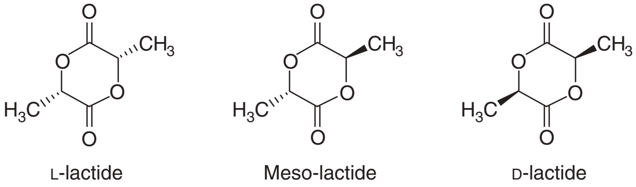
The polymer is formed either by (1) direct condensation of lactic acid or (2) via the cyclic intermediate dimer (lactide), through a ring-opening process (Fig. 5.2).[2]

Polycondensation of lactic acid

This process involves the removal of water by condensation and the use of solvent under high vacuum and temperature; the approach was originally used by Carothers who discovered PLA in 1932. With this route, only low to intermediate molecular weight polymers can be produced, mainly due to the difficulties of removing water and impurities. Other disadvantages of this route are the relatively large reactor required, the need for evaporation, recovery of the solvent and increased color and racemization. Most work has focused on the ring-opening polymerization, although Mitsui Toatsu Chemicals have patented an azeotropic distillation using a high boiling solvent to drive the removal of water in the direct esterification process to obtain high molecular weight PLA.



5.3 The stereoisomers of lactic acid.

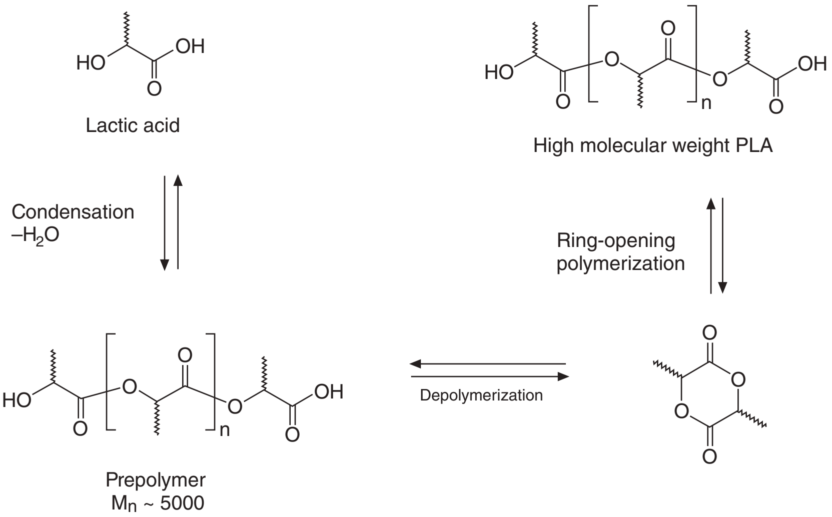


5.4 Dimeric lactic isomers.

Ring-opening polymerization

This method is a better way to produce a high molecular weight polymer, and has now been adapted commercially due to advances in the fermentation of corn dextrose which have significantly reduced lactic acid production costs. The fermentation of sugar produces chiral lactic acid inexpensively in high yield. Chiral molecules exist as 'mirror images' or stereoisomers; lactic acid can exist as the L- or D-stereoisomer (Fig. 5.3). Chemically synthesized lactic acid gives the racemic mixture (50% D and 50% L), however, fermentation is very specific, allowing the production of essentially one major stereoisomer; fermentation derived lactic acid consists of 99.5% of the L-isomer and 0.5% of the D-isomer.

The process is based on removing water under milder conditions, without solvent, to produce a cyclic intermediate dimer, referred to as lactide. This monomer is readily purified under vacuum distillation. Ring-opening polymerization of the dimer is accomplished under heat, again without the need for solvent. By controlling the purity of the dimer, it is possible to produce a wide range of molecular weights. Production of the cyclic lactide dimer results in three potential forms: the D,D-lactide (called D-lactide), L,L-lactide (called L-lactide) and L,D- or D,L-lactide (called meso-lactide) (Fig. 5.4). Meso-lactide has different properties from D- and L-lactide; D- and L-lactide are optically active, meso- is not. Before polymerization, the lactide stream is split into a low D-lactide stream and a high D-/meso-lactide stream. Ring-opening polymerization of the optically active types of lactide can yield a 'family' of polymers with a range of molecular weights by varying the amount and the sequence of D-lactide in the polymer backbone. Polymers with high L-lactide levels can be used to produce crystalline

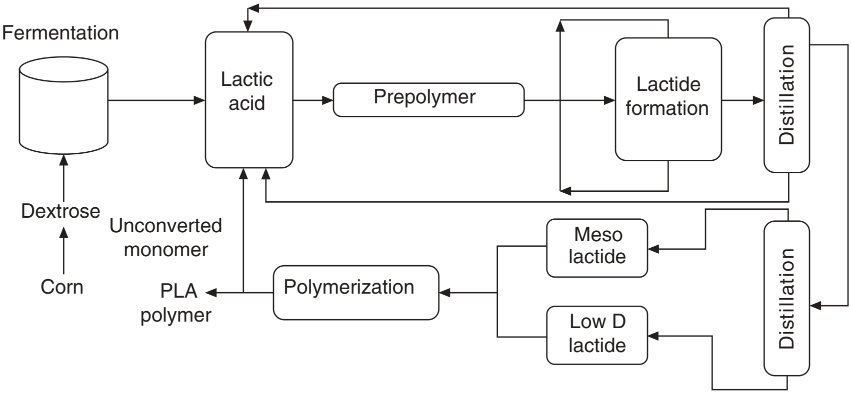


5.5 Production of high molecular weight PLA via prepolymer and lactide.

polymers while the higher D-lactide materials (>15%) are more amorphous. By controlling the purity of the lactide it is possible to produce a wide range of molecular weights and by varying the amount and sequence of D-lactic units in the polymer backbone, the product properties can be changed. These changes impact melt behavior, thermal properties, barrier properties, and ductility.[8]

Based on this lactide intermediate method, NatureWorks LLC has developed a patented, low cost continuous process for the production of lactic acid-based polymers.[9] The process combines the substantial environmental and economic benefits of synthesizing both lactide and PLA in the melt rather than in solution and, for the first time, provides a commercially viable compostable commodity polymer made from annually renewable resources. The process starts with a continuous condensation reaction of aqueous lactic acid to produce low molecular weight PLA pre-polymer (Fig. 5.5).

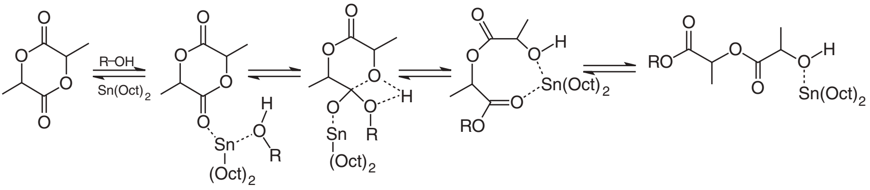
Next, the pre-polymer is converted into a mixture of lactide stereoisomers using tin catalysis to enhance the rate and selectivity of the intramolecular cyclization reaction. The molten lactide mixture is then purified by vacuum distillation. Finally, PLA high polymer is produced using a tin-catalyzed, ring-opening lactide polymerization in the melt, completely eliminating the use of costly and environmentally unfriendly solvents. After the polymerization is complete, any remaining monomer is removed under vacuum and recycled to the beginning of the process (Fig. 5.6).



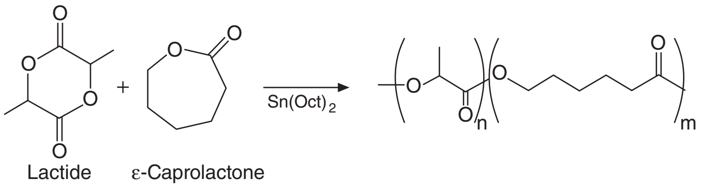
5.6 Non-solvent process to prepare poly(lactic acid).

5.2.2 Catalytic polymerization of lactide

Many catalyst systems have been evaluated for the polymerization of lactide including complexes of aluminum, zinc, tin, and lanthanides. Metal alkoxides are the most common metal-containing species for the ring-opening polymerization of cyclic esters. Simple sodium, lithium, and potassium alkoxides are effective; however, the high basicity of these ionic species leads to side reactions such as epimerization of chiral centers in the polymer backbone. Alternatively, covalent metal alkoxides are much more selective and therefore widely used. Initiators such as Al-alkoxides,[10] yttrium and lanthanide alkoxides,[11] and recently iron alkoxides[12] have been shown to give a controlled and living polymerization of lactides via a so-called coordination–insertion mechanism with ring opening of the lactide to add two lactic acid molecules to the growing end of the polymer chain. Depending on the catalyst system and reaction conditions, almost all conceivable mechanisms (cationic,[13] anionic,[14] coordination,[15,16] etc.) have been proposed to explain the kinetics, side reactions, and nature of the end groups observed in lactide polymerization. Tin compounds, especially tin(II) bis-2-ethylhexanoic acid ($Sn(Oct)_2$), are preferred for the bulk polymerization of lactide due to their solubility in molten lactide, high catalytic activity, and low rate of racemization of the polymer; the mechanism is also via a coordination–insertion mechanism[7] (Fig. 5.7). Conversions of >90% and less than 1% racemization can be obtained while providing polymer with high molecular weight. High molecular weight polymer, good reaction rate, and low levels of racemization are observed with $Sn(Oct)_2$ catalyzed polymerization of lactide. Typical conditions for polymerization are 180–210°C, $Sn(Oct)_2$ concentrations of 100–1000 ppm, and 2–5 hours to reach *circa* 95% conversion. The polymerization is first



5.7 Generalized coordination–insertion chain growth mechanism of lactide to PLA; R = growing polymer chain.



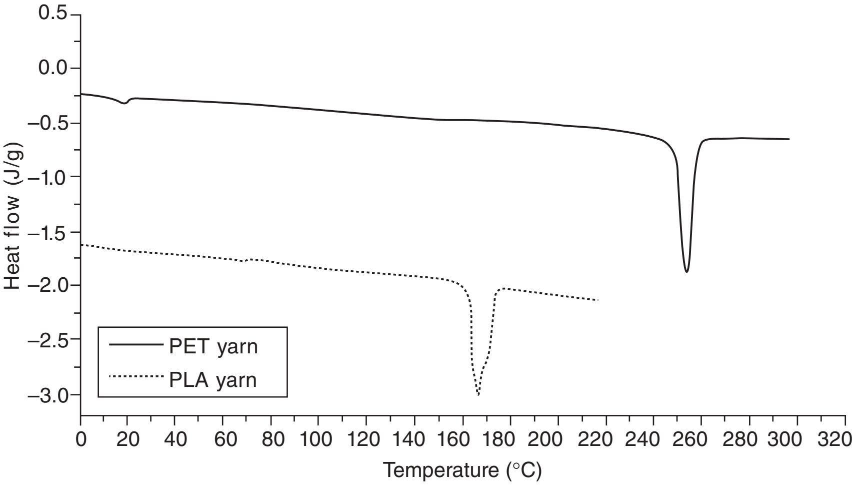
5.8 Copolymerization of lactide and caprolactone.

order in both catalyst and lactide. Frequently, hydroxyl-containing initiators such as 1-octanol are used to both control molecular weight and accelerate the reaction.

Copolymers of lactide with other cyclic monomers such as ε-caprolactone[17] can be prepared using similar reaction conditions (Fig. 5.8). These monomers can be used to prepare random copolymers or block polymers because of the end growth polymerization mechanism. Cyclic carbonates, epoxides and morphinediones have also been copolymerized with lactide.

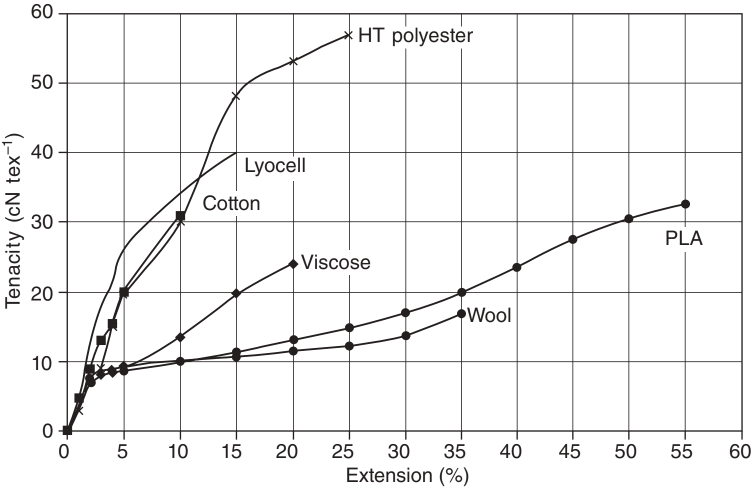
5.3 PLA fiber properties

PLA fiber has a number of characteristics that are similar to many other thermoplastic fibers, such as controlled crimp, smooth surface and low moisture regain. One unique property in comparison is that it is the only melt-processable fiber from annually renewable natural resources. The physical properties and structure have been studied by several researchers,[18] and these works confirmed that this polymer has significant commercial potential as a textile fiber. Its mechanical properties are considered to be broadly similar to those of conventional PET,[19] and, probably due to its lower melting and softening temperatures, comparisons to polypropylene are also appropriate.[20] A résumé of the properties is given, although further detail about specific properties will be covered, as appropriate in Section 5.4, 'PLA Applications':



5.9 DSC scans of PET and PLA.

- *Appearance.* Fibers are generally circular in cross-section and have a smooth surface.
- *Density.* The specific gravity is 1.25 g cm^{-3}, lower than natural fibers and PET.
- *Refractive index.* The refractive index of 1.35–1.45 is lower than PET (1.54). Trilobal and other shapes can be made, and give improved anti-soiling characteristics.
- *Thermal properties.* PLA is a stiff polymer at room temperature. The glass transition temperature (T_g) is typically between 55–65°C. The melting temperature (T_m) of PLA containing either the L- or D-isomeric form alone, is between 160–170°C. The DSC scans for PLA and PET are shown[21] (Fig. 5.9). It can be seen that PLA exhibits an endothermic peak (T_m) at approximately 166°C, whereas the T_m of PET is approximately 254°C. This low melting point compared to PET underlines one of the main restrictions for PLA in developing suitable applications. However, as mentioned before, the properties of PLA can be modified by adjusting the ratio and the distribution of the D- and L-isomers in the polymer chain, and melting points as low as 130°C and as high as 220°C have been obtained.
- *Crimp.* PLA can achieve good degree of crimp and good retention level through processing.
- *Fiber types.* Both filament yarns and spun yarns can be made, as with PET.
- *Tenacity.* The tenacity at break (32–36 cN tex^{-1}) is higher than for natural fibers although, of course, it can be varied according to the



5.10 Tenacity-extension curves for PLA and other common textile fibers (20°C, 65% RH).

degree of drawing that is applied to the undrawn yarn. It is relatively unaffected by changes in humidity at ambient temperature, though as with other manufactured fibers there is a small but measurable increase in elongation. As the temperature is increased the tenacity does reduce quite quickly with a concomitant increase in fiber extension, a feature commonly found in synthetic fibers.

- *Tensile properties.* The tensile properties of PLA fiber as used in staple form for textile processing are shown in Fig. 5.10. Clearly they are very different from those of high tenacity polyester and more akin to wool with a high fiber extension when stressed and relatively low final tenacity. The initial modulus (at 2% extension) is very similar to many other textile fibers, but the yield point is very marked, the fibers (and spun yarns) stretching very easily once past this point. A consequence, however, of the high elongation is that the work of rupture is relatively high giving yarns and fabrics an acceptable performance in commercial use. Elastic recovery is affected by the yield point and is particularly good at low strains. At 2% strain, the recovery is 99.2% +/− 0.75%, and 92.6% +/− 1.60% at 5% strain, higher than for most other fibers. The unusual tensile properties could be expected to have an influence on some of the commercial applications in fiber blend developments. For example, intimate spun yarn blends with cotton (and lyocell) are relatively weak due to the contrast of fiber properties, and this might possibly limit applications to knitted fabrics. However, wool blends well with PLA, and with their load-elongation curves being very similar, this would enable the full properties of both fibers to be exploited.

Table 5.1 Comparison of PLA and PET flammability properties

Fiber property	PLA	PET
Flammability	Continues to burn for two minutes after flame is removed	Continues to burn for six minutes after flame is removed
Smoke generation	63 $m^2\ kg^{-1}$	394 $m^2\ kg^{-1}$
LOI	26%	22%

- *Moisture regain*. At 0.4–0.6%, PLA has extremely low moisture regain, much lower than natural fibers and slightly higher than polyester.
- *Flammability*. Although PLA is not a non-flammable polymer, the fiber has good self-extinguishing characteristics; it burns for two minutes after a flame is removed, and burns with a white and a low smoke generation. PLA also has a higher LOI (limiting oxygen index) compared to most other fibers, meaning that it is more difficult to ignite as it requires a greater oxygen level. Table 5.1 compares PLA with standard PET.
- *UV resistance*. Unlike other synthetic fibers, PLA does not absorb light in the visible region of the spectrum; this leads to very low strength loss compared to petroleum-based fibers when exposed to ultraviolet light.
- *Moisture transport*. PLA shows excellent wicking ability. This property and the additional properties of fast water spreading and rapid drying capability give the fiber a very positive inherent moisture management characteristic.
- *Biological resistance*. Although PLA fibers are not inherently 'antimicrobial' without suitable after-finish treatment, they do not provide a microbial food source. In addition, testing by Odor Science and Engineering showed that PLA fiber-based fabrics outperformed PET-based fabrics for low odor retention.[22]
- *Chemical resistance*. As PLA is a linear aliphatic fiber, its resistance to hydrolysis is therefore relatively poor. This feature means that care must be taken in dyeing and finishing of the fiber.
- *Solubility*. With regard to other chemicals PLA has limited solubility and is unaffected by dry-cleaning solvents for example.

5.4 Applications

The ease of melt processing, coupled with the unique property spectrum and renewable resource origin, has led to PLA fibers finding increasing acceptance across a variety of commercial sectors. It would also seem that with the estimated global increase in fiber demand, there is an opportunity for viable alternative materials. The total fiber business in 2002 was estimated to be some 55 million tonnes, and projections suggest that this could increase to 83 million tonnes by 2015. Particularly relevant within these figures is the growth of man-made fibers from 33 million tonnes in 2002 to 57 million tonnes by 2015, and that the major fibers creating this increase will be synthetic materials, mainly PET.[23]

With approximately 50% of the fibers in the market today being synthetic materials from petrochemicals, it is clear that without synthetic fibers there would be insufficient fiber materials to meet the demands, particularly as natural fibers alone (mainly cotton) could not cover this. It is considered that cotton is already at near peak production, so as the world population and the fiber requirements increase, the opportunity to use such a product as PLA is both logical and in line with our need to address the environmental problems we face.

5.4.1 Apparel

The apparel fiber business in 2002 was estimated at approximately 30 million tonnes (Table 5.2) and projections for 2015 indicate that it will grow to 42 million tonnes. The sector is dominated by two fibers, cotton and PET, and as the total requirement increases, it is PET that is projected to become the majority material. Apparel is by some way the largest sector in the global fiber business, and is a highly technical, fast changing, and demanding industry in terms of design, fashion, color, aesthetic, and performance. However, despite the steady growth in the apparel fiber market size, there has been a reduction in the price points, therefore creating a real pressure on costs through the whole supply chain. In many respects,

Table 5.2 Apparel mill consumption by fiber type 2002

Fiber type	Million tones	%
Cotton	13.0	43
Wool	1.3	4
Polyester	10.2	34
Acrylic	2.0	7
Cellulosic	1.8	6
Nylon	1.2	4
Others	0.5	2
Total	30.0	100

it would seem that the existing range of fibers could meet all the possible consumer needs, either by virtue of their inherent properties, or with some chemical or physical processing technique within the downstream processing. For a new fiber, the entry into the apparel market could therefore be seen as both a very exciting challenge, but also a very difficult one. Against this backdrop, the real opportunity for PLA lies in the combination of both the fiber's inherent performance properties and the positive environmental advantages of being sourced from annually renewable natural resources, which, at the end of the product life, can be easily composted or recycled.

Kanebo, Inc. introduced a PLA fiber under the trade name Lactron™ fiber at the February 1998 Nagano Winter Olympics, under the theme of 'Fashion for the Earth'. Kanebo exhibited several garments from PLA or PLA/natural fiber blends. More recently, in 2003, Cargill Dow LLC (now NatureWorks LLC) announced their PLA fiber brand Ingeo™ (ingredient from the earth), and this is now being adopted across a wide range of garment categories globally by leading garment brands.

It is one of the features of PLA that it can be produced as both filament and spun yarns. Fabrics produced from spun yarn have a 'natural' hand and are considered to feel similar to cotton in this respect. Fabrics from filament yarns have a cool and soft hand and exhibit a high fluidity or drape with a degree of elasticity. NatureWorks LLC product development suggests, for example, that a 1.2 dpf PLA achieves the softness of a microdenier PET (e.g. 0.7 dpf).

With the opportunity to create a range of fabrics with attractive aesthetic properties, there are a number of performance properties of PLA that are significant to its positioning and progress in the apparel sector:

- The moisture management properties of good wicking, faster moisture spreading and drying mean that garments are comfortable. This is an important consideration for next-to-skin garments and particularly in the sportswear market. In terms of comfort under normal and active wear conditions, independent laboratory testing by the Hohenstein Research Institute demonstrated that PLA fibers perform better than PET and cotton, either when combined with cotton or as 100% PLA fabric. This testing included a series of different tests, including thermal insulation, breathability, water vapor transport, and buffering capacity to liquid sweat (several tests in this series). The results of the Hohenstein testing concluded that wearers of PLA/cotton fabric would experience improved physiological comfort versus equivalent PET/cotton fabric.[24]
- The elastic recovery and crimp retention properties provide excellent shape retention and crease resistance.

Table 5.3 AATCC Test Method 61-1994 (35% PLA/65% cotton blend knitted shirt, simulates five washings)

Simulated conditions	AATCC Test	Burst strength (psi)	% Dimensional change (width/length)	M_n	M_w
Control		83	–	57694	117970
Cold hand wash (40°C)		79	0/–3.82	56343	107835
Same, no bleach	1A	82	0/–3.13	52123	108115
Cold machine wash (40°C)	–	75	0/+4.17	56281	111206
Same, no bleach	–	78	0/–3.82		
Warm machine wash (50°C)	5A	74	+6.25/–7.98	57190	112036
Same, no bleach	2A	78	+7.64/–7.98		
Hot machine wash (70°C)	4A	74	+2.00/–6.25	58005	112510
Same, no bleach	3A	76	+2.00/–6.25		

- Thermosetting capability of the fiber provides for controlled fabric stability, with garments having a low shrinkage through repeated washings.
- The flammability properties described earlier show the potential in specific segments of the apparel market. PLA fabrics with no flame retardant treatments have passed the US tests 16 CFR 1610, and have also achieved the standards specific for children's sleepwear, 16 CFR 1615 and 16 CFR 1616.
- High resiliency and lower specific gravity than natural fibers can give fabrics a light and lofty feel. These properties have been used in garments to provide an effective wadded layer, e.g. ski jackets.
- The after-care properties of garments in washing are very positive. There is no damage in repeated laundering of PLA fabrics: testing has been carried out under simulated conditions in accordance with AATCC standards, with no degradation observed (Table 5.3).[7] Also, the fabric appearance remains extremely good after washing, without creasing and very clean surface. It would seem that any fiber work-up, which is quite normal under such conditions, is removed during the washing cycles.

Additional to the above properties that could all be described as positive attributes, there are certain factors in this relatively early stage of technical and commercial development that are somewhat restrictive to the development across a full apparel spectrum:

- The melting point of the yarns that are commercially available today is relatively low at 170°C. This does cause limitations in some of the downstream processing technologies, but the main concern is for the consumer after-care of garments. Garment pressing and ironing temperatures have to be lower than the popular fibers of cotton and PET, and despite the appropriate care labeling instructions being used, it is a fact that consumers often disregard these.
- Hydrolysis degradation of the polymer can occur, particularly under combined aqueous high temperature and alkaline conditions; the degree of hydrolysis is influenced by the time, temperature and pH. This is of particular significance in the dyeing and finishing processes, as it will cause a reduction in the molecular weight of the polymer and therefore the strength of a yarn or fabric, if the appropriate finishing conditions are not observed.

Through all of the manufacturing stages of the supply chain – spinning, fabric formation, dyeing and finishing, and garment making – the existing machinery can be used. There is no need for any specialized capital investment when processing PLA. In many of the downstream processing technologies, PLA processes and products are compared and are comparable to PET; both are melt spun, both are available in filament and staple form, weaving and knitting set-up conditions are similar, fabrics can be heat treated to give dimensional stability, and they are both dyed with disperse dyes. However, both fibers are unique and they do behave differently. It is therefore important that processors acknowledge this fact, and that the operating details are refined accordingly.

Yarn spinning

There is now a wide selection of commercial yarns being produced. In spun yarns, commercial products currently span the range Ne 5 to Ne 60 while in filament production, typical products such as dtex 70–68, dtex 150–72, are being produced. For both spun and filament yarns spinners have confirmed the processability of the material. An interesting feature of PLA is that processing temperatures are more typical of polyolefins (approximately 240°C), although the properties more typically combine many of the features found in rayon, nylons, acrylics and polyesters. PLA pellets are supplied with a maximum moisture content of 400 ppm. It is important to reduce the moisture content to 100 ppm during processing to prevent hydrolytic degradation, similar to PET and nylon products. For short staple yarns, because the characteristics of PLA are comparable to other thermoplastic fibers, the processing conditions are similar to those for PET. For long staple yarns also, processing can be carried out on conventional long staple equipment as used for thermoplastic fibers in blend with wool.

Fabric formation

There are no special requirements for knitting, and machine settings are comparable with those for PET. In weaving, the additional points for attention would be: if a size is being applied, to use a PVA or water-soluble size to avoid any need for strong alkali desizing, and to minimize tensions due to the high fiber extension. Woven filament fabrics give a very soft hand, and have a high fluidity/drape compared to PET.

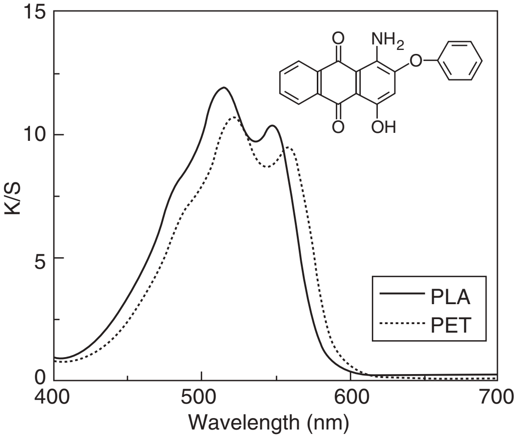
Garment making

The low melting point may mean that precautions are taken at those stages where fiber–metal friction could generate sufficient heat, namely the fabric cutting and the garment panel sewing operations. Care is also needed at the final pressing stage.

Dyeing and finishing

As is usual with any new fiber, the coloration and wet processing technologies demand significant attention. Color is so important, not only because it is the prime driver when purchasing a new garment, but also because the various applications and subsequent finishing treatments have the most chemical and physical effect on any fiber or polymer. Similar to PET, PLA is dyed with disperse dyes. However, dye selection is most important, as the individual dye behavior is quite different from dyeing on PET. In general terms, dyes show their maximum absorption at a shorter wavelength than on PET and tend to look brighter[25] (Fig. 5.11). Dyes also show a much greater variation in exhaustion levels; Yang and Huda[26] studied the exhaustion of ten disperse dyes on PLA and PET fabrics and found that the percentage dye exhaustion of all the dyes was lower on PLA than on PET. However, the color yield of the dyed PLA was higher than on PET because of the lower reflectance of PLA.

Several of the major dye manufacturers have studied their ranges of disperse dyes to provide the most appropriate selection for applying to PLA. DyStar GmbH & Co. have worked closely with NatureWorks LLC to further the commercial dyeing technology for PLA and have recently provided details for dyeing both 100% PLA as well as blends with cotton and wool.[27] The optimum dyeing conditions recommended by DyStar for dyeing PLA is 110°C for 30 minutes at pH 5. Practical experience has shown



5.11 K/S curves of C.I Disperse Red 60 on dyed PLA and PET.

that the use of higher temperatures or longer times of dyeing can cause degradation of the polymer.

One of the observations in the dyeing of PLA is that obtaining dark shades is more problematic, compared to PET. A reason for this is attributable to the lower exhaustion levels, although, of course, dye selection has to balance many other factors including fastness requirements, reproducibility, and levelness.

There are indications that the color exhaustion and color yields can be increased by modification of the basic PLA polymer, altering the proportions of the D-and L-isomers, and thereby changing the amorphous/crystalline ratios. Higher D-levels have more amorphous and less crystalline regions and allow for increased dye exhaustions.[28] Comparison of PLA fabrics with varying D-isomer content revealed differences in the enthalpy of fusion, and, hence, percentage crystallinity; high D-fibers have more amorphous and less crystalline regions in the polymer, with respect to low D-fibers. High D-fabrics display greater dye exhaustion and color strength with respect to low D-fabrics in all dyes and all concentrations as a result of the greater number of amorphous regions in high D-fibers with respect to low D-fibers. In application of a dye mixture for a black shade high D-fibers are able to be dyed to an excellent black shade, whereas low D-fibers appear very brown, due to less exhaustion of the blue component of the mix. In terms of wash fastness, there is very little difference between high D-fibers and low D-fibers; this is because the glass transition temperature for both fibers is very similar.

Color fastness figures tend to be slightly lower than on PET. One reason for lower wet fastness is believed to be due to more movement of dye to the surface by thermomigration, during post-heat treatments. It may also be that the lower thermosetting temperature for PLA (130°C) compared to PET (190°C) means less sublimation of the dye from the surface.[29]

With the introduction of PLA into apparel, developments and commercial adoptions have included fabrics made from 100% PLA as well as in blend with other fibers. The main blends are either with cellulosic fibers (cotton, lyocell) or wool. Apart from any aesthetic or performance benefits, such blends also have the feature of being biodegradable compared to their PET counterparts.

The wet processing of cellulosic blends need to be adapted to recognize the sensitivity of PLA to alkali treatments. This causes some limitations, as bleaching and dyeing systems for cellulosic fibers generally use alkaline processes. However, the potential significance of this blend has been recognized, and methods are available for all stages of wet processing. These include the use of neutral bleaching systems based on TAED (tetraacetylethylenediamine), and direct dyes, as well as the more conventional alkaline bleaches and selected reactive dyeing systems. A detailed study into the effect of the various wet processes on the molecular weight and physical strength of PLA was carried out at UMIST, and this confirmed the feasibility for suitable processing.[30,31] Dyeing of PLA/wool blends does not present such a problem, as both fibers have the same characteristic with regard to alkali. Indeed, with their similar stress–strain profile, there would seem to be some benefits compared to PET/wool.

There is much still to learn about the dyeing of PLA but it would seem that processes are available to achieve commercial viability. In real terms, it is not that long ago that fibers such as lyocell and indeed PET were introduced to the textile world, with many technical difficulties in their processing. These are now well accepted fibers and it will be interesting to watch as PLA follows a similar course.

5.4.2 Homeware

Typical products encompassed in this segment range from pillows, duvets, blankets, mattress pads, carpet tiles, office panel fabrics, drapes to bonded fiber products such as mattresses. As in the other sectors, the unique origin of these fibers, being derived from natural sugars obtained from annually renewable resources, coupled with the performance benefits, is proving to have a strong appeal to consumers in various geographies. The resistance to UV and low flammability, low smoke generation and low toxic gas on burning are attractive properties for this market segment, which differentiate PLA fabrics manufactured from conventional petrochemical-based synthetics.

Superior resilience found in crimped staple fiber products such as fiberfill, coupled with the natural wicking performance of the fiber are added features, which further enhance the scope of opportunities for PLA. Since this moisture wicking behavior is inherent to the fiber and achieved without the use of finishes this behavior should not decrease over time. Independent testing indicates the wicking behavior of untreated PLA fibers is superior to either untreated or treated polyester fibers.[32] Laboratory UV resistance testing using a Xenon Arc[33] indicates that in comparison with polyester and acrylic fibers, PLA fabrics have superior strength retention than polyester and far superior resistance to discoloration than acrylics.

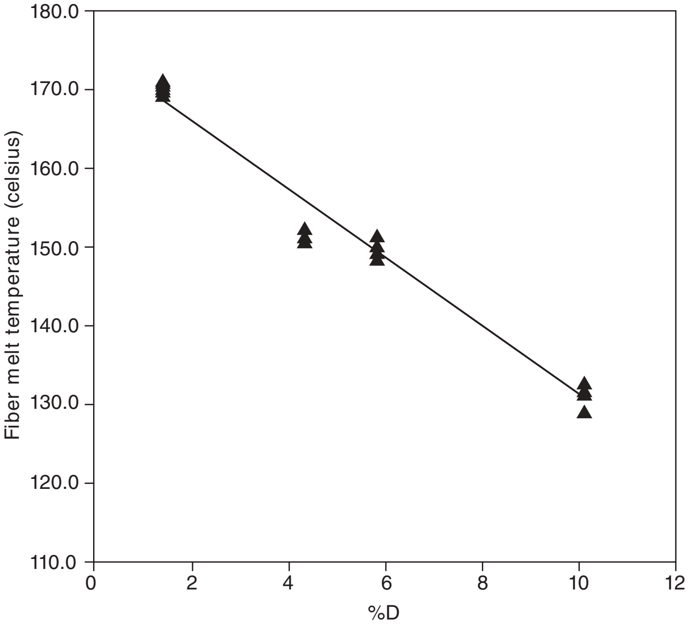
Independent testing by the Hohenstein Institute[34] shows that PLA fibers when used in duvets provide a better microclimate between the body and the duvet. The superior wicking properties of PLA fibers, compared with polyester, results in the dynamic adjustment of the moisture level by dissipating moisture as the humidity level changes. In pillows, testing has shown that PLA fibers offer outstanding filling power and resilience after three years of simulated usage.[35]

Flammability testing indicates a Limiting Oxygen Index value for PLA fibers of 24–28 when tested according to ASTM D2863. This is superior to untreated PET fibers, cotton, rayon and acrylics and equivalent to natural protein-based fibers such as wool. In addition, flame propagation and time to extinguish are properties of considerable interest in the furnishings segment. Fabrics made from untreated PLA fibers show far shorter burn times than cotton and polyester fibers. Untreated PLA fibers meet the test criteria for UNI 8456(1986), UNI 9174(1987) and UNI 9174/A1 (1996) that measure the time to self-extinguish (after the fabric is removed from the heat source). This test also measures the rate of flame propagation, char length, and time of flaming of any dripping materials to extinguish. The results enable 100% PLA fabrics to be classified as Category 1 as required by the Italian Drapery Industry.[36]

Fabrics made from PLA fibers have also passed flammability tests such as NFPA 701, which covers the fire safety requirements for textiles used in interior furnishings for public occupancy buildings.[36] Typical products include drapery, cubicle curtains, wall covering and protective outdoor coverings such as tarpaulins and tents.

Finally, a prototype mattress made from 100% PLA fibers successfully passed Cal 129 testing for furniture flammability.[36] All these tests were conducted on 100% PLA without any flame retardant additives. However, individual results will depend upon fabric construction and the use of finishes or dyestuffs.

The unique resistance to staining and soiling of PLA Bulk Continuous Filament (BCF) has led to significant interest in PLA fibers for use in carpets. Presently, PLA fibers are used in carpet mats for the hybrid Toyota Prius in Japan as well as in carpet tiles for domestic and institutional markets.



5.12 PLA fiber melt temperature as a function of % D-isomer.

In the technology development area PLA/PLA binder fibers are finding application in mattresses, and other bonded batting areas.

As described earlier, PLA bicomponent technology utilizes the unique polymer properties induced by the two optically active forms of the lactic acid monomer. By controlling the ratio and distribution of the D- and L-isomers in the polymer chain, it is possible to induce different crystalline melting points during melt processing; this feature offers distinct benefits particularly in the binder fiber area. Bicomponent fibers with a sheath softening point of 60°C (amorphous) up to a crystalline melting point of 175°C can be produced (Fig. 5.12). As well as bonding to other PLA fibers or petroleum-based synthetics, PLA bicomponent binder fibers are increasingly being used to bond natural fibers such as jute and hemp in automotive applications for spare wheel covers and door panels. Bicomponent PLA technology is also finding applications in self-crimping and micro denier technologies. Technology growth areas are in sheath/core, side by side, segmented pie and islands in the sea structures.

Overall, PLA binder fibers can replace existing synthetic polymers where renewable resource is a benefit or where additional performance such as controlled temperature bonding, controlled shrinkage or lower temperature processing is required. In addition, improved or reduced adhesion and alternative approaches to soluble/non-soluble island/sea combinations are all possible and under development.

5.4.3 Nonwovens

Nonwoven products are a major application segment offering great potential for the unique benefits of PLA fibers. Outside of the fiberfill products the major markets are in spun bond, industrial and household wipes, hygiene and filtration areas. Spun bond PLA products can be produced on typical polyester spun bond lines in a variety of fabric weights. Filament velocities of 3500 $\mathrm{m\,min^{-1}}$ and above are needed to produce fabrics with the required low shrinkage performance. Key applications are in carpet backing, hygiene, and compostable geotextiles for soil erosion control and plant as well as crop protection. Under the correct conditions of temperature and humidity PLA fabrics are completely compostable and return naturally to the soil releasing carbon dioxide and water. Under normal storage conditions and use, however, the fabrics are durable enough to meet the various market and supply chain requirements.

Industrial/household wipes

In recent years there has been a significant growth in the wipes market, and in particular the wet wipes segment across a variety of applications. Most wet wipes comprise a blend of cellulose, viscose or rayon with a synthetic fiber such as polyester or polypropylene. Up to 50% of the wipe comprises these synthetic fibers. Recent surveys indicate a 6.5% annual growth in personal care wipes versus 2.5% in baby wipes in the US.[37] Similar trends are being seen in Europe and Japan. New product introductions in personal care and household cleaning markets are occurring rapidly. Typical new trends and applications for wet wipes include:

- Feminine hygiene, facial cleansing, hemorrhoid treatment, etc.
- Functional treatments (antimicrobial, cleaners, abrasives, etc.).
- Decorative patterns.
- Continued push toward cloth-like aesthetics.
- Environmentally friendly materials and processes.

Spun laced investments have recently been announced by Jacob Holm, Spuntech, Orlandi, and Green Bay Nonwovens. In addition, Japan has large spun lace capacity with markets that are seeking environmental solutions. Wipes converters globally are expanding capabilities and expediting line extensions. PLA fibers show superior wicking performance when compared with the petroleum-based synthetics used in these applications. This inherent property leads to increased rates of liquid absorption,[32] in addition the appeal of an all-natural-based wipe has demonstrated strong consumer pull. The wipes market is, however, extremely price sensitive; recent price fluctuations in the price of oil coupled with the advances made in

PLA fiber and resin production means that pricing differences between the petrochemical-based and PLA fibers continues to narrow.

Hygiene

PLA fibers, because of their natural wicking properties, are finding utility in the diaper and feminine hygiene markets, both in spun bond top sheets and acquisition/distribution layers. Again the ability to replace petroleum-based fibers with enhanced performance with a natural-based fiber has strong consumer appeal. An additional benefit is that since PLA fibers are fully compostable the products can be disposed of by composting if the infrastructure for disposal is in place.

Filtration and separation

Two areas of potential applicability of PLA polymers have appeared in the industry in recent years.

- Triboelectric media to improve filtration efficiency.
- Filters, for example in the automotive and chemical industries, as well as single use applications.

The unique combination of properties displayed by PLA fibers offers promise in these areas. Untreated PLA fibers are repelled by glass surfaces and are attracted to polypropylene, indicating that they are somewhat electropositive. Disposable filters are also an area of interest for PLA fibers.

5.4.4 Medical applications

Textile fibers can be used to cultivate different human organs. The process involves culturing and growing living cells, taken from human organs, on a textile scaffold, to the desired 2-dimensional and/or 3-dimensional shapes. The scaffold is made from biodegradable and resorbable fibers which are in turn produced from biocompatible and degradable polymers. The major bioresorbable fibers used in implants are PLA and PGA (polyglycolic acid). They can either be used as a single polymer or by blending a copolymer of PLA and PGA. Varying the proportions of PLA and PGA alters the degradation rate and strength retention time of the fiber. These properties can therefore be varied in this way according to the requirements of specific medical applications. During the process of degradation, fibrous connective tissues replace the degrading implant. The key advantage is that no further surgery is required to remove the products since they slowly degrade in the body without any side affects. The US Food and Drug Administration (FDA) has approved the use of PLA for certain human clinical applications. Also, PLA-based materials have been used for bone support splints.

5.4.5 PLA as a plastic

Although it is outside the scope of this chapter, it is important to recognize the tremendous scope for PLA as a plastic in several applications. The material has significant potential use in fresh food rigid packaging, bottles for beverages like milk, juice and non-carbonated water. PLC can also be made into an ideal film for use as labels, wrappers and windows.

5.5 Environmental sustainability

The previous sections of this chapter have examined the manufacturing of PLA, its various properties as a polymer and a fiber, and considered the potential for its use in a range of commercial applications. Additionally, the environmental aspects for producing and using PLA products must be appraised in any discussion about its significance as a sustainable commercial polymer material.

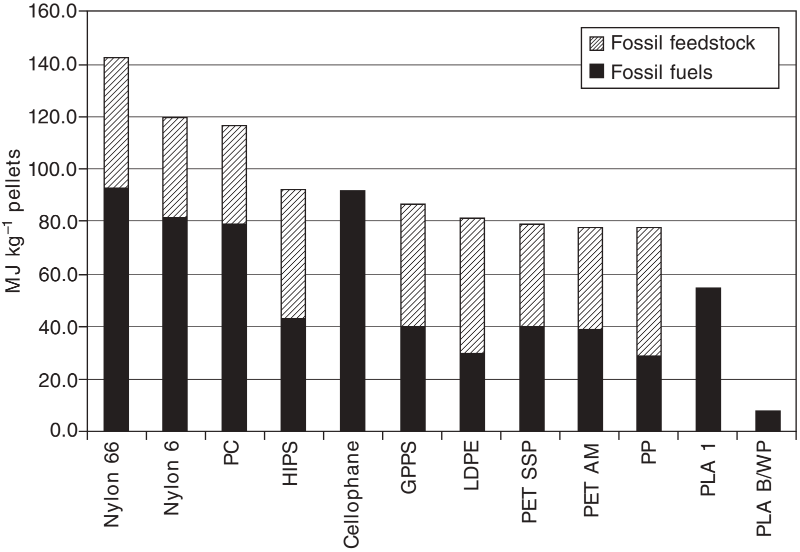
Environmental sustainability is about making products that serve useful market and social functions with lower detrimental environmental impact than the currently available alternatives. The case for PLA in this respect would seem to be very strong and needs to be appraised in any discussion about its potential as a significant polymer material. The ideal environmentally sustainable product provides equivalent function as the product it replaces and is available at competitive costs. It is made from renewable resources, can itself be constantly renewed without degradation in quality or performance, and has a minimum environmental impact. Such a product is made using only substances known to be safe for both humans and the environment. Ideally the life cycle of the sustainable product is in balance with the surrounding ecosystem.

5.5.1 Polymer processing and environmental measures

According to Vink *et al*.[38] there are probably three items that are generally considered to have an increasing global importance with regard to environmental concerns: fossil energy use; greenhouse gas emissions; and water use.

Fossil energy use

The existing range of petrochemical-based plastics is diverse, specialized and mature, so that precise and exact comparisons with PLA, a single



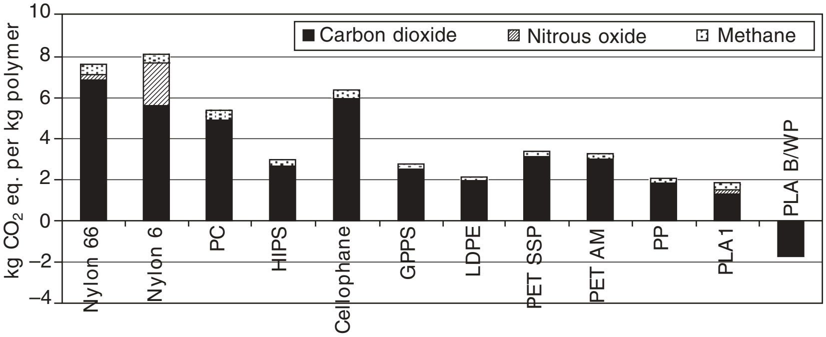
5.13 Fossil energy requirement for some petroleum-based polymers and polylactide. The cross-hashed part of the bars represents the fossil energy used as chemical feedstock (the fossil resource to build the polymer chain). The solid part of each bar represents the gross fossil energy use for the fuels and operations supplies used to drive the production processes. PC = Polycarbonate; HIPS = High impact polystyrene; GPPS = General purpose polystyrene; LDPE = Low density polyethylene; PET SSP = Polyethylene terephthalate solid state polymerization; (bottle grade); PET AM = Polyethylene terephthalate Amorphous (fibers and film grade); PP = Polypropylene; PLA1 = Polylactide (first generation); PLA B/WP (Polylactide, biomass/windpower scenario).

product performing multiple functions, are difficult, especially considering the great number of impact categories compared. Figure 5.13 plots the fossil energy requirement for these products. Data for the petroleum-based polymers was supplied by the Association of Plastics Manufacturers in Europe (APME). The data is valid for the polymers as produced in Europe. A key finding of the analysis is that the first generation polylactide production system (PLA1) uses 25 to 55% less fossil energy than the petroleum-based polymers.[38,39] Process improvements are targeted by NatureWorks LLC for the near future involving the use of biomass (B) and wind power (WP) as energy sources in the PLA production process (PLA B/WP), and with these improvements the use of fossil energy can be reduced by more than 90% compared to any of the petroleum-based polymers being replaced. This also will give a significant reduction in fossil energy related air and water emissions. This comparison represents the outstanding potential for environmental benefits for polymers made from renewable resources.

It needs to be recognized that the data for PLA1 and PLA B/WP represent engineering estimates. In addition, there is good reason to expect improvements in the actual performance versus the estimates.[38] Despite years of development work, the commercial manufacturing process for PLA is in its infancy. If the experience from petrochemical-based polymers offers any instruction, it is that process improvements implemented in the early years of a technology typically lead to substantial cost improvements. This is because the pursuit of cost improvements for competitive reasons often targets energy use due to its relatively high contribution to overall material costs. For example, through work on biocatalyst and lactic acid manufacturing process, NatureWorks LLC expects to achieve improvements that should further improve the performance of their production plant and simultaneously reduce energy demand. There is therefore good reason to expect a performance improvement trajectory for PLA1 that mirrors the experience from the current incumbent materials.

Global climate change

Global climate change has been identified as perhaps the most important environmental issue of this century.[40] Greenhouse gas emissions are not exactly the same as combusted fossil fuel emissions, because several non-combustion gases can contribute to global climate change as well. For example, methane (CH_4) is a potent greenhouse gas that can emanate from natural gas system leaks, decomposition of biological materials, and chemical/industrial processes. However, greenhouse gas emissions are closely correlated to fossil fuel emissions because combustion of fossil fuels is the source of most anthropogenic greenhouse gases. NatureWorks LLC has undertaken a comparison of the contributions to global climate change from a range of petrochemical-based polymers as well as the two PLA cases described above.[38] This comparison is depicted in Fig. 5.14. In conducting this analysis, Vink *et al.*[38] relied upon the 100-year time horizon Global Warming Potentials for greenhouse gases, a time period generally accepted as the mean atmospheric residence time for the most volumetrically significant greenhouse gas, carbon dioxide. A check of the data revealed that use of the 20- and 500-year time horizons generates the same ranking among the products studied. According to the Intergovernmental Panel on Climate Change (IPCC) the relative global warming potentials of the three largest (volumetric) greenhouse gases are: CO_2-1, CH_4-21, and N_2O-310.[41] These factors were used in NatureWorks LLC's analysis. As in the comparison of fossil energy use, the analysis compares conventional polymers with PLA from cradle to pellet (from raw materials to the point



5.14 Contributions to global climate change for some petrochemical polymers and the two polylactide polymers (for key to polymers see Figure 5.13).

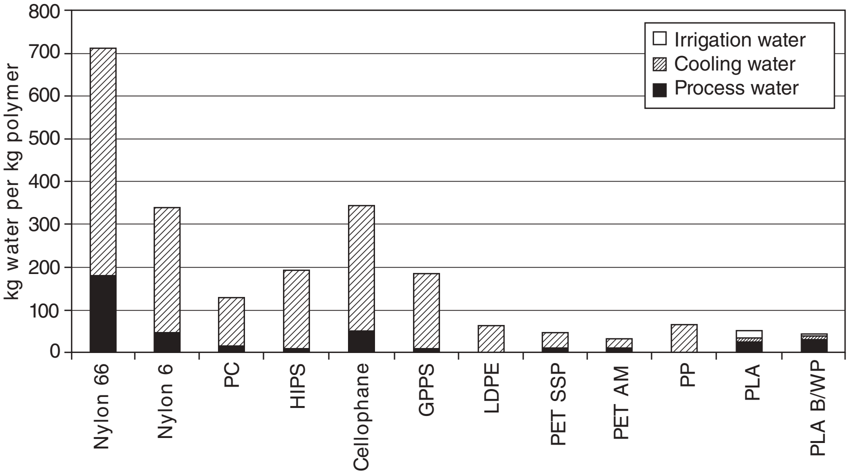
where the product is ready for shipment to a converter or fabricator). All emissions values were converted to CO_2 equivalents in order to facilitate comparison.

The analysis demonstrates that the PLA1 production process enjoys a substantial advantage over most polymers, and is comparable to several others. Even more exciting are the greenhouse benefits that derive from the transition to biomass feedstocks and reliance on wind energy for the balance of plant energy requirements. The utilization of the lignin fraction of lignocellulosic feedstocks for process heat generation 'closes the loop' on carbon related to energy generation, and in combination with other factors yields a negative greenhouse gas impact for PLA pellets. A most appealing result of the use of agricultural feedstocks for the PLA polymer production and most of the process energy requirement means that customers using PLA cannot only use PLA as a product, but as a component of their greenhouse gas reduction strategies.

Life cycle assessment reveals that no petroleum-derived polymer can rival the greenhouse gas sink effect of the improved PLA process. Although disposal of PLA products – whether by combustion, composting or other conventional means – results in a return of carbon dioxide to the atmosphere, this advantage survives.

Water use

Vink *et al.* also studied the water use.[38] Figure 5.15 gives the gross water use of the traditional polymers and the two PLA cases (PLA1 and PLA B/WP) as described above. The gross water use is the sum of public supply, river, canal, sea and well water and used as cooling water, process water and irrigation water. Despite the use of irrigation water during corn growing



5.15 Gross water use by petrochemical polymers and the two PLA cases (for key to polymers see Figure 5.13).

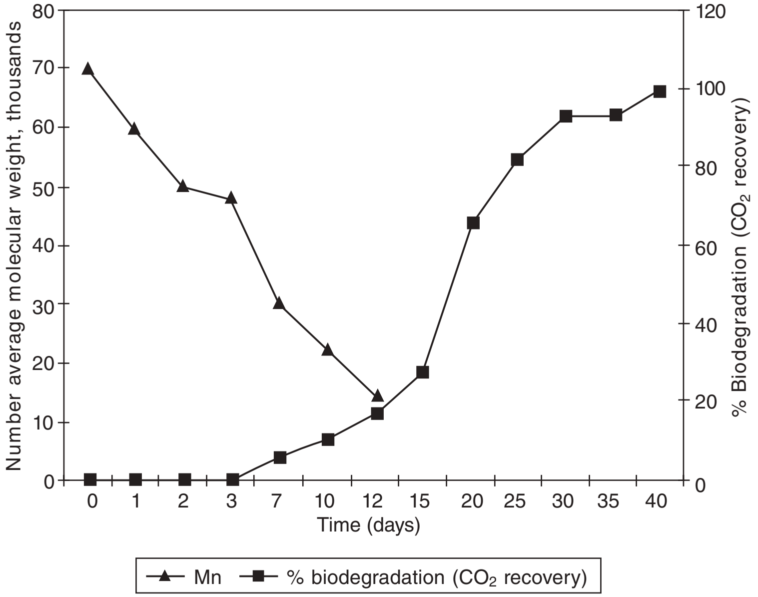
and the two water-based processes (dextrose and lactic acid production) the total amount of water required is competitive with the best performing petrochemical polymers.

5.5.2 Disposal options

The most common waste management options for the fossil fuel-based polymers are incineration, landfill and mechanical recycling. In addition to these traditional processing routes, the PLA waste streams can also be processed using composting, chemical recycling and anaerobic digestion.

Composting

Composting is a beneficial waste management system, particularly where landfill sites are limited, and in more densely populated locations. It does require an appropriate infrastructure to be set up, but progress is being made, particularly in parts of Western Europe.[42] Composting is a method of waste disposal that allows organic materials to be recycled into a product that can be used as a valuable soil amendment. The primary mechanism of degradation of PLA is hydrolysis, catalyzed by temperature, followed by bacterial attack on the fragmented residues. In composting, the moisture and the heat in the compost pile attacks the PLA polymer chains and splits them apart, creating smaller polymer fragments, and finally, lactic acid. Microorganisms, found in active compost piles, consume the smaller polymer fragments and lactic acid as energy source. Since lactic acid is



5.16 Biodegradation of PLA in compost at 60°C + 95% humidity.

widely found in nature, a large number of naturally occurring organisms metabolize lactic acid. At a minimum, bacteria and fungi are involved in PLA degradation. The end result of the process is carbon dioxide, water and some humus.[7] In summary, via composting, the carbon dioxide which has been harnessed during corn growing flows back into the atmosphere and the short cycle carbon dioxide loop has been closed. The degradation process is temperature and humidity dependent. PLA is compostable at industrial composting facilities, but will not degrade sufficiently fast in domestic composting piles since the minimum required conditions are typically not present.[43] A typical degradation curve of PLA under composting conditions is shown in Fig. 5.16.

Chemical recycling

Vink *et al.* describe[43] the possibilities of chemical recycling as a promising future alternative waste disposal route. The PLA polyester polymer is formed from reversible polycondensation reactions and can be depolymerized by hydrolysis. This equilibrium results in recycling advantages for polyesters such as PLA. Manufacturing waste, converter waste, or post-consumer PLA materials can be recycled by chemical means to produce lactic acid monomers and oligomers. These materials can then be fed to the front end of a manufacturing process for making PLA lactide, ethyl lactate, or other lactide derivatives. The recycling can be carried out with water at a wide range of temperatures (100–250°C). The reaction rate is enhanced by a catalyst such as nitric acid as is common in the PET recycling industry. The reactor residence times for PLA hydrolysis are in the order of hours, and depend on reactor temperature and catalyst level.

Chemical recycling should be considered in any waste management system for PLA, since from a life-cycle perspective, it represents a relatively small amount of net chemistry compared to the CO_2-to-PLA cycles for incineration or composting. Simple hydrolysis can turn waste PLA back into fully functional lactic acid, at potentially low economic and environmental cost, contributing to the total sustainability of PLA production.

The inferences from the studies of Vink *et al.*[43] confirm the positive impact that PLA has in addressing the key environmental concerns of today when compared to petrochemical-based polymers. They also show the additional benefits that can be gained by making environmentally responsible modifications to the existing manufacturing process. The commercial producer of PLA, NatureWorks LLC, states that its commitment and ethos is based on 'making plastics from annually renewable resources which meet the needs of today without compromising the earth's ability to meet the needs of tomorrow'. Its philosophy is based on 'reducing the environmental footprint' and on 'designing products with end-use disposal in mind'.[44] The company is committed to environmental responsibility and therefore it would seem that the polymer market as we know it today will experience some very significant changes in the near future.

5.6 Future trends

The vision for PLA fibers is more than just developing new performance products; it encompasses the additional goal of reducing total environmental impact. The result is a product that is more sustainable than comparable polymers on the market today. PLA fibers have made significant steps towards creating more sustainable products with unique performance attributes.

This technology allows one of the world's most commonly used materials, plastics, to be made from simple plant sugars, which are then turned into fibers using conventional melt spinning equipment and processes. Made from annually renewable resources, PLA plastics and fibers use 20 to 50% less fossil fuel resources than is required by conventional petroleum-based resins. Fossil resource use in the manufacture of these materials will continue to decrease as plans are put into place to switch feed stocks to biomass (corn stalks, leaves, etc.) and possibly integrate alternative energy sources, such as windpower. With PLA, carbon dioxide is removed from the atmosphere when growing the feedstock crop and is returned to the earth when PLA is composted. Since this process recycles the earth's carbon, PLA emits less CO_2 compared to other petroleum-based fibers. Disposal of PLA fits within the existing disposal systems but also includes the additional option of composting.

PLA fibers are increasingly penetrating markets traditionally occupied by petroleum-based synthetics. The rationale for this trend is the increasing public concern over the depletion of natural resources and the accompanying atmospheric pollution. Various studies indicate that reserves of oil and gas will eventually be depleted, although the actual time scale is a topic of considerable debate. It is evident, however, that the use of annually renewable crops as a means of producing the materials we need to sustain our everyday lives will continue to accelerate.

PLA fibers offer the promise of ultimately reversing the damage we have imposed upon the earth while extending the usable life of the diminishing oil and natural gas reserves. Ultimately the technology of using natural crops to produce fibers and packaging will become widespread across the globe. The use of waste products, referred to as biomass, will also provide the fuel to drive the factories used to convert these polymers to the variety of products needed to sustain the ever-increasing demands for an improved quality of life. The key to this transformation lies in the economical manufacture of these renewable resource-based products coupled with meeting the performance demands of the targeted applications.

PLA fibers and packaging products are well on the way to realizing this goal. Presently these fibers are produced from natural corn sugar. However, as the technology develops, any starch-based crop will be used. Advances in farming practices will enable higher crop yields with subsequent improved economics. Additional improvements in the fermentation and polymerization processes along with economies of scale will also contribute to the improved cost basis for these products.

PLA products have come a long way from the early work of Carothers in 1932. The ability to economically manufacture packaging and fiber products has led to rapid growth. This growth will continue. We are at the beginning of a new industrial revolution in which PLA fibers are playing a leading role. In addition, PLA fibers are still in their infancy: improvements in chemistry and downstream process development will lead to new applications and a bright future for these renewable resource-based melt-spinnable fibers.

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6

Environmental impact of polyester and polyamide textiles

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6.1 Introduction

Every event has some impact on the environment. From the apocryphal fluttering of a butterfly's wings in the Amazon rain forest to the detonation of a hydrogen bomb, a side-effect affecting our planet's health occurs to cause an ecological imbalance that may or may not be recoverable. A balanced environment is essential if the Earth is to survive in a habitable form, and natural phenomena that have temporarily caused problems have been dealt with by the Earth's natural functioning for millions of years.

Unfortunately, the advent of our technologically-skilled species has inflicted stress on the planet in ever-increasing proportions, with major consequences for its stability and survival prospects of all species on it, including humans. The textile industry, though not the only or most significant contributor, is exerting some impact and the contribution of polyesters and polyamides must be taken into account. Any aid that can be provided to reduce environmental harm will be of help in some small way to extending the life of the Earth.

6.2 Types of environmental impact

Environmental impact can take various forms (Slater, in preparation), some familiar and others not generally recognised. The former include energy consumption and pollution caused, together with global warming, melting ice-caps, rising sea levels and increasing frequency of adverse weather conditions. Less well-known problems include depletion of vital resources, rarity factors and ancillary effects like noise emission, radioactivity, odours, etc. There is usually little or no consideration of total impact, because most workers dealing with environmental concerns concentrate only on their own limited area.

6.3 Pollution types

Types of pollution that need to be recognised are encountered during production and use of polyesters and polyamides. The first is air pollution, in which harmful agents, including gaseous oxides of carbon, sulphur or nitrogen and particulate solids, such as dust, substances introduced during processing, or fragments of fibrous and other foreign matter, are released into the atmosphere. The gases may cause global warming, acid rain, toxic clouds, breathing difficulties, or other undesirable effects, while the particulate matter may exacerbate lung diseases, allergic reactions, visual obscurity, or soiling of fabrics.

Water pollution, the second possibility, occurs when salts, toxic agents, heat, chemicals, radioactivity, fibrous wastes or oil and petrol run-off are discarded. The chemical agents may affect food supplies or impinge on the natural world, while the heat and radioactivity can cause changes in life forms encountered. Solid waste can interfere with natural processes, such as stream flow and plant or animal access to sunlight, while oil-based materials can be absorbed into plants and cause diseases (such as cancer) in animals (including humans, directly or when animals are eaten) consuming the plants.

Land pollution arises when waste materials are discarded on to the earth's surface. The materials may be harmful (chemicals or salts toxic to animals or plants, or causing a slippery surface) or may be harmless in this respect but damaging by occupying space and producing unpleasant sights or interfering with natural habitats of animals. Discarded substances can attract undesirable life forms (vermin, mould, bacteria, etc.) to bring about potentially harmful risks for human beings.

Noise pollution arises when the area around a site is subjected to loud sound levels. There are tables (Peterson and Gross, undated) of acceptable sound pressure levels that can be tolerated by human beings and above which exposure can cause deafness or psychological side-effects, but the disturbance of animals in their natural habitats is also a drawback.

Visual pollution is seldom recognised. Discarded waste materials fall into this class. It can also arise from permitting the use of billboards, hoardings or garish lighting in advertising. Coloured substances not in harmony with the natural world are significantly noticeable and hence pollution. In considering the polymers under review in this book, there are approaches that will reduce (but not eliminate) harm to the planet.

6.4 Pollution prevention and control

There are differences between prevention and control of pollution. Prevention implies that pollution is never generated, while control indicates that pollution is inevitable but attempts are being made to restrict its quantity or effects.

6.4.1 Prevention

The only effective means of prevention is elimination of its source, by modifying production or re-using waste. Recycling, touted as a means of prevention, needs energy and produces waste. This is typical of human claims of pollution control; the pollution is not reduced or controlled, but merely hidden or transformed into another pollution, merely removing it from the vicinity where 'reduction' is taking place.

Waste minimisation can best be achieved by attention to detail in production. Enhancement of machine efficiency to avoid excessive friction, for example, can reduce pollution at the point of generation, or near the machinery if noxious fumes are also emitted. In addition, controls of temperature, humidity, quantities of reagents and other variables can lower waste. In re-use, reprocessing of 'waste' fibres is common, either yielding new textile goods or manufacturing a different product, such as artificial wood or road beds, that can use up the material and place it in a stable, non-polluting form into the environment.

6.4.2 Control

The attempt to control pollution (usually without significant success) is occupying much time in modern life. The aim is the subject of legislation in various regions, but the will to tackle problems of defining the situation is geographically varied. There is a lack of commitment in governments to do anything but pay lip service to the environmental lobby. There are plenty of examples, the most obvious being the refusal of several governments to ratify the Kyoto Accord. The earlier Earth Summit of Rio de Janeiro has also not produced any tangible action.

6.4.3 Legislation

Some legislation to reduce planetary harm exists. Germany has established regulations (Anon., 1998a) to limit or eliminate environmental and health hazards for textile and leather processing industries. Arias (1999) describes criteria that a manufacturer must meet to use the European Union's eco-label, aimed at reducing air and water pollution and increasing human health and awareness of problems, as well as lowering water and energy consumption. McCarthy and Burdett (1998) provide details of labelling regulations for the industry and benefits of environmental awareness.

Achwal (1998) feels that the eco-label guarantees environmentally-friendly production.

It is interesting to examine work associated with the eco-labelling movement. Burdett (1997) notes that it stems from a system that was originally voluntary and widespread throughout Europe. Methods of testing were based on well-known standards, and additional national and 'private' systems were used. An anonymous author (1997) in India points out that, when firms compulsorily start adopting such practices, the standard soon becomes the norm. This can be expected to have a positive financial benefit for environmentally-based stocks, since products not meeting the new standards will be rejected due to the lack of eco-labelling. Morris and Crosby (1995) note, in an article on quality requirements for textiles and clothing in Europe, that legislative actions have taken place to improve public information on activity and the textile industry. These include laws on eco-labelling, eco-auditing, waste management and recycling.

A further anonymous article (2000a) points out that the textile sector must adapt to the concept of 'Green Productivity' to have products competitively poised in the market through eco-labelling, which would form the collective practices for this GP. Joshi (2001) carries out a case study on implementation of ISO 14001 in a textile unit based in North India, while Nadiger (2001) indicates that a price must be paid for eco-labelling, including a ban on certain chemicals in processing and containment of pollution to satisfy different eco-labelling schemes. In general, though, the legislation relating to textile production is weak and inconclusive, none of it being specifically directed at polyesters or polyamides. The major reason for this reluctance may be economic, since laws to provide adequate protection could decimate or eliminate synthetic fibre production. What is needed is a clear view of what damage can be tolerated, followed by laws to enforce limits more strictly.

Current regulations are unsatisfactory, because they are neither effective nor severe enough. It is true that there are laws about what can and cannot be done in releasing compounds, or engaging in activities with ecologically-undesirable effects, to the environment. These usually set limits for each substance or activity, regarding how much can be tolerated in a specific time. They include emission of air or water pollutants, and display of advertisements, signs or other types of visual pollution, as well as specifying the intensity of sound levels. All are excellent in intention but five drawbacks make them ineffective. These are non-uniformity of standards, lack of enforcement, insignificant penalties for flouting the law, disagreement on what is pollution, and lack of quantitative measures applicable to violation assessments.

The first arises from the fact that different standards are adopted in different areas. It is not too long ago that North American textile producers were shipping goods to Mexico or South-east Asia, where laws were lax, to have finishing carried out there that would have been illegal in their own countries. The finished goods were then returned to the original manufacturer to be sold as 'domestically-produced' ones. Some authorities are trying to improve the situation; this example is no longer applicable, because changes in laws in the former 'dumping' countries make it not worth while to pay transportation costs, even though standards there are still lower than in the host countries. Legislators are slowly responding to pressure from constituents to enact laws enhancing ecological responsibility, but changes tend to be 'too little, too late'.

The second problem is lack of enforcement of standards. There are underlying reasons for this failure to protect the planet. First, there may be too few inspectors, usually as a result of shortage of money, to carry out effective policing. Second, the manufacturer may be part of a political lobby that threatens withdrawal of support if a government is too diligent in providing ecological protection, or there may be 'financial encouragement' in operation that convinces inspectors to turn a blind eye to contraventions of the law. There may also be conflicts of interest, where the manufacturer's activities are profitable for legislators, who have no wish to curb harmful proceedings and persuade colleagues to agree with their lenient judgement.

Even where enforcement is evident, there is another reason why planetary damage continues. In many cases, the penalty applied for flouting pollution laws is relatively minor. If a manufacturer knows that, if convicted, he will only suffer a small financial penalty, he will continue to pollute and pay the insignificant fine regularly. If conviction frequency is low, he can write off fines as a business expense to pass on to his customers.

A further problem is the lack of agreement on what should be classed as illegal pollution. In most western nations, heavy emission from vehicles or factories is unacceptable, and the owner of the source is fined or forced to cease operation. At the same time, authorities in many countries of Eastern Europe, Africa, South America or Asia disregard these sources of harm, and some cities there are shrouded in toxic fumes that would close down the municipality in less tolerant countries. The excuse offered is that such nations are still catching up with Western competitors, and can't afford to attack the problem until their economies are stronger.

An important reason why environmental efforts may not be effective is that inability to measure pollution accurately may lead to lenient sentences. In most countries, innocence is assumed until guilt is proved. If legislation depends on a quantitative assessment of pollution that cannot be measured precisely, there is no point in prosecuting an offender unless the pollution is so excessive that there can be no possibility of mistaken measurement as a defence. Pollution that exceeds considerably the amount permitted may be overlooked, rather than risking losing a case.

6.4.4 Environmental auditing

To minimise difficulties of pollution assessment, environmental auditing has been developed. Its major benefit is that it enables unexpected changes to be detected and can pinpoint where pollution is produced or undesirable additives taken up by the textile goods. Investigation can detect the source of the problem, which can subsequently be corrected. There are, however, difficulties that arise.

In theory, the process measures (by weighing) every component that enters or leaves a process. Thus, if (say) six raw materials are used to make a product, the weight of all six materials entering is compared with the weight of product. There will, in general, be a difference in the two readings. If this is negative (i.e. weight of product is less than the sum of component weights), then unexplained loss of material has taken place. This could be from evolution of some by-product (an undetected gas, liquid or solid that has escaped the measurement process) resulting from burning of fabric, evaporation of water, differences in atmospheric conditions when measurements were taken, or fibrous material lost as fly. If there is a positive difference (i.e. product weight is greater than component weights), then unexplained gain has taken place. Possible reasons include (as before) a change in measurement ambient conditions, chemical reaction with air or moisture, or accumulation of foreign matter (such as dirt or an adsorbed chemical) on the fibres. Smith and Lee (1998) identify trace impurities that can cause pollution, such as fibres, metals, VOC, or toxic organics. The work is complex and one outcome is the evaluation of analytical methods for polyesters, polyamides and other fibres. Kalliala and Nousiainen (1999) develop an environmental index model based on life-cycle assessment to determine total environmental impact, including energy in laundering, of a range of fabrics. They find that, for instance, laundering 100% cotton needs 20% more energy than a 50/50 cotton/polyester blend.

The first practical drawback of environmental audits concerns accuracy. The technique demands very precise measurement to ensure that all materials are detected. If an operator fails to note the existence of a material, or fails to measure its presence accurately, the error indicates the presence of lost or acquired mass. Time can be wasted in seeking this non-existent component, adding to the cost of production. It is possible, too, for workers to falsify results in the belief that management representatives want to hear good news, or may blame workers for large quantities of pollution. The discrepancy may not come to light until an inspector checks the audit figures, finding that unreported defects are in fact present. He may then levy a fine or other penalty that is more costly than fixing the problem in the first place. There may be situations where, no matter how good the audit, pollution cannot be rectified. If a vital process produces large quantities of undesirable by-products, society may be faced with the choice of accepting it or agreeing not to need the product. If the product is essential (as in military or space applications), then no amount of auditing or fines will solve the problem.

It is for situations of this kind that legislation to permit trading pollution quotas was developed. The principle is that a company producing less than its permitted quota can ‘sell’ its unused quota to a company with excessive pollution. The latter is allowed to exceed its own pollution quota by paying for the privilege of producing excess. This exempts the ‘dirty’ company from prosecution and enriches the ‘cleaner’ company, but does nothing to help planetary overload. The worst aspect is that, as more companies are developed, added pollution permits are issued, no effort being made to reduce the quotas issued to existing companies to prevent increases in overall pollution.

A further difficulty is the need for vigilance to ensure that new (or the same) problems do not crop up later. If detection of a problem leads to a solution that saves money for the manufacturer, results are welcome. If there is merely a need to remove pollution without financial benefit, the manufacturer is less willing to participate. There is, too, another aspect that needs to be considered; short life expectancy for a textile product can add to the pollution load on scrapping it.

6.5 Environmental impact of textile production processes and use conditions

McKenzie (1999) suggests that natural fibres are not necessarily less environmentally harmful than man-made ones, by comparing ecologically-relevant production steps for natural, regenerated and synthetic ones. In a later paper (McKenzie, 2000), she observes that, although demand for organic cotton has grown, consumers will not pay higher prices for environmental conservation. She notes (McKenzie, 1999) that ecofashion costs more until mass production output is attained, but there can be no mass production until demand rises, which will only happen when cost decreases.

The actual techniques used in production are described adequately elsewhere in this book, and it is not intended to repeat them in any detail in this chapter. Instead, attention will be paid to the environmental aspects of each portion of production to consider its overall contribution to the impact of the life cycle of the two types of fibre. However, there is evidence that the actual experience of working in a factory where polyester or polyamide is produced might be harmful to health. Hours *et al.* (1986) study mortality rates of personnel in such a factory and find that exposure to phthalates, nickel catalysers and other chemicals can cause serious problems.

6.5.1 Fibre and yarn production

Both polymers are currently produced almost exclusively from oil, and the extraction of this resource is environmentally costly, requiring extensive drilling with high energy machinery and causing pollution in the form of discarded waste and damaging spills during shipping. Once the oil is gathered, it is separated into fractions by heat energy, followed by conversion of the appropriate fraction by chemical reaction (again using heat) into the polymeric starting material for fibre production. The operation uses large amounts of energy, produces waste gas, liquid or solid by-products and can be unpleasant for the people working in it. Thiemens and Trogler (1991) reveal that nylon manufacture releases nitrous oxide, a more harmful cause (by a factor of up to 200) of greenhouse warming than carbon dioxide. Zenker, Borden and Barlaz (2003) report that 1,4-dioxane, a human carcinogen, is formed as a by-product in polyester manufacture, suggesting the need for further research into the development of cost-effective biological treatment processes. Spinning and extrusion steps are responsible for ecological problems. Melt spinning uses complex (and hence environmentally costly to manufacture) machinery that consumes large amounts of energy. Extrusion can bring about degradation of the polymers if temperature control is inaccurate, so causing waste to be discarded.

6.5.2 Transportation

It is appropriate to consider a pervasive environmental hazard that is constantly repeated throughout textile production and use. Textile materials have to be transported by vehicles during and after production. Vehicles are environmentally costly, but they also have a more sinister effect. Like textile machinery, they are large and complex, with the customary resultant costs, but there is also fuel combustion to take into account. Exhaust gases contain toxic or carcinogenic emissions, and legislation has been introduced in various countries to ban some components (notably lead) by modifying fuel chemistry. Approximately half of all air pollution is caused by vehicle emissions (Ross, 1972) and, although the textile industry is not responsible for all these, it must bear a fair share.

Exhaust gases remaining after removing (if possible) dangerous products cannot yet be eliminated, so attempts are made to improve fuel economy, but this is rendered ineffective by tremendous increases in the number of vehicles produced annually. The most critical emission gases, in terms of immediate damage, include compounds of sulphur, heavy metals and organic by-products of combustion, all environmentally undesirable for obvious reasons. Even if these could all be removed by some miracle of science, the unavoidable production of carbon dioxide, a greenhouse gas, would still make exhaust by-products a source of harm in the long term. Transportation, too, uses oil extensively, as a lubricant as well as a fuel source, and we have already seen how harmful a substance this can be.

Not only the shipping of goods, but also the transportation of people to and from work, has a contributory effect. Vehicles cannot travel without roads, and the establishment of these is a major cause of environmental difficulties, from the extraction of raw materials to the mechanical devices used to lay them down. Their presence also eliminates land on which plants for food (or textiles!) can be grown, or on which animals could graze, thus introducing a somewhat different category of environmental factor. Its contribution to the ecological cost of textile production should be borne in mind.

6.5.3 Noise

Two further problems, noise and dust, are common ones. Both cause difficulties for humans, as well as for the environment, but are different from factors so far considered, so should be given special recognition. Of the two, noise is more difficult to classify quantitatively. Noise can be defined as any sound which, because of volume, frequency, speed or harmonic content, produces discomfort or pain in the listener. The vagueness of this definition provides scope for ambiguity, but some sounds are undeniably and universally classed as noise. There are two criteria that should be used in deciding where the sound fits in the desirable/undesirable continuum, that of intensity (or volume) and that of ability to please. The two may occasionally be in conflict, so that a sound which should be classed as noise because it is painfully loud may occasionally be acceptable because it stirs some deep inner emotional chord.

Textile equipment can be included in such a category. If a machine is running smoothly, with a quiet and steady, gentle hum, then its sound might be regarded as pleasant by the engineer responsible for its maintenance. If volume is extremely high, though, to the point where it is painful to the hearing, or is a shrill, high-pitched note, pleasure disappears and noise is excessive, even to the most dedicated engineer. The test of volume and frequency can be applied to any textile machine to determine its position on the noise spectrum. As sound intensity rises, the scale of measurement is arbitrarily defined (Peterson and Gross, undated) in such a way that an increase of 3 dB(A) represents a doubling of volume. The net result of this is that a sound intensity of about 30 dB(A) represents a comfortable conversational tone and one of about 140 dB(A) is loud enough to cause physical damage instantaneously in the ears of somebody exposed to it.

In most industrial countries, the danger of subjecting people to high intensity sound has been recognised, and legislation exists to limit the exposure time of workers. Typically, people are not legally allowed to remain in a noisy area at 90 dB(A) for more than eight hours in the working day, and may not be allowed to enter the area at all if sound intensity is 115 dB(A) or higher, with shorter times being permitted at intermediate levels. The legislation also permits exposure at higher levels if approved hearing protection is worn, though there are two problems with this loophole. The first is that brain damage can occur via skull bone transmission even if the ears are protected, which means that the protection must include a helmet with acoustic insulation; the usual hearing protection, earplugs, is useless in preventing harm, even though it meets the law. The second problem is that of the machismo image. Because it is regarded by many textile plant operatives as 'soft' to protect their hearing, they refuse to wear appropriate devices unless forced to do so by supervisors.

Noise costs money. The cost may be direct or indirect, but it is considerable and should be recognised as a genuine financial, as well as environmental, one. The direct cost arises as a result of some process taking place in a machine. This may be an explosion, as in internal combustion, or frictional contact between two surfaces in a gear train or other mechanism. Noise is energy and as such must be generated by a power source. The electricity (or other fuel) used in the process cannot then be harnessed to carry out work, so is wasted. Money is paid to generate electricity, so the cost for this waste is irretrievably lost from profits. As a final point, energy generation is environmentally costly, and again the waste cannot be reversed.

Indirect costs are more subtle. Work carried out in various industrial premises has brought to light the suspicion (Slater, 1975) that hearing damage from noise exposure can cause social harm. Workers may experience boredom and loneliness or become withdrawn from social contact as their deafness worsens. In some cases, they may blame the machines that have caused their deafness, and deliberately take revenge by harming these perceived sources of a disintegrating lifestyle. Neglect of maintenance, slow correction of operating faults, or even deliberate sabotage, may occur in senseless acts of vengeance. All these cost money, and can exert a cost on the environment in the form of wasted energy or raw materials and excess exhaust gases.

6.5.4 Dust

Dust consists of tiny solid particles produced when materials break into fragments from mechanical, chemical or biological action. Because of their small size, they are easily blown about by air currents, or may float in the air for long periods of time without settling. In textile production, they are of two types, extraneous matter brought into the factory (as packaging, for instance) and fragments of fibres produced during processing.

Once they are released into the air, their behaviour can cause problems, an obvious one being the formation of a contaminant film on nearby surfaces. This necessitates frequent cleaning, requiring extra labour. When particles fall on machinery, they can interfere with operation, by increasing frictional force or lubricant viscosity and cause a breakdown if not removed. They can make a product dirty, so that it has to be washed (with detergents or cleaning materials and increased energy consumption) or rejected, causing significant environmental loading, as well as increasing production cost.

The second dust problem is health hazard, because of the chemical composition or size of particles. Cotton dust causes brown lung disease, while asbestos dust is responsible for lung cancer and dust from other fibres can cause allergenic reactions, sneezing attacks, asthma and related diseases. Dust can interfere with plant health by coating leaf surfaces, preventing them from absorbing carbon dioxide and releasing oxygen. Polyester and polyamide production is not a major cause of dust hazards, but some effect is noted during later production steps (drawing, blending and spinning, for instance). For all these reasons, limits of permissible dust production are being established in the industrial world and applied to textile processes. Chellamani and Chattopadhyay (1998) stress the need to reduce fly and fluff production for workers' health, and suggest control measures such as moisture addition, infrared lamps at strategic points, floating condensers, acid treatment of roller cots and use of overhead cleaners. Van Nimmen and van Langenhoven (1999), noting a sharp increase in contamination of fibres by foreign matter, such as plastics or wrongly-coloured stray fibres, give an overview of proposed solutions to the problem, with benefits and drawbacks of each one.

6.5.5 Fabric production

Once a yarn has been produced, there are several ways in which it can be made into a fabric. For polyesters and polyamides, these include weaving, knitting, non-wovens, fibre-to-fabric, film fibrillation, coating, laminating (Fung, 2002), needle-punching, bonding, tufting, and stitch-knitting. In every case, mechanical action creates risks of dust production, fibre breakage, and hence waste. In environmental effects, familiar factors of machine size and complexity, and of energy consumption, still exist. The need for lubricants to reduce breakage (and hence waste) is also essential in today's high-speed machines. In traditional looms, waste energy and loud noise are environmentally harmful, sound pressure levels reaching 110 to 125 dB(A), making the weaving shed dangerous (Slater, 1974) for hearing preservation of workers. Sizing to prevent yarn breakage and desizing also brings about ecological damage. Stöhr (2002) notes that an ideal size would be one that could be reused repeatedly, indefinitely and without limitation, and deliver optimum sizing results. He recommends a new material, UCF-4, which meets these criteria. Non-wovens, fibre-to-fabric, coating, laminating and bonding, using polymeric materials, hot glue or high pressure, also incorporate the same type of chemical loading, though an anonymous author (2001) describes a spunbonding and spunlacing process using a single-step water-jet method to reduce its impact. Despite this claim, the usual hidden environmental costs already noted are inevitably present.

Tufting is one of the most widely-used manufacturing steps in which polyester and polyamide are involved, in view of the fact that most carpets are currently made by it. Environmentally, apart from the usual concerns about machine size and energy consumption, its most significant drawback is the need to apply glues or resins. These are not only toxic or otherwise harmful, but their subsequent treatment by heating to cure them can bring about gas evolution to create air pollution. Membranes, providing a waterproof and breathable fabric (Bajaj, 2001), involve sandwiching microporous polytetrafluoroethylene (PTFE) between two layers of fabric, usually polyester, to prevent delamination of the fragile PTFE. Making the fabrics and the adhesive needed imposes environmental costs. Coatings (Kubin, 2001) provide a compromise between microporous membranes and finishes and are felt to be more satisfactory (Fung, 2002) from the ecological perspective.

6.5.6 Fabric chemical processing

Once a clean fabric is available, finishing can begin. The type selected depends on the fibre content or end-use of the fabric, and synthetic fibres need fewer finishing treatments than natural ones. They do not, for instance, generally require protection against microbiological hazards or fire and, in other treatments, such as moiré finishing, machinery and energy factors (plus steam when it is used) are the only environmental costs. Protection from ultraviolet degradation is often needed and includes chemical substances (including amines, sulphonated or benzoyl compounds and other complex organic reagents) that may be damaging to the planet.

The main cause of environmental concern in chemical processing, though, is coloration by dyeing or printing, and Christie (2007) has recently edited a volume dealing extensively with this subject. Benisek (1999a) provides a summary of eco-friendly dyes, but dyestuffs are frequently toxic or carcinogenic and, when released in waste waters from a plant, are visible. Natural dyes are ineffective for synthetics, so new synthetic dyeing techniques with lower planetary loadings are being developed. Swett, Thwigg and McCaleb (1984) compile a data base of 1434 commercially-significant dyes and pigments used in the USA, providing information on toxicity, economic costs and producers. The use of disperse dyes, plasma treatments (Wakida *et al.*, 1998; Anon., 1998b) or supercritical dyeing (Lennox-Kerr, 2000; Kawahara *et al.*, 2001) is recommended by various other workers to reduce economic and environmental costs. Anis and Eren (2001) note that the use of reactive dyes for improved washfastness carries an unexpected environmental impact of added rinsing needed to remove excess dye not absorbed by fibres. They report the development of new bioreactive molecules to reduce (but not eliminate) this drawback. The same authors (Eren and Anis, 2005) later compare the environmental impact of polyester alkaline dyeing with five different after-treatments, noting that the technique is successful in reducing harmful effects if the correct dye and after-treatment combination is used. Paylor, Ayers and Bell (1986) propose biological techniques in laboratory and field trials to demonstrate that chemical testing alone is unreliable in predicting toxicity level in a mixture of textile and domestic waste. Kwok, Xin and Sin (2003) attempt to predict toxicity of dye effluent and create a toxicity index to aid in the aim of reducing environmental damage. Riva and Valles (1994) attempt to determine the toxic effects of surfactants used in the mothproofing process on freshwater microalgae species, since no toxicity data exist for these compounds. Bae, Freeman and Kim (2006) examine the influence of new azo dyes on the aquatic system, showing that the copper incorporated in them has an adverse impact and suggesting a new method to evaluate the effects of dyes on the aquatic environment.

Printing uses the same reagents as do dyeing treatments, together with a printing paste that can cause water pollution. In compensation is the fact that a printing paste can be more easily collected, with lower amounts lost, than can a dye liquor. In addition, because the purpose of printing is to force colours into fibres, there is less need to wash out excess colour, so leading to lower quantities of discarded pollutants. Pollution from coloration occurs because, when dye is applied, it is not all picked up by the fibres and there are inevitably residual amounts that cannot be adsorbed.

Despite efforts to recycle them, large quantities cannot be re-used, either because the shade is not applicable for the next fabric batch, or because dilution is too great to make recovery economically viable. Flock printing and heat transfer printing overcome this drawback, but ecological aspects of fibre dyeing and fixing agents have to be considered in the former case, while the need to make special paper and a separate printing stage using heat for dye application, together with disposal of the paper, are important in the second. Both methods, though, remove the need for liquids and printing pastes, and omit washing, steaming and drying steps, so reducing ecological harm.

Emissions to water are the obvious example of substances released into the environment, and a report (Anon., 2000b) confirms that waste water discharges from wet processing are toxic and likely to have immediate or long-term harmful environmental effects, though 'smart rinsing' (Bradbury *et al.*, 2000) can provide more effective use of waste. Reife and Freeman (2000) summarise possibilities of pollution prevention by waste minimisation and source reduction in producing dyes or pigments, while purification before discharge is attempted (Bischefberger *et al.*, 1999; Canziani and Bonono, 1998; Ibrahim *et al.*, 1998; Papić, Koprivanoc and Božić, 2000; Gonçalves *et al.*, 2000; Slater and Barclay, 1998), using sand filters, cross-linked wood sawdust composites, coagulation/flocculation processes, anaerobic sludge blanket reactors or inorganic clays with other materials to absorb dyestuffs.

Air emissions should be mentioned briefly. These can arise from many segments of the industry, and their removal is often attempted before discharge to air or water. Recovery of waste process heat (anon, 1999a) and air cleaning installations (Anon., 2002; Freiberg, 1998) can help in reducing environmental impact.

A contemporary preference in many cases is to try to minimise resource depletion and pollution production as much as possible by re-using or recycling materials, these being extended (Benisek, 1999b) beyond water treatment to all materials used by the industry and including biological treatment of waste water, digestion techniques, neutralisation of alkaline effluents, reduction of mothproofing effluents, spray dyeing and fibre identification. The recycling of fibre or fabric materials is also regarded as useful (Kohler *et al.*, 1999; Raje and Rekha, 1998; Diounn and Apodaca, 1999; Methner-Opel, 1998; Roberts, 1999), with interest ranging from fibres and fabrics to end-products. Polyester figures in some of this work (Mannhart, 1998; Hansler, 1999; Goynes, 2000; anon, 1999b) and carpet polyamide recycling is also prominent in publications (Anon., 1998c; Realff *et al.*, 1999; Tullo, 2000). Woolridge *et al.* (2006) show that, for every kilogram of recycled polyester used in garment manufacture, energy consumption is 90 kWh lower than when virgin fibre is used.

6.6 Use conditions

Even after the textile end-product has been manufactured, it may be a cause for concern regarding its ability to cause environmental problems. When a product is discarded, it can be a source of harm to the environment. First, it is a visual pollutant if thrown on to the earth's surface. If it is burnt or buried, it can inflict damage, as a source of toxic or greenhouse gases in the first case or harmful decomposition products in the second. Polyesters and polyamides are particularly damaging in this respect, since they tend not to be completely biodegradable. Long life expectancy is thus a major factor in reducing the environmental impact of textile products.

6.6.1 Apparel and household goods

The most common reasons for discarding apparel relate to consumer dissatisfaction and there are various reasons for this. Comfort, whether physical or psychological, is a common cause for complaint and synthetic fibres are often regarded as problematic. Perspiration discomfort in high humidities, or static shocks at low ones, are cited as drawbacks unless adequate finishes have been applied. Even then, comfort level can decrease gradually if the finish is removed by continual laundering. In compensation, synthetic fibres are usually more durable than natural ones, so will not be discarded as quickly if comfort problems can be solved. The same is true for household goods, which are not usually as critically affected by discomfort problems due to humidity. Sources of degradation responsible for reducing life expectancy include heat, light, and chemicals used in cleaning or maintaining fabrics; again, polyesters and polyamides have advantages over natural fibres as they are less easily harmed.

6.6.2 Industrial textiles

Industrial textiles tend to be used in more severe situations than domestic ones. They are generally required to have better resistance to weathering and mechanical attack, because they are normally used in outdoor conditions with abrasive, tensile or other stresses imposed on them. Again, synthetic fibres are preferred for superior strength and resistance to biological degradation. Construction to give a stronger fabric and finishing to impart resistance to ultraviolet degradation are arguably the most critical factors in enhancing durability.

Sollinger, Levsen and Wünsch (1993) estimate indoor air pollution by emissions of volatile organic compounds (VOCs) from polyamide textile floor coverings, while Kriek *et al.* (2001) study VOC emissions taking place during polyamide resin production. They calculate an emission factor for each set of processing conditions, to be applied by a scaling operation from laboratory results to commercial manufacturing situations as a predictor of the quantity of each substance released as a fraction of the resin produced.

6.7 Pollution control strategies

Current attempts to control pollution are aimed in general at a few areas of concern, these being primarily air, water and (to a lesser extent) land or noise problems. The usual technique is to establish permissible limits, then try to enforce legislation that ensures these are not surpassed. As mentioned earlier, this approach is unlikely to be successful, so others must be tried.

6.7.1 Air pollution

Rey (1998) provides guidelines on the technology available for controlling smoke and odours from textile finishing, and Holme (1998) recommends a three-faceted method (considering emissions, efficiency and economy) for pollution reduction or prevention. The main objection to these lines of approach, their uneven application in specific regions, is still present. Smoke stacks continue to pour out noxious fumes, but the traditional solution, still tolerated in some countries, has been to build the stack higher to allow toxic gases to be dissipated further into the atmosphere. Legislation tends to accept this compromise, yet it is not effective for lowering pollution, as is becoming more and more obvious as the number of stacks, and the amount of gas discharged from them, increase steadily. Air pollution is not localised; harmful gases are carried by air currents to other regions and, eventually, all parts of the world. Absorption is no solution, since it merely transforms the air pollution into another type when the neutralised gases are discarded on the land.

There are other examples of global dissipation of environmentally-dangerous substances. Dioxins and furans, among the most toxic chemicals known because they can bring about poisoning or adverse genetic mutations in extremely small concentrations, can be emitted from textile finishing treatments. Their discharge is, in theory, strictly forbidden in most developed countries, yet there are frequent reports in these very countries of their appearance in waste streams; it is cheaper to discard them, as long as their source is not detected, than to deal with them effectively and responsibly, simply because their destruction is technically difficult and hence costly.

6.7.2 Waste water treatment

It is in waste water treatment where there is greatest concern, and hence where the greatest amount of interest is focused. Water treatments range from simple to complex, on continuous or batch basis. The simplest way of dealing with the problem is to avoid creating it, and some workers have suggested modification of production to lower environmental impact. Anis and Eren (2003) use an oxidative clearing method with mononicotina-tetriazine reactive dyes to eliminate fastness problems when a one-step polyester/cotton dyeing process is used to reduce the amount of water discharged. The same authors (2004) later discuss the selection of suitable dyes for this process and specify rigorous conditions that have to be met. Fan, Hoskote and Hou (2004) note that batch dyeing of polyester and nylon usually involves the discharge of large quantities of waste dyestuff and suggest lowering effluent by optimising pH and salt control or by re-use of spent dye. Yin and Jiao (2005) adopt a new sizing mixture for polyester/cotton blends to reduce cost and environmental damage.

Supercritical dyeing, already mentioned, is commended for reducing ecological impact. Draper, Montero, Smith and Beck (2000) measure the solubility of various disperse dyes in supercritical carbon dioxide, while Montero, Smith, Hendrix and Butcher (2000) provide an overview of the process. They note that, if carbon dioxide can supplant water as dye carrier, there is no liquid effluent to discard (though, of course, there is an escape of some greenhouse gas). Hendrix (2001) expands on the idea, noting added benefits, such as the lack of need for any drying and hence the reduction in economic, as well as environmental, cost. Montero, Hinks and Hooker (2000) continue the work by providing a typical example of how cyclic trimer deposits can be reduced in a supercritical dyeing process.

Once discharge of a pollutant has occurred, steps are possible for reducing its impact. They can be classed in three stages of effectiveness. In the first, a simple mechanical filter is placed in the path of the water requiring treatment. This removes solid contaminants, the size of fragments removed being dependent on the mesh of the filter. Waste cloth, fibres, or solid detritus are examples of pollutants removed by this treatment.

The second type includes agents, such as clays, with surfaces on which pollutants are adsorbed. This is suitable for dissolved substances and particulate matter too fine for filtration to be applicable. Barclay (2000) surveys the available techniques and reports the use of sodium bentonite and activated carbon, together with flocculants, such as iron or aluminium salts, dissolved-air flotation, or organoclay derivatives. Continuous treatment techniques in this category tend to be less useful than batch ones over time, since the active agent in the treatment needs to be replenished occasionally and its effectiveness is reduced as its life cycle progresses. Batch processing, though, is more expensive, because it is slower and uses more removal agent than is necessary to ensure that all pollution has gone. In terms of effectiveness, Barclay's work indicates that removal of dyestuffs, mordants, suspended solids, silicone emulsions and resin finishes can be almost complete, depending on the treatment regime chosen, and that there are specific optimum removal processes for each type of pollutant. Uner *et al.* (2006) evaluate a coagulation-flocculation on a COD-based molecular size for a textile finishing mill effluent in an effort to establish optimum treatment alternatives.

In the third approach, a chemical agent is added to the water to bring about some kind of physicochemical activity that removes residual pollutants by precipitation or chemical reaction, such as oxidation. This is the basis of water treatment at the municipal level, but can be used if necessary in the plant before an effluent is discharged.

The next technique to be investigated recently is the use of light radiation as a mechanism for degrading dyestuffs. Chaturvedi *et al.* (2003) use three types of reactor and a continuously-stirred batch operation in sunlight, finding reductions of up to 99% in colour and 84% in COD under the optimum combination of dye and photocatalysis conditions. Arslan-Alaton and Dogruel (2004) combine photodegradation of dye effluents with silicadodecatungstate as catalyst, finding that regeneration of this catalyst (a major stumbling block in earlier techniques) is simple. The same two authors, with colleagues, also use (Uner *et al.* 2003) ozonation to treat dyehouse effluents, a process evaluated by Radetski *et al.* (2002) and found to be relatively effective in reducing toxicity.

Bioremediation has also found popularity as a means of reducing harmful emissions from textile processes to water. Walsh *et al.* (1991) use marsh plants to develop tests for toxicity data from textile effluents as a standard for regulating permissible discharges. Kulkarni and Kanekar (1998) use *pseudomonas aeruginosa* MCM B-407 to destroy the unused monomer raw material of nylon-6 production, epsilon-caprolactam. Rozzi *et al.* (2000) develop a pilot-scale membrane bioreactor, using reverse osmosis with two types of flow operation conditions to enable re-use of secondary textile effluents to be adopted. Pan and Zhou (2001) clean polyester waste water by anaerobic hydrolysis, followed by biological treatment in a bioreactor. Rehorek *et al.* (2002) also use a bioreactor with membrane to monitor degradation of azo dyes. Yen, Kang and Yang (2002) adopt a polyamide membrane to separate effluents for re-use and this principle is adopted by Malpei, Bonomo and Rozzi (2003) with a hollow-fibre modification. Koyuncu (2003) incorporates nanofiltration into a membrane system and investigates optimum conditions for procion dye removal. Brik *et al.* (2004) investigate effects of ozone, chlorine and hydrogen peroxide on the effectiveness of colour removal in a bioreactor and subsequently (2006) carry out a quantitative evaluation of a bioreactor to allow re-use of textile effluents to be considered. In a review of bioreactor studies, van der Zee and Villaverde (2005) discuss the effectiveness of a combined anaerobic-aerobic treatment technique for use with azo dyes.

All these methods of treating effluent water are accompanied by environmental consequences. In every case, the treatment agent must be manufactured, by mechanical processing or by chemical production techniques requiring machinery, raw materials and energy. Chemical treatment may bring about unanticipated reactions, the usual example quoted being the production of dioxins or other toxic substances when excess chlorine is used to treat drinking water. In all cases, the waste removed, in the form of solids discarded to the land or chemical agents that need disposal, cannot be ignored. Their removal is again an example of the fact that pollution is never ‘removed’ but merely transformed into another type or transferred to another location.

6.7.3 Land pollution removal

Land pollution falls into two types, visible or unseen. Visible pollution includes solid waste, thrown on the ground deliberately or blown there by winds, and waste located at specific landfill dumps. In addition, waste products dissolved in water can be discarded on the land and soaked up by it, thus being hidden (except in the case of some coloured agents staining the ground) from direct observation. In general, the latter type is more dangerous than the former, since its presence is not recognised, so cannot be counteracted, and tends to include harmful substances easily transferred to underground sources of drinking water.

Removal of visible waste can only be achieved by collection, either by hand or (if the unit size is large enough) by a mechanical device like a suction vehicle or rake. Hand removal is not often used because of financial cost, but mechanical techniques are dependent on machinery manufactured by environmentally-costly processes and using energy during both manufacture and use. Hidden waste is much more difficult to remove. If it is dissipated into the water table, it is impossible to retrieve it and water has to be treated before using to avoid poisoning by oral ingestion or skin contact absorption. If the pollution is localised (as an oil spill, for example), there is a possibility of removing it. In large-scale spills, the usual approach is to break up the oil by means of detergents, but this is just another instance of hiding pollution, since the small globules are still present even though invisible. For smaller spills, soil remediation is the customary solution, pumping a solvent into the ground then extracting the solution before separating the oil from the solvent. Again, this is expensive, financially as well as environmentally, so is less than satisfactory. Newer techniques use supercritical carbon dioxide for extraction, an approach which is less costly but still leaves a greenhouse gas.

6.7.4 Noise pollution control

The best way to control noise pollution is not to produce it in the first place and it makes economic, as well as environmental, sense to prevent its initial production. Noise is created when gases expand rapidly or when surfaces are rubbed together under frictional contact. Control of noise can therefore be attempted by supplying expansion chambers for releasing gases at a lower rate, or by lubricating contacting surfaces. Expansion chambers must be designed for each application, and the viscosity of lubricants must be selected carefully to ensure that high frictional contact between the surfaces is prevented without hindering machinery operation by having too viscous a separation medium. In textile processing, new techniques using shuttleless looms reduce high noise levels in weaving.

6.8 Eco-friendly technology options

The term eco-friendly has been coined to define a process that is effective without harming the environment, an impossible aim since all processing is damaging to some extent to the earth. McDonough and Braungart (2002) claim that a 'not too bad' solution to an environmental problem is worse than a 'bad' one, since the former lulls us into a sense of false security in which we pay lip service to environmental responsibility without achieving any satisfactory goal. They note that the common trust in the effectiveness of reduction, recycling and reuse is misplaced, since each tends to use added energy (even if only for transportation) and more resources to achieve a new end-product that is inferior in properties in comparison with the starting material and has toxic or otherwise harmful reagents added in the transition from original to new material.

Thus, the permissible limits set by various authorities on air emissions (and their control) are not a solution to the pollution problem. All that is achieved by lowering emission levels is a reduction in the rate of planetary destruction. We have reached the point where the earth's corrective mechanisms are incapable of dealing with the load placed on the ecosystem and we are compounding the problem by removing aids to correction (such as trees or soil particles) that are the only means of reducing pollution by natural processes.

The subject of eco-friendly technology, as it relates to polymers, is reviewed by Khare and Deshmukh (2006) in a report on attempts to reduce the impact of plastics on the environment. They include substitution of non-renewable resources, such as petroleum, by bio-materials, but ignore the inevitable (and large) environmental costs of producing these latter. Bajaj (2001) focuses on the challenges facing the textile finishing sector in an overview of various eco-friendly treatments. The same author later (2002) reviews changes that have taken place in finishes designed to meet consumer demand in such areas as comfort, ease of care, heath or hygiene without causing as much environmental damage as the traditional techniques. Ibrahim *et al.* (2005) discuss chemical pre-treatments that they feel can help to maintain eco-friendly pigment printing with enhanced colour depth. Shin, Son and Yoo (2007) show that plasma grafting can be used to increase dye uptake, as well as moisture regain, for polyester, thus possibly providing potential reduction in ecological impact by reducing the treatment time and types needed. At the same time, of course, the comfort aspect is improved, serving to prolong life and hence reduce environmental impact.

6.8.1 Biodegradable polyesters and polyamides

Natural fibres, because they are degraded quite rapidly without producing harmful by-products, have long been considered more eco-friendly, and much work at present is focused on the effort to manufacture polymers that achieve the same type of property. Unfortunately, easy degradation goes hand-in-hand with short life, defeating one of the major benefits of polyesters and polyamides. In addition, emissions to water during the production of five types of biodegradable polymers are shown by Arfsten *et al.* (2004) to inhibit plant growth.

Problems arise because the so-called biodegradable synthetic fibres at present are not totally and easily biodegradable. The traditional technique is to produce fibre molecules composed of an admixture of polymer with starch particles that allow breakdown of the grain structure to take place rapidly. This ‘solution’ is highly undesirable. When the fibre is discarded, weathering or other degradative mechanisms destroy the starch, but the polymer is still present. The microscopic particles, though invisible, are so small that they present a large surface area to the environment, making them susceptible to rapid decomposition. Thus, the toxic end-products of decay are released far more quickly and are able to contaminate their surroundings at a much higher rate, making the situation more dangerous than it would otherwise have been.

Recent efforts are mainly directed in three avenues of approach, photo-oxidation, bacterial activity and the use of fungi. Andreopoulos and Theophanides (1994) compare the suitability of photodegradation and biodegradation technologies for speciality applications, reviewing research on degradable polymers at the same time. Andreoni, Baggi, Guaita and Manfrin (1993) note that three mixed cultures of aerobic bacteria are able to grow on low-MW polyamides, but a MW above 11 000 inhibited growth. Growth was greater as MW decreased and appeared to use cyclic and linear oligomers of up to eight monomeric units present in the polymeric matrix. The work on photo-oxidation does not appear to have been pursued beyond that preliminary reference yet, and bacterial degradation seems to be popular at present.

Matsumoto and Doi (2003) suggest that the best way of dealing with the problem is to use a family of polyesters actually synthesised originally by bacteria, which are thus readily biodegradable. Their main drawbacks are, first, their high cost and, second, their inferior properties in comparison with petrochemical-based polyesters, and the authors are carrying out research to attack both of these problems.

Zheng and two colleagues (2005) review the topic of plastic waste biodegradation and note that aliphatic polyesters are easily attacked by microorganisms directly because of the potential hydrolytic cleavage of ester or urethane bonds in their structures, in contrast to aromatic polyesters. Gu (2003) feels that, although our understanding of polymer degradation has advanced recently, the subject is still inadequately addressed, as indicated by the lack of information on mechanisms and microorganisms involved. New techniques and tests currently emerging are also described briefly. Teeraphatpornchai *et al.* (2003) screen microorganisms isolated from soil samples for their ability to degrade various polyester-based plastics. The most active strain, designated as TB-13, was selected as best, but requires additional carbon sources in the form of enzymes to thrive. Kim and Rhee (2003) report the development of a variety of biodegradable polyesters to reduce the environmental impact of waste plastics. They confirm that aliphatic polyesters are more easily attacked than aromatic ones, but suggest that fungi, rather than bacteria, may be more likely to attack recalcitrant molecules. They note, though, that work on these agents is scarcer than that on bacterial degradation and report recent advances in knowledge.

6.8.2 Water conservation techniques

One of the more useful ‘earth-saving’ processes is reducing water use, and the textile industry takes an active interest in developing this form of environmental economy. Heat transfer printing, already mentioned, is a case in point; the costs are not so severe that they outweigh the reduction in damage achieved by removing the need for using water and releasing dye solutions. A second positive step is the substitution of supercritical dyeing, also mentioned, for aqueous methods. As long as the pressure can be maintained and the major part of the carbon dioxide (or other solvent) can be recovered, the ability to achieve deep and even shades of dyeing without water (and without releasing aqueous dye solutions into the environment) is an excellent step in the right direction. Knittel and Schollmeyer (1995) note, when recommending supercritical fluid dyeing of polyester or polyamide to eliminate water use, that the technique costs less, avoids the need for auxiliary agents and saves time.

Environmentally-friendly dyeing has also been an aim of the industry for a number of years. Tajiri and Matsui (1973) conduct laboratory and pilot plant experiments to study the recovery of lactam monomer from waste water in nylon manufacture, using activated carbon. Schoeberl and co-workers (2005) take the further step of recycling the textile waste water itself, using ultrafiltration instead of the more complex and expensive bioreactor membrane. They suggest that the idea has the potential to cut down water use by 87.5% in washing, that COD is reduced by 80% and that consumption of washing agents can be lowered by 20%.

A further advance is the result of increased care taken over a process. It is possible, by good process design, to minimise costs by using the correct amounts of chemical agent and energy to bring about the desired reaction. Measurement precision is easily attained with modern equipment and can be used, in conjunction with minimal processing temperatures, to achieve significant reduction in planetary harm. A further suggestion for planetary conservation, still experimental, is the idea of making polyester or polyamide from a natural source, corn being the usual example quoted. Since corn is a renewable source, the argument goes, fibres can be made from it without harming the earth. Sadly, this is not true. The growing and harvesting of corn for food already puts a tremendous strain on the planet, because of the fertilisers, herbicides, pesticides and equipment essential by modern standards, and subsequent processing to separate the husks and convert them into fibres can only be done at considerable cost to the eco-system. All the process actually achieves is a reduction in the use of oil and, although this is a laudable aim, the drawbacks of the complex processing are an unacceptable price for this end-result. Yet another drawback is the fact that land potentially available for food growing is sacrificed to make fuel.

6.9 Future trends

Future prospects will be controlled by environmental concerns. We are at a stage where planetary damage is approaching the point of no return, one in which an uncontrollable runaway state is almost upon us. The passage of time merely serves to bring to light more examples of the way in which human damage is destroying the earth's ability to cope with our presence, and there is a growing tide of opposition to actions failing to take into account environmental health. Thus, the textile industry of the future, if it is to survive, must strive to reduce ecological harm. Dixit (1998) feels some companies may be forced to close because of inability to meet the ecological challenge and emphasises the importance of safer and better treatments for reducing pollution to satisfy newly-emerging regulations. Shaver (1999) stresses the need for companies to enhance management of environmental responsibilities and feels that this will be accompanied by a reduction in costs.

For example, financial benefits of ecological responsibility, in the form of tax deductions (Battersby, 1999), improved production (Moore, Money and Orzada, 1999), cost savings from water recycling (Wakeling, 2001; Hohn 1998) and benefits of new design (anon, 2000c) are reported. There are, though, costs that cannot be ignored, financial as well as environmental. The energy taxes proposed in the EU (Russell, 2001) will be heavily biased against the textile industry because its processes are energy-intensive. Taxes also allow increased pollution to continue as long as the producer (and hence the consumer) is prepared to pay a higher price for the privilege.

6.10 Sources of further information and advice

A more detailed discussion of many of the points made in this chapter may be found elsewhere (Slater, 2003), but some critical facts need to be stressed. First, the emission of any harmful compounds, especially some of the breakdown products mentioned, is undesirable, so the industry must recognise that the earth cannot tolerate this abuse indefinitely. Because emissions are similar in different regions of the earth, standards of safety, or of environmental protection, need to be harmonised over the planet to be effective. If there is a difference, then an unscrupulous manufacturer (as mentioned) will merely move 'dirty' production activities to a part of the world where standards are less severe to take advantage of lax laws there, and will continue to pollute the planet rather than clean up production methods. This activity must be forbidden if the problems of environmental irresponsibility are to be overcome.

Second, one point seldom made is that the cure for an environmental problem may be environmentally harmful. If, for instance, a specific machine or reagent is needed to remove a pollutant, then the cost of manufacturing that machine or reagent provides a burden to the planet that is usually ignored. The result of its use, too, may leave a pollutant of a different kind; absorbing an acid gas in a chimney stack by scrubbing through a water trap, for instance, leaves an acidic solution to be discharged to the water system. If an alkali is used to absorb the gases, or to neutralise this solution, then a salt is produced, to be deposited on the land. Pollution is again not removed, merely disguised to meet restrictive legislation. Thus, because the total effect on the planet is undiminished, many efforts put forth are ecologically useless. This is true at all stages in the manufacturing process; wherever a problem is 'solved' by any method other than reduction of consumption or production, the 'solution' leaves behind a residue that can create an ecological nightmare when disposal is attempted.

At any stage in a production train, there are factors that do not belong to the step being considered. All raw materials, for instance, are assumed to be present as if by instant creation, as are items of equipment needed to carry out the step. Nevertheless, each of these has an associated environmental cost that should be taken into account for complete evaluation of the step. The principle of the analytical procedure has been described in detail elsewhere (Slater, 1994) and leads to a complicated process of iterative calculation that can trace costs back to the initial step of extracting minerals from the earth for the production of metals or polymers used in manufacturing the equipment. Additionally, the costs of acquiring and using the sources of energy necessary to operate the machinery at all stages in production, from fibre and iron ore, etc., to working equipment and yarns, can be derived. The net result is that no process is free of environmental cost. If one is strictly pedantic, even the production of carbon dioxide (an important source of global warming) by people breathing can be considered an environmental cost. When the need to provide them with food, housing, transportation, working space, and other luxuries used at the planet's expense are taken into account, it becomes more and more clear that human beings are a major source of environmental cost, whether or not they operate textile machinery. The crucial point about this method of analysis is that, if the production at any stage is faulty, the cost to the environment does not just include that of wasting the product of the step where it is discarded, but also the entire production train to that point. The later in the overall process a rejection occurs, the more cost to the environment is involved. This is a parallel cost to the financial one, fortunately, which leads manufacturers to avoid such waste by finding an alternative use for substandard materials instead of rejecting them.

6.11 References

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