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Research Article

Advance in Environmental Waste Management & Recycling

Strategies for Separating and Recycling Textile Blends

Sasi Kumar U[1], Suman Mundkur[2] and Ashok Athalye[3*]

[1]*M.Tech Student, Institute of Chemical Technology, India*

[2]*Visiting Faculty, Institute of Chemical Technology, India*

[3]*Professor, Institute of Chemical Technology, India*

[*]Corresponding Author
Ashok Athalye, Professor, Institute of Chemical Technology, India.

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Abstract
With the growing environmental issues caused by the overuse of non-biodegradable synthetic materials, attention has switched to sustainable textile fibres and a circular economy utilising the recycling method. The growing human population, improved living standards, increasing per capita consumption, and the fast fashion trend are generating a huge volume of post-consumer textile waste. Such solid waste is a major cause of concern as whether it goes for landfilling or incineration, it impacts the environment. The blend of natural and synthetic fibres is widely used in various textile materials to achieve the required performance. Blends must undergo end-of-life (EoL) treatments since they are difficult to dispose of. Blend recycling is difficult because of their mixed compositions and properties, so sorting becomes tedious. Single-component textile wastes are pretty easy to recycle than that blend compositions. This article elaborates on the different blends used in textile materials, their uses, and separation methods.

Keywords: Fibre Blends, Chemical Composition, Enzymatic Processing, Mechanical Recycling, Polymer Separation

1. Introduction

Over the past few decades, rising human activity has produced vast quantities of end-of-life materials that must be disposed of. Most are disposed of in landfills or become land or ocean waste, resulting in severe environmental and health hazards. Although recycling offers the best chance of reducing the issues brought on by improper waste disposal, the need for effective recycling technology severely undermines the desire to recycle waste. Because of the inconsistent chemical composition and material qualities, mixed wastes are far more challenging to segregate and recycle than those made of a single substance.

The rapid advancement in material science has made the creation of composite materials made of different polymers and blends possible. Because of its strong mechanical properties, chemical resistance, and biological inertness inclusion of blend fibres have strong prospects in the fashion and technical textile industries. However, as these parts end their useful lives, more plastic trash is produced, which ends up in landfills. For managing blended trash, the conventional waste treatment methods of landfilling and incineration are not environmentally beneficial. The government urges the production industries through extended producer responsibility (EPR) regulation to investigate cutting-edge and effective recycling techniques.

Recycling is the practice of reusing waste materials. The circular economy is a business model that permits the recycling, reuse, and remanufacturing of things when they have used up all their useful lives. A circular economy aids in the reduction of waste and harmful materials as well as the development of goods with suitable mechanical characteristics. The design and management of recycling plants must consider the various polymers present in the feed and the presence of additional materials, both factors to the sources of plastic waste, both virgin and used. Most of the time, the polymer-made products that belong to the previous source class, these early-stage plastic wastes, are free of contamination by non-polymers and/or other polymers. These reflect the better polymer waste classes. The latter source class includes end-of-life plastic wastes (i.e., post-consumer waste). These latter can have significant variations in number and quality depending on the source of the collection and/or the tactics used. This paper discusses the different blends used in textile materials, the reason for mixing different materials, and the performance improvement of those mixing on overall output material. Later the different separation methods for separating the blend material at the end of its useful life have been reviewed.

2. Need Blends Used in the Textile Industry

A blend of two or more different raw fibres is used to create blended fabrics. They are combined and spun to produce yarns and then fabric, which impart desired end-use properties which are scarcely achievable by single raw fibres. The commonly found blends of textiles are Polyester / Cotton, Polyester/ Viscose, Polyester / Wool, Nylon / Wool, Linen / Silk. Table 1 explains the performance and cost benefits of the blended material.

MATERIAL	PERFORMANCE
Acetate	Increases drapability, adds gloss and sheen, decreases the cost of cloth
Acrylic	Imparts softness and confers performance similar to wool
Angora	Enhances fluffiness and bulkiness
Cotton	Enhances comfort, absorbency, and dyeability while decreasing static
Polyester	Boosts wrinkle resistance, durability and lowers the cost of the cloth
Rayon	Enhances moisture absorption and adds shine
Spandex	Provides elasticity and stretchability
Silk	Gives comfort, lustre, and prestige
Wool	Enhances absorbency and wrinkle resistance, adds warmth and density

Table 1: Different Blend Materials and Their Performance

Some common fabrics produced by fibre blends are

- Denim - Cotton/elastane, Cotton/Polyester/Elastane
- Jersey - Cotton/elastane, Polyester/Elastane
- Woollen - Wool/Acrylic, Wool/Polyester
- Swimwear - Nylon/Elastane, Viscose/Polyester
- Canvas -Cotton/Linen

Denim is a mixture of natural and synthetic fibre. Natural fibre gives comfort and breathability, whereas synthetic fibres stretch the fabric. In some clothes, synthetic material is blended with other synthetic materials, such as athleisure clothing manufactured from performance knit, nylon, and elastane blend. Although both fibres offer good stretch and recovery, the combination, in this case, may increase durability and abrasion resistance. Blending provides advantages like a reduction in cost when costly wool material is blended with cheaper acrylic or cashmere wool to bring down the overall cost. It also enhances wrinkle-resistance properties for easy care of the fabric.

Recently some fibres were discovered from organic sources that can be used for blending, like Tencel, bamboo, and Modal fibre. Tencel is ideal for hot weather because of its moisture absorption, heat retention and biodegradability. Also, this fabric is exceptionally breathable, wrinkle-free, and easy to maintain. Denim Tencel is easily found on the market and is incredibly comfy. Bamboo is biodegradable, just like Tencel. It is commonly lauded for its eco-friendly fabric, which is cool to the touch and luxurious to wear. The bamboo microfiber in shirts is also excellent in wicking away perspiration from the body and moving it to the outside, where it may more easily evaporate. Because it feels and appears more expensive than cotton, bamboo is generally seen as a more environmentally friendly alternative. Cotton and beech tree fibres are combined to create modal, a softer-to-touch fabric that shrinks less and is more absorbent than pure cotton. Although more prone to damage, garment care guidelines are comparable to those for cotton materials.

This blended fabric challenges the circular economy because recycling and remaking as a new product is difficult. Thus, primarily materials made of a blend composition at the end-of-life lead to waste disposal in landfills or incineration to produce heat and energy. These are not eco-friendly. Moreover, let us take a garment as a whole from the waste; other than the blend of two textile materials, these consist of different materials such as labels, zippers, tags, and related accessories made of a different polymer, such as PET, PU, PP, or PE. Hence, sorting and recycling these materials is a tedious process. Some separation technologies that can be used in textile recycling facilities are detailed in the following section. The technologies to be utilised will be determined by the feed's characteristics and the output material's desired quality.

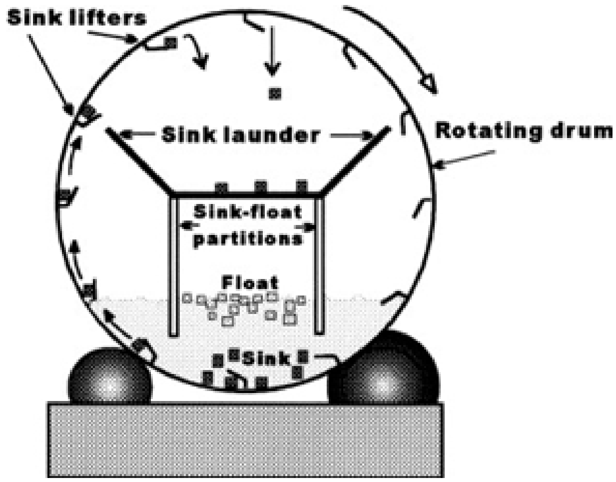
3. Methods of Polymer Separation

Chemical, mechanical, and enzymatic recycling are all viable options for plastic trash. They must first be sorted, typically done automatically using various technologies like spectroscopy, electrostatics, infrared, flotation, and fluorescence.

3.1. Sink – Float Separation

Using the various densities of materials is the foundation of sink-float separation methods. The principle of separation is based on the idea that a heavier substance will sink, whereas a lighter one will float when introduced to a tank holding a fluid with a particular density. When materials exhibit significantly differing densities, a sink-float separation unit is effective. This method separates polymers of different densities (such as PET from PP/PE). Polyolefins (PP, LDPE, HDPE), which have quite similar densities, cannot be separated using this method. [1].

Hydrophobic and hydrophilic materials can be separated via the method of froth flotation. Hydrophilic materials sink into the water and one which is hydrophobic floats on the water's surface. Using the microwave treatment, it is possible to selectively and suitably separate chlorinated plastic polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS) [2].



Source: https://doi.org/10.1016/S0301-7516(01)00056-4
Figure 1: Sink Float Drum Separator

3.2. Magnetic Density Separation

A recycling technology known as magnetic density separation (MDS) efficiently separates various plastic particle types using magnetised fluids. Magnetic fluid comprises water and magnetic particles floating in the liquid [3]. A mixture of plastics is divided into items that float (light) and settle (heavy). MDS separates various particles in a mixture using the Archimedes principle for fluids (the buoyancy force on an object equal to the weight of the fluid displaced by the object). Magnets at the top and bottom of a flow channel magnetise a fluid in DMS. The magnets alter the fluid's hydrostatic pressure and produce a gradient in apparent mass density. In other words, the fluid's apparent density varies depending on the fluid's height. Upon introducing the plastic particle mixture, the particles travel to areas where their mass density is equivalent to the apparent fluid density [4].

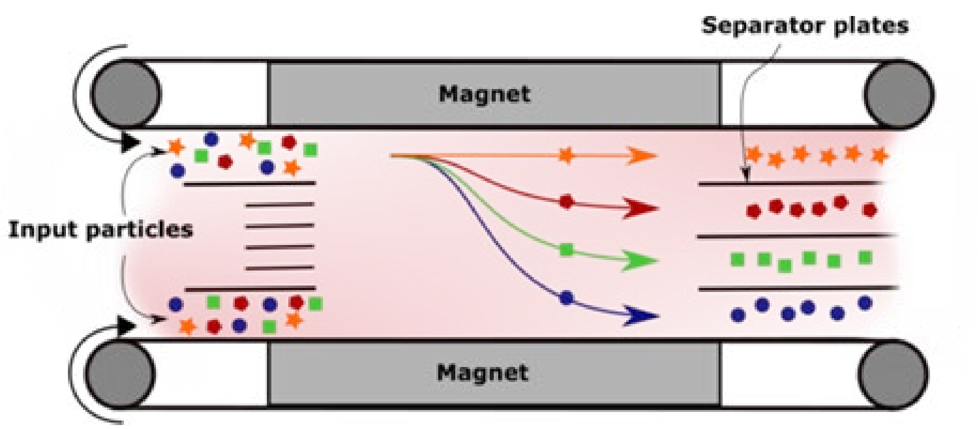
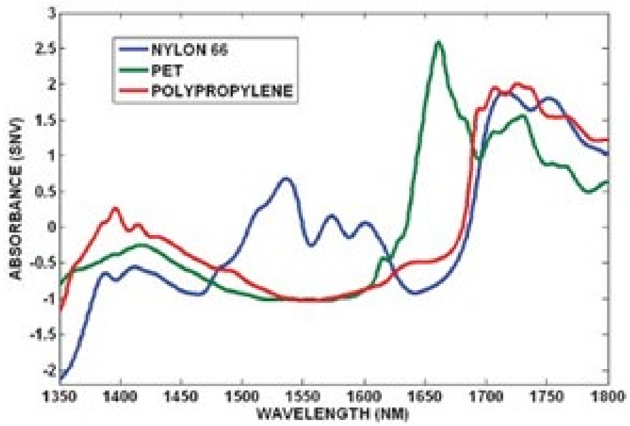


Figure 2: Separating Plastics with Magnetic Separation [4]

3.3. Near-Infrared Spectroscopy

Near-infrared spectroscopy (NIR) is the most often utilised technology in plastic recycling. It depends on a set of light-activated polymer spectra that have been reflected. The NIR sensor sorting system comprises the conveyor belt, illumination system, optical sensor, separation unit, and compressed air nozzles. Its adaptability, quick detection and identification, multiple detections, and lack of colour interference contribute to its widespread use. Sensing probes are distinguished by a physical dimension that affects the single sensing unit's picture field and analytical spatial resolution. The typical wavelength range of the investigation is 1000–700 nm; occasionally, it is expanded to the SWIR area (1000-2500 nm). Since many different polymers (such as PP, PET, and PS) have different spectral signatures in this wavelength region, near-infrared sensors can distinguish between them. Black or exceptionally dark polymers are practically impossible to distinguish due to their poor surface reflectivity [5].

High-speed spectral cameras operating in the MWIR [3000-5000] wavelength range can sort black polymers that cannot be distinguished by sensors operating in the commonly studied spectral ranges (400-2500 nm) due to higher light absorption and low reflectance [6].



Source: https://www.researchgate.net/publication/290227807

Figure 3: Near Infrared Spectra of Different Polymers

3.4. Electrostatic Separation

In electrostatic separation, Compressed air was used to convey the particles along a PVC transfer line. The triboelectric effect charged them when they hit one another and the chamber walls. The positive and negatively charged particles get separated when passing through a chamber with two electrodes separated by 10,000 volts. Step 1 involved collecting two fractions at each electrode, and step 2 involved placing a jar beneath each electrode to capture the particles the electrodes had failed to retain [7]. This separation can be successfully used for various polymers per the triboelectric charging sequence (+) PP - PC - PET - PE - PTFE (-). When two plastics in this sequence are rubbed against one another, the plastic closest to the positive end of the series is positively charged, and the plastic closest to the negative end is negatively charged. For instance, when PVC and PET are rubbed against each other, PVC is negatively charged, and PET is positively charged. On the other hand, when PET and PP come into contact, PET becomes positively charged, whereas PP becomes negatively charged [8].

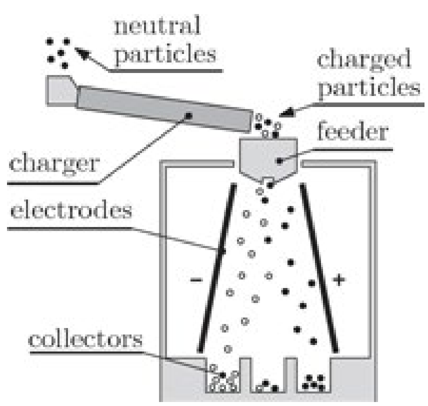


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Figure 4: Schematic of Electrostatic Separation

3.5. X-ray Fluorescence

Sorting based on X-ray fluorescence (XRF) involves using a sample that has been exposed to X-rays in the past and whose atoms release energy to produce an X-ray fluorescence radiation. The equipment consists of

(i) Source of illumination

(ii) Filter system - noise-reduction technology that uses a copper filter

(iii) XRF detection - employing silicon, high purity germanium detectors, with counts per second varying from 200,000 to 1,000,000).

(iv) Electronic data processing- detector output to identify the tracers [9].

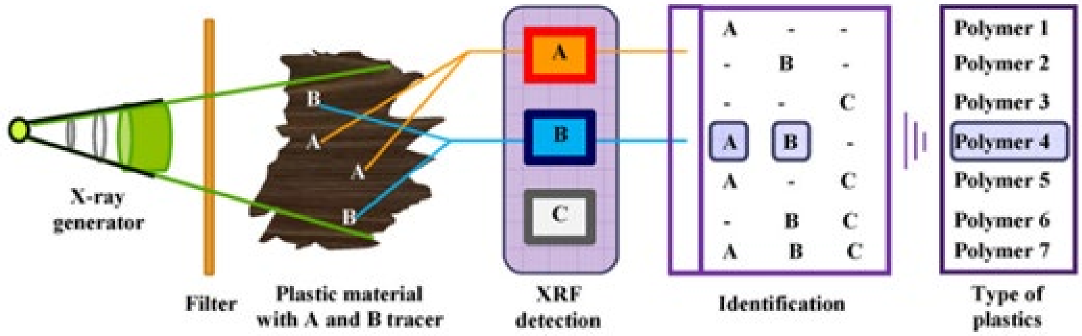

Figure 5: X-Ray Fluorescent Detection System

This method is mainly used in the waste plastic industry to separate PVC from PET. Bromine is frequently employed as a flame retardant, particularly in electronic equipment, which is considered impurities on the polymer surfaces that XRF can easily detect. It does not require sample preparation to identify black or dark polymers or the presence of impurities on polymer surfaces. This method's limitations include its inability to sort polymers other than PVC/PET [10].

4. Methods of Textile Blend Recycling

4.1. Chemical Recycling

The primary method of chemical recycling is the depolymerisation of synthetic fibres. This eliminates the laborious hand-selection process for separating natural and synthetic fibres.

Cotton can be extracted from cotton/polyester blends by dissolving the cellulose from shredded and mixed post-consumer waste into a new ionic solvent by reacting 1, 5-diazabicyclo [4.3.0] non-5-ene with acetic acid. The textile material was prepared with several reagents to remove impurities (silicate, metals) and bleached before being treated with the ionic liquid. New fibres were produced by dry-jet spinning the cellulose solution. Filtration-recovered solid polyester can be utilised to create new composite materials and new fibres [11].

Cotton/polyester mixes can be broken down into parts by hydrothermally treating them with diluted hydrochloric acid. The polyester is purified to recover it as such. The cellulose in cotton has undergone some hydrolysis. Filtration of the solid left over from the first solution's water dilution recovers the non-hydrolysed cellulose. The diluted water solution yields glucose and other carbohydrate oligomers [12].

A post-consumer carton made of paper, polyolefin, and polyamide was directly converted to up to 19.2% of levoglucosenone and 8.6% of furfural in tetrahydrofuran containing 10-20 mM H_2SO_4 at 210-230 °C by selectively decomposing the paper component. A solvent-dissolution process was used to separate the residual particles, which mainly contained intact polyethylene and polyamide and a tiny amount of char produced from paper. The xylene-soluble fraction was made from recycled polyethylene-like material. The xylene-insoluble fraction contained char made from paper as well as polyamide. Caprolactam was the sole significant vapour product of pyrolysis. The char that is still there, which is made from paper, has the potential to be a superior solid fuel [13].

Cotton fibres in worn clothing can be depolymerized by acid hydrolysis to create a glucose solution that can be used to make chemicals or fuels. Although a sulfuric acid one-step process could not produce a high amount of glucose, a two-step process that blended concentrated and diluted sulfuric acid to take advantage of both concentrations produced a glucose yield of over 90% [14].

Tetrahydrofurfuryl alcohol and ɣ-valerolactone were used to efficiently dissolve the elastane from polyester/elastane and polyamide/elastane blends. To make it simple to filter out and reuse any remaining polyester or polyamide for creating new versions of any product [15].

Nitric acid treatment was employed to reclaim the cellulose included in denim waste. The colours are eliminated with the used acid, which is then cleaned using activated carbon. A green switchable hydrophilicity solvent was used to break down polyester and separate it from cotton. CO_2 was added to the solution, which regenerated the polyester and solvent. The solidified polyester is separated using filtering. For waste from jeans that contain 84% (weight) cotton and 16% (weight) polyester, the system achieves a recycling rate of over 96%. Nitric acid only leaches the dye in the strong acid reagents (HNO_3 or H_2SO_4). Sulfuric acid, on the other hand, dissolves all of the components of the denim waste, according to preliminary experiments used to choose the leaching media [16].

Polyamide 66 (PA 66) selective dissolution from cellulose fiber blend utilises calcium chloride, ethanol, and water (CEW). Water was added to reprecipitate the dissolved PA 66. No change in mechanical strength was seen in the cellulose following separation, indicating that the treatment had not harmed the polymer. Although some polyamide remnants were left on the cellulose, carding was able to get rid of a significant amount of them. The PA 66 initially contained in the combinations was recovered to the extent of 80–90%. It is discovered that effectively removing calcium residues from recovered PA 66 is essential because calcium content in the polymer larger than 0.8 wt% is observed to alter melt behaviour [17].

The recent development of a Polylactic Acid (PLA) based biopolymer as an eco-friendly replacement for the widely used PET has gained wide interest. This natural polyester is derived from corn or sugarcane and is biodegradable and compostable. It has a look and feels that is quite similar to PET. As a result of its widespread use, the recycling sector began to express concern about using this biopolymer because PLA contamination of the PET recycling stream could negatively affect the physical characteristics, such as the molecular weight, of extruded rPET, rendering the material unusable. HSI in the NIR region (1000-1700 nm) was successfully implemented to identify and categorise PET and PLA polymer flakes [18].

4.2. Enzymatic Recycling

Enzymatic recycling breaks down blends by using enzymes that are originally microorganisms generated. To lessen negative environmental effects and recover important components from plastic trash, biocatalytic depolymerization, mediated by enzymes, has developed as a viable and long-term alternative. Protein engineering can enhance the performance of enzymes that break down plastic by increasing an enzyme's thermostability, substrate binding to the enzyme active site, substrate interaction with the enzyme surface, and catalytic activity.

A wool/polyester blend was subjected to protease treatment, which caused the wool to hydrolyze and the polyester fibres to be recovered. The recovered polyester fibres can be recycled to make yarn and new products, like the cotton and polyester blend. The amino acid-rich wool hydrolysate can be utilised as fertilizers, microbial growth media, animal feed, and more [19].

Combining a cellulase and a -glucosidase enzyme resulted in better glucose recovery from waste cotton/polyester blends. Cellobiose, a cellulase inhibitor, is converted to glucose by the enzyme -glucosidase, which also aids in the fragmentation of cellulose. Finding the ideal values for the substrate/enzyme ratio, pH, temperature, and pretreatment conditions led to establishing the ideal conditions. About 90% was the best yield for recovering glucose [20].

A fungal cellulase was created by submerged fermentation of textile waste made of a Polyester/cotton (60/40) blend. The *Trichoderma reesei* ATCC 24449 fungus demonstrated the highest activity for cellulose hydrolysis. Before the enzymatic treatment, the textile materials were broken into tiny pieces and treated with alkaline reagents. pH 4.8 was used for the fermentation. A figure close to 44.6% was obtained with a commercial cellulase, compared to 41.6% of glucose recovered with the in situ low-cost produced enzyme. The polyester was recovered in its original form, and melting and spinning can be used to prepare it for reuse [21].

4.3. Mechanical Recycling

The most basic technology typically used for recycling is mechanical recycling. Recovering plastic waste using mechanical means, such as sorting, washing, drying, grinding, re-granulating, and compounding, is known as mechanical recycling. Polymeric materials can be reused and recycled several times thanks to mechanical recycling, which maintains the material's chemical composition and creates a closed loop.

Films, cardboard, and other bulky items must typically be manually sorted at the start of the recycling process. Screening is done to get rid of tiny items like glass and stones. Drum or vibrating screens are common pieces of screening equipment. Waste is typically broken down into three fractions: undersize (less than 50 mm), middle size (between 50 and 300 mm), and oversize (more than 300 mm). Typically, the middle size percent is where plastic is concentrated.

Plastic waste can be sorted via mechanical recycling in one of two ways: macro or micro scale.

Plastic macro sorting is typically carried out when the waste flow stream contains the polymers to be recovered as macro items that are easier to identify and separate. In this scenario, waste plastics, typically bottles, and containers, are separated before any specific mechanical action (i.e., size reduction or screening) is undertaken. Specialized sensors are used to initially identify particular polymer qualities, which are then further segregated based on their features, typically using air-blow techniques. Although plastic containers are labelled today with the comprising polymer and/or blend of polymers on the side, manual separation tactics are still used, and human expertise is the foundation of the separation. This is a labour-intensive, expensive, and ineffective approach.

Plastic micro sorting is typically used when waste plastics are collected as flakes, or those produced by milling operations, in a flowing stream of mixed garbage with various physical and chemical characteristics. In this scenario, handling expenses are lower, and trash production is significantly higher, but more complicated and frequently advanced technology must be created, put into place, and used. Size reduction, screening, separation, and other methods are frequently used in succession. In the latter scenario, sorting units and associated logic focused on separating and/or evaluating recovered polymer flow stream quality are paramount. Various sizes of recyclates can be recovered and isolated by screening them into resin-rich powders and fibers. The recycled materials also contain material flakes.

The effect of mechanical recycling of PA66 polymeric composites supplemented with 30% CFs. Using a baby last injection moulding machine, pristine PA66CF30 granules from the market were shaped into a dog-bone shape, and test specimens were aged. Recycling, however, had little to no impact on the mechanical qualities except for a slight reduction in tensile strength. The morphological examination also revealed that all new, used, and recycled composites exhibited a similar failure pattern [22].

The mechanical recycling technique with the process variables for recycling the GFRP composite. The original GFRP contained 50 mm-long fibres and 30% GFs. Moreover, comparisons were made between process parameters such as fibre length distribution, percentage resin content, and fibre shape. The findings showed that the HVF approach has 2.6 times more specific energy than mechanical recycling, where the fibre lengths were only distributed up to 5 mm; however, utilising the HVF approach, up to 9 mm of fibres were found in recycled materials. Moreover, mechanical recycling and HVF had resin contents ranging from 49% to 59% and 32% to 37%, respectively. In contrast to mechanical recycling, HVF creates clean and longer fibers with a lower resin concentration [23].

4.4. Analysis of Best Closed-Loop Recycling Techniques

Each year, the world produces more than 400 million metric tonnes of plastic garbage, which causes pollution and depletes resources. For closed-loop polymer recycling technologies, as well as enzymatic hydrolysis, glycolysis, and vapour methanolysis, have been analyzed based on that the best economic (9%−73% lower than competing technologies) and environmental performances (7%−88% lower effects) are demonstrated by mechanical recycling and PET glycolysis. In contrast, dissolution, enzymatic hydrolysis, and methanolysis offer the best recyclate material quality (2%–27% higher) [24].

5. Summary

Due to environmental problems brought on by the waste of various plastic materials, there has been considerable interest in developing sustainable materials and solutions. The heterogeneous character of the polymer blend textile materials brought on by natural and synthetic fibres makes recycling complex. This review raised significant issues with blended textile waste and offered a variety of strategies to address them. This analysis highlighted a few recent advancements in the recycling and remanufacturing plastic/polymer blend textile products.

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