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REVIEW

Challenges of textile waste composite products and its prospects of recycling

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Abstract

Every year, a massive volume of textile waste is disposed of in a landfill or incinerated, contributing to resource loss and environmental consequences. Researchers are using textile waste to simultaneously develop composite materials to address both issues. Although manufacturing composites temporarily solves the problem, these composites will eventually wind up in landfills at the end of their service life unless appropriate manufacturing and recycling methods are followed. This review assessed the feasibility, benefits, drawbacks, and limitations of various composites manufactured from textile waste and their recycling procedures in terms of having minimal or no environmental impact after their end-of-life. This paper discusses two alternative composite manufacturing technologies and various recycling processes. Based on the review, developing biocomposites from textile waste comprised of natural components is one of the most promising options regarding sustainability and environmental friendliness. Moreover, by adopting this method, some partially biodegradable composites can be transformed into fully biodegradable materials, resulting in various benefits, including improved mechanical properties. Then, as one of the potential solutions, ionic liquids are discussed. Ionic liquids can dissolve a wide range of fibers. Most crucially, ionic liquids can dissolve a specific fiber from a blend of fibers, which is traditionally considered the main difficulty with textile waste. Furthermore, for some fully non-biodegradable and partially biodegradable composites, several recycling strategies have been discussed and, in part, used by numerous companies to recover waste fibers and keep them out of landfills. The advantages, downsides, and limitations of each recycling process have also been explored. Finally, applications and future perspectives for these manufacturing and recycling processes are emphasized.

Keywords Composite · Sustainability · Recycling · Ionic liquid · Textile waste · Green composite

Introduction

The world's population is rising, and people's lifestyles are changing rapidly, putting strain on resources and the ecosystem's carrying capacity [1]. The formulation, including composites traditionally made of glass, carbon, and other synthetic fibers, is deemed essential due to environmental concerns [2]. The current and proposed Waste Management legislation includes overly strict landfill and incineration policies, so the fiber-reinforced composite industry, manufacturers, and suppliers must deal with the problem by identifying possible recycling solutions to ensure the sustainability of their goods for the construction sector [3]. Simultaneously, scientists are exploring alternative materials to replace petroleum polymers due to strong constraints on their preservation and product end-life cycle performance [4]. Many articles have been reported in the literature focusing on the development of new composites comprising various materials, such as natural fiber from vegetable sources (bamboo, banana, coconut, flax, hemp, jute, kenaf, sisal, wood) and animal sources (wool, silk), agricultural residues (citrus, coconut shell, duck feather, rice husk, sunflower husk), textile fiber waste, for example.

According to research findings, chemical and textile fiber's synthesis surged more than four times between 1975 and 2018, from 23.94 million metric tons to 105.6 million metric tons, a 40-year increase [5]. As shown by the Food and

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Agriculture Organization (FAO), 3.7 kg of textile fiber was consumed per person in 1950, and this amount has steadily climbed to 11.1 kg per person in 2007 [6]. According to the European Environment Agency (EEA) briefing, the manufacture of apparel, footwear, and home textiles for Europeans contributed to an estimated 654 kg of CO_2 equivalent emissions per European Union (EU), representing textiles as the fifth greatest source of CO_2 emissions related to private consumption [7]. The awareness of environmental issues grows together with the increase in CO_2 emissions [8]. Every year, a large volume of fibrous textile waste is dumped into landfills worldwide [9]. Wide varieties of textile wastes have environmental consequences since these are not biodegradable and may discharge poisonous fumes into the environment [10]. Global concerns regarding textile waste disposal and management have recently intensified in recent years [11]. Considerable research and industrial initiatives have been launched as a tactic for restoring textile waste from landfills. They suggest that the proposed technical solution has much potential in managing textile waste and aiding the recovery of natural textile wastes as value-added products into natural fiber-reinforced composites [12].

Although textile wastes are employed in composite materials and reduce pollution, composite materials are discarded or incinerated after being used. As a result, after a few days, contamination from textile waste will emerge. The composite material comprises various types of textile fibers that damage land, air, and water when disposed of or incinerated. These synthetic fibers are highly hazardous to humans and other living things. It has also been reported that every year, approximately 100,000 marine animal species and over a million sea birds die as a direct result of ingesting plastic debris [13]. Different forms of fiber from textile waste, such as nylon, polyester, polyamide, rayon, and others, are contained in this plastic garbage. Seafood eating is the principal source of these fibers in the human body. According to reports, approximately 20 kg of seafood is consumed per capita each year [14]. Chronic inhalation of these fibers has been linked to lung infection and inflammation, stomach, liver, and kidney damage, cardiovascular difficulties, brain damage, cancers, and human reproductive abnormalities [15].

Researchers seek ways to implement various waste management and recycling technologies to prevent undesirable environmental impacts and maximize raw material utilization. Stanescu [16] discussed the valorization of post-consumer waste using several approaches, such as novel materials (non-woven and composite), fibers, and various compounds (cellulose derivatives, graft polymers, succinic acid, ethanol, and activated carbon) as carbon and energy sources. Rahman et al. [17] proposed a slew of novel construction materials and geotechnical engineering solutions, including polymer concrete and composites, thermal and acoustic insulation, asphalt concrete, fiber-reinforced soil, rammed earth, and so on. Sivakumar and Mohan [18] studied polymer composites and nanocomposite materials from leather and textile fiber waste. Rotimi et al. [19] looked into the existing literature on sustainability within the fashion industry's supply chain to identify available sustainable methods for dealing with post-consumer textile waste (PCTW) at the end of the garment's lifecycle. Santos and Campos [20] analyzed and characterized post-consumer textile waste management procedures in garments and then examined them using environmental, economic, and social factors. Zhou et al. [21] presented innovative techniques for handling textile waste, such as its utilization value and transformation processes, to aid in remediation and mitigate environmental consequences. Wojnowska-Baryła et al. [22] discussed a bio-based textile management system based on sorting, pretreatment, and recovery of textile materials, as well as the production of bioethanol, biogas, and composting from textile waste. Several recent review papers imply that textile wastes are becoming increasingly popular in manufacturing composite materials. Mishra et al. [23] published a review that presented textile waste as a raw material source for producing various value-added goods, such as plastic composites and composites for construction applications. Sotayo et al. [24] examined the different manufacturing procedures that use carpet waste as a raw material to create possible composite materials for structural load-bearing applications. For the advancement of the automotive industry, Darshan et al. [25] conducted literature research on waste silk fiber-reinforced polymer composites (FRPCs) made from various silk waste fibers. Patti et al. [26] discussed using textile waste across multiple polymer matrices such as thermosetting resins, thermoplastic polymers, natural matrices, hybrids, and concrete matrices. Tran et al. [27] studied the engineering performance of textile waste fiber-reinforced concrete. These reviews represent initiatives aiming to produce textile waste composites (TWC) to reduce textile waste in landfills and utilize raw materials. However, none of them contemplated what would happen if these composites reached the end of their lifespans and were landfilled or incinerated, contributing to pollution. This review discussed the current TWC manufacturing process and its environmental consequences and impact on human health. Then, alternative TWC manufacturing and recycling processes were examined as potential solutions to ensure that these TWCs have minimal or no environmental impact after their end of life. The feasibility, benefits, downsides, and limitations of these processes are also analyzed in this review.

Textile waste

The world's population, which is already 7.6 billion, might increase to 8.6 billion in 2030, 9.8 billion in 2050, and 11.2 billion in 2100 [28]. Global demand for textile products is rising continuously, a trend predicted to remain as the world's population grows [29]. By 2025, the global textile and apparel market is expected to have grown at a compound annual growth rate of 3.7 percent, surpassing 100 million tons [30]. In 2018, however, global fiber production crossed 107 million metric tons, manufacturing significantly more than expected [31], showing a much higher production than predicted. Correspondingly, annual textile waste is estimated to reach 26.0, 1.0, and 12.4 million tons in China, the United Kingdom, and the United States (US) [30]. The Council for Textile Recycling found that between 1998 and 2009, there was a 40% spike in textile waste but only a 2% increase in landfill diversion. They responded by setting a goal for the US to create zero landfill-bound textile waste by 2037 [32]. Until 2013, the EEA certified a quantity of textile waste of 5.6 million tons (Mt): 20% of the textile waste was reused or recycled, 1.5 Mt was shipped outside of the EU, and the remaining 80% was lost [33]. More than 20 million tons of textile waste in China, but only 2.33 million tons (less than 10%) are recycled yearly [9]. The situation in Hong Kong is likewise dire, with around 293 tons of textile waste generated daily [34]. In 2009, Portugal created 293,000 tons of textile waste [35]. In 2011, Spain solely produced 301,600 tons of textile waste [36]. These large amounts of waste that end up in landfills and incineration lead to environmental hazards and waste many resources for not being used effectively.

Selection

Google Scholar was initially used to find out the targeted articles. Articles on composite materials made from TWC are the targeted ones. In this criterion, a total of 92 articles were found. These 92 articles are then assorted into two groups. One group, known as non-biodegradable composites (both the matrix and reinforcing agents are non-biodegradable), is listed in Table 1 and has 34 articles. The other 58 articles are in Table 2, considered partially biodegradable composites (matrix or reinforcing agent, one is biodegradable). Four possible cases considered in this criterion are given below:

- Natural Fiber (Biodegradable) + Synthetic Matrix (Non-Biodegradable)
- Synthetic Fiber (Non-Biodegradable) + Natural Matrix (Biodegradable)
- Synthetic and Natural Fiber Mix + Synthetic Matrix
- Synthetic and Natural Fiber Mix + Natural Matrix

Finally, how these two types of composites can be manufactured using more ecologically friendly procedures is addressed.

Composite from textile waste

Every year, a massive amount of textile fiber waste is landfilled or incinerated, causing a slew of environmental issues, such as groundwater contamination and the production of greenhouse gases during decomposition [126]. Thus, it is essential to find ways to recycle these materials to lessen environmental effects and save energy [10]. This recycling of textile fiber waste contributes to long-term sustainability. Reusing and recycling more textiles might minimize the manufacturing of raw textile fibers and, in the case of reuse, avoid engineering activities later in the textile product's life cycle, which would positively influence the environment [127]. Recently, textile fiber waste has been incorporated into composite products. Nylon and polypropylene fibers from carpet waste [48], polyamide fiber from tire waste [38], cotton [72], polyester [50], wool [113], silk [89], and other textile fibers from fabric (woven, non-woven, knit) waste are all examples of textile fibers that can be reused. These composites are widely employed in construction [46], sound absorption materials [45], the automobile industry [120], furniture materials [116], polymer concrete [50], the food packaging industry [128], and many other applications.

The most common difficulty faced while recycling textile fiber is that both natural and synthetic fibers are used simultaneously in making yarn or fabric. For this reason, choosing a specific recycling process becomes very difficult as these multiple fibers have multiple characteristics. It often requires various recycling techniques to separate them; sometimes, even multiple techniques are not enough. This scenario is also true for TWCs, which often contain numerous fiber types as reinforcing or matrix agents in a single composite. That is why these composites are complicated to recycle and will harm the environment as textile waste in just a delayed manner. It is necessary to segregate these TWCs, requiring different approaches to make them environmentally friendly, to overcome these problems. The chosen articles make two categories (non-biodegradable and partially biodegradable). Table 1 summarizes previous research into non-biodegradable TWCs. Whereas Table 2 lists some prior studies on partially biodegradable TWCs. Tables 1 and 2 also show which composite parts were made from waste textiles. Although these composite materials' usage is presented in the chart, some are not addressed in the peer-reviewed literature.

Table 1 Non-biodegradable composite materials produced from textile waste

Non-biodegradable composite materials				
Serial No	Reinforcement	Matrix or Binder	Application	References
1	Polyamide, Polyacrylic, Modal (TW)	Polyurethane foam	SIM	[37]
2	Polyamide, Rubber granules (Tire waste)	Epoxy	Renovation of machine parts Roofing material	[38]
3	Chopped Garment (TW) Fly ash	Epoxy	Ceiling panels, Roof tiles SIM Park benches, Chairs	[39]
4	Acrylic (TW)	Epoxy	N/M	[40]
5	Wool, Nylon, Polypropylene (TW)	Colemanite Ore	Insulation material	[41]
6	Rubber (TW)	Polyurethane foam	Thermal insulating material	[42]
7	Synthetic fiber (TW)	Polyvinyl acetate	Puzzle, Toys	[43]
8	Nomex, Kevlar, Polyester (TW)	Low-Melting Point Polyester	Protective materials	[44]
9	Polyester Waste (TW)	Polyurethane, Dimethylformamide	SIM	[45]
10	Glass, Polyester, Polypropylene fiber (TW)	PC	BM	[46]
11	Polyester (TW) Polypropylene	Needle punching technique was used to hold the reinforcing material	Non-woven composite	[47]
12	Nylon, Polypropylene yarn (TW)	Silty Sand	Soil reinforcement	[48]
13	Polyester, polypropylene (TW)	Melted Polypropylene Non-Woven Selvedge waste	SIM	[49]
14	Polyester (TW)	Polypropylene Low-Density Polyethylene	SIM BM	[50]
15	Polyacrylonitrile, Polyamide, Polyester (TW)	Polychloroprene	SIM	[51]
16	Polyester (TW)	PC	BM	[52]
17	Nylon, Jute (TW)	Low-Density Polyethylene	Automotive BM	[53]
18	Polyamide Fabric	Polyamide (TW)	Tents, facade coverings, container linings, and tarpaulins	[54]
19	Nylon (TW)	Polyamide (TW)	Textile bioreactor	[55]
20	Activated Carbon (TW)	Phenolic Resin	Textile effluent (Anionic dye removal)	[56]
21	Polyacrylonitrile (TW)	Multiwall Carbon nano tube	Textile effluent (Dye removal)	[57]
22	Polyacrylonitrile, Polyamide, Polyester (TW)	Polystyrene Cork Polyethylene	SIM	[58]
23	Polyacrylonitrile (TW)	Co-Zn ZIF/MoS2 hybrid nanosheet	Geotechnical cloth, filtration and household textile	[59]
24	Polyamide (TW)	Gypsum	BM	[60]
25	Rubber (TW)	Fly ash Activator Solution	BM	[61]
26	Polypropylene (TW) Palm Oil Fuel Ash	PC	BM	[62]
27	Polypropylene (TW)	PC Rice husk ash	BM	[63]
28	Polybutylene terephthalate, Polyethylene terephthalate, Polyamide (TW)	Fly Ash	BM	[64]
29	Polypropylene (TW)	PC Palm Oil Fuel Ash	BM	[65]
30	Acrylic (TW) Wood chips	Urea Formaldehyde	Wood based panel	[66]
31	Polypropylene	Cot Rubber (TW)	Damping application	[67]
32	Nitrile butadiene rubber Chlorinated Polyethylene	Rubber (TW)	High damping film material	[68]

Table 1 (continued)

Non-biodegradable composite materials

Serial No	Reinforcement	Matrix or Binder	Application	References
33	Aramid (TW)	Low-Melting Point Polyester Aramid Composite board	N/M	[69]
34	Nylon, Polyester (TW)	PC Silty Sand	BM	[70]

Reinforcing agents and matrices, as well as which part came from the textile waste, are mentioned. Applications of these composite materials in real life are also listed, but some of them are not mentioned in the respective articles

TW textile waste, *N/M* not mentioned, *PC* portland cement, *SIM* sound insulation material, *BM* building material

Challenges of composite waste products

The composite material that comprises textile waste such as tire waste, carpet waste, wear gloves and masks, used textile garments, and fabric scraps are employed in building, automobile, food packaging, and particleboard industries. These composite materials are incinerated or landfilled following their use, polluting water, land, and air. Synthetic fibers discovered in these composite materials generated from textile waste have an adverse effect on birds and fish. Humans eat these fish and consequently develop infections.

Effect of terrestrial microfiber pollution

The terrestrial environment is the primary source of microfiber pollution, with approximately 400 million tons of plastic produced worldwide yearly [129]. Synthetic fibers' inorganic and non-biodegradable properties are the primary drivers of terrestrial pollution and environmental change, ultimately leading to the next level. Synthetic fibers are also delivered to sewage for various causes and through diverse methods. It is estimated that 80–90% of garment fibers are detected in sewage, with polyester (66%) and acrylic (7%) accounting for the majority [130].

Sludge from sewage treatment plants is used as a cheap fertilizer on agricultural lands, and it is a typical practice in developing nations on a large scale [131]. These microplastics (MPs) have a deleterious effect on the soil, the living organisms, and the plants that grow in it. Due to contamination with microfibers, De Souza Machado and colleagues showed a rise in soil bulk density and aeration [132]. These MPs impede plant seedlings' growth and development [133]. MPs also directly impact the plant by obstructing seed pores, which slow or stop water uptake by sticking to the surface of seed pores [134]. Additionally, soil-dwelling microorganisms may be harmed as chemicals are required to make MPs [135]. In several experiments, MPs are poisonous to earthworms [136], microbes [137], and plants. Furthermore, MPs have been shown to reduce the microbial population in the soil [138]. Since plants, organisms, and soil are all part of an ecosystem and interdependent, changing one negatively influences the other. Plant and agricultural growth could be significantly impacted by MPs' reduced microbial activity [139] (See Fig. 1). According to Boots and coworkers, soil contamination with high-density polyethylene (HDPE) lowers soil pH, affecting microbial activity [140]. Besides, MPs contamination could alter the carbon-to-nitrogen ratio in the soil [141], which could affect the entire plant population. Changes in soil composition and structure may also reduce the growth of microorganisms in the rhizosphere, lessening soil fertility [141]. Plants interact with both beneficial and harmful communities in the soil through the rhizosphere, a virtual interface [142].

Effect of aquatic and marine microfiber pollution

Because of the presence of microfiber, aquatic pollution has received much attention in recent decades. These microfibers are derived from synthetic fibers that migrate to the ocean from various landfills and incineration sites via rain and wind.

If nothing is executed, it is estimated that plastic debris in the ocean will increase by 850 Mts by 2050 [144]. Sunlight, strong waves, and ultra violet (UV) light break down these synthetic fibers into microfibers (see Fig. 2). These partially degraded particles end up in the ocean, where it is predicted that 100,000 particles accumulate per cubic meter on the surface of the water in the marine environment around the world [126]. Synthetic fabrics also degrade partially to form synthetic microfibers, which are non-biodegradable and will remain in the ocean perpetuity. Around 60% of microfibers in freshwater systems near metropolitan centers emerge from synthetic clothes made of polyester, polyethylene terephthalate (PET), and other synthetic fibers. According to reports, nearly 85 percent of microplastic fibers present in global seashore lines are polyester, nylon, and polyvinylchloride. This problem is not confined to aquatic systems; studies have found that drinking water [143], bottled water [145], sea salt, seafood [146], sugar, beer, and other products are adulterated with plastic fibers. If this pollution continues, it will

Table 2 Partially biodegradable composite materials produced from textile waste

Partially Biodegradable Composite Materials					
Serial No	Reinforcement	Matrix or Binder	Biodegradable Part	Application	References
1	Cotton, Jute (TW) Glass fabric	Unsaturated Polyester Resin	Cotton, Jute, Unsaturated Polyester Resin	N/M	[71]
2	Cotton (TW) Graphene oxide	Epoxy	Cotton	FM AP	[72]
3	Cotton, Nylon, Viscose, Polyester (TW)	PC	Cotton, Viscose	BM	[73]
4	Rubber Crumbs Flax (TW)	Polyurethane foam	Flax	SIM	[74]
5	Cotton (TW)	PC	Cotton	BM	[75]
6	Cotton, Wool, Polyester, Polypropylene, Polyamide (TW)	PC	Cotton, Wool	BM	[76]
7	Wool Polyester (TW) Recycled Paper	Glue	Wool	SIM BM	[77]
8	Cotton (TW) Jute	Epoxy	Cotton, Jute	AP FM Leisure equipment BM	[78]
9	Polyester (TW) Coconut Fiber	Low-Melting Point Polyester	Coconut Fiber	SIM	[79]
10	Alpaca powder (TW) Polyacrylonitrile	Dimethyl Sulfoxide Solvent	Alpaca powder	Composite fiber	[80]
11	Cotton (TW)	Urea Formaldehyde	Cotton	Particleboard	[81]
12	Lycra, Polyester, Cotton (TW) Fiber glass	Epoxy	Cotton	SIM	[82]
13	Cotton (TW) Virgin Polypropylene	Polypropylene	Cotton	N/M	[83]
14	Green Palm Fiber Cotton, Wool, Polyester (TW)	NPT	Green Palm, Cotton, Wool	Composite Non-woven BM	[84]
15	Cotton (TW) Glass fiber	PC	Cotton	Thermal Insulator	[85]
16	Cotton (TW)	Soil	Cotton	BM	[86]
17	Cotton, Polyester (TW)	PC	Cotton	BM	[87]
18	Cotton (TW)	Low-Density Polyethylene	Cotton	Different types of indoor and outdoor application	[88]
19	Cotton, Silk (TW)	Polycarbonate	Cotton, Silk	N/M	[89]
20	Cotton (TW)	Polypropylene	Cotton	AP Packing materials Engineering materials	[90]
21	Polypropylene (TW)	Unsaturated Polyester Resin	Unsaturated Polyester Resin	BM	[91]
22	Wool (TW)	Tetra Pack waste	Wool	SIM	[92]
23	Glass fiber Flax, Cotton (TW)	Unsaturated Polyester Resin	Flax, Cotton, Unsaturated Polyester Resin	N/M	[93]
24	Polyester, Cotton (TW)	Epoxy	Cotton	SIM	[94]
25	Silk, Cotton (TW)	High Density Polyethylene	Cotton, Silk	N/M	[95]
26	Jute, Cotton, Polyester, Polypropylene (TW)	Poly Lactic Acid (PLA)	Jute, Cotton, PLA	N/M	[96]
27	Stubble, Sunflower Stalks Cotton (TW)	Urea Formaldehyde	Stubble, Sunflower Stalks, Cotton	Thermal Insulator	[97]

Table 2 (continued)

Partially Biodegradable Composite Materials					
Serial No	Reinforcement	Matrix or Binder	Biodegradable Part	Application	References
28	Microcrystalline Cellulose (MCC)	Nylon (TW)	MCC	AP	[98]
29	Jute	Medical Gloves. (TW)	Jute	Partition purpose	[99]
30	Cotton. (TW)	Polyester Waste	Cotton	N/M	[100]
31	Polyester, Cotton (TW)	Natural Rubber	Cotton	SIM	[101]
32	Cotton (TW) Glass Mesh fiber	Gypsum	Cotton	Non-structural partition walls BM	[102]
33	Cotton (TW)	Phenolic Resin	Cotton	SIM	[103]
34	Wool, Acrylic (TW)	NPT	Wool	Non-woven composites Thermal Insulator	[104]
35	Flax (TW)	Acrylic acid Acrylamide	Flax	Superabsorbent for modern agriculture and horticulture	[105]
36	Silk, Jute (TW)	Epoxy	Silk, Jute	N/M	[106]
37	Cotton, Synthetic Fiber (TW)	Natural Hydraulic Lime	Cotton	BM	[36]
38	Sisal, Glass Carbon Waste (TW)	Polypropylene	Sisal	Industrial parts (Gears, Bearings, Seals, Brakes)	[107]
39	Cotton (TW) Fly ash Barite	Epoxy	Cotton	BM	[108]
40	Wool, Acrylic (TW)	PC Natural Hydraulic Lime	Wool	BM	[109]
41	Cotton (TW)	Allyl glycidyl ether Bisphenol diglycidyl ether	Cotton	N/M	[110]
42	Polyester, Cotton, Wool (TW)	Epoxy	Cotton, Wool	N/M	[111]
43	Sawdust	Polypropylene (TW)	Sawdust	BM	[112]
44	Wool (TW)	Polyethylene terephthalate	Wool	BM	[113]
45	Cotton, Polyester (TW)	Natural Rubber Latex	Cotton	SIM	[101]
46	Cotton, Polyester, Flax (TW)	PC	Cotton, Flax	Facade cladding, raised floors, and pavements	[114]
47	Cotton (TW)	Natural Rubber Latex	Cotton	Wearable strain sensors	[115]
48	Hemp (TW)	Polypropylene	Hemp	AP FM	[116]
49	Cotton, Polyester blend (TW)	Polyester waste	Cotton	N/M	[117]
50	Cotton, Polyester, Silk, Rayon (TW)	Epoxy Foundry Sand	Cotton, Silk	BM	[118]
51	Cotton (TW)	Recycled polyethylene terephthalate	Cotton	3D printing applications	[119]
52	Cotton, Flax, Hemp (TW)	Linear Low-Density Polyethylene	Cotton, Flax, Hemp	AP	[120]
53	Wool, Cotton, Nylon (TW)	PC	Wool, Cotton	BM	[121]
54	Jute (TW)	Natural Rubber Latex	Jute	SIM AP	[122]
55	Cotton (TW)	Phenol formaldehyde	Cotton	BM	[123]
56	Cotton, Hemp (TW)	Polyurethane	Cotton, Hemp	Ships, Building materials, furniture, automobile	[124]
57	Cellulose Waste (TW)	Polypropylene film	Cellulose	FM SIM	[125]

Table 2 (continued)

Partially Biodegradable Composite Materials

Serial No	Reinforcement	Matrix or Binder	Biodegradable Part	Application	References
58	Cotton, Wool, Acrylic, Polyester, Polypropylene, Nylon (TW)	Polypropylene	Cotton, Wool	BM	[29]

Reinforcing agents and matrices, the part that came from the textile waste and the part that is biodegradable, are mentioned. Applications of these composite materials in real life are also listed, but some of them are not mentioned in the respective articles

TW textile waste, *N/M* not mentioned, *PC* portland cement, *BM* building material, *SIM* sound insulation material, *AP* automotive parts, *FM* furniture material, *NPT* needle punch technique was used to hold the reinforcing material

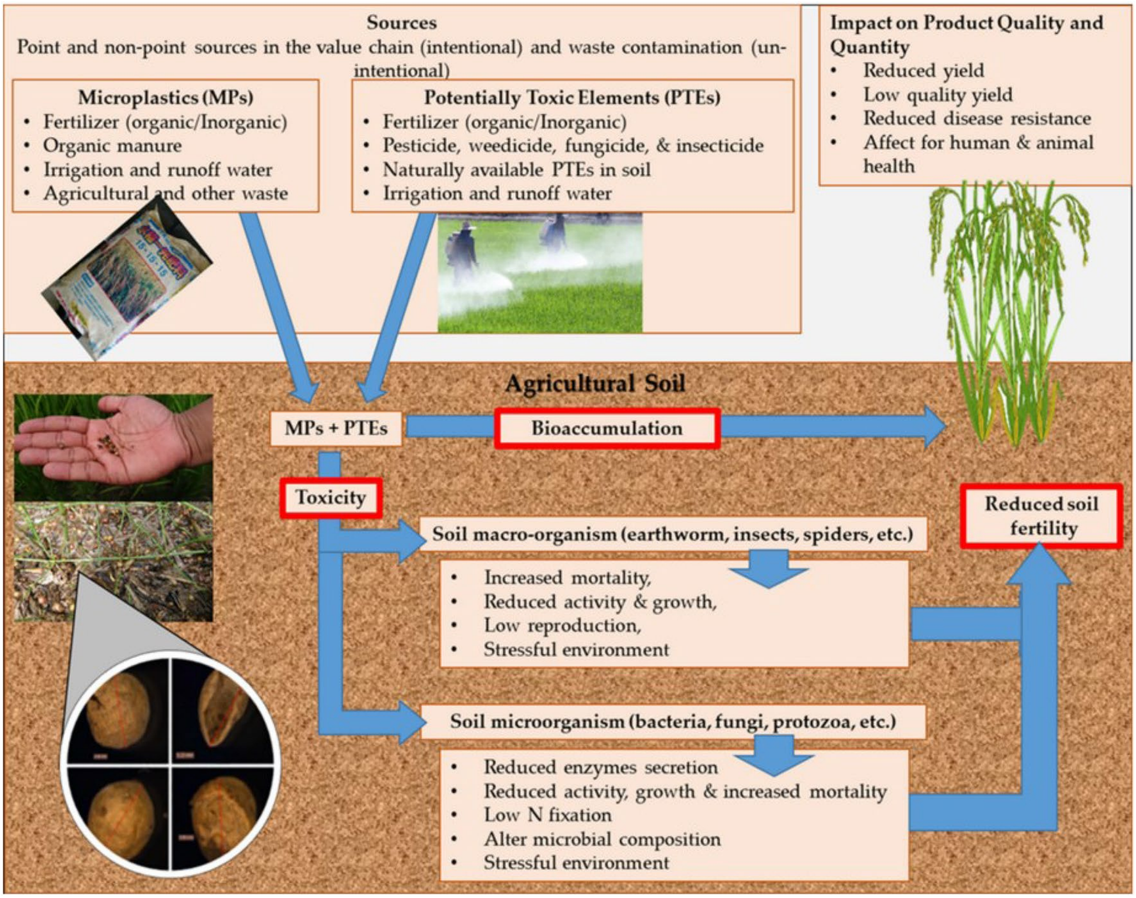

Fig. 1 Exposure and bioaccumulation of microplastics (MPs) and potentially toxic elements (PTEs) in agricultural soil [241]. (Reproduced with permission)

influence the aquatic ecosystem and the different ecosystems connected to it.

Microfibers have a negative impact on marine life as well. Synthetic fibers and composite materials made from textile fiber waste migrate from landfills and incineration sites in the marine environment. With the aid of wind and rainfall, these synthetic fibers first enter lakes and rivers before making their way to the sea. These pollutants adversely influence the terrestrial to marine environment and appear to be a threat to aquatic fauna [148]. Microfibers are manufactured from synthetic textile fiber waste, soaking up all toxic chemicals, heavy metals, and oil in the water [149]. As a result, the concentrations of these micropollutants are much higher in seawater than in terrestrial water. A variety of marine wildlife, along with corals, phytoplanktons, zooplanktons, fish, sea urchins, lobsters, turtles, penguins, crustaceans, seabirds, and others, misjudge these tiny fibers for food, causing them to

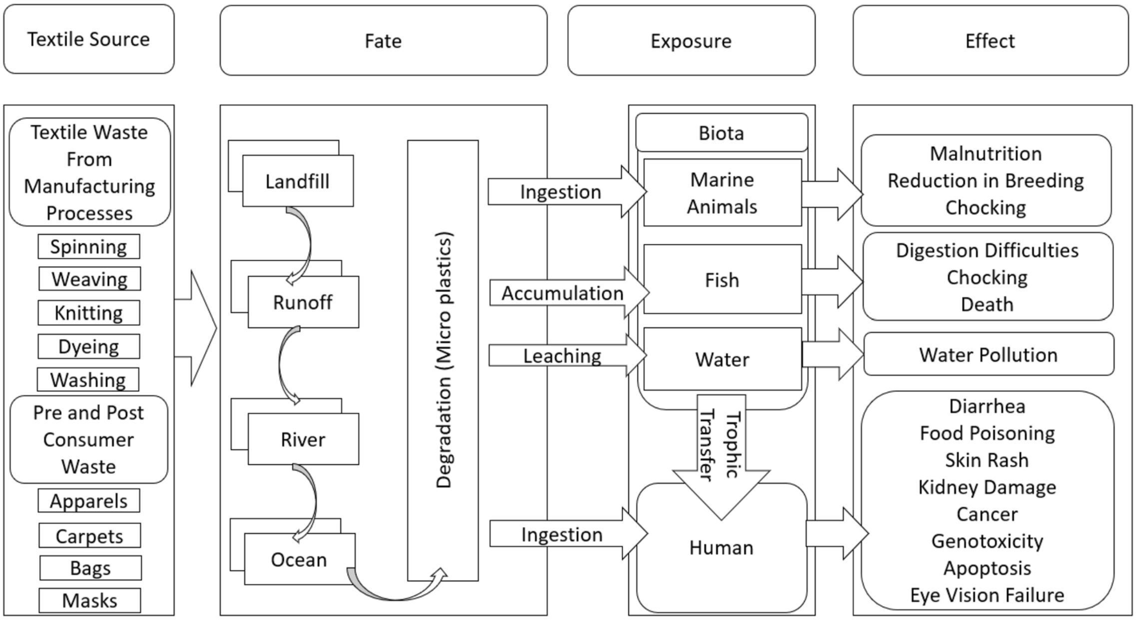

Fig. 2 Sources, pathways and fate of microfibers in environmental systems and its effect on aquatic biota, marine biota and human health [147]. (Reproduced with permission)

be moved to higher nutritional ranks and wreaking havoc on the entire food chain [150].

Fabric contaminants have a negative impact on plankton, which are the base of the aquatic food chain [151]. Furthermore, these have been identified in the digestive systems of benthic fish species in the marine environment and differently sized plastics in their intestines [152]. Half of all sea bird species are threatened with extinction due to the destructive, hazardous pollutants ejected by microfibers, which have a detrimental effect on their bodies, causing changes in feeding behavior, reproduction, and mortality [153]. Similarly, many routine whale deaths have been reported due to a significant amount of MPs stock in their stomach [154]. Microfibers and synthetic fibers have been confirmed to endanger sea birds, turtles, seals, polar bears, and whales. Choking, fiber accumulation in gastro intestine tracts, poisoning due to the contaminated food source, and other problems may occur in these animals. According to Lamb et al. (2018), approximately 124,000 corals from 159 reefs are at risk of illness due to direct exposure to synthetic plastic fibers, leading to a rise of these fibers from 4 to 89 percent in the Pacific coastal regions of Asia [155]. Ingestion induces choking at the digestive organs [156] and hinders animals from being fed, contributing to death as a result of starvation and malnourishment. In a variety of marine animals, declines in feeding capacity [157], digestion rate, predator performance [152], and swimming velocity [158] have been well recorded (see Fig. 2).

Effect of microfibers on human life

Synthetic fibers derived from textile waste fiber composite material have been presented in a broad range of human environments and enter the body via food, water, and air, elevating concerns about human wellbeing. Human exposure to microfiber pollutants occurs primarily through consuming seafood, a required nutritional component since seafood accounts for 20% of animal protein consumed by the world's 4.3 billion people [159]. Aside from sea-derived foods, synthetic MFs have been found in honey, beer, and sugar worldwide, polluted by airborne fibers. These fibers have been claimed to be present in drinking water and have emerged as a matter of anxiety in human health [160]. The contamination test using Nile Red tagging in eleven bottled water brands collected from 19 different areas in nine countries found that 93% of the 259 processed bottles had evidence of microplastic contamination [145]. As these fibers are deposited in lung tissues, humans and animals who breathe horrendously become infected with lung infection and inflammation [161]. The bioaccumulation of synthetic microfibers in the human gastrointestinal tract and lungs [162] has been reported. These microfibers can cause various adverse symptoms, including inflammations, genotoxicity, oxidative stress, and apoptosis in the human body [15](see Fig. 2). These also affect the immune system and cell health by transferring from the digestive system to the circulatory system [163] and depositing in the secondary organs. The chemical configurations of synthetic materials, such as phthalates, polychlorinated biphenyls (PCB)

[164], and bisphenol A (BPA) [165], may have a multitude of consequences for human health, including damage to the intestines, liver, and kidneys; blood infection [166]; breast cancer, and hormonal imbalance in female reproductive systems.

Potential solutions and future research

The hazards of microfibers and plastics derived from TWC on human and animal life are extreme. However, it is believed that some solutions to these challenges already exist. There are two types of textile waste fibers: natural and synthetic. Bio-composite materials may be a practical solution for producing TWC, where the waste is entirely composed of natural fiber. These materials, also known as green composites, are extremely environmentally benign, reducing disposal and incineration challenges. Table 3 lists some studies on biocomposites created from textile waste, where many researchers found it to be a suitable alternative for producing different end products. Sect. "Biocomposites" goes into detail about biocomposites made from textile waste. Recycling can be employed when TWC is manufactured entirely of synthetic fiber waste, and the matrix component is non-biodegradable. Recycling reduces landfilling and incineration by providing recycled materials that are the same as the original material's integrity, alleviating environmental concerns about landfilling solutions. Furthermore, these recycled fibers are used in the automobile industry, pointing to a possible economic benefit. Sect. "Recycling of Composites" discusses many recycling systems, each with its advantages, disadvantages, and restrictions. One main issue with textile waste that makes it challenging to manage is that it contains both natural and synthetic fibers in the waste component. This problem makes the process of separation very difficult to use the above two options. Ionic liquids can be helpful in some instances. Ionic liquids have already been demonstrated to be solvents capable of dissolving a wide range of compounds. The key benefit of employing ionic liquid is that it can dissolve a specific synthetic and natural fiber blend component. Therefore, ionic liquids can dissolve both natural and synthetic elements. Many studies on ionic liquids are discussed in Sect. "Ionic Liquids", and various applications are also addressed.

Biocomposites

Green composites or biocomposites are composite materials that are entirely bio-based, indicating that both the matrix and the reinforcing agents are derived from renewable sources [190]. Recently, the findings of investigations on environmentally friendly composites based on plant fibers and the diversity of matrices degrading in the environment were announced [191]. Green composites will lessen waste disposal issues, notably in agricultural fields and contamination, and can be used in many engineering, electronic, and vehicular areas. Green composites have additional benefits, including reduced machinery wearing, low abrasiveness, and lack of health hazards during manufacturing, application, and disposal [192]. Natural fiber-reinforced polymer composites have been proven to be perfect in structural and non-structural applications, including heat isolation and cover soundproofing, throughout the last few decades. Recently, textile waste has been applied in the field of biocomposite. Textile waste has the benefit of lowering expenses even more while also contributing to trash reduction and reuse, which is one of the sustainable development agendas. Table 3 demonstrates the application and type of textile waste utilized to make biocomposites in the realm of composite materials.

The use of textile waste in composite materials is becoming increasingly prevalent. Textile waste is used to make many composite products that are only partially biodegradable. There are two types of partially biodegradable composites. One has a biodegradable reinforcing material but not a biodegradable matrix or adhesive. On the other hand, another type has a non-biodegradable reinforcing agent and a biodegradable matrix. Serial numbers 5, 19, 27, 28, and many others have a biodegradable reinforcing agent and non-biodegradable resin, as shown in Table 2. The outer layer of such a composite is composed of epoxy resins, polyurethane, phenol–formaldehyde, low-density polyethylene (LDPE), and other non-biodegradable materials, where it does not satisfy the objective of a partially biodegradable composite. The organic part of these composites is enveloped by thermoplastic, making them unlikely to come into contact with air, water, or microorganisms [193]. As an outcome, the strengthened material's decomposition is prevented and will worsen the environment. It will be utterly biodegradable if the non-biodegradable matrix can be replaced with a biodegradable matrix such as unsaturated polyester resin, polylactic acid (PLA), green epoxy resin, mineral binder, and natural rubber latex. Besides, some TWCs are entirely non-biodegradable. As these composites are created from textile waste, separating the synthetic fiber from the waste will be challenging. In today's world, several types of fibers with diverse qualities are blended to create products, making it almost impossible to distinguish between them. So, if the matrix is biodegradable, the composite will be partially biodegradable, reducing the negative environmental impact.

Table 3 Bio-composite materials produced from textile waste

Bio-composite Materials				
Serial No	Fibers	Matrix or Binder	Application	References
1	Rice husk Wheat husk Wood fiber Cotton (TW)	Polybutylene adipate-co-terephthalate PLA	BM	[167]
2	Jute (TW)	Green Epoxy	To develop a value-added product	[168]
3	Cotton, Flax (TW)	PLA	SAM	[169]
4	Wood Jute (TW)	Mineral Binder (clay)	SAM	[170]
5	Cellulose Nanocrystal (TW)	Soy protein film	Thin film composites PM	[171]
6	Cotton (TW)	Unsaturated Polyester Resin	Eco-friendly substitute of the glass fiber composite	[172]
7	Cotton (TW) Carbon particles	Green Epoxy	Electrically conductive material EMI shielding material	[173]
8	Microcrystalline Cellulose (TW)	Natural Rubber Latex	Not Mentioned	[174]
9	Wood Jute, Wool (TW)	Wheat flour Clay	SAM	[175]
10	Cotton (TW)	Wheat fiber	Insulator material	[176]
11	Cotton (TW) Wood fiber	Sodium alginates adhesives	BM	[177]
12	Cotton (TW) Jute	Bio resin	BM	[178]
13	Flax, Jute (TW)	Unsaturated Polyester Resin	Particleboard Industry	[179]
14	Cotton (TW)	PLA Chitosan	PM	[128]
15	Jute (TW)	PLA	PM	[180]
16	Cotton (TW) Coconut fiber Sugarcane	Green Epoxy Resin	BM AP Household furniture	[181]
17	Wool (TW)	Chitosan	SAM	[182]
18	Wool (TW)	Gum Arabic Chitosan	SAM	[183]
19	Cotton (TW)	PLA	Industrial Application	[184]
20	Cotton (TW)	1-butyl-3-methyl imidazolium acetate	AP Furniture and indoor construction Sports and leisure equipment	[185]
21	Silk (TW) Bamboo	PBS	P/S	[186]
22	Wool, Jute (TW) Wood	White Acrylic Copolymer Ecologic Acrylic Copolymer	SAM AP	[187]
23	Cotton (TW)	Soil	BM	[188]
24	Cotton, Hemp (TW) Wood	PLA	Production development	[189]

Reinforcing agents, matrices, and the part from textile waste are mentioned. Applications of these composite materials in real life are also listed, but some of them are not mentioned in the respective articles

TW textile waste, *PLA* poly lactic acid, *PBS* thermoplastic aliphatic polyester, *SAM* sound absorbing material, *P/S* panels or shells, *BM* building material, *PM* packaging material, *AP* automotive parts

Recycling of composites

When it comes to composite materials that are approaching their End-of-Life (EoL), the concern of what to do with them emerges. Landfill disposal, incineration, and recycling are the three basic EoL alternatives for managing composite waste. The effect of each was well displayed by Witik et al. in a 2015 article [194], which is shown in Fig. 3.

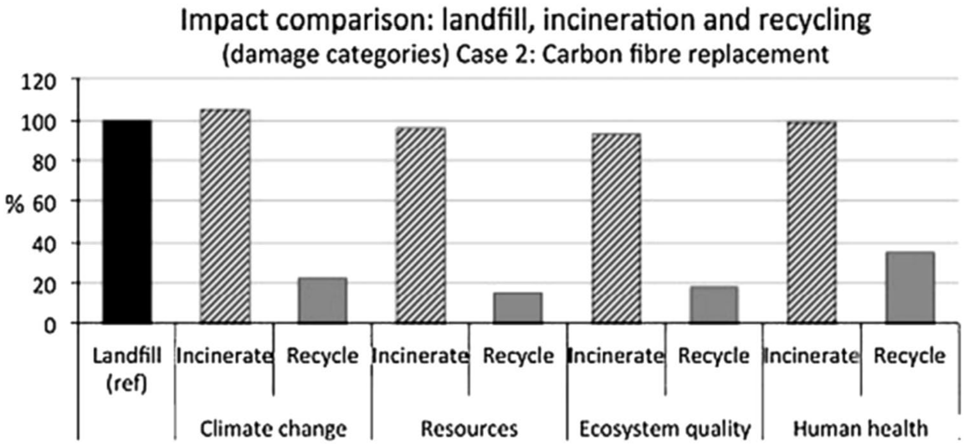

Fig. 3 Comparison of impacts from landfilling, incineration and recycling on climate change, resources, ecosystem quality and human health for the carbon fiber (CF) replacement case [194]. (Reproduced with permission)

According to Amanda Jacob, these inquiries are escalating yearly, suggesting that the composites sector and its consumers are no longer satisfied with landfills and incineration as traditional disposal options [195]. According to the European Composites Industry Association (EuCIA) [196], political drivers are also behind this trend. Thus, conventional waste treatment routes such as landfill and incineration are becoming severely limited and suspended, and composites industries and their users are looking for more green technologies. Composite materials recycling, which initially began during the Hybrid Technology Integration Phase, has become one of composite research's fastest-growing areas [197]. Over the last two decades, there has been a push to reduce weight, lower composite material costs, and create composite recycling technologies [198]. Extensive recycling activities have been carried out, and various technologies that are to be implemented have been established in three categories: mechanical recycling [199], pyrolysis or thermal recycling [200], and chemical recycling [201]. Shredding and grinding are proceeded by screening to segregate the fiber-rich to the resin-rich fractions for reuse [202]. Pickering [199] describes pyrolysis as the thermal decomposition of polymers. However, this recycling approach necessitates a significant amount of heat energy to remove the matrix. Chemical recycling is another option. Chemical de-polymerization or matrix removal is achieved by utilizing chemical dissolution reagents for fiber liberation [203]. Other than these, solvolysis [204] and fluidized bed techniques [205] aim to reclaim individual fibers in the fiber-reinforced composite. The advantages, disadvantages, and limitations of these recycling processes are shown in Table 4.

Due to the low utilization of natural resources, energy, labor, and near-virgin fiber quality, the recycled fibers from this technology have an additional market value [215]. Palmer et al. [207] explored closed-loop thermoset composite recycling involving grinding and reincorporation, with the aim of expanding the mechanical integrity of recycled composites through separation and reformulation. Considerably higher volumes of recyclable materials are used, implying that the recycled composites' mechanical integrity is not always inferior to the original content [216]. These recycled materials are employed in a variety of industries. Recycled fiber-reinforced polymers (FRPs) can be found in aircraft and automobiles [217]. In the automotive industry, for example, recycled materials can be used as exterior materials in a variety of ways. The BMW Group and Airbus collaborated in 2012 to cooperate on carbon fiber recycling and reuse solutions [218]. Shredded short fibers can be employed to deliver non-woven sheet molding compound (SMC) semi-finished goods [219], such as the C-pillar with SMC utilizing fibers in the BMW i7 series or the SMC material for the hatch door frame in the Mitsubishi Rayon (Toyota) [220].

Ionic liquids

Ionic liquids (ILs) are ionic substances that contain both an organic cation and an anion. Because of their unique physical and chemical properties, such as low vapor pressure, good solubility, and high thermal stability, ILs are widely studied in organic synthesis and catalysis, separation and retrieval, electrochemistry, materials science, and other fields with the development of green chemistry [221]. The flexibility to alter the properties of an ionic liquid enables a wide range of applications to profit from its use [222]. With the advent of green chemistry and the demand for environmental regulation [223], ionic liquids have garnered much attention as green and designable solvents. One of the goals of green chemistry is to employ ILs to produce a cleaner, more sustainable chemistry and gain steam as eco-friendly solvents in many synthetic and catalytic processes [224].

In recent years, ILs have become popular solvents for organic synthesis, catalysis, and media for extraction operations [225]. Ionic liquids have already been proven to dissolve a wide range of biomacromolecules with high efficiency, notably cellulose [226], silk fibroin [227], lignin

Table 4 Summary analysis of different recycling process [206]. (Reproduced with permission)

Process	Advantages	Disadvantages	Limitation	Citation
Mechanical	Recovery of both fibers and resin[a] No use or production of hazardous materials	Significant degradation of mechanical properties[a] Unstructured, coarse, and non-consistent fiber architecture[b] Limited possibilities for re-manufacturing	Only synthetic fibers are recycled	[a][199] [b][207] [d][208] [e][209] [m][210] [g][211] [o][212] [r][213] [s][214] [u][201] [w][206]
Pyrolysis	High retention of mechanical properties Potential to recover chemical feedstock from the resin[d] No use of chemical solvents	Possible deposition of char on fiber surface[e] Sensitivity of properties of recycled fibers to processing parameters[e] Environmentally hazardous off-gases[g]	Only synthetic fibers are recycled	
Fluidized bed	High tolerance to contamination[a] No presence of residual char on fiber surface[m] Well-established and documented process	Strength degradation between 25 and 50%[o] Fiber length degradation[o] Unstructured (‘‘fluffy”) fiber architecture[o] Impossibility of material recovery from resin[r]	Only synthetic fibers are recycled	
Chemical	Very high retention of mechanical properties and fiber length[s] High potential for material recovery from resin[u]	Commonly reduced adhesion to polymeric resins[s] Low contamination tolerance[u] Reduced scalability of most methods[u] Possible environmental impact if hazardous solvents are used[w]	Only synthetic fibers are recycled	

[228], starch and zein protein [229], chitin/chitosan [230], wool keratin [227]. According to Swatloski et al. [231], [BMIM] + Cl- was a suitable solvent for cellulose dissolving. The traditional system, which uses toxic chemicals for separation, is the fundamental reason for the popularity of ILs. An additional reason for its appeal is the flexibility of ionic liquids to dissolve textile waste fibers. Johansson et al. [232] employed cotton waste dissolved in 1-butyl-3-methyl imidazolium ionic liquid to make a composite. From a material standpoint, the current fundamental impediment to textile recycling is the lack of sorting and separation techniques [233]. However, most fabrics are made of various fibers, such as cotton/polyester and wool/polyester blends, which can be difficult or impossible to separate once blended [233]. One of the most significant issues with composites manufactured from textile waste is that synthetic fiber will be evident in several cases.

Ionic liquids' versatility allows them to be used in a broad array of applications, such as optical thermometers, bio catalysis and separation processes, polymer and catalytic chemistry, electrolytes, biosensors, analytic devices, lubricants, solvent substitute applications, and lunar telescopes, to mention a few [234]. High molecular weight cellulose can be dissolved with the above ionic liquids at rather large concentrations, around 15–20 percent. Electrospinning of cellulose and its composites has been attempted using ionic liquid as a spinning solvent [235]. The technology suggested here will allow researchers to apply ionic liquids as a common platform to disperse nanoparticles and then dissolve a number of natural, sustainable polymers to build nanocomposites in one step, thanks to their ability to dissolve a wide range of natural polymers [236]. In polymer science, ILs are not confined to a typical polymerization medium [237]. ILs have also been studied as components of polymeric matrices (such as polymer gels). Ueki and Watanabe [238] recently published a review of polymer and IL-based gels, focusing on the physical parameters and interactions in so-called ion gels. A few researchers have recently used ionic liquids to treat chitin to create films, fibers, gels, and foams [239]. Additionally, Abdulkhani et al. [240]examined the physical and mechanical properties of regenerated biocomposite films and studied the performance of dissolution cotton linter in ILs [emim][Cl] and [dmim][MeSO4]. These characteristics identify the ILs as an extremely impressive lignocellulosic biomass pretreatment technology. The pretreated material might be used as reinforcements or fillers in a myriad of thermoset and thermoplastic polymer matrices. Johansson et al. [232] created a composite material from textile waste fiber that might be used in aircraft, automobiles, corrugated board applications, and sound absorption materials. Baghei et al. [185] manufactured composites for automotive interior parts, furniture and indoor construction, sports, leisure equipment, and more.

Conclusion

The study concludes that biocomposite and ionic liquid manufacturing methods to fabricate TWC can reduce environmental issues while ensuring raw material utilization. Moreover, rather than only landfill or incineration, it may be inferred that the existing recycling options can contribute to reducing environmental repercussions if implemented.

Biocomposites have multiple benefits, such as low abrasive, fewer health hazards, lightweight, moderate mechanical properties, and soil contamination prevention. These materials are used in various value-added goods, including sound absorption materials, thin film composites, electromagnetic interference (EMI) shielding, particleboard industries, building materials, and furniture. Some partially biodegradable composites with natural reinforcing agents can be easily converted to biocomposites, which is a unique feature of biocomposites. One significant drawback is that this procedure only utilizes textile waste from natural fibers. If the waste contains blended fibers (natural and synthetic), this approach is ineffective, making it only suited for a fraction of the waste.

The unique feature of ionic liquids is their ability to dissolve a particular fiber from a multi-fiber mixture, which solves one of the most challenging problems in the textile industry: fiber separation. Natural and synthetic fibers from cotton/polyester and wool/polyester blends can be dissolved by ILs. Ionic liquids have a wide range of applications, covering nanocomposites, polymerization media, thermoset and thermoplastic, and polymer matrices. ILs could be employed in aircraft, automobiles, corrugated board applications, sound absorption materials, furniture, indoor construction, sports and leisure equipment, and other applications. Although ILs can dissolve a broad array of waste fibers, more research is needed for frequent industrial practices.

There are two critical problems with recycling composites: whether the method is environmentally friendly and whether the recovered fibers have the desired market value. The answers for both of them are yes. According to the findings of this study, recycling not only retrieves resources but also has a favorable impact on climate change, ecological quality, and human health. Additionally, recycled fibers are highly valued in the aircraft and automobile industries. Recently, recycled materials have been seen in renowned automotive industries such as BMW and Toyota. Mechanical recycling, pyrolysis, fluidized bed recycling, and chemical recycling are all discussed in this review. Pyrolysis and chemical recycling ensures high mechanical property retention, which mechanical recycling cannot achieve. Material recovery from resin is achievable by mechanical, pyrolysis, and chemical methods, with the latter two having the most potential for recovery. However, unlike the other three methods, the fluidized bed approach cannot recover components from resin.

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