Hindawi
International Journal of Polymer Science
Volume 2023, Article ID 5872605, 21 pages
https://doi.org/10.1155/2023/5872605

Review Article

Circularity in Materials: A Review on Polymer Composites Made from Agriculture and Textile Waste

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Received 3 April 2023; Revised 12 September 2023; Accepted 13 September 2023; Published 26 September 2023

Academic Editor: Peng He

Agriculture and textiles have the highest production yields among all sectors to meet mankind's basic needs, i.e., feeding and clothing; however, they are top contributors to environmental pollution and global waste generation. Their wastes and byproducts are precious organic materials, they have great potential as raw materials for the manufacturing of valuable products. This review sheds light on various textile and agricultural wastes, waste management issues, and their existing utilization. Current waste processing methods are mostly based on waste-to-energy routes or material reclamation; however, both methods are hazardous for the environment and are inefficient. During the past decade, many researchers have utilized agriculture and textile wastes in the fabrication of composites. Textile and agricultural wastes and byproducts can be efficiently used for composite fabrication and can be suitable alternatives to existing raw materials. Using textiles and agricultural wastes for composite manufacturing can not only address waste management issues and replace non-eco-friendly materials in the composite industry but also significantly improve composite properties.

1. Introduction

At the turn of the previous century, the world witnessed a massive growth in population, vast human capabilities to manufacture and produce commodities on a gigantic scale, and economic and technological developments. Despite these advancements having improved purchasing power and improved living standards and well-being of people, along with monetary costs, there are costs in terms of depleting resources and adverse effects on the ecosystem. Furthermore, improvements in the living standards of the modern world gave rise to throwaway culture [1]. This throwaway culture promoted a linear model of the economy that dominated the globe until mankind realized that this would not work for long [2]. On one hand, natural resources are depleting at a faster pace than ever seen before; on the other hand, the mass production of goods and waste generated by production, consumption, and their end-of-life waste generation also irreversibly impact the environment in multiple ways. For instance, petroleum is a widely used resource for energy generation and raw material acquisition for various industries; its reserves are depleting at a fast pace. The materials that we can manufacture today using fossil fuel resources may not be available after a few decades due to rapidly depleting petroleum reserves [3]. Advancement in industrial production and engineering practices may have many benefits, but with increasing production, industrial waste generation also increases [4]. The waste produced globally has adverse impacts on the environment; according to UNEP, waste generation is roughly around 11.2 billion tons annually. Ineffective disposal of wastes causes contamination of drinking water that leads to various infections and diseases whereas debris pollution adversely impacts the ecosystem [5–13].

Agricultural and industrial activities contaminate the environment in all possible ways including the emission of harmful gases, contaminating water resources, and producing enormous solid waste. Agriculture activities produce approximately 24% whereas industries produce 21% of all greenhouse gases emitted due to human activities [14, 15]. The greenhouse gases only produced by agriculture and food systems are roughly 16.5 billion tons annually [16]. Although agriculture advancements and scale have enabled us to feed a huge population, the agriculture sector has one of the highest carbon footprints. Similarly, the textile industry is the 2nd largest sector; on the one hand, it meets the needs of clothing (basic need to live) for billions of people while on the other hand is also the 2nd largest waste-producing sector globally [17–19]. Textile processes have become extraordinarily efficient in the past few decades in terms of production, but the scale of pollution caused by production, transportation, consumption, and disposal of textiles has adverse impacts on the environment, water, and soil [20].

Waste management has evolved to become a global issue, and mismanagement of waste is causing problems related to environmental contamination, economic sustainability, and social inclusion [21]. Agriculture and textiles are among the major waste producers in today's world. By 2050, the world's population is expected to reach 10 billion; the food and clothing production will increase significantly, thereby increasing the overall waste generated [22]. All these produced wastes are abundant if mismanaged and very dangerous to human health and the ecosystem, and these wastes lead to contamination of soil, water, and the atmosphere. These wastes on the one hand include biodegradable ingredients whereas some are not biodegradable [23].

The mass scale of wastes produced as byproducts of agriculture is often discarded or incinerated [24]. Discarding agricultural waste in open grounds poses enormous challenges in solid waste administration whereas incineration is hazardous to the natural atmosphere of the planet; meanwhile, using these both ways, we keep on losing precious organic byproducts that could have served as raw material for many value-added applications [25]. Agriculture and textile waste and byproducts if consumed efficiently and completely would not only provide inexpensive raw materials but can also help conserve the environment and natural resources [26]. In the past few years, changing environment, global warming, and climate change along with increasing solid waste management problems have brought the huge interest of researchers, industrialists, and governments in exploring green methods of manufacturing, conservation of resources, protection of the environment, efficient utilization of wastes and byproducts, and circular end of life of products.

One efficient method of utilization of agriculture and textile wastes and byproducts is their incorporation into composite materials [27–31]. Composite materials are made up of two constituents' reinforcement and matrix [32]. Collectively, the materials in composites are constituted in such a manner that the weaknesses of one material can be covered by the strengths of the other material. Reinforcement is usually responsible for load bearing whereas matrix provides load distribution and environment protective properties to the composite. Their combination can provides properties better than their counterparts individually. Additional properties can also be integrated with the addition of fillers and functional materials [33]. In recent years, several academics have examined the use of byproducts and waste materials for composite fabrication. This review paper sheds light on recent trends in the use of textile and agricultural wastes for composite fabrication, their properties, and their applications.

2. Global Environmental Impact of Waste

Due to climate change and increasing concerns and awareness regarding the environment and sustainability, the problems related to managing solid waste are pain points of modern society [34]. The most rapid way to get rid of textile waste is by incineration, but it produces toxic gases including carbon dioxide, polycyclic aromatic hydrocarbons, and benzene derivatives [35]. Another method of waste management is dumping into the ground called landfills. Economic development causes the generation of waste which increases with time and the depletion of natural resources. As a result, ecological degradation and pollution are becoming the main problem around the globe [36].

Cotton is a common example of both agriculture and textile, grown and harvested in the agriculture sector and used as raw material for the production of apparel in the textile industry. Cotton cultivation impacts the environment in many ways including but not limited to the use of land, huge water consumption, pesticides, and emission of greenhouse gases. Cultivation of only one kilogram of cotton uses 140 megajoules of energy and produces 5.3 kg of carbon dioxide [37]. According to an estimate just to produce a pair of jeans, 3781 liters of water is consumed [37]. Even though the production of textiles harms the environment, their end of life impacts the environment more adversely. For example, the landfills of textile waste pose issues like long decomposition time, contamination of groundwater, and pollutant emission in the surrounding soil, releasing carbon dioxide and methane gases [34] whereas incarceration directly emits harmful greenhouse gases. Therefore, the best way to deal with waste is neither dumping nor burning.

To date, municipal solid waste management seems more effective and practical through waste-to-energy routes (it can be thermal, biological, or chemical) than conventional municipal solid waste management techniques [38, 39]. The composition, accumulation, and generation of municipal solid waste vary by geographical areas and socioeconomic factors, especially in developing countries. But the major problem with waste-to-energy route is its adverse effects on the environment as using waste for energy involves either burning and releasing harmful gases in the atmosphere or through biodegradability that can contaminate soil and water resources if improperly managed. Therefore, the linear system of the economy is hazardous to the environment and unsustainable. A new approach to the circular economy is required to keep the materials in a close loop [40].

3. Legislation Related to Waste Materials

Waste generation is expected to reach 3.8 billion tons globally by the year 2050; without proper regulations in place, no nation seems to prosper [41]. Although waste management policies in the developing world may present a blurry view, developed countries have explicit and strict waste management compliance systems. For example, the European Union has enacted legislation to address the generation and management of wastes in an ecofriendly manner formally prescribed under various directives at various times; these directives are related to packaging and packaging waste, landfill waste, incineration waste, integrated pollution, end-of-life vehicles, and electrical and electronic wastes. Moreover, Japan also has strict legislations and set up various directives at various times including waste management and public cleaning, containers and packaging recycling, construction material recycling, effective resource utilization, home appliances and utensil recycling, food recycling, and promoting green [42]. The United States Environmental Protection Agency (USEPA) has also established waste regulation directives including hazardous waste management, recycling, atomic energy, clean air, chemical safety, marine protection, oil pollution, pollution prevention, and toxic substances [43]. The regularization of waste management policies is becoming mature and strict especially for organic wastes; for example, in 2016, the European Union's legislation regulated landfilling of organic materials as illegal and almost all textile materials are organic [35].

Textile and agricultural byproducts and wastes are becoming the topmost priority of many governments due to their contribution to total waste generated globally, but still, a lot is required to efficiently tackle these wastes. For example, in 2020, textile waste produced in the UK was approximated to be 1.7 million tons, and the US produced 15.1 million tons whereas China produced 26 million tons [37]. Even developed countries like Denmark and Germany recycle only 20% of produced textile waste whereas China only recycles below 10% of its textile waste [37]. From 2006 to 2008, the techniques of the utilization of agricultural waste have evolved from transforming into animal feed to obtaining biofuels and bioenergy. It requires a lot of technological involvement in this new for a low-carbon economy to achieve sustainable development goals SDG (2015). Global research networks are involved in this new model of bioeconomy development techniques. China has had the strongest contribution to agricultural waste research in the last 13 years and developed strategies related to biotechnology in the economy. The new Agenda 2030 for SDG 2015 and the millennium development goals (MDGs 2010) show that governments are focusing on the low-carbon production and reuse of agricultural residues [44].

4. Energy and Resource Utilization and Waste Generation from Textile and Agriculture Overview

The textile industry accounts for 10% of all greenhouse gas emissions and consumes more energy than the shipping and aviation industries collectively; furthermore, 20% of the global wastewater is solely generated by the textile industry [45]. Even after all these burdens on the ecosystem, all textile raw materials or even finished products are not completely consumed; if consumed, they are rapidly discarded, and ultimately, every year, textile sector produces more than 92 million tons of solid waste globally [46]. Similarly, the agriculture sector produces 24% of all greenhouse gas emissions produced due to human activities, whereas agriculture and food activities also consume 30% of the energy produced globally despite all these resource utilizations' agriculture and food systems generate 5 billion megagrams of waste [47]. A common example of both agriculture and textile sectors collectively can be seen in the production of a pair of jeans. Fabrication of a pair of jeans requires one kilogram of cotton fiber, and cultivation of this much cotton fiber requires ten thousand liters of water. According to an estimate, this ten thousand liters of water is enough for 10 years for one person to drink. The pressure of textile production on the environment is further superimposed again because eighty-five percent of all textile products ever made are dumped into landfills or incinerated within a short period. Textile waste can be a precious raw material as it can be reused to manufacture alike products [45].

5. Textile Waste

According to an estimate, every year, the textile industry produces approximately a hundred million tons of waste along with the consumption of eighty trillion liters of water. Despite addressed hazards and publicized environmental impacts, the textile industry continues to flourish. Fast and rapid changes in fashion trends, nondurable and cheap garments, and frequent use of textiles in our daily lives make textiles one of the major polluters of the natural environment [46]. Textile waste administration is an emergent issue and needs immediate resolution [48]. The rapid increase in population and fast changes in fashion trends are the core reasons for the accelerating increase in textile waste generation every year [49]. Textile production has increased from 78 million tons to above 103 million tons only in the last decade [35].

Cotton is the most widely used natural fiber whereas polyester is the most widely used man-made fiber [50]. Firstly, cotton production requires a lot of water, pesticides, and fertilizer which is not good for the environment [34]. Synthetic fibers have grabbed a huge portion of raw material 63% for the production of textiles [34], and hence, proportional waste is generated, whereas cotton represents 24% of all textile waste [1, 37]. Annual denim jeans waste is approximately 2.16 million metric tons, most of which is dumped into landfills [51]. Although natural fibers are biodegradable, synthetic fibers mainly do not decompose naturally [49]. The scale of waste generation can be seen by taking silk as an example because silk is one of the costliest and most limited-produced fibers, but annually eleven million tons of silk waste is generated globally. Recently, industrial production of textiles has nearly doubled whereas textile product lifetime has been reduced by roughly forty percent, so

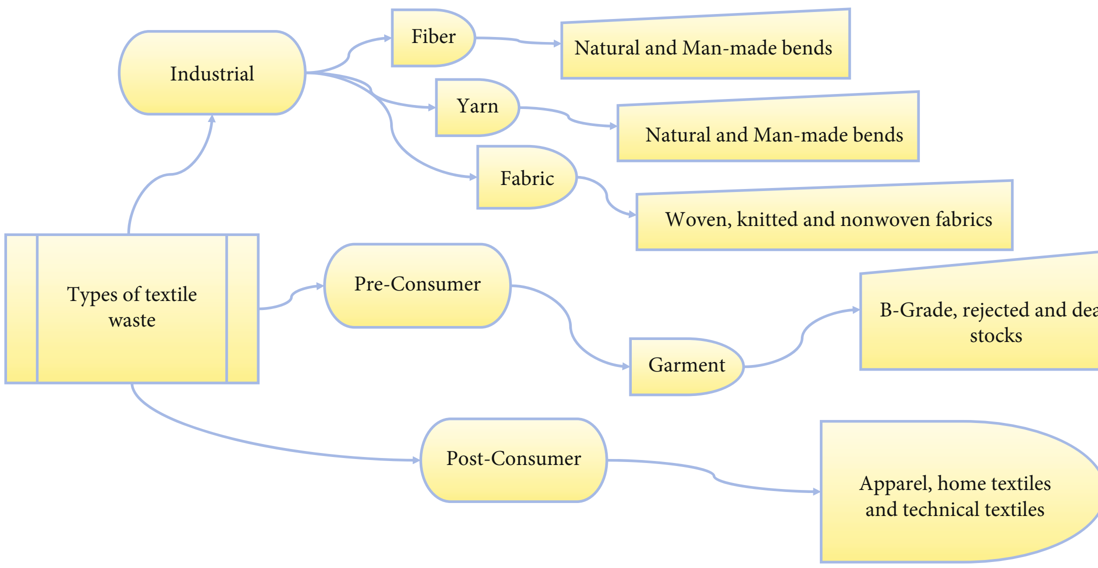

Figure 1: Types of textile waste.

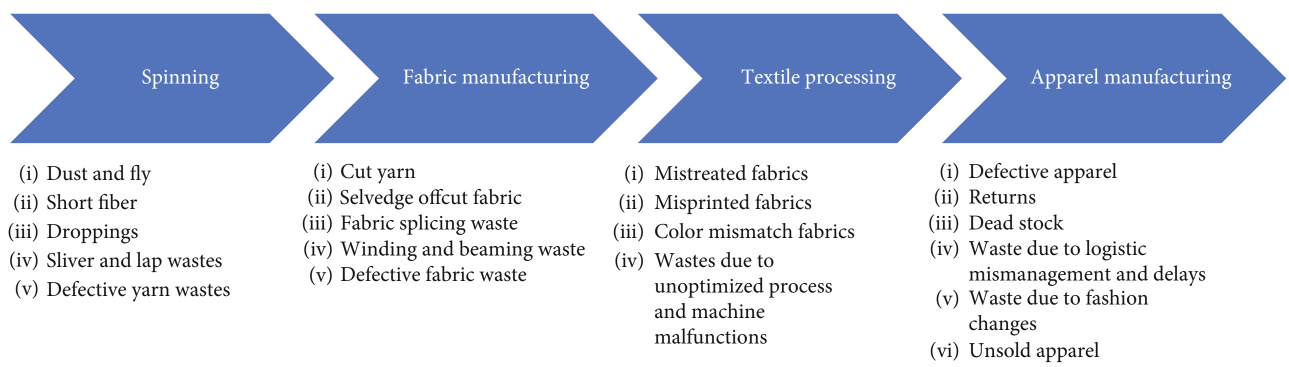

Figure 2: Textile preconsumer industrial wastes.

it would not be difficult to assume that the pace of textile waste production would also accelerate in coming years, so a proper policy needs to be in place before these textiles reach their end of life [52].

5.1. Types of Textile Wastes. The surge in the worldwide population is directly linked to textile production and textile waste generation [7]. Textile waste is broadly classified as industrial waste, preconsumer waste, and postconsumer waste as shown in Figure 1 [7].

6. Textile Industry and Preconsumer Waste

This category includes waste produced at each step during the fabrication of textiles. These processes encompass yarn manufacturing, fabric manufacturing, chemical processing, and garment manufacturing; the respective types of waste are summarized in Figure 2.

The wastes produced in Textile industry are broadly classified as soft waste and hard waste. Soft waste is in loose fiber form and is mostly consumed again by mixing with raw materials, whereas hard waste is not suitable for mixing again with raw materials. Therefore, hard waste is mostly incinerated or dumped into landfills.

6.1. Spinning. Some examples of hard wastes from the spinning industry are provided in Figure 3 [7]. Yarn spinning produces a lot of wastes in each process, but this waste becomes considerable when the combed yarn is produced [50]. The comber noil is considered waste that mainly consists of short fibers and is used for filling and stuffing applications [50]. A breakdown of waste generated in the spinning industry is given in Figure 3 [7, 53].

6.2. Fabric Manufacturing. Likewise, spinning enormous amounts of waste is also generated in fabric manufacturing industries. These wastes include woven fabrics, knitted fabrics, nonwoven fabrics, and yarns. Similarly, a lot of wastes are produced by faults in textile processing industries due to improper recipes and processes, and later on, huge waste is generated in the garment manufacturing industry during cutting as a byproduct and improper cut fabrics; additionally, the dead stock and rejected garments also account huge amounts of wastes generated.

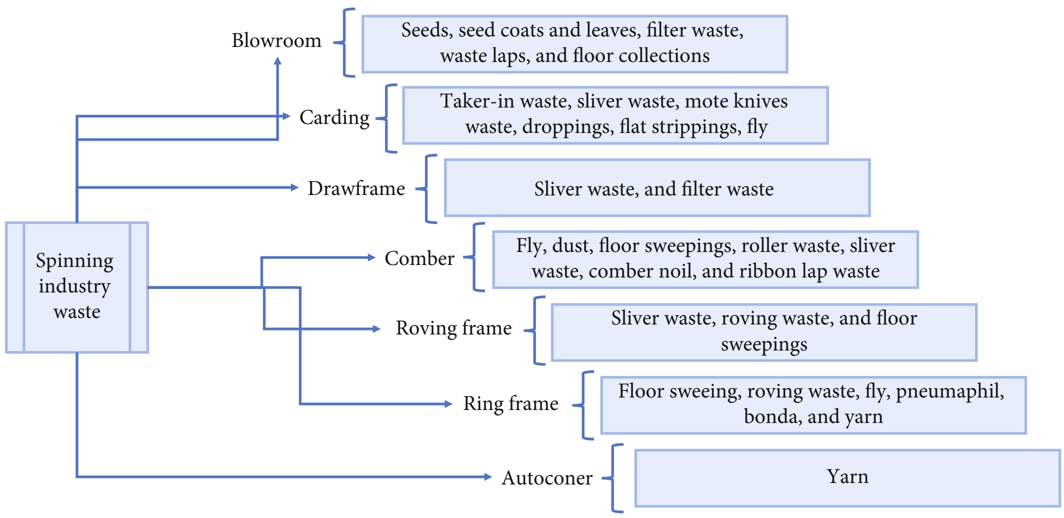

FIGURE 3: Types of hard wastes produced in the spinning industry.

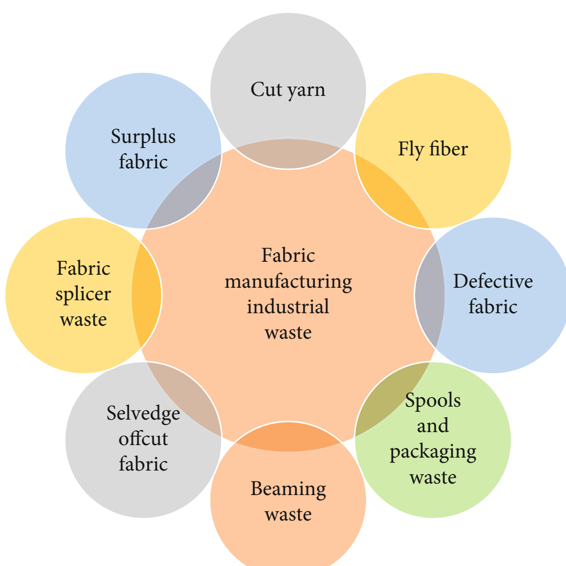

FIGURE 4: Fabric manufacturing industrial waste.

In the fabric manufacturing process, the main types of solid wastes produced are fiber fly, cut the yarn from winding process, surplus fabric, defective greige fabric, unfinished fabric, fabric splicer waste, selvage offcut fabric, beaming, excess fabric, and spools and packaging [54] as shown in Figure 4.

6.3. Textile Processing. Textile processing industrial waste is one of the most significant industrial wastes when it comes to wastewater contaminated with harmful chemicals and dyes generated, drained untreated, and mixed with natural water resources. In textile processing industries, solid textile waste is generated due to wrong or unoptimized processes, and its examples include rejected colored fabric and misprinted or degraded fabric as shown in Figure 5.

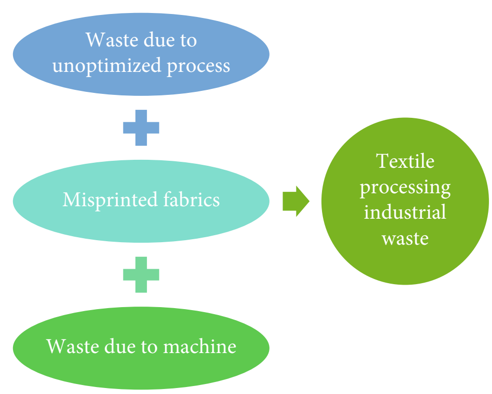

FIGURE 5: Textile processing industrial waste.

6.4. Apparel Manufacturing. Apparel waste is generated in two forms; one form arises in the industry that includes fabric cutting waste, roll ends, unfinished products in the garments manufacturing industry, and home textiles manufacturing industry, sample development waste, dead stock, B-grade, and rejected apparel whereas the latter is generated due to fast fashion changes, shipment mishandling unsold garments, returns, delays in logistics, and dead stocks in warehouses [54] as shown in Figure 6.

7. Postconsumer Textile Waste

Textile waste produced by end consumers that is usually comprised of discarded garments and home textiles is collectively included in postconsumer textile waste. The garment lifecycle is rapid; for example, the average life of apparel is only 3 to 3.5 years. Postconsumer textile waste makes up 22% of the global mixed waste generated; these huge amounts can be seen from the fact that advanced countries have a high waste generation of textiles; for example, textile waste per person annually in Australia is 27 kg, and in the

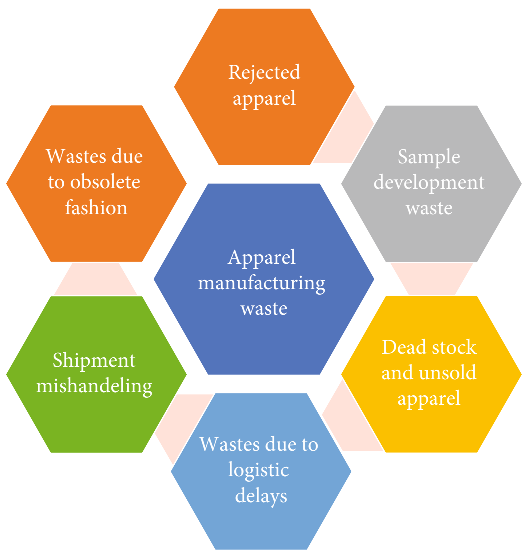

Figure 6: Preconsumer apparel wastes.

US and the UK, it is 30 kg, whereas in Finland, its 13 kg, and in Denmark, it is 16 kg [46].

Postconsumer waste management is limited due to the inability and absence of systems preplanned and redesigned for efficient identification and sorting of textiles after end-user abandonment. Organization of postconsumer waste is a complicated task mostly due to the heterogeneous nature of different types of waste. Sorting textile materials up for recycling is a complex and laborious task, and various methods have been devised including sorting according to the material as mentioned on the product label; this task is very hectic and insignificant as labels are worn out during the lifetime of the product and product information is not always accurate [55]. Another method devised is using Fourier transform infrared spectroscopy, but due to its complexity, this technique seems impracticable, at least by now [56]. Near-infrared spectroscopy can also be utilized to sort textile waste according to chemical composition. This technique has successfully demonstrated the ability to differentiate cellulosic, protein-based, and synthetic materials. The only problem faced using this method is materials made up of blended fibers [56, 57]. One possible solution to sorting could be the use of RFID tags or barcoded with preinstalled sorting information, and the only challenge with this technique is the durability of tags; harsh laundering conditions and number of laundering cycles during product use significantly damage these tags [58].

7.1. Technical Textile Waste. Waste generated massively by industrial applications including industrial ropes, conveyor belts, medical textiles, carpets, and technical textiles collectively accounts for a huge amount of waste. The special thing about this category is that they are produced in bulk, and like products usually have the same composition. Before recycling, they may or may not require sorting; in some cases, medical gowns can be collected once in huge amounts and may have the same composition. But on the other hand, they may be difficult to recycle in cases like fire retardant and high-strength apparel. Only medical textile waste is huge as millions of medical textile products are produced annually with a market size of 17.5 billion USD, and they exhibit the shortest life span; due to hygiene issues, almost all medical textiles are virtually disposable; if proper techniques of recycling along with disinfection are employed, medical textile waste could be recycled instead of direct incineration [59]. The market size of overall technical textiles is 175.73 billion; hence, they also exhibit a relative part in textile waste generation, and the real twist here is that technical textiles are designed for high-performance applications [60], so they are durable, but their high-performance constituents may pose difficulties in recycling; for example, Kevlar fiber is used in bulletproof vests and is chemically inert, so chemical recycling of Kevlar is not possible; moreover, Nomex being flame retardant can be very difficult to incinerate or recycle via the thermochemical method. Moreover, as technical textiles are designed for specific purposes sometimes, they end up discarded after performing their purpose, for example, cleaning cloth, wipes, diapers, sanitary napkins, agricultural nets, and many other similar applications, so there is an urgent requirement to design waste management strategy for technical textile specifically.

8. Agriculture Waste

As the population increases, to fulfill their needs, food production and agricultural waste generation are also increasing. According to an estimate, 5 billion megagrams of waste and byproducts is produced by the agriculture sector globally. This wastage comes from crop remains and agricultural industries, livestock, and fish farming. Approximately 5 billion tons of crop byproducts is generated annually, mainly comprising residues from crops like wheat, corn, sugarcane, and rice. These wastes are majorly composed of cellulose, lignin, and hemicellulose in various compositions depending upon the crop type [22]. Global warming is increasing due to the burning of agricultural waste and burying it in soil [61]. Moreover, the waste produced by forestry, animal farming, and fish farming is also significant. Agricultural waste is significantly produced in Asian countries where each country significantly contributes to overall waste, and this waste is mostly burned in open lands; for example, in India, 92 metric tons of crop residue is burned annually in the open that air pollutes the air directly. Asia produces 47% of crop residues, 29% are produced in America, 16% in the EU, 7% in Africa, and 1% in Oceania [47]. Agriculture waste has adverse impacts on society, the economy, and the environment [62].

8.1. Types of Agricultural Wastes. There are numerous kinds of agricultural wastes, and almost all of them contain cellulose; this cellulose is biodegradable. For example, bagasse fibers are one of the most abundant agriculture wastes and inherently antimicrobial, and when used with biodegradable resin, they are completely biodegradable [6]. Bagasse fiber and potato starch composites are known for their excellent mechanical properties and biodegradability [6].

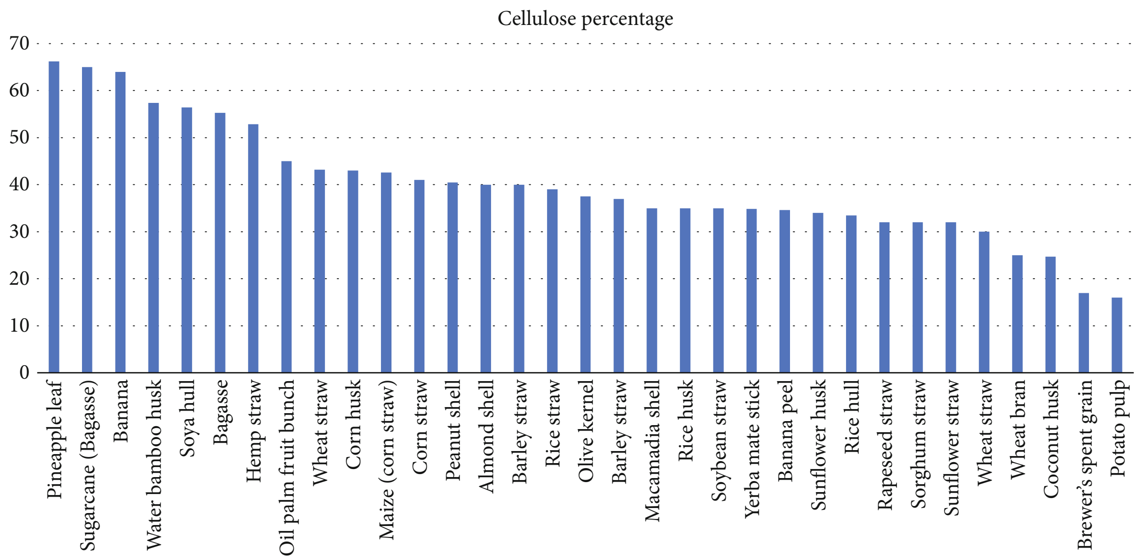

Figure 7: Cellulose composition agricultural wastes and byproducts.

Many crops produce byproducts that are primarily composed of cellulose; in Figure 7, few examples of these waste byproducts are given [3, 63].

9. Current Utilization of Waste

As textiles are mostly made up of more than one type of material like fiber blends, dyes, finishes, and auxiliaries, recycling them is a complex process. Textile waste after being collected should be sorted according to the nature of the material, i.e., to separate them according to biodegradable and nonbiodegradability; this task becomes more complex when textile products are composed of fiber blends from various origins. Cellulosic textile materials are biodegradable whereas textile materials of synthetic origin may not be biodegradable or may take a very long time to feasibly get degraded [52].

Recycling each kilogram of textile waste can save 6000 liters of water, 0.2 kg of insecticide, 0.3 kg of chemical fertilizer, and carbon dioxide emissions of roughly 3.6 kg [49]. The environmental impacts of cotton do not stop here as each processing step and logistics have its side effects on the environment [37]. Some current strategies to recycle cotton waste are opening and blending with raw material to produce yarn, manufacturing reinforcement for composite fabrication, synthesis of cellulose nanocrystals, regenerated cellulose fibers, materials for absorption and biofuels [37, 64].

It is generally preferred that textile waste should be organically recycled [52]. Current cotton recycling methods involve chemical, mechanical, and biological recycling. Although inefficient mechanical recycling is the most promising technique even if it produces low-value products with low dynamometric properties, textiles recycled via mechanical recycling cannot be recycled again. Chemical recycling uses different chemical processes to decompose but uses harsh treatments, provide low yield, and has huge costs. Biological recycling is mostly used for energy recovery by bacterial decomposition to produce biofuels that are of less value.

Various processes have been developed for recycling textiles like treatment with ionic liquids, decomposing via enzymes, and by the action of various dilute and concentrated acids [52]. Various textile waste recycling techniques work by biodegrading textile wastes using different routes; such techniques include biochar-assisted hydrolysis [65], hydrolysis using fungus-secreted enzymes [66], ethanol fermentation [67], composting [68], anaerobic digestion [69], and submerged fungus fermentation [70, 71].

Although complete recycling of apparel is a complex task even if textile material is recycled successfully, the properties of recycled textiles are inferior to virgin fibers making them unsuited for clothing purposes [37]. According to an estimate, around 73% of textile waste turns to landfills and incineration and 12% is recycled whereas only 1% is used to make new clothing [52]. Cotton dominates by around 90% in all cellulosic fibers consumed for textile production, but the molecular structure of cotton does not allow the high yields of biogas and enzymatically derived products by biodegradability [52]. So, a strong desire to upscale the recycling of textiles still exists [37]. Composites, owing to a wide range of applications, can completely incorporate textile waste as reinforcement without complex pretreatments and processes and with no discrimination of synthetic or organic origins and yet provide wonderful applications.

Agriculture byproducts are enriched with cellulosic components, and huge interest has been seen in exploring their utilization in value additions for energy applications including bioethanol, biodiesel, and biogas and manufacturing applications like biobricks, bioplastics, industrial enzymes, organic acids, biofertilizers, and biocoal [61].

Conversion of organic waste mostly consists of two major techniques broadly categorized into biological degradation and thermochemical techniques, whereas various

Table 1: Organic waste current utilization methods.

Method	Feedstock	Products
Anaerobic digestion	Food waste/agricultural waste	Biogas
Extraction	Food waste	Food additives, therapeutics Cosmetics
Fermentation	Food waste	Biofuels, organic Acids, enzymes Single-cell protein
	Agricultural waste	Biofuels, biogas Organic acids
	Textile waste	Biofuels Cellulose Succinate
Gasification	Food waste	Biofuels
	Agricultural waste	Gas, char
	Plastic waste	Biofuels
Hydrothermal carbonization	Municipal solid waste, agricultural waste	Hydrochar
Hydrothermal liquefaction	Agricultural waste	Biofuels
Pyrolysis	Food waste	Biofuels
	Agricultural waste	Biofuels
	Textile waste	Activated carbon, char, syngas, fiber, biooil
	Plastic waste	Pyrolysis oil, gas, char
Transesterification	Waste oil	Biodiesel
Torrefaction	Food waste/agricultural waste	Biocoal, gas
Pretreatment method	Feedstock	Yield impact on products
Alkaline treatment (using NaOH, CaO, KOH, $Ca(OH)_2$, etc.)	Agricultural waste	Glucan, cellulose, glucose, xylose, ethanol, methane, etc.
Acidic treatment (using H_2SO_4, HCl, HNO_3, H_3PO_4, acetic acid, maleic acid, etc.)	Agricultural waste	Glucose, monosaccharide, cellulose, ethanol, etc.
Ionic treatment	Agricultural crop waste	Glucan, sugar, cellulose, ethanol, etc.
Organosolv treatment	Agricultural crop waste	Lignin, glucose, sugar, cellulose, hemicellulose, methane, etc.
Ozonolysis	Agricultural crop waste	Methane, ethanol, glucose, xylose, hemicellulose, sugar, etc.

pretreatment methods can be used for the recovery of valuable products along with biofuels, and they significantly increase the product yields; these include physical, chemical, physiochemical, and biological methods. Physical methods of pretreatment are decisive but use huge energy input and are therefore cost-intensive. Chemical pretreatment methods are more industry-oriented, but the use of chemicals can further pollute the environment. Biological pretreatment methods are nontoxic and ecofriendly, use less energy but require more processing time, and have higher costs than other pretreatment methods [72]. A few examples of biological and thermochemical conversion techniques along with their inputs and outputs [73] and chemical pretreatment methods [72] are listed in Table 1.

10. Composite Materials

Composites are materials made up of two or more constituents at a macro scale. Composites are comprised of matrix and reinforcement. Reinforcement provides strength to the composite whereas the matrix binds together and protects the reinforcement from the environment. One or both constituents of composites can be thermosets and thermoplastic. Thermoset materials offer superior dynamometric properties than thermoplastics, therefore widely used in many applications [49], but the challenge with thermosets is that once cured, they require a huge amount of energy and resources to get recycled; therefore, thermoplastics even though provide lower mechanical properties are of huge interest.

10.1. Composites Developed from Waste Materials and Their Potential Applications

10.1.1. Composites Made Using Reinforcement of Waste Material. Various forms of waste materials have been utilized by researchers in various composites, and both agriculture and textile wastes have been utilized in many studies as reinforcement in composites. Many textile and agricultural wastes due to their high strength have great potential to be used in composites.

Most researchers have focused on using industrial (preconsumer) waste for composite fabrication. For instance, Salleh et al. fabricated composite from blow room waste and comber noil with polyester resin, and they found that both blow room waste and comber noil-reinforced polyester composites had better flexural and tensile strengths. They found comber noil better performer in the composite than blowroom waste [50]. Kamble et al. studied epoxy-reinforced nanocomposites with shoddy (i.e., fibers obtained from waste cotton fabric) in 0.1 to 0.4 VF and graphene oxide, and they registered as fiber volume fraction is increased and storage modulus also increases, while the flexural modulus increased for GO up to 0.5% and then decreased. The developed composites were recommended for furniture and automobile applications [40]. In another study, Özkan Buzğan et al. investigated the thermal insulation and mechanical aspects of composites made by using spinning industry air conditioner dust. This dust is collected in air conditioner filters and mainly consists of short fibers, leaf particles, cotton bolls, and other small particles. For composite manufacturing, polyurethane 0% rigid foam was used reinforced with 10, 25, and 40% with air conditioning waste. These particles acted as varied nucleation locations due to which the particle size of rigid foam declined increasing cell quantity. Dust agglomeration caused irregular cell formation, thus affecting mechanical properties. The volume expansion decreased with an increase in dust particles, thus reducing expansion and volume. Thermal insulation properties deteriorated relative to plain PU. This study concluded that using air conditioning waste deteriorated the properties of polyurethane [4]. Similarly, Möhl et al. studied composites made up of polylactic acid (PLA) and PLA Ingeo™ yarn as a matrix and reinforced it with cotton and flax fiber waste from the spinning industry. They blended all materials to produce hybrid yarn and later on unidirectional fabric. The fabric was melted at 180°C for 2 hours to produce composite sheets. The developed composites were subjected to tensile and flexural tests. Cotton-reinforced composite provided a tensile modulus of 9.95 GPa whereas flax-reinforced composites showed a tensile modulus of 12.14 GPa, and the flexural modulus of cotton-reinforced composite was found to be 6.9 GPa and 9.87 GPa for flex-reinforced composite. The developed composites were suitable for lightweight construction applications [34]. Fajrin et al. developed composites from kenaf fiber industrial waste and tested their tensile strength and flexural strength. Fibers were treated with 2% sodium hydroxide for 12 hours, later on, neutralized with acetic acid, and washed. The vacuum bad molding technique was used to develop polyester-reinforced composites using unidirectional, longitudinal, and woven reinforcements. They found that unidirectional composite had the highest tensile and flexural strengths, i.e., 76.5 MPa and 151.3 MPa, respectively. The developed composites were recommended for civil engineering applications [74]. Apart from manufacturing composites for load-bearing applications, a few researchers also utilized preconsumer waste to fabricate functional composites. Vu et al. developed composite aerogels using leaf fibers extracted from pineapple and waste cotton fibers after the carding process. They prepared reinforcement by milling the pineapple fibers to make 100 micrometers of fine particulates. The pineapple particulates and cotton waste fibers were mixed in ratios, i.e., 1 : 1, 1 : 2, and 1 : 4, then dispersed into sodium hydroxide and urea aqueous solution, and then frozen at 0°C for 15 minutes. After 24 hours at 0°C, it was defrosted; then, later on by creating hydrogen bonds between fibers, it was heated at 60°C with ethanol and washed to remove excess chemicals. The slurry was then frozen for four hours at -50°C temperature and freeze-dried for fifty hours. The aerogel composites were made from this mixture by chemical vapor deposition using methyltrimethoxysilane. The developed composites have high porosity, low density, and compressive modulus up to 203 kPa. The composites demonstrated an absorption capacity of 16 times their weight whereas the composite with the highest cotton fiber content showed better adsorption. The developed composite was found promising for removing organic pollutants in water [75]. Gedif and Atalie prepared a composite using waste cotton fabric and unsaturated polyester. The garment industry waste was collected and cut into small pieces ranging from 10 mm to 20 mm and used as reinforcement from 10% to 40%. The pieces were later impregnated with resin and cured under a weight of 120 kg for 24 hours at room temperature. The developed composites presented 198 MPa tensile strength and 30.1 MPa flexural strength at 33% loading. 40% fiber-reinforced composite shows better impact strength, i.e., 40.31 J/cm^2. The developed composites were thus recommended for ceiling panels [76]. Su et al. manufactured composite via pultrusion molding using waste polyethylene and polyester fibers. Polyethylene was reinforced with 5% to 25% polyester waste fibers. It was noted that 20% polyester-reinforced composite provided maximum tensile strength. The developed composites demonstrated low interfacial adhesion between these two constituents [77].

Some researchers used postconsumer waste to fabricate composites; for instance, Juciene et al. developed a panel using waste denim with ecofriendly resin, i.e., cornstarch. Developed composites were assessed for acoustic properties using meteorological testing equipment and mechanical properties. Waste denim was used in two forms, i.e., yarns extracted from denim and denim cuts. The recommended applications for the developed composite included acoustic panels in building applications [48]. Masood et al. studied the relative impact of using waste along with virgin fibers; for their study, they prepared composites from textile waste cotton and jute fibers and virgin glass fibers in various ratios. They found that the mechanical properties of composite decrease if one kind of waste fiber is used in the composite as compared to glass fiber composites, but when used in blended forms, the properties were comparable [78]. In another study, Wang et al. developed a 3D needled composite from denim fabric waste and polypropylene fibers. For this study, they extracted fibers from denim waste, blended these waste fibers with polypropylene fibers, and produced webs; the web was bonded through three-dimensional needle punching at 373 needles/cm^2 and compression molding at a temperature range from 180°C to 220°C for 3 min to 9 min, and fiber weight fraction percentage was 50% to 70%. Samples were subjected to bending strength and sheer strength tests. The resulting composites offered a strong interface. Resulting composites were recommended for furniture and architecture applications [73]. Zeeshan et al. prepared composites using waste cotton, glass, and flax fibers. For this purpose, they used waste cotton yarn only in the weft direction, and tests were later performed in this direction only. The flax and waste cotton reinforcements were used in 100/0, 90/10, 80/20, 65/35, 50/50, and 0/100 ratios. The glass, flax, and cotton reinforcements were used in 80/10/10, 65/25/10, and 50/40/10 ratios. They found that as waste cotton content increases in composite, the mechanical properties get reduced whereas the addition of flax improved composite mechanical properties. Moreover, moisture absorption and coefficient increased with an increase in waste cotton. They concluded that using waste cotton impacts mechanical properties but can reduce costs if incorporated in composites [79]. Haque and Naebe manufactured biodegradable composites from waste denim and cornstarch. Denim waste was cut into snippets of 0.2 mm, 1.0 mm, and 4 mm and used as reinforcement of cornstarch keeping a fiber matrix ratio of 1 : 1. They found that 0.2 mm snippets gave better tensile strength and interfacial binding. The developed composites were recommended for single-use packaging applications [51]. Some researchers have developed composites from waste along with virgin materials to investigate and compare their relative effects. For example, Khan et al. used waste fibers to prepare concrete composites. For this study, they used glass, polyester, and polypropylene wastes and prepared fiber-reinforced concrete composites. They reported that glass fiber has more significance on compressive and flexural strengths followed by polypropylene and polyester fibers. In the case of impact strength, polyester had better results than polypropylene [80]. Mostly postconsumer waste consists of two or more types of fibers. One major problem is faced when materials from natural and synthetic origins are mixed in waste, and this imposes huge difficulties for the separation and manufacturing of new products. Recycling this type of waste into textiles is very challenging, but when used in composites, they may have the potential to be used without further processing. In their study, Dong et al. fabricated composite aerogel using cotton and polyester waste fibers and PVA and glutaraldehyde as a crosslinker. Textile fibers were modified via chemical vapor deposition using methyltrimethoxysilane. The developed composites had low density, high absorption, and insulation properties [35]. Similarly, Baccouch et al. developed composites from epoxy reinforced with recycled cotton polyester and PC-blended nonwoven recycled waste. Nonwoven fabrics were infused with resin via vacuum and cured at 20°C at room temperature. The resulting cotton non-woven-reinforced composite showed 38 MPa/gcm^3 specific tensile strength, and composites had lower sound absorption than reinforcements whereas the thermal behavior of epoxy remained unchanged. The developed composites were suited for building construction and automobile applications [49]. Umar et al. prepared composites using preconsumer textile waste. For reinforcement development, they used comber noil from the yarn manufacturing industry and prepared twill fabric from these waste fibers. Later on, they manufactured composites from these fabrics and unsaturated polyester resin. The fiber volume fraction was kept constant at 30%, and a total of 8 layers of fabric was used in various stacking sequences. Composites were cured at room temperature and postcured at 120°C for 3 hours. The prepared composites were compared to glass fiber-reinforced unsaturated polyester composites. They reported that the impact strength of cotton waste-reinforced composites was comparable to glass fiber-reinforced composites whereas tensile and flexural strengths were low. They concluded that although strengths were relatively low but were comparable, the waste reduced composite cost by up to 20%; therefore, they could be an alternate material to glass for composite fabrication [81]. Karahan et al. compared composites made by various researchers from textile waste individually and in blended forms and blends of cotton, jute, and glass fibers. They reported that composites developed from individual waste fibers had lower mechanical performance than virgin fibers, whereas the fibers used in various blend ratios had better properties that were comparable to composites developed using virgin materials. They emphasized that although the incorporation of waste reduces the mechanical properties of composites but this waste can still be used in composites instead of being dumped in landfills or incineration [82].

Fibers can be extracted from various parts of the plant including seed, fruit, leaf, and bast whereas grass, wood, and other wastes from agriculture can also be used to produce fibers; fibers extracted using these methods are sustainable and can be circular [83]. Using agricultural byproducts in the form of ash has been reported by many researchers in recent years. In this method, agricultural waste is converted into ash by some burning or through thermal methods. This technique may provide some advantages as the fiber or waste product becomes ready in one single step, i.e., burn or decompose, converting to ash eliminating various preparation, washing, and cleaning requirements, and they might provide some good mechanical aspects. However, burning itself is not an organic solution and may cause harmful impacts on the environment. For example, Madhu et al. studied sugarcane bagasse ash filler-reinforced glass fiber and epoxy for their dynamometric properties. As sugarcane bagasse is highly produced as a byproduct of sugarcane processing, according to an estimate every year, around 223 million tons of sugarcane bagasse is produced. In this study, they used three filler ratios for composite fabrication 0%, 5%, and 10% and kept the glass fiber ratio fixed at 40%. They tested the developed composites for flexural, tensile, and compressive strengths. The study concluded that the 5%

use of bagasse ash filler increased the tensile and compressive strengths by up to 11% and 4%, respectively, whereas flexural strength was enhanced by 59% when 10% bagasse filler was incorporated. This study was conducted without using any dispersing agent; moreover, the chemical bonding between filler and resin was not studied. The limiting values of filler percentage could have been improved if more filler percentage could have been used with proper dispersion and chemical bonding study [6]. Zhang et al. prepared biochar-reinforced HDPE composites. For biochar, they conducted rice husk pyrolysis at 600°C in a nitrogen atmosphere for 2 hours after that particles were filtered keeping the particle size only at 150 micrometers. For composite manufacturing, biochar and HDPE were mixed at high speed for 10 minutes followed by extrusion via a micro twin screw extruder at 180°C. The biochar ratio was increased from 0% to 70%, and samples were studied for tensile strength, flexural strength, creep resistance, storage modulus, and antistress relaxation tests. This study demonstrated the incorporation of huge amounts of biochar, meanwhile improving tensile and flexural properties at 50 to 60 percent biochar loadings while improving the thermal stability and the limiting oxygen index of the composites [84]. Barczewski et al. prepared a sunflower husk-reinforced composite with ultra-low-density polyethylene. The sunflower husk was prepared by milling and treating it with (3-aminopropyl)-triethoxysilane for 24 hours at 80°C; the composite was then prepared by mixing at 3000 rpm and extrusion at 180°C keeping a filler ratio of 5%, 10%, and 15%. It was found that filler addition improved stiffens, elastic modulus, and tensile strength. The prepared composites were recommended for mechanical vibration damping and impact resistance [85]. During linseed oil production, linseed cake is obtained as a byproduct. Barczewski et al. prepared a linseed cake-reinforced HDPE composite and studied its thermomechanical properties. The linseed filler ratio was kept at 5%, 10%, 20%, and 30%. It was noticed that the addition of linseed filler reduced the dynamometric properties, reduced melting point, and improved crystallinity. It was examined that linseed filler inherently contains high amounts of crude oil that could alter the chemical composition of resin, and the lack of interfacial adhesion could have caused lower mechanical performance; these composites were more suited for low-strength composites [86].

Awais et al. prepared reinforcement for composite from banana tree agricultural waste. For this purpose, they used waste stems that are known as agricultural waste from banana harvesting, crushed them, and extracted fibers that were later combed, washed, and dried. For composite fabrication, the banana and jute fibers were wet-laid and dried to form a web. Various blends of jute and banana fibers were impregnated with unsaturated polyester resin and cured at room temperature and later postcured for 2 hours at 120°C to form respective composites. They found that the properties of banana fiber-reinforced composites were lower than jute-reinforced composites but were comparable to such an extent that banana fiber can be a possible alternative to jute as reinforcement in composites [87]. Shaker et al. used Argyreia speciosa plant waste to develop composites. This plant is an agricultural byproduct and is mostly landfilled or burnt. The fibers were extracted from this plant via water retting, treated with an alkaline solution at 90°C for 30 minutes, and converted to fine particles via ball milling. To prepare composites, this fine powder was blended with waste jute fibers extracted from waste packaging. It was found that using alkali-treated, fine powder as filler increased tensile strength by 30%, flexural strength by 18%, tensile modulus by 34%, and flexural modulus by 33%. They concluded that agricultural waste could enhance the mechanical properties of composites [88].

Kellersztein et al. prepared wheat straw fiber-reinforced polypropylene composites. The fibers were prepared by the steam explosion at 220°C and silane surface modification, and it is established that steam explosion can remove natural impurities like lignin oil, fats, and waxes. Another benefit of the steam explosion is defibrillation and delignification of fibers whereas silane treatment reduces hydrogen bonding in between fibers so the fibers can bind to resin chemically. Composites were prepared via compounder extruder at 190°C keeping the fiber volume ratio 20%. The resulting composites had improved impact and tensile strengths up to around 50%, higher heat deflection, and higher stiffness and toughness, and these composites have the potential for high-strength structural applications [89]. In another study, Suffo et al. created sugar beet waste-based thermoplastic matric for composite fabrication. They used LLDPE and Carbocal and blended them followed by melting in a process. The developed resin was used to manufacture glass-reinforced composite with 20%, 30%, 40%, and 50% fiber volume fractions. They concluded that an increase in carbonyl content improved composite strength, whereby at 50% content, Young's modulus increased by up to 175% [90]. Asrofi et al. prepared sugarcane bagasse fiber-reinforced tapioca starch composites. Sugarcane bagasse fiber was used as 1% of the starch dry weight, and fabrication was done by solution casting method under 0, 5, 10, and 15 minutes of ultrasonication. Ultrasonication improved the strength of the composites up to 2.5 MPa under 15 minutes of sonication at 40 kHz and 50°C temperature [91]. Bortolatto et al. prepared soybean hull-reinforced cornstarch and polyvinyl alcohol composites using extrusion molding. Five formulations of ground soybean hull were used ranging from 4% to 19%. It was observed that an 8% soybean hull increased the tensile strength up to 20% in comparison to plain plastic [92].

10.1.2. Composites Made Using Matrix from Waste Material. Many studies in the literature have focused on the use of thermoplastic waste materials as a matrix for composite fabrication. For instance, Singh et al. studied composite material made up of waste plastic material with various reinforcements including bast fiber, date palm leaf fiber, wood flour, and bamboo fiber. The developed composites significantly improved the mechanical properties of composites [93]. Shaker et al. prepared composites from preconsumer and postconsumer denim waste. For this purpose, preindustrial denim waste was collected from the garment industry and used as reinforcement of polythene and postconsumer polycarbonate waste keeping fiber column fraction from 30% to 65%. They found that polycarbonate performed as a better matrix material than polyethylene in terms of tensile, flexural, and impact strengths. They found the developed composites suitable for interior building furnishing and automotive interior applications [94]. The waste polyethylene bags, polypropylene bags, and polyester fabric waste can be potential wastes to derive a matrix for composite fabrication. Fernandes et al. formulated epoxy resin using waste vegetable oil and developed glass fiber and flax fiber-reinforced composites. Waste vegetable oil was first filtered and diluted in a saturated solution of NaCl at 60°C; mixture was extracted and dried with MgSO, purified via activated carbon in HNO_3 solution, and later epoxidized with m-chloroperbenzoic acid and used with Super Sap CLR. Flax fibers and glass fibers were used in a ratio of 1 : 2 as reinforcement. The consequent composites had better impact properties, low weight, and better thermal stability. These composites are best suited for stiff, tough, and lightweight structures [95, 96]. Nukala et al. developed a composite matrix from plastic waste and reinforced it with recycled wood. For composite fabrication, they used a mixture of low-density and high-density polyethylene, cleaned it with 20% NaOH, and later treated it with 10 M HCl, washed it with distilled water, and oven dried for 24 hours at 60°C. Wood particulates were used in concentrations of 10%, 20%, 30%, and 40%. Extrusion molding was used for composite fabrication at 155°C. The composites were tested for thermal and mechanical properties. It was found that an increase in recycled wood waste demonstrated tensile strength up to 34.30 MPa and hardness up to 19.72 HV. The developed composites were found suitable for railing, decking, and fencing applications [97]. Pan et al. developed thermoplastic composites using waste carpets for mechanical and acoustical properties. They used compression molding to develop composites from polypropylene/nylon and polypropylene and polyester carpet waste. The composites developed from polypropylene/nylon provided 45% higher sound insulation, 37% higher flexural strength, 9% better impact strength, and 10% more water stability [98]. In another study, Pan et al. developed composites using nylon 1 and nylon 6,6 carpet waste. They used the compression molding method, and the results depicted that using compression molding instead of extrusion for these composite fabrications helped achieve 124% more flexural strength, 59% greater elastic modulus, 32% greater impact strength, and 40% greater sound absorption [99]. Zhao et al. developed composites from polypropylene carpet waste and jute/polypropylene using the compression molding method. The composites developed from PP/carpet waste had 58.3% greater sound absorption, 20% higher elastic modulus, 20% greater impact strength, 14% more flexural strength, and 14.5% greater water stability in comparison to jute/polypropylene composites [100]. Lazorenko et al. prepared geopolymer composites using waste polyethylene terephthalate reinforced with fly ash. The matrix was extracted from waste plastic bottles and converted to various shapes including ground particles, flakes, and strips. It was observed that ground particles had the best flexural strength of all compositions used and were close to the plain sample, whereas tensile and compressive strengths were reduced due to poor interfacial interaction [101]. Zou et al. developed composites from cotton/polyester-blended fabric using compression molding with and without additional polyester matrix. The cotton/polyester composites without additional matrix material provided 153% greater elastic modulus, 36% greater Young's modulus, and 36% higher impact strength but at a cost of 44% less tensile strength and 36% lower flexural strength as compared to composite with additional polyester matrix *tensile strength and hardness of composites* [102]. Soni et al. prepared rice husk ash and silica sand-reinforced waste high-density and low-density polyethylene thermoplastic composite. Rice husk ash was incorporated in 10%, 20%, and 30% by weight of the composite. Composites were prepared by static compression molding under 20.7 MPa pressure. The resulting composites provided up to 26.39 MPa compressive strength, 4.9 MPa flexural strength, and 3.25 MPa tensile strength. The resulting composites were found suitable for floor tile fabrication [103]. Soni et al. developed silica sand-reinforced waste plastic composites. For the matrix, high-density and low-density polyethylene and polyethylene terephthalate were used, whereas silica sand was used as reinforcement in ratios of 30% and 50% by weight. The mixed plastic waste was shredded into 15 mm pieces and later mixed homogeneously with silica sand under elevated temperature. Compression molding was used for composite fabrication under pressure of 20.7 MPa. The developed composites were tested for compressive and flexural strengths, water absorption, and siding wear. The developed composites demonstrated 46.2 N/mm^2 compressive strength and 4.24 N/mm^2 flexural strength. Minimum water absorption was 0.039%, and the minimum sliding wear rate was0.143×10^{-8} kg/m. The developed composites were found suitable for floor tiles fabrication [104]. Huang et al. prepared wood laminate sanding dust-reinforced waste polypropylene composites. Wood dust was used in a ratio of 60% by weight of the composite. The developed composites had a tensile strength of up to 42 MPa, impact strength of up to 6 kJ/m^2, and flexural strength of up to 46 MPa [105]. Mohan et al. prepared sand-reinforced matrix derived from medical industry waste. They prepared the matrix using personal protective equipment kits commonly found in hospital waste. The waste PPE kits were collected, washed, dried, and stored for 28 days before further processing, later, shredded, mixed with sand from 66% to 86%, and heated at 180°C under the pressure of a hydraulic press. The developed composites had a maximum tensile strength of 4.2 MPa and a compressive strength of 35 MPa. The developed composites were found suitable for construction purposes [106].

The summary of composites developed using waste materials along with their potential effect on composite properties is given in Table 2.

11. Recyclability of Composites Made from Waste

Due to the diverse and heterogeneous nature of composites, recycling them is complex; based on composition, some

Table 2: Composites developed from waste and the impact of using waste materials.

Composite type	Waste reinforcement	Waste matrix	Comments about performance	Reference
Cotton/polyester	Yes	No	(i) Comber noil provided better mechanical strength	[50]
Shoddy/epoxy	Yes	No	(i) Better storage modulus	[40]
Yarn manufacturing AC dust/polyurethane	Yes	No	(i) Thermal properties deteriorated	[4]
Cotton, flax/PLA	Yes	No	(i) Good mechanical properties (ii) Suitable for lightweight applications	[34]
Kenaf/polyester	Yes	No	(i) Unidirectional reinforcement performed best. Suitable for civil engineering applications	[74]
Denim fabric/UP	Yes	No	(i) Good mechanical properties	[76]
Polyester/polyethylene	Yes	Yes	(i) Low interfacial adhesion	[77]
Denim cuts/cornstarch	Yes	No	(i) Can be used as acoustic panels	[48]
Denim/polypropylene	Yes	Yes	(i) Recommended for furniture and architecture applications	[23]
Demin/cornstarch	Yes	No	(i) Better tensile strength and interfacial binding (ii) Recommended for single-use packaging applications	[51]
Glass fiber, polyester fiber, and polypropylene fiber/concrete	Yes	No	(i) Glass fibers provided the highest compressive and flexural strengths (ii) Polyester provided the highest impact strength	[80]
Cotton-polyester/PVA	Yes	No	(i) Low density (ii) High water absorption (iii) Better insulation properties	[35]
Cotton-polyester/epoxy	Yes	No	(i) Suited for building construction and automobile applications	[49]
Cotton (comber noil)/UP	Yes	No	(i) The impact strength of cotton waste-reinforced composites was comparable to glass fiber-reinforced composites (ii) Overall tensile and flexural strengths were low	[81]
Biochar/HDPE	Yes	No	(i) High loadings improved tensile and flexural properties at 50 to 60 percent biochar loadings (ii) The thermal stability and the limiting oxygen index were improved	[84]
Sunflower husk/ULDP	Yes	No	(i) Improved stiffens, elastic modulus, and tensile strength (ii) Recommended for mechanical vibration damping and impact resistance	[85]
Linseed cake/HDPE	Yes	No	(i) Lower mechanical performance due to a lack of interfacial adhesion	[86]
Banana fiber, jute/UP	Yes	No	(i) The mechanical properties of banana fiber composites were lower than jute-reinforced composites but were comparable	[87]
Argyreia speciosa fiber powder	Yes	No	(i) Only alkali-treated, fine powder as filler increased tensile strength by 30%, flexural strength by 18%, tensile modulus by 34%, and flexural modulus by 33%	[88]
Wheat straw/propylene	Yes	No	(i) Improved impact and tensile strength up to 50%, higher heat deflection, and higher stiffness and toughness (ii) Potential for high-strength structural applications	[89]
Sugar beet/LDPE	Yes	No	(i) Using carbonyl additive improved composite strength at 50% content Young's modulus increased by up to 175%	[90]
Sugarcane bagasse/tapioca starch	Yes	No	(i) The strength improved up to 2.5 MPa under 15 minutes of sonication at 40 kHz and 50°C temperature	[91]
Soybean hull/cornstarch	Yes	No	(i) 8% soybean hull increased the tensile strength up to 20% in comparison to plain plastic	[92]

Table 2: Continued.

Composite type	Waste reinforcement	Waste matrix	Comments about performance	Reference
Denim fabric/polycarbonate	Yes	Yes	(i) Polycarbonate performed as a better matrix than polyethylene in terms of tensile, flexural, and impact strengths	[94]
Glass fiber and flax fiber/waste vegetable oil-derived resin	No	Yes	(i) Better impact properties (ii) Low weight (iii) Better thermal stability	[96]
Wood particulates/HDPE, LDPE	Yes	Yes	(i) An increase in recycled wood waste demonstrated tensile strength up to 34.30 MPa and hardness up to 19.72 HV	[97]
Fly ash/PET	Yes	Yes	(i) Ground particles had the best flexural strength (ii) Tensile and compressive strengths were reduced due to poor interfacial interaction	[101]
Rice husk, silica sand/HDPE, LDPE	Yes	Yes	(i) The resulting composites provided up to 26.39 MPa compressive strength, 4.9 MPa flexural strength, and 3.25 MPa tensile strength (ii) The resulting composites were found suitable for floor tile fabrication	[103]
Silica sand/HDPE, LDPE	No	Yes	(i) Composites demonstrated 46.2 N/mm^2 compressive strength and 4.24 N/mm^2 flexural strength (ii) Minimum water absorption was 0.039%, and the minimum sliding wear rate was 0.143×10^{-8} kg/m (iii) These composites were found suitable for floor tile fabrication	[104]
Wood laminate sanding dust/polypropylene	Yes	Yes	(i) Tensile strength up to 42 MPa, impact strength up to 6 kJ/m^2, and flexural strength up to 46 MPa were achieved	[105]
Sand/polypropylene	No	Yes	(i) A tensile strength of 4.2 MPa and compressive strength of 35 MPa were achieved	[106]
Pineapple particulates/methyltrimethoxysilane	Yes	No	(i) These composites absorbed water 16 times its weight (ii) Suitable for removing organic pollutants in water	[75]

composites may be recycled while others may not be recyclable at all.

Composites are manufactured using both thermoplastic and thermoset polymers. Thermoplastic polymers can be molded in molten form, whereas thermoset polymers are used as resin and curing agents. This resin and curing agent form irreversible crosslinks at curing temperature that sets the polymer in solid form; this crosslinking turns resin into an infusible and insoluble form. Although thermoset polymers are renowned for their mechanical properties, this irreversible bonding makes it very difficult to recycle them. Contrary to thermoset polymers, thermoplastics offer the best possibilities to recover polymer from composite by mere heat application. Although thermoplastic polymers offer far lower properties than thermosets but due to their recyclability prospects, they are becoming widely interesting for many composite manufacturers and academicians [107]. A broad classification of thermoset composite recycling comes under three classes: chemical, mechanical, and thermal recycling methods. Some methods of composite recycling are mentioned in Figure 8 [108].

Recycling thermoset composites is completely possible if the biodegradable matrix is used for manufacturing them. Another prospect lies in the synthesis of matrix material that can trigger debonding without utilizing a lot of energy [109]. Recyclable thermoplastic polymers are subdivided into three categories, i.e., crystalline, semicrystalline, and amorphous. These polymers depict performance in accordance with their structure, and they are categorized similarly. As far as thermoplastic composites are concerned, they can be relatively easily separated from reinforcement and recycled by the application of chemical, thermal, and mechanical methods. Conclusively, it is widely accepted that polymers lose their performance properties after recycling, but some additional remedies can help in countering this loss in properties [107].

12. Challenges Associated with Using Textile and Agriculture Wastes in Composites

A huge research literature is available dedicated to composites developed from textile and agricultural wastes; in most cases, composites also present a straightforward solution by utilizing wastes without intensive processing and without distinction between sorted and unsorted wastes. Utilization of these wastes in composite also presents various issues and potential challenges. Most of these issues are related to mass production, the robustness of the process, process limitations, environmental impact end-of-life circularity of developed composites, etc.

Many researchers have used postindustrial waste (PIW) in composites, but it is not recommended as postindustrial waste predominately consists of material with known

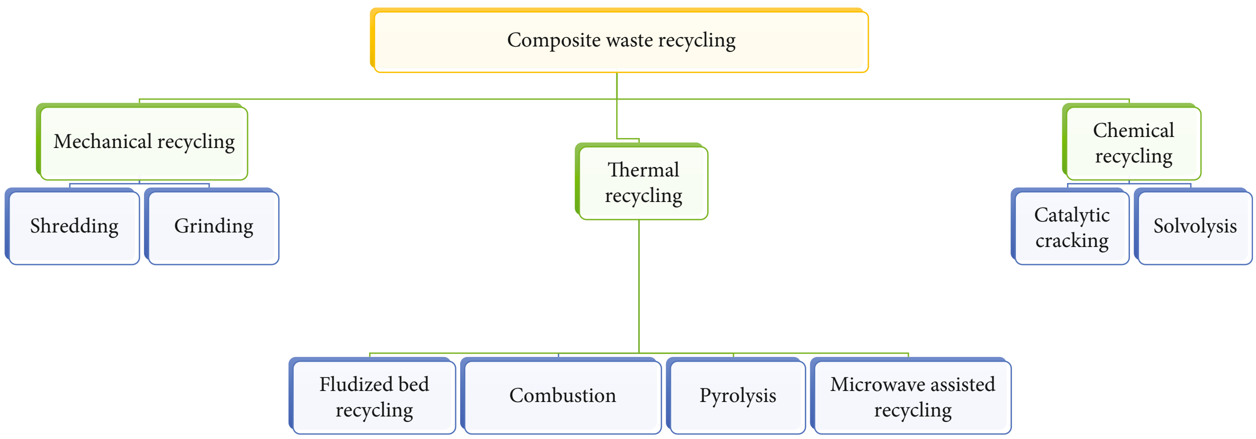

Figure 8: Composite recycling techniques.

composition. Post-industrial waste can be processed directly by mixing with virgin raw material in case of soft waste or can be processed to reclaim fibers in case of hard waste. So, it is more fruitful to use PIW in the same stream to get maximum benefits from the fibers as use them to produce like materials. One such example is a composite made by Salleh et al. where they used blow room waste and comber noil for its preparation [50]. Utilization of post-consumer textile waste (PCW) into composites is a very interesting field subjected to mass disposal of clothing around the globe. Using PCW in composites is beneficial in multiple ways, post-consumer waste mostly consists of fibers from different origins, and intensive sorting is required; sorting itself is a very demanding process and may not be always feasible due to worn-out labels after the end of life of textiles. The best significance of utilizing PCW in composites is that composites can incorporate multimaterial postconsumer waste without necessarily sorting them. A lot of studies have been carried out for manufacturing composites using fabric pieces cut from PCW without focusing on composition, and these composites in many cases have shown promising mechanical aspects too. The inbuilt problems associated with these composites are scaling to mass production and their recyclability after completion of their service life. The fabric pieces cut from PCW may not be the same size, so they cannot be used to produce the same composites with the same composition and internal structure every time. Also, these cut pieces may not be suitable to produce large composite parts. Such composites were prepared by Juciene et al. [48] and Haque and Naebe [51] where they used denim fabric cut pieces from PWC for composite preparation.

Some researchers developed nano and hybrid composites from waste material by integrating nanoscale materials to enhance properties. Although they may be successful in enhancing the mechanical aspects of composites, integrating nanoscale materials itself can increase the number of materials required for composite preparation. This can cause a diversion from circularity and can hinder the recycling process. Such composite was prepared by Kamble et al. by integrating graphene oxide particles [40]. The same is valid for using various kinds of fibers; although it can be a very good utilization when they are used as reinforcement, in many cases, using multiple types of waste fibers can enhance mechanical properties, but they bring multimateriality into composites. Such composites may encounter issues when they are recycled after they reach their end of life. This may impose diversion from a circularity perspective and thus should be avoided, and incorporation of multiple wastes into composites should only be carried out when there is no other route available for the waste to be reprocessed or upscaled. Such an example of composites can be seen in a study conducted by Masood et al. in which they used cotton and jute textile wastes in combination with glass fibers [78].

Using dead waste in composites is a very good opportunity to bring the material back in a circular loop. Dead waste can be in the form of fibers with very short lengths that may not be suitable for utilization in the same process. It may seem to be a very good idea instantly, but utilizing dead waste in composite can be problematic as the control of dead waste during preparation of composites can be challenging and a very optimized strategy should be followed. Even if composites are successfully developed using dead waste, the robustness of the process and the consistency of manufacturing can be daunting. Özkan Buzğan et al. prepared composites using air conditioner dust that consisted of short fibers, leaf particles, cotton boll pieces, etc. They faced the issues with control of material during composite fabrication [4]. Another study of dead waste was conducted by Barczewski et al. in which they prepared composite from linseed cake (a byproduct from the linseed oil extraction process) but could not achieve good mechanical properties [86].

Many examples of incorporation of agriculture waste are present in literature where researchers have crushed waste materials into small particles or fibers; many such studies show promising results in enhancing composites of composites, but new techniques should be formulated that can help in the maximum retention of properties of reinforcement. Such composites were prepared by Shaker et al. using the Argyreia speciosa plant by extracting fibers followed by a ball milling process to crush fibers that were later used as reinforcement. Such utilization may cause a decrease in the properties of composites and therefore should be avoided

[88]. Another method of incorporation of both textile and agriculture wastes is by converting waste into ash by using high-temperature degradation. A lot of literature is available on this technique. This technique has widely been used in many studies and successfully incorporates multimaterials into composites both from textile and agriculture origins without distinction between any origins of waste. The first problem associated with this method is that the burning of waste is not environmentally friendly, and implementing this technique on a mass scale can produce huge amounts of greenhouse gases. Further, the degradation of waste by high temperature or by burning reduces its mechanical properties; therefore, it is not recommended when opportunities to upscale this waste are available. Such examples include composites developed by Madhu et al. by using sugarcane bagasse ash with glass fibers as reinforcement [6], and another study by Zhang et al. was conducted using biochar as reinforcement [84]. These studies, although show promising properties in developed composites, may be included in downcycling and non-eco-friendly, and therefore, manufacturing such composites on a mass scale should be avoided. The matrix material plays a crucial role in composite circular end of life. Two kinds of matrices can be used to prepare composites, i.e., thermoplastic and thermoset matrices.

Huge literature exists on composites developed from waste materials as reinforcement; many of these studies claim to have developed circular composites too, but in fact, when a material is incorporated into a thermoset resin, it becomes very difficult to upcycle it to a new composite without crushing it into a fine powder. Even if the matrix is incinerated or degraded by using chemicals to reclaim reinforcement parts, that is not an ecofriendly process. Thermoplastic composites on the other hand are easily recyclable, but they may not provide enough mechanical aspects to composites as their thermoset counterparts. The composites provide a very good opportunity for utilizing waste materials from both textile and agriculture origins, but there are still various issues related to manufacturing processes, scaling, product features and properties, end-of-life circularity, and environment safety that need to be addressed.

13. Significance of Textile and Agriculture Waste Recycling

The waste generated and global environmental footprint by the agriculture and textile sectors are enormous, but as these two sectors meet the basic needs of humans to live, therefore, their importance in meeting these needs is inevitable. Despite tremendous advancements in production and management, the waste generated by these sectors is unavoidable, and therefore, strategies of waste collection, utilization, recycling, and bringing it into a close loop of mankind's significance should be studied and incorporated at each step of waste generation. Waste recycling offers tremendous benefits in various ways; for example, waste recycling can provide cheap or zero-cost raw material availability and help save the environment from contamination that would otherwise have been caused by the manufacturing of new goods including greenhouse gas emissions and reduction of a further generation of waste during manufacturing of raw materials that could be made possibly from recycled waste [110, 111]. Furthermore, recycling makes the process and products sustainable, and recycled materials are renewable if recycled again and again [112]. Now with the advancements in geological mapping, we also know that most fossil fuel reserves are depleting at a fast pace and the materials available today for manufacturing goods may not be available fifty years from now, so these recycled materials can help people tomorrow to fulfill their needs. Another great challenge faced today is climate change, deforestation, and shortage of land for agriculture. All these issues can never be met until or unless all the materials acquired from Mother Nature are utilized to the fullest possible span without wasting any bit of it, all this is impossible without recycling of materials again and again into the loop of circularity [113, 114]. The linear model and throwaway culture are not sustainable, and circulating these materials in a closed loop is an urgent need of time; moreover, governments and the UN are working together to incorporate recycled materials in all products manufactured [115]. It should be noted that governments alone can never meet these standards alone, and the private sector should come forward to cope hands with governments and invest in end-of-life circularity businesses.

14. Prospects in the Field of Polymer Composites Made Up of Textile and Agriculture Wastes

Textile and agriculture sectors produce enormous waste; these wastes can be upcycled by utilizing them in composites as reinforcement and matrices. A vast literature provides evidence that utilizing these waste materials in composites can enhance composites' properties. This waste can be used separately as well as in combination. Despite the huge number of studies conducted on the properties of various wastes, various potential gaps still exist that need to be further studied and explored. Combining textile and agriculture wastes can promote a significant perspective for interfield researchers to collaborate and share a common perspective to conduct future research on textile and agriculture waste utilization into valuable composite products. The development of composites from textile and agriculture waste would be a gigantic milestone towards a circular economy. It will help in reducing pressure on the consumption of nonrenewable resources and deforestation and help in solid waste management.

Numerous gaps still exist in designing processes for the successful incorporation of these wastes into composites such that the properties of waste materials are utilized to the maximum extent possible.

Although lab scale demonstration shows promising prospects of composites with enhanced properties when utilizing these waste materials, but still a lot of research is still required to implement this on a mass scale, and further research is required to enhance reproducibility, robustness of processes, and consistent composite properties. Further, a lot of research is required to design circular end-of-life composites that can be recycled, repurposed, and reused. The researchers also can play a vital role in developing marketable products from recycled textile and agriculture wastes, studying and developing sustainable processes of waste collection, transportation, sorting, grading, and product development. As evident from the literature, composites have the potential to incorporate all sorts of waste materials from both sectors while successfully enhancing mechanical properties. Industries should focus more on using recycled waste materials rather than costly virgin materials, and this would be beneficial in saving raw material costs and increasing profits. Governments, policymakers, and environmental protection agencies should develop and implement legislation that promotes the use of these waste materials, beside policies. They should also facilitate and pave ways to help and guide private businesses in establishing supply chains among various parties involved. All these are only possible when governments, environmental agencies, researchers from all fields of science, and businesses cooperate and develop marketable circular products and relevant business models, so the precious organic waste from these two sectors does not go to waste in the future.

15. Conclusion

Landfills and incineration of both textile and agricultural wastes are harmful to the environment. Meanwhile, we also lose precious organic materials; therefore, landfills and incineration should be avoided. A vast literature comprising successful examples of composites prepared using textile and agricultural wastes with enhanced properties is available. Composites can be prepared from both of these wastes without significant preparatory processes and distinction of material types. These waste materials are available in huge amounts, and if used properly, they will be able to provide an endless supply of raw materials for many other value-added applications including composites. Circulating waste and byproducts from these sectors can significantly reduce the burden on the environment in multiple ways including reduction of pollution and conservation of natural resources. Various gaps for research still exist related to manufacturing processes, product development, scaling, exploring recyclable matrices, and ultimately developing composite products with the circular end of life. Various research and business opportunities revolve around the complete supply chain of these waste materials, composites, their applications, and the recycling of these composites.

Data Availability

The data can be provided on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work is funded under HEC's project GCF-63.

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