

Use of different kinds of waste in the construction of new polymer composites: review

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ABSTRACT

Waste valorization is one of the current research areas that has attracted a great deal of attention over the past few years as a potential alternative to the disposal of a wide range of residues in landfill sites. In particular, the development of environmentally friendly and innovative strategies to process several kinds of wastes is an area of increasing importance in our current society. Landfill, incineration, and composting are common, mature technologies for waste disposal. However, they are not satisfactory due to the generation of toxic methane gas and bad odors, high energy consumption, and slow reaction kinetics. The scope of this manuscript is to give a clear overview on the recent development of waste valorization strategies in polymeric matrices for the sustainable production of new polymer matrix composites. In other words, this work should be regarded as a review, providing guidelines for the sustainable development of various industries for the benefit of the society. In fact, the incorporation of waste and/or by-products into polymer composites may represent a new resource and a successful approach to materials suitable for specific applications that promote a circular economy approach. According to this study, there is a considerable amount of research on the application of solid wastes, in particular agricultural wastes, as fillers for thermoplastic and thermoset matrices to obtain composites suitable for application in components subjected to light to moderate loads. As a main drawback, surface pre-treatment is necessary in many cases to increase the adhesion between matrix and fillers and the final mechanical, thermal, and chemical properties of polymer composites.

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1. Introduction

In recent years, the increase of tighter regulations regarding waste and the demand for renewable chemicals and fuels are

pushing the manufacturing industry toward higher sustainability to improve cost-effectiveness and meet customers' demand.

The disposal of waste to landfills and the limited availability of natural resources lead to an increased interest in searching for innovative alternatives that can contribute to a circular economy.

According to International Solid Waste Association data, currently around 4 billion tons of waste are produced in the world every year, and this volume is expected to increase by the year 2025 [1]. Around half of these are municipal wastes, while the residue amount arises from industrial and production activities, with continued growth in both developed and developing countries due to population, living standard, and urbanization growth [2]. In particular, even if many kinds of waste are produced worldwide, special attention is paid to materials that are not biodegradable [3,4] or to residual that, even being biodegradable, are produced in great quantities and can cause high environmental impacts, including climate-harming emissions by illegal dumping, such as crop wastes, eggshells, crustacean shells, and others [5]. In this

Abbreviations: AD, anaerobic-digestion; AM, additive manufacturing; ATH, alumina trihydrate; CRT, cathode ray tube; DBTL, dibutyltin dilaurate; DCP, dicumylperoxide; FAO, Food and Agriculture Organization; FA, fly ash; GRT, ground tire rubber; HDPE, high density polyethylene; ISWA, International Solid Waste Association; LSF, Lagenaria siceraria fiber; MA, maleic-anhydride; MMA, Methyl methacrylate; PAA, polyacrylic acid; PAA-g-GRT, polyacrylic acid grafted ground rubber tire; PCMs, polymer matrix composites; PP, polypropylene; RIB, Mineral Insulation Boards; RS, rice straw; SBR, Styrene-Butadiene-Rubber; TCWS, transparent composites using wheat straw; UPR, unsaturated polyester resin; WEEE, waste of electrical and electronic equipment; WSF, wheat straw fibers; WTR, waste tire rubber; VOCs, volatile organic compounds; VTMO, vinyltrimethoxysilane.

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perspective, the productive use of wastes represents a possible way of reducing some of the problems associated with their management, reducing the use of natural resources and, in some cases, resulting in the production of environmentally friendly products. In this regard, several research groups are working on waste valorization, and one of the main used approaches is to recycle wastes, in particular solid waste, by mixing them with polymeric matrices to obtain new composite materials. Generally, polymer matrix composites (PMCs) are composed of various types of organic polymers mixed with different fillers with several size, size distributions, and composition to enhance several polymer properties. The polymer matrix generally used in the composite preparation and its main physical and mechanical properties are reported in Tables 1 and 2, for thermoplastic and thermoset matrixes, respectively [6–18].

Among the recycling technologies available to produce new PMCs with low environmental impact, the use of natural fillers from plants (jute, sisal, flax, ...) or non-biodegradable wastes have gained attention during the last decades. As discussed elsewhere [19], material preparation methods involve, in general, the crushing and milling of recycled fractions into smaller particles; further processing on recyclates depends on the type of material. A possible process for manufacturing composites containing waste is presented in Fig. 1.

It is important to stress that the main challenge for composite preparation by using both natural and non-biodegradable wastes is to investigate how properties of these materials can be influenced by the adhesion between fillers and matrix, by filler particle morphology and size, and by resin to filler compositional ratio [20]. The role of chemical waste treatment on composite properties was reviewed in detail in several publications [21,22]. In any case, the nature of each specific waste will have an impact on the final filler-matrix compatibility and, moreover, its chemical composition, as well as its purity can have a significant impact not only on the mechanical properties but also on the visual appearance (Fig. 2) of the product.

Several reviews have already illustrated the possible use of agricultural waste and the possible use of municipal solid waste in polymer matrix. However, several aspects are not well investigated: the effect, for each type of waste, of waste content and waste surface treatment on the composite properties, as well as the discussion on the eventual applications are inconsistent [23,24]. This paper comprehensively reviews the results obtained by various researchers on the properties of polymer composite materials (based on both thermoplastic and thermosetting resins) containing different types and percentages of biodegradable and non-biodegradable wastes. It provides a comprehensive overview of the fillers treatments to evaluate the inherent differences in compatibility and processing when using natural and non-biodegradable waste, with and without the aid of compatibilization pretreatments.

For these reasons, this review aims to provide a general overview and discussion of polymer composites obtained using different solid wastes, including their modifications, resultant properties, and applications.

Consequently, the present work conducted a systematic review of the literature on waste valorization in PMCs. First, an initial list of

publications was collected on various factors: relevance of the topic, type of waste, polymer matrix in which they were used, and data on filler treatments. Bibliographic databases, keywords, and the search strategy were identified. An initial assessment was necessary to determine which publications to consult, based on the quality of their information. For each publication collected, an analysis was carried out to establish the relevance of its contents to the survey, as well as the tests performed, main results, and conclusions. This allowed a comprehensive exploration of the existing information on several factors, and enabled several conclusions to be drawn regarding the use of solid waste in polymer matrices in PMCs production, the effect of possible waste treatments, and applications.

Therefore, this research is suitable for the academia and industry to gain insight into different wastes, which can potentially be used in the development of new waste-based composites, spreading the concept of sustainability and circular economy.

2. Solid waste

Waste generation has grown rapidly with the population growth. It has been estimated that global waste generation will nearly double by 2050. In this scenario, the world's solid waste accounts for 5% of the global carbon emissions, and its burning further increases this number. Solid wastes are all the wastes arising from human and animal activities that are normally solid and are discarded as useless. There are several different ways of classifying solid wastes. One way is to classify them according to where they are generated: industrial sources, agricultural sources, residential sources, electronic and electrical waste, etc. Another way is based on whether the waste is biodegradable or not. Biodegradable solid wastes are those that can be broken down into their constituent elements by bacteria and other micro-organisms. Non-biodegradable solid wastes are those that do not decompose by microbial action. These wastes include plastic containers, scrap metal, food and drink cans, plastic bags, etc.

The World Bank reported that high income countries, with a population of 16% of the planet's inhabitants, produce about 34% of the planet's waste [25]. The largest amount of wastes were found to be industrial (12.73 kg per capita), followed by agricultural waste (3.35 kg per capita) [25].

Thus, in addition to the industrial waste, a massive amount of agro-waste generated during manufacturing processes is commonly disposed to landfills, and its decomposition process takes a significant amount of time. In fact, referring exclusively to agro-industrial wastes included in the 'biomass' definition (European Directive 2009/28/EC), the production in Europe is almost 250 tons per year, of which 12 million tons in Italy alone. Only a small part is recovered, while the remaining quantity causes management problems: seasonal increase of organic material in separate collection, demand for new landfills, illegal dumping, microbiological instability, production of toxic compounds (land pollution), etc. In Table 3, the estimated global solid waste composition is reported [26]. Agricultural wastes such as husks, shells, powders, grape marcs, stalks, or other living organism shells can be defined as organic by-products. In Table 4, the major components of various

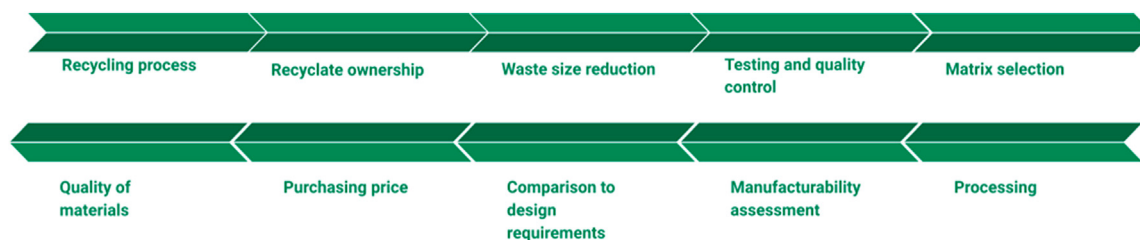
Table 1
Main physical and mechanical properties of thermoplastics matrixes [8,10,11,15].

Thermoplastics	Density (g/cm ³)	Tensile modulus (GPa)	Tensile strength (MPa)	Melting temperature (°C)
Polypropylene (PP)	0.90–0.91	1.1–1.6	20–40	175
Polyethylene (PE)	0.91–0.95	0.3–0.5	25–45	115
Polyvinyl chloride (PVC)	1.38	3.0	53	212
Polystyrene (PS)	1.04–1.05	2.5–3.5	35–60	240

Table 2

Main physical and mechanical properties of thermosets matrixes.

Thermosets	Density (g/cm ³)	Tensile modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)	Compression strength (MPa)
Polyester	1.0–1.5	2–5	40–90	1–3	90–250
Epoxy	1.1–1.6	3–6	28–100	1–6	100–200
Vinyl ester	1.2–1.4	3–4	69–86	4–7	86
Phenolic	1.29	3–5	35–62	1–2	210–360

**Fig. 1.** Manufacturing process of composites from waste fillers.**Fig. 2.** Extruded wood-plastic composites from recycled raw materials (LUT University and Linnaeus University).

lignocellulosic wastes are reported. The organic waste fillers are biodegradable, making them innocuous to the environment in contrast to industrial waste that are relatively more difficult to be biodegraded [27,28].

In this review paper, the possibility of reusing both agricultural and industrial wastes in polymer composite applications are discussed, taking into account their mechanical properties and environmental impact.

2.1. Agro-waste valorization

In the last 15 years, there has been a growing research interest in agricultural residues as alternative fillers for the manufacturing of composites due to not only the increasing environmental awareness but also to their specific properties and recyclability [33].

Natural filler composites are indicated for application in components subjected from light to moderate loadings. Typical applications include civil construction, furniture, packing, and mainly the automotive industry [34,35], where natural fillers were used in

association with both thermoplastic and thermoset matrix to substitute fillers or fiberglass composites [36,37]. In particular, the insertion of natural fillers in the industrial, building, and commercial market sectors has experienced a growth rate of 13% over the last 10 years, with an annual use of 275 million kilograms, approximately [38]. Due to their large availability throughout the world and low cost, sisal, flax, jute, coconut, and ramie are the most used reinforcing fillers. Other alternative fillers for the manufacturing of composites can be the agricultural residues such as wheat cereal straws [39], rice husk [40], bagasse [41], and kenaf [42], to mention a few examples. Jiwei Tong et al. [43], fabricated transparent composites for light-transmitting building applications using wheat straw fibers (WSFs) and agricultural residues produced in huge amounts around the world. In fact, *Triticum aestivum* (bread wheat) is a cereal crop with a cultivated area of 214 Mha, and a yield of 734 million tons (Food and Agriculture Organization, 2018) [44]. The obtained transparent composites were successfully prepared by impregnating pre-polymerized methyl methacrylate to WSF. The prepared bio-based composites had high light transmittance and mechanical properties similar to wood fiber transparent composites. The authors showed that the transparent composites using wheat straw, with a thickness of 3 mm and 30 wt% WSF, had a light transmittance of 74.63%, haze of 54.87%, tensile strength of 58.19 MPa, and impact strength of 4.26 kJ/m². Moreover, a thermal property test showed that the heat conductivity of transparent composites using wheat straw was 0.07 W/m/k, displaying excellent thermal insulation performance, excellent thermal dimensional stability, and UV resistance. These results showed the possibility to reuse WSFs to obtain new composites with potential application

Table 3

Estimated solid waste composition (projection for 2025) [1].

Waste composition	Quantity (%)
Organic	46
Paper	17
Plastic	10
Glass	5
Metal	4
Other	18

Table 4
Components of different lignocellulosic wastes.

Composition (%)	Rice husk [27]	Peanut hull [28]	Hazelnut husk [29]	Coconut shell [30]	Wheat straw fibers [31]	Grape stalks [32]
Wax	2	—	—	—	—	—
Lignin	37	28	35	32	25	17
Holocellulose	46	69	55	—	—	—
α cellulose	—	43	35	—	—	—
cellulose	—	—	—	31	39	30
Hemicellulose	14	—	—	31	24	21
Inorganics (ash)	—	—	8	—	—	—
Extractives	—	—	—	6	—	16

prospects in the field of transparent buildings. However, even if wheat straw has similar chemical constituents to wood (i.e., cellulose, hemicellulose, lignin, and extractives), the comparatively poor surface properties of wheat straw with hydrophobic components can reduce the interfacial bond quality between the substrate and polymer binder [45,46]. To overcome this problem, Mehdi Chougan et al. [47] used on wheat straw hot water, steam, and microwave to mitigate the surface quality deficiencies for an intimate interfacial bond between substrate and polylactic acid matrix. With this procedure, the tensile strength, elongation at break, elastic modulus, and toughness increased by 166%, 18%, 68%, and 285%, respectively, if compared to untreated wheat straw bio-based composites. Being one of the main problems in the use of agro-wastes, several treatment processes are performed to enhance the interfacial bond quality between fillers and polymer matrix. For example, rice straw (RS) is another type of agricultural waste that can be used as substitute of wood-based raw materials [48]. RS is less homogeneous than wood, and contains a relatively large amount of vessel elements (i.e., sclerenchyma fibers, epidermal cells, and parenchyma cells) as compared to the wood material [49], which may influence the interaction between the RS and polymer matrix. Jiun Hor Low et al. [49] explored the fabrication of pristine RS based high-density polyethylene (HDPE) bio-composites (without using any coupling agent) by using the injection molding technique. To investigate the effect of RS particle size on the bio-composites, the RS and HDPE (30:70 by weight) as well as the dispersing agent lubricant (Ultra-Plast TP01) and binding agent (Ultra-Plast TP10) were mixed in a high-speed mixer and then melt compounded using a co-rotating and intermeshing twin screw extruder at a temperature of 180–190 °C. Even if the fabricated bio-composites achieved the highest tensile strength at the particle size of 250–300 μ m, the incompatibility between the hydrophilic RS and hydrophobic polymer chain affects the final mechanical properties of the composites by proving that it is necessary to perform agro-waste treatment to improve the compatibility of lignocellulosic materials, in both the particle and fiber form, with synthetic resins. Then, to improve the surface interaction, Rahman et al. [50], reported the use of vinyltrimethoxysilane (VTMO) as coupling agent between RS and HDPE. In this work, vinyltrimethoxysilane as the crosslinking agent, dicumylperoxide as the initiator, dibutyltin dilaurate as the condensation catalyst were used. After drying at 70 °C for 24 h, RS, ground and sieved, was mixed with HDPE and then compounded with a co-rotating and intermeshing twin screw extruder. This formulation was designed and optimized to produce a new injection grade crosslinked RS/HDPE biocomposite. Resorcinol-hexamethylenetetramine mixture was employed as a chemical treatment for kenaf fiber waste to improve the interfacial adhesion between the kenaf fiber-polystyrene matrices, and to make the fiber more hydrophobic [51]. As well as in thermoplastic matrix composites, agro-waste fillers are often used for composites made from thermosetting resins [52]. In general, thermoset resins, unsaturated polyester resin (UPR), and epoxy resin are the most commonly used, with those

natural fillers, to produce low-strength materials. In particular, UPRs are the most common in preparing composites, comprising 80% excess of all thermoset resins [53]. Though they provide excellent properties such as chemical and weather resistance with relatively low cost, in general, the mechanical properties are inadequate for many structural purposes, without the addition of the appropriate fillers as load carrying constituents of composites. UPRs having good dimensional stability, easy manufacturing, and limited moisture absorption are the most commonly used resins with those natural fillers to produce low-strength materials. For example, Taurino et al. [54] investigated the possibility to use agro-residues of the vinification process as a cheaper and eco-friendly filler to prepare unsaturated polyester composites for the interior design building sector. Millions of tons of agro-waste are produced per year by the wine industry in many European countries, such as Italy, France, Spain, Germany, and Portugal. In fact, in Italy, the annual potential production of wine residues is about 0.5 T as dry matter, more than 60% deriving from grape marks and stalks. Indeed, winery waste can represent an alternative source for the production of composites for interior furniture. For example, in this work, unsaturated polyester-based resin composites, reinforced with grape stalks, were prepared by a simple casting technique. However, the main disadvantages of using such fillers in composites are their hygroscopicity and difficulty in achieving acceptable levels of dispersion in the polymer matrix. Uniformity of the filler/matrix surface has a major impact on the load carrying capacity, and thus on the properties of composites. Better results can be achieved using compatibilizers that reduce the tension between phases, or modifying the cellulose surface to obtain a less hydrophilic one [55]. For example, the addition of a silane coupling agent was necessary to increase the interface adhesion between resin (UPR) and grape stalks [54], resulting in good mechanical and physical properties of silanized composites that are satisfactory for the production of interior furniture composites. The combination of a thermal treatment and silanization was performed to increase the addition adhesion between UPRs and digestate residues from anaerobic digestion. In particular, another study [56] assessed the potential of using digestate residues from anaerobic digestion process of organic substrates as fillers for thermosetting matrix (UPR resin) to prepare a new solid surface material. Solid surface is a common term applied to a small range of materials, characterized by a distinctive appearance, with different chemical compositions or thicknesses, but sharing many functional similarities. Polymer resins used for producing solid surface materials are, in general, filled acrylic polymers, filled UPRs, and filled acrylic-polyester blend polymers. The composition of a typical solid surface component is characterized by 35% of thermoset resin and 65% of alumina trihydrate (ATH), by weight. In general, solid surface materials are applied to countertops, sinks, and shower floors [56]. To improve fillers surface adhesion, residual organic components of the digestate material were removed by thermal treatment (calcination at 550 °C), and additional silane treatment was carried out. Here, the tensile strength

and Young's Modulus decreased after the compatibilizer addition, and an increase in the percentage of elongation and energy at the maximum load was measured due to the formation of flexible polysiloxane (Si–O–Si) from self-condensation reaction of silane. In this case, thermoset resin was used as a matrix material, with the advantage to work with a very low viscosity material, which can be mixed with the agro-fillers at low pressures. In fact, thermosets can be processed by simple processing techniques such as hand lay-up and spraying, compression, resin transfer, injection, compression injection, and pressure bag molding operations. By K. John et al., no significant effect on the flexural properties has been observed by silane treatment, but a small increase in the mechanical properties has been observed by alkali treatment of sisal/glass hybrid composites [57].

Other thermosetting resins used as a hosting matrix for agro-residues are the epoxy resins. Epoxy resins are materials reserved for the manufacture of elements having to undergo high mechanical and thermal stresses, and are also considered as the most dominant matrix materials for lightweight polymer composites. Moreover, several studies showed that epoxy composites reinforced using kenaf, coir, coconut fiber, banana, sisal, jute, flax, and pineapple leaf have better mechanical properties, thus, making them attractive in low load carrying applications including furniture application. For instance, ternary composites of rice husks/glass fibre/epoxy composites with higher, hardness, Young's modulus, impact strength, and wear resistance than the glass fibre/epoxy were produced [58,59]. The epoxy composites of natural fillers of different materials are used for newer applications. By this way, the α -cellulosic micro fillers, which are isolated from *Cocos nucifera* var *Aurantiaca* Peduncle (CAP) through chemical treatment process, were systematically utilized by K.J. Nagarajan et al., as a reinforcing material in thermoset epoxy polymers and as a replacement of carbon, ceramic fillers, and wood derived products. The results on mechanical properties such as tensile, flexural, and impact test revealed that the properties of the α -cellulosic micro fillers—reinforced epoxy composites linearly increased from 3 to 15 wt% of the filler loading, and 15 wt% showed the superior behavior in terms of mechanical properties [60]. Since epoxy resins have excellent mechanical and chemical properties and dimensional stability, they are widely used in lamination to prepare composite panels. Composites laminated for broader applications, such as for the furniture industry, based on new agro-waste, alkali-treated, and untreated *Lagenaria siceraria* fiber were prepared [61]. The authors investigated the effect of four different fiber lengths of 3, 5, 7, and 9 mm with five different fiber contents of 15, 20, 25, 30, and 35 wt% on the composites mechanical strength. Compared to a neat epoxy resin, the mechanical properties are enhanced for increase in the fiber length up to 7 mm and 30 wt% of untreated and treated fiber; however, further increase of both fiber content and fiber length results in a decrease of the mechanical properties for both treated and untreated *Lagenaria siceraria* fiber-reinforced composites. In the study by Imana Taha et al. [62], tomato stalks-based panels have been prepared. In particular, they analyzed the effect of particle size and weight concentration on the mechanical and physical performance. The tensile strength and tensile modulus are relatively low if compared to flax and bagasse-based particleboards. The primary reason behind this decrease is the fair cellulose content compared to the other resources. In fact, cellulose is the main component providing strength, stiffness, and structural stability, while the low lignin percentage of tomato stalks facilitated the chopping process of stalks [63]. As suggested by Nemli G. et al. [64], chemical surface treatments such as the acetylation of fibers prior to their incorporation into the resin mix can improve bonding between hydrophobic matrix and hydrophilic fibers to meet the

minimum requirement specified by the European standard EN 312:2010 for particleboards.

Table 5 summarizes key information from the literature here commented and related to the use of agro-waste fillers in polymer composites.

To conclude, as discussed previously, the main disadvantage of using agro-waste in the composites is their hygroscopicity and difficulty in achieving acceptable levels of dispersion in the polymer matrix. Several approaches to improve the compatibility between resin and organic fillers are summarized in Fig. 3. Physical pretreatment method was mainly focused on the size reduction of biomass; therefore, fragmentation methods like cutting, shredding, grinding, and milling were employed [65,66]. Chemical pretreatment methods are based on chemical reactions taking place in aqueous solution between lignocellulosic biomass and various chemical compounds. Most common are the treatments with acid and alkaline solutions. The acid pretreatment aims at breaking up the lignin structure as well as dissolving hemicellulose and depolymerizing cellulose. It takes place at acid concentrations of 10–30%, elevated pressures and temperatures, and reaches hemicellulose degradation rates of up to 90% [67]. The alkaline pretreatment is based on the saponification process. The presence of ammonia, as well as sodium or calcium hydroxides [68], causes swelling of the biomass. Thereby, the reduction of cellulose crystallinity results in an increase in the specific surface. Then, several physicochemical pretreatment methods combining the usage of chemicals, with the application of physical forces, were used. For example, Liquid Hot Water, steam explosion, and supercritical water (simultaneous application of high temperature and pressure in aqueous solution) have been used. Lastly, microwave irradiation is a way of heating the biomass, resulting in the disruption of lignocellulosic structures [69].

2.2. Non-biodegradable wastes valorization

Non-biodegradable wastes, such as fly ash (FA), tire rubber, glass waste, and waste concrete, are other types of wastes commonly found in the environment and proposed as reinforcements or fillers for the preparation of polymer composites [70,71].

One of the main types is FA, a mineral by-product produced by combustion and constituted by metallic oxides, such as SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , K_2O , and many elements, such as Cr, Pb, Ba, Sr, S, and Zn. This material, annually produced in large quantities (about 750 million tons a year) [72], is dangerous and harmful to the environment and human health, but its compatible with other materials (e.g., polymeric ones). This means that the recovery of FA is an efficient way to prevent such danger and to contribute to further waste reduction and set the standard for industrial-scale recycling [73,74]. In the study by Mateusz Gargol et al. [75], utilization of FA and silica gel as replacement of standard fillers was made to increase the thermal resistance and rigidity of polymeric composites based on polypropylene (PP) matrix. Several samples with different amounts of fillers and reference materials were synthesized in two different ways. The data obtained during the thermal analysis confirmed that different amounts of fillers affect the thermal properties of the samples. Samples without fillers were characterized by the worst thermal stability that instead increases with the increasing inorganic filler content. Moreover, the use of FA reduces the amount of monomers, decreasing the cost of such materials. Many experimental studies using FA have shown that the presence of filler increases the stiffness of the polymer composite but, like most fillers, reduces the impact resistance. To improve these properties, other components should be added to the composite formulation. Pardo et al. [76–78] investigated the deformation and

Table 5
Polymer composites using agro-waste fillers.

References	Fillers	Polymer matrix	Key findings	Application
Jiewei Tong et al. [37]	Wheat straw fibers	Methacrylate resin	High light transmittance. Excellent thermal insulation performance	Transparent panels for buildings
M. Chougan et al. [41]	Wheat straw fibers treated in hot water and microwave	Poly(lactic acid)	Increase of tensile strength, elongation at break, and toughness	Packaging
J.H. Low et al. [43]	Rice straw	High-density polyethylene	Highest tensile strength, poor adhesion between fillers and matrix	Packaging
W.A.W.A. Rahman et al. [44]	Rice straw modified vinyltrimethoxysilane	High-density polyethylene	Increase of thermal stability	Packaging
H. Moustafa et al. [45]	Kenaf fiber	Polystyrene	Increase of storage modulus and composite hydrophobicity	Sustainable automotive application
R.Taurino et al. [48]	Grape stalks modified by vinyltrimethoxysilane	Unsaturated polyester resin	Increase of the interface adhesion between resin resulting in good mechanical and physical properties	Interior furniture composites
R.Taurino et al. [50]	Digestate residues modified by thermal treatment and surface silane treatment	Unsaturated polyester resin	Decrease of Young Modulus. Increase of ductility. Low water absorption	Shower floors
I.O. Oladele et al. [53]	Of pawpaw-glass fiber hybrid	Epoxy resin	Improved thermal conductivity. Increase of wear resistance	Application where erosion property is important
S. Nagappan et al. [55]	Alkali-treated Lagenaria Siceraria fiber	Epoxy resin	Enhanced mechanical properties	Laminates for furniture industry
T. Iman et al. [56]	Tomato stalks	Urea formaldehyde	Decrease of minimum requirements for particle boards	—

fracture behavior of PP/ash composites with different ash contents, and analyzed the effect of a silane coupling agent too. They found that the incorporation of a silane coupling agent in the formulations led to composites with slightly improved tensile and fracture properties. This could be due to improved interaction between PP and ash or changes in the crystallization behavior of PP. Khan et al. [79] studied the effect of polyethylene-grafted maleic anhydride as a compatibilizer, and showed improvement in modulus and tensile strength properties of the low-density polyethylene and waste ash. Sengupta et al. [80] studied a renewable, low-cost chemical-like furfuryl palmitate as an effective coupling agent for FA-reinforced recycled PP matrix composites. The highest enhancement in properties was observed in 2 wt% furfuryl palmitate-coated FA-filled composites. Greater tensile toughness and higher resistance to deformation under higher bending loads can be obtained after the addition of silanized FA in the epoxy-based composites. In particular,

in the work of Tanakorn et al. [81], the epoxy composite containing 10 wt% treated FA showed the best mechanical properties, with respect to the unmodified composite. Moreover, the transmittance of visible light through all epoxy composites containing treated FA was reduced to 10%, suggesting that epoxy composites containing 10 wt% treated FA are suitable for interior light partition applications. Other researchers showed that it is possible to increase the final mechanical properties of FA/epoxy composite by controlling the particle size and volume fraction of FA and fabrication conditions. Viscosity conditions must be optimized by controlling the temperature of the slurry (mixing resin and filler) [82]. The result of optimum FA content and particles size to improve the tensile properties was found to be 30 vol% with the particle size lower than 50 μm . A comparative study of the performances of FA with epoxy resin reported that a combination of FA and epoxy resin can provide higher mechanical strength than epoxy composite containing silica fume [83]. Similarly, epoxy composites containing, as fillers, the waste from the production of Mineral Insulation Boards showed higher flexural strength, better abrasion resistance, and better impact resistance. The Mineral Insulation Boards is a waste from the production of insulation boards made of mineral wool, and containing a high proportion of recycled glass (>80%). This is the dry by-product of the production process that falls off from below a pulper in front of a hardening chamber, so it does not contain any organic elements, and it is, therefore, possible to classify this as recycled glass without organics.

In view of the high mechanical resistance of glass and also because of its pleasant aesthetics, glass waste has been used in epoxy-related applications, such as countertops, and as replacement for standard grit in friction floors [84]. Every year, thousands of tons of waste glass are sent to landfills without a proper reuse. The global market produces 130 million tons of glass annually. Global recycled glass volumes are estimated to be around 27 million tons, which represents only 21% of the glass produced annually [85]. Even if the glass waste is one of the most recyclable materials in the world, to the best knowledge of the authors, there were only a few studies conducted on the potential valorization of glass waste in PMCs. Glass waste can be classified into two main categories: glass cullet, which in general after the collection, can be

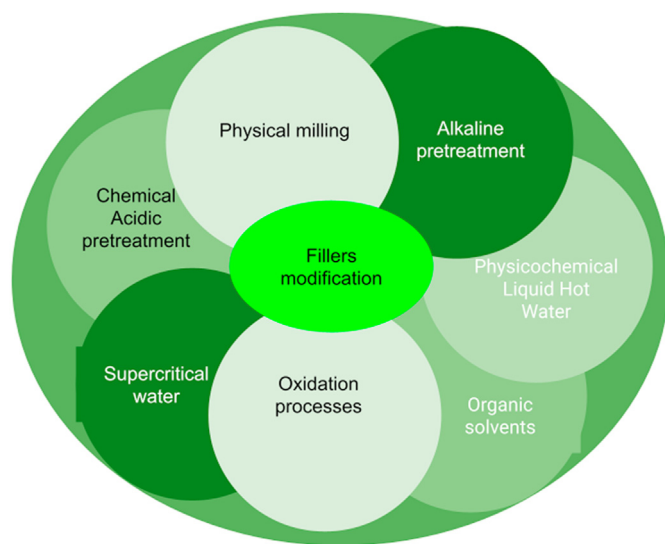


Fig. 3. Overview of organic fillers treatment methods used to improve the mechanical, surface, thermal, and chemical properties of polymer composites.



Fig. 4. Glass waste converted into coarse aggregates and fine glass powder (part of the photo is taken from Ref. [84]).

reused in glassworks and glass fines (mixtures of flat glass, Pyrex, ceramics, etc., which are difficult to reuse). One of the common applications of fine glass is to replace natural coarse and fine aggregates (see Fig. 4) in concrete, in asphalt paving mixes, and then in various construction applications. In the polymer matrix, glass fine powders could possibly be used as a filler, where the hardness does not disturb the processing, or can be used in fiber form. For example, funnel and panel fibers obtained from the recycling of cathode ray tube (CRT) were used as reinforcement for thermoplastic resin (PP). The CRT is a glass waste coming from the waste of electrical and electronic equipment consisting of 85% of glass and 15% of plastics, ferrous, and non-ferrous metals. The CRT glass is made up of mainly two different types of glass: funnel glass, containing lead and other heavy metals, and panel glass, which is a very homogeneous barium-strontium glass. In Table 6 the typical chemical composition of funnel and panel glass is reported [86]. A lot of works analyzes the possibilities to use the CRT glasses as secondary raw materials in the ceramic industry [87], but the possibility to use fibers obtained by the recycling of funnel and panel glasses in PP matrix was also evaluated, and final mechanical and physical properties were discussed. Thus, the study showed that panel and funnel glass fibers/PP composites provided good mechanical and physical properties similar to the E glass fibers/PP composite, but a clear disadvantage of PP matrix material for composite applications is its apolar character with respect to glass waste, which leads to limited wettability and poor fiber–matrix adhesion. Matrix modification with maleic-anhydride (MA-PP) was used to increase the thermal and mechanical properties [Izod impact properties, HDT, tensile strength, and modulus] [88]. The need to identify new applications of glass wastes led Taurino et al. to the development of a technology that uses fluorescent glass waste as a raw material in PCMs with a composition typical of a

solid surface. The polymeric resin used for producing solid surface materials is filled unsaturated polyester (35% of thermoset resin, and 65% of ATH by weight). In this study, ATH fillers were replaced by glass waste in coarse morphology and were finely ground. In this case as well, a silane coupling agent (vinyltriethoxysilane) was added to the resin in order to increase the compatibility between the two components (fillers-resin). As expected, the presence of coarse glass particles decreases the ductility of the resin, resulting in lower absorbed energy during the impact. Only the processing of a bilayer composite with fine waste glass can give an increase of the impact strength and, thus, in the maximum load that can be tolerated by the material.

Another kind of solid waste proposed as filler or reinforcement, in order to manufacture composites with thermoplastic, thermosets, and rubber matrixes with interesting tensile, electrical, or acoustical properties, is the tire rubber [88,89]. In fact, the increase in the number of waste tire rubber (WTR) has resulted in serious environmental concerns due to their toxicity, flammability, and non-biodegradability [90]. It is estimated that the tire waste annually produced might reach 200 million tons by 2030 [91]. Additionally, discarded tires represent an ideal breeding ground for mosquitoes, vermin, and other disease-carrying insects [92]. The tire rubber is a material obtained through vulcanization of natural and synthetic rubber blends, with the addition of chemical additives such as vulcanizing agents, fillers, and extenders [93]. Typically, tires contain 14% natural rubber, 27% synthetic rubber, 14% high carbon steel wire, 28% carbon black, and 16% fabric and others [94]. Its use for purposes such as filler in the production of several composites (Table 7) has been established. Furthermore, the composition and the irreversible cross-linking of rubber macromolecules do not make it as easy to recover and process as most thermoplastics. To this end, there is a growing interest in recycling used tires into ground tire rubber (GTR) products and then as filler in host material [95]. This approach allows the recovery and reuse of part of a tire rubber, avoiding their disposal in landfills, but, as discussed above, the main challenge for composite preparation by using both non-biodegradable and biodegradable wastes is to investigate how properties and development of these materials are influenced by the compatibility between fillers and polymer matrix. In the case of tire rubber, when it is blended with polymer matrices (HDPE, PP, SBS, etc.), the fiber-matrix compatibility is expected to be low. To increase the compatibility between both components, a pretreatment of the waste is generally carried out. For example, grafting of polymers and compatibilizing of agents were used on tire powder to obtain useful materials, improving the interfacial adhesion [96]. In the work of Yagneswaran, S et al., poly acrylic acid- grafted ground rubber tire were obtained and used as filler in epoxy composites. The poly acrylic acid-grafted ground rubber /epoxy composite showed higher mechanical properties,

Table 6
Chemical composition (wt.%) of the funnel and panel glasses.

Oxide	Panel glass	Funnel glass
SiO ₂	57.87	51.45
Na ₂ O	12.89	10.21
K ₂ O	7.29	9.47
CaO	—	3.77
SrO	8.52	0.89
BaO	7.95	1.28
PbO	0.02	18.40
ZnO	0.63	0.41
Al ₂ O ₃	3.76	3.21
MgO	—	1.43
ZrO ₂	1.41	0.21
TiO ₂	0.38	0.07
Fe ₂ O ₃	0.22	0.13
NiO	0.03	0.03
CoO	0.01	0.01

Table 7

Summary of mechanical and physical properties of several ground tire rubber (GTR) composite materials.

Composite	Mechanical properties	Physical properties
Polypropylene (PP)/GRT [84]	Decrease of Young modulus, tensile strength, elongation at break, and toughness	Increase of conductivity
Polyvinyl chloride (PVC)/GRT [88]	Increase of stiffness and Young modulus, Decrease of tensile strength and elongation at break	Increase of noise absorption coefficient
Polyurethane (PU)/GTR [89]	Increase of tensile strength and elongation at break. Decrease of Young modulus.	Decrease of dynamic heat generation
Epoxy resin/Poly acrylic acid grafted-GRT) [90]	For composites with 10 wt% GRT. Increase in tensile strength, tensile modulus, flexural strength, flexural modulus. Decrease of elongation at break.	—
Styrene-butadiene rubber (SBS)/GRT [91]	Elongation at break and tensile strength increased significantly with the increment of filler content	Positive effect for wet grip
PP/GTR-MA GTR modified with sulfuric acid [92]	Increase of Young's modulus. Reduction of the elongation at break and tensile strength	Increase of the crystallization temperature of PP. Decrease in the percent of crystallinity in the composites.
Acrylonitrile-butadiene-styrene copolymer (ABS)/GTR [93]	Decrease of tensile strength and young's modulus. Reduction in cut-off frequency. Improvement in the overall damping ratio.	Decrease of the overall density

with an increase of modulus up to 180% as compared with the neat GTR/epoxy composite [97]. Another way to increase the compatibility between components is to increase the interfacial bond by pre-treating with acid. For instance, Hernandez et al. [98] introduced a GTR-PP composite material, and studied the effect of sulfuric acid treatment on its mechanical and thermal properties. The addition of acid-treated GTR increased the specific surface area by approximately 625% in relation to the untreated GTR, improving the mechanical properties and, in particular, the Young's modulus by about 275% with respect to the composite obtained with the untreated GTR. Moreover, Araujo-Morera et al. [99] performed a mechanical-chemical treatment of the GTR particles, which were then used as fillers in Styrene-Butadiene Rubber composites. A combination of cryo-grinding mechanical processes along with acidic treatment was used to modify the surface of GTR and improve its adhesion and compatibility to the host polymer. These methods, however, make the final products more expensive; alternative studies by R. Mujal-Rosas et al. showed that significant changes in properties can be obtained when the size of the particle reinforcement changes [89]. In particular, with reference to particle size, when the particles are small ($<200\ \mu\text{m}$), they adhere better to the matrix (PP) due to their high specific stiffness and to the small size of both pores and cracks. On the other hand, the increase of the real conductivity as well as the permittivity and dielectric loss factor prove that the modification of reinforcement particles size, without any prior pre-treatment with acids, is effective and cheap. The modification of GTR particles with various chemicals can be very beneficial when GTR particles are introduced into the epoxy resin. Furmann et al. [100] performed photochemical grafting of methacrylic acid onto GTR particles and then introduced them into the epoxy matrix. The increase of impact strength was observed, and a decrease of material stiffness expressed by a 15% drop of Young's modulus. Another method to enhance the interfacial interactions between the epoxy matrix and waste tire rubber filler is a partial devulcanization [101] treatment of waste rubber particles with microwave. A well-developed interface between the rubber particles and epoxy resin led to the enhancement of flexural stress, modulus, as well as fracture toughness of the material.

Currently, there are already some studies that explore the potential of additive manufacturing in the development of 3D printable GTR-reinforced composite materials. Different mixtures of GTR/Acrylonitrile-butadiene-styrene copolymer composite materials were fabricated, varying the amount of GTR to thoroughly investigate the effects of the rubber additive. The manufacturing

process utilized an inexpensive Fused Filament Fabrication printer. Experimental modal analysis revealed that, despite the reduction in overall mechanical strength properties, the introduction of GTR into the composite significantly improved the overall vibration isolation characteristics of the 3D printed composite. Furthermore, the density of the composite gradually decreased, producing a lightweight composite material [102] that can be easily applied to multiple industry needs and components across a wide variety of applications.

3. Potential environmental impacts of composites filled with wastes

One of the main objectives in developing composites from recycled materials is to reduce the carbon footprint of products. The technical properties of composites made from recycled materials have been studied over a long period of time. The production of composites using waste fillers is an ecologically better alternative to production from virgin materials. The environmental benefits depend on the formulation of the composite and the waste processing methods required. Waste materials, which can be used as fillers, must have low maintenance requirements and sufficient strength, which is essential, for example, in the construction industry [103]. A high filler content in composites and the use of locally sourced recycled material can have a positive environmental and social impact in countries with poor waste management practices [2,104]. In fact, the cost of products manufactured from recycled materials is influenced by several factors, such as transportation costs, landfilling fees, recycling process, volumes, material quality, plant operating costs, and waste taxation [105]. Measures identified by policymakers to influence the cost factors include green taxes, green public procurement, and standardization of recycled materials [106]. Potential applications of new composites waste based are slowly expanding to include even more technically demanding applications, such as compression-molded door panels, molded with stiffening ribs, thickness variations, and molded-in holes [107].

In general, there are no recent studies available to calculate product or material costs for alternative composite fillers in composites. According to the studies by Petri Sormunen et al. [102], the impact of composite production ranged from 440 to 510 kg CO₂-eq in all scenarios. No differences were expected between the impacts of composite production from plastic, wood, and other waste. The impacts were the same because the expected energy consumption

for their pre-treatment is the same. Slightly less electricity was required for the preparation of mineral wool and plasterboard due to their lower strength compared to the other waste materials. The production of composites has a high climate change mitigation potential, if one takes into account the replacement of conventional products made from virgin plastics. In addition, the European Commission's investments in the Horizon 2020 projects on waste management contribute to the local economy, and make collectors and informal recyclers healthier and safer in the workplace [89].

4. Conclusions

Waste generation has grown rapidly with the population growth, creating significant environmental problems such as soil, water, and air contamination, and also impacting human health. In particular, inadequate solid waste management causes the alteration of ecosystems; this study, therefore, examined recent development in solid waste valorization strategies for the sustainable production of new composite materials. As is evident, there is a considerable amount of research on the application of agricultural waste as fillers in thermoplastic and thermoset matrices to obtain composites suitable for application in components subjected to light to moderate loads. Typical applications include civil construction, furniture, packing, and automotive industry. For example, transparent composites for light-transmitting building applications and laminated composites for wider applications, based on agricultural residues, have been produced. Composites reinforced with natural fiber using kenaf, coir, coconut fiber, banana, sisal, jute, flax, vakka, and pineapple leaf have shown improved mechanical properties. Their surface pre-treatment is necessary to increase the adhesion between matrix and fillers and the mechanical, surface, thermal and chemical properties of polymer composites. On the other hand, few reports have been found on the use of industrial wastes such as FA, tire rubber waste powder, and glass waste as fillers in PMCs. Therefore, the importance of the proposed investigation is based on the fact that it can contribute to the better utilization of agro-wastes for the production of new composite materials, resulting in reduced environmental pollution, preservation of valuable land-fill space, and conservation of natural resources. Furthermore, the utilization of agro-waste could also benefit farmers as an additional income, which can be an important motivating factor in promoting an efficient collection and management.

Despite this, the application of these new composite materials is limited. Further research is needed to study the actual behavior or performance of solid waste composites materials in their practical applications because properties such as long-term performance can best be studied. In addition, a major disadvantage of these composites is that they are not biodegradable after end use, which could be addressed to some extent by using biodegradable polymer matrix with natural fillers.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the link and code

References

- [1] D. Hoornweg, P. Bhada-Tata, What a waste: a global review of solid waste management 2012-3.

- [2] M. Safiuddin, M.Z. Jumaat, M. Salam, M. Islam, R. Hashim, Utilization of solid wastes in construction materials, *Int. J. Phys. Sci.* 5 (13) (2010) 1952–1963.
- [3] P.S. Roy, G. Garnier, F. Allais, K. Saito, Strategic approach towards plastic waste valorization: challenges and promising chemical upcycling possibilities, *ChemSusChem* 14 (2021) 4007–4027, <https://doi.org/10.1002/cssc.202100904>.
- [4] X.-L. Zhou, P.-J. He, W. Peng, S.-X. Yi, F. Lü, L.-M. Shao, H. Zhang, Upcycling waste polyvinyl chloride: one-pot synthesis of valuable carbon materials and pipeline-quality syngas via pyrolysis in a closed reactor, *J. Hazard Mater.* 427 (2022), 128210, <https://doi.org/10.1016/j.jhazmat.2021.128210>.
- [5] A. Schüch, G. Morscheck, M. Nelles, Technological options for biogenic waste and residues-overview of current solutions and developments, in: S. Ghosh (Ed.), *Waste Valorisation and Recycling*, Springer, Berlin/Heidelberg, Germany, 2019.
- [6] G. Cantero, A.A. Rodrigo, L.-P. Iñaki Mondragon, Effects of fiber treatment on wettability and mechanical behavior of flax/polypropylene composites, *Compos. Sci. Technol.* 63 (2003) 1247–1254, [https://doi.org/10.1016/S0266-3538\(03\)00094-0](https://doi.org/10.1016/S0266-3538(03)00094-0).
- [7] L. Wei, A.G. McDonald, C. Freitag, J.J. Morrell, Effects of wood fiber esterification on properties, weatherability and biodegradability of wood plastic composites, *Polym. Degrad. Stabil.* 98 (2013) 1348–1361, <https://doi.org/10.1016/j.polydegradstab.2013.03.027>.
- [8] U. Hujuri, S.K. Chattopadhyay, R. Uppaluri, A.K. Ghoshal, Effect of maleic anhydride grafted polypropylene on the mechanical and morphological properties of chemically modified short-pineapple-leaf-fiber-reinforced polypropylene composites, *J. Appl. Polym. Sci.* 107 (2008) 1507–1516.
- [9] H. Jiang, D.P. Kamdem, Development of poly(vinyl chloride)/wood composites. A literature review, *J. Vinyl Addit. Technol.* 10 (2004) 59–69, <https://doi.org/10.1002/vnl.20009>.
- [10] Anatole A. Klyosov, *Wood-plastic Composites*, Polymer Science & Technology General, Wiley, 2007.
- [11] D. Verma, P.C. Gope, M.K. Maheshwari, R.K. Sharma, Bagasse fiber composites-A review, *J. Mater. Environ. Sci.* 3 (2012) 1079–1092.
- [12] S. Rimdusit, S. Damrongsakul, P. Wongmanit, D. Saramas, S. Tiptipakorn, Characterization of coconut fiber-filled poly(vinyl chloride/acrylonitrile styrene acrylate blends, *J. Reinforc. Plast. Compos.* 30 (2011) 1691–1702, <https://doi.org/10.1177/0731684411427484>.
- [13] T.G. Yashas Gowda, M.R. Sanjay, K. Subrahmanya Bhat, P. Madhu, P. Senthamarai Kannan, B. Yagesha, Polymer matrix-natural fiber composites: an overview, *Cogent Eng* 5 (2018), 1446667, <https://doi.org/10.1080/23311916.2018.1446667>.
- [14] M. Thejvidi, M.M. Shekaraby, N. Motiee, S.K. Najafi, Effect of chemical reagents on the mechanical properties of natural fiber polypropylene composites, *J. Polym. Sci. Part. 27* (2006) 563–569.
- [15] A. Trigui, M. Karkri, L. Pena, C. Boudaya, Y. Candau, S. Bouffi, F. Vilaseca, Thermal and mechanical properties of maize fibers-high density polyethylene bio composites, *J. Compos. Mater.* 47 (2013) 1387–1397, <https://doi.org/10.1177/0021998312447648>.
- [16] A.S. Wood, Big buildup in polycarbonate supply big buildup in polycarbonate values, *Mod. Plast.* 66 (1989) 34–37.
- [17] A. Atiqah, M. Jawaid, M.R. Ishak, S.M. Sapuan, Moisture absorption and thickness swelling behaviour of sugar palm fibre reinforced thermoplastic polyurethane, in: *Advances in Material & Processing Technologies Conference Procedia Engineering*, vol. 184, 2017, pp. 581–586.
- [18] A. Campos, J.M. Marconcini, S.H. Imam, A. Klamczynski, W.J. Ortiz, D.H. Wood, L.H.C. Mattoso, Polycaprolactone reinforced with sisal fibers Morphological, mechanical properties and biodegradability of biocomposite thermoplastic starch and polycaprolactone reinforced with sisal fibers, *J. Reinforc. Plast. Compos.* 31 (2012) 573–581, <https://doi.org/10.1177/0731684412441092>.
- [19] M.C.S. Ribeiro, A. Fiúza, A. Ferreira, M.D.L. Dinis, A.C. Meira Castro, J.P. Meixedo, M.R. Alvim, Recycling approach towards sustainability advance of composite materials' industry, *Recycling* 1 (2016) 178–193, <https://doi.org/10.3390/recycling1010178>.
- [20] M. Kaleem, J.D. Satterthwaite, D.C. Watts, Effect of filler particle size and morphology on force/work parameters for stickiness of unset resin-composites, *Dent. Mater.* 25 (2009) 1585–1592, <https://doi.org/10.1016/j.dental.2009.08.002>.
- [21] M. Islam, C.M. Yeng, K.S. Chun, H.S. Huey, The influence of fibre orientation and chemical treatment on the performance of unsaturated polyester/chrysanthemum stem fibre composite, *Polym. Polym. Compos.* 29 (2021) 1103–1113, <https://doi.org/10.1177/0967391120954067>.
- [22] T.A. Negawo, Y. Polat, F.N. Buyuknalçaci, A. Kilic, N. Saba, M. Jawaid, Mechanical and dynamic mechanical thermal properties of ensete fiber/woven glass fiber fabric hybrid composites, *Compos. Struct.* 259 (2021), 13221, <https://doi.org/10.1016/j.compstruct.2020.113221>.
- [23] E. Kuram, Advances in development of green composites based on natural fibers: a review, *Emerg. Mat.* 5 (2022) 811–831, <https://doi.org/10.1007/s42247-021-00279-2>.
- [24] C. Flávio Cabrera, Eco-friendly polymer composites: a review of suitable methods for waste management, *Polym. Compos.* 42 (2021) 2653–2677, <https://doi.org/10.1002/pc.26033>.
- [25] What a waste 2.0: a global snapshot of solid waste management to 2050. Available online: <https://openknowledge.worldbank.org/handle/10986/30317>.
- [26] Daniel Hoornweg, Perinaz Bhada-Tata, What a Waste : A Global Review of Solid Waste Management. Urban Development Series;knowledge Papers No.

- 15, World Bank, Washington, DC, 2012. © World Bank, <https://openknowledge.worldbank.org/handle/10986/17388>.
- [27] T.P.T. Tran, J.C. Benezet, A. Bergeret, Rice and Einkorn wheat husks reinforced poly(lactic acid) (PLA) biocomposites: effects of alkaline and silane surface treatments of husks, *Ind. Crop. Prod.* 58 (2014) 111–124, <https://doi.org/10.1016/j.indcrop.2014.04.012>.
- [28] C. Güler, Y. Copur, C. Tascioglu, The manufacture of particleboards using mixture of peanut hull (*Arachis hypogaea* L.) and European Black pine (*Pinus nigra* Arnold) wood chips, *Bioresour. Technol.* 99 (2008) 2893–2897, <https://doi.org/10.1016/j.biortech.2007.06.013>.
- [29] O. Pinar, K. Karaosmanoglu, N.A. Sayar, C. Kula, D. Kazan, A.A. Sayar, Assessment of hazelnut husk as a lignocellulosic feedstock for the production of fermentable sugars and lignocellulolytic enzymes, *Biotech* 7 (2017) 1–9, <https://doi.org/10.1007/s13205-017-1002-4>.
- [30] L.D.M.S. Borel, T.S. de Lira, C.H. Ataíde, M.A. de Souza Barrozo, Thermochemical conversion of coconut waste: material characterization and identification of pyrolysis products, *J. Therm. Anal. Calorim.* 143 (2020) 1–10.
- [31] L. Zhang, A. Larsson, A. Moldin, U. Edlund, Comparison of lignin distribution, structure, and morphology in wheat straw and wood, *Ind. Crop. Prod.* 187 (2022), 115432, <https://doi.org/10.1016/j.indcrop.2022.115432>.
- [32] S.O. Prozil, D.V. Evtuguin, L.P. CruzLopes, Chemical composition of grape stalks of *Vitis vinifera* L. from red grape pomaces, *Ind. Crop. Prod.* 35 (2012) 178–184, <https://doi.org/10.1016/j.indcrop.2011.06.035>.
- [33] A. Atiqah, M.A. Maleque, M. Jawaid, M. Iqbal, Development of kenaf-glass reinforced unsaturated polyester hybrid composite for structural applications, *Compos. B Eng.* 56 (2014) 68–73, <https://doi.org/10.1016/j.compositesb.2013.08.019>.
- [34] M.P. Ho, H. Wang, J.H. Lee, C.K. Ho, K.T. Lau, J.S. Leng, D. Hui, Critical factors on manufacturing processes of natural fibre composites, *Compos. Part B* 43 (2012) 3549–3562, <https://doi.org/10.1016/j.compositesb.2011.10.001>.
- [35] T.P. Sathishku mar, P. Navaneethakrishnan, S. Shankar, Tensile and flexural properties of snake grass natural fiber reinforced isophthalic polyester composites, *Compos. Sci. Technol.* 72 (2012) 1183–1190, <https://doi.org/10.1016/j.compscitech.2012.04.001>.
- [36] K. Deepaka, S.V.P. Vattikutia, B. Venkatesh, Experimental investigation of jute fiber reinforced nano clay composite. In the 2nd international conference on nanomaterials and technologies (CNT 2014), *Proc. Mat. Sci.* 10 (2015) 238–242.
- [37] Shaikh, S.A. Channiwalla, To study the Characteristics of jute polyester composite for randomly distributed fibre reinforcement, in: *Proceedings of the World Congress on Engineering II*, vol. 2010, WCE, London, 2010, 2010.
- [38] N.F.C.M. Report, Natural Fiber Composite Market Report, Little Falls, Kline and Company, New Jersey, 2004.
- [39] D. Wang, X.S. Sun, Low density particleboard from wheat straw and corn pith, *Ind. Crop. Prod.* 15 (2002) 43–509, [https://doi.org/10.1016/S0926-6690\(01\)00094-2](https://doi.org/10.1016/S0926-6690(01)00094-2).
- [40] P. Leiva, E. Ciannamea, R.A. Ruseckaite, P.M. Stefani, Medium-density particleboards from rice husks and soybean protein concentrate, *J. Appl. Polym. Sci.* 106 (2007) 1301–1306, <https://doi.org/10.1002/app.26545>.
- [41] X. Xua, F. Yaob, Q. Wub, D. Zhoua, The influence of wax-sizing on dimension stability and mechanical properties of bagasse particleboard, *Ind. Crop. Prod.* 29 (2009) 80–85, <https://doi.org/10.1016/j.indcrop.2008.04.008>.
- [42] H. Kalaycioglu, G. Nemli, Producing composite particleboard from kenaf (*Hibiscus cannabinus* L.) stalks, *Ind. Crop. Prod.* 24 (2006) 177–180, <https://doi.org/10.1016/j.indcrop.2006.03.011>.
- [43] J. Tong, X. Wang, B. Kuai, J. Gao, Y. Zhang, Z. Huang, L. Cai, Development of transparent composites using wheat straw fibers for light-transmitting building applications, *Ind. Crop. Prod.* 170 (2021), 113685, <https://doi.org/10.1016/j.indcrop.2021.113685>.
- [44] FAO—FAOSTAT (food and agriculture organization of the united nations), <https://www.fao.org/statistics/en/2018>.
- [45] S.H. Ghaffar, et al., Interfacial properties with bonding and failure mechanisms of wheat straw node and internode, *Compos. Part A Appl. Sci. Manuf.* 99 (2017) 102–112, <https://doi.org/10.1016/j.compositesa.2017.04.005>.
- [46] S.H. Ghaffar, M. Fan, An aggregated understanding of physicochemical properties and surface functionalities of wheat straw node and internode, *Ind. Crop. Prod.* 95 (2017) 207–215, <https://doi.org/10.1016/j.indcrop.2016.10.045>.
- [47] M. Chougan, S.H. Ghaffar, M.J. Al-Kheetan, M. Gecevicius, Wheat straw pretreatments using eco-friendly strategies for enhancing the tensile properties of bio-based polylactic acid composites, *Ind. Crop. Prod.* 155 (2020), 112836, <https://doi.org/10.1016/j.indcrop.2020.112836>.
- [48] H.S. Yang, D.J. Kim, H.J. Kim, Rice straw—wood particle composite for sound absorbing wooden construction materials, *Bioresour. Technol.* 86 (2003) 117–121, [https://doi.org/10.1016/S0960-8524\(02\)00163-3](https://doi.org/10.1016/S0960-8524(02)00163-3).
- [49] J.H. Low, N. Andenan, W.A.W. A Rahman, R. Rusman, R.A. Majid, Evaluation of rice straw as natural filler for injection molded high density polyethylene bio-composite materials, *Chem. Eng. Trans.* 56 (2017) 1081–1086.
- [50] W.A.W.A. Rahman, N. Adenan, R.R. Ali, H. Sulaiman, Effect of silane cross-linker on the thermal properties of rice straw/HDPE biocomposite, *J. Appl. Sci.* 9 (2009) 3041–3047, <https://doi.org/10.3923/jas.2009.3041.3047>.
- [51] H. Moustafa, A.E.-A.A. El-Wakil, M.T. Nour, A.M. Youssef, Kenaf fibre treatment and its impact on the static, dynamic, hydrophobicity and barrier properties of sustainable polystyrene biocomposites, *RSC Adv.* 10 (2020), 29296.
- [52] A. Chabros, B. Gawdzik, B. Podkościelna, M. Goliszek, P. Paczkowski, Composites of unsaturated polyester resins with microcrystalline cellulose and its derivatives, *Materials* 13 (2020) 62, <https://doi.org/10.3390/ma13010062>.
- [53] P. Penczek, P. Czub, J. Pielichowski, Unsaturated polyester resins: chemistry and technology, *Adv. Polym. Sci.* 184 (2005) 1–95, <https://doi.org/10.1007/B136243>.
- [54] R. Taurino, L.S. De Bortoli, M.L. Schabbach, F. Bondioli, Development of glass-stalks-unsaturated polyester hybrid composites, *Compos. Commun.* 22 (2020) 100428, <https://doi.org/10.1016/j.coco.2020.100428>.
- [55] Y. Pan, Y. Pan, Q. Cheng, Y. Liu, C. Essien, B. Via, X. Wang, R. Sun, S. Taylor, Characterization of epoxy composites reinforced with wax encapsulated microcrystalline cellulose, *Polymers* 8 (2016) 4158, <https://doi.org/10.3390/polym8120415>.
- [56] R. Taurino, P. Pozzi, G. Lucchetti, L. Paterlini, T. Zanasi, C. Ponzoni, F. Schivo, L. Barbieri, New Composite materials based on glass waste, *Compos Part B* 45 (2013) 497–503, <https://doi.org/10.1016/j.compositesb.2012.09.017>.
- [57] K. John, S. Venkata Naidu, Effect of fiber content and fiber treatment on flexural properties of sisal fiber/glass fiber hybrid composites, *J. Reinforc. Plast. Compos.* 23 (2004) 1601–1605, <https://doi.org/10.1177/0731684404039799>.
- [58] S. Vigneshwaran, M. Uthayakumar, V. Arumugaprabu, J.J.R. Deepak, Influence of filler on erosion behavior of polymer composites: a comprehensive review, *J. Reinforc. Plast. Compos.* 37 (2018) 1011–1019, <https://doi.org/10.1177/0731684418777111>.
- [59] I.O. Oladele, O.T. Ayanleye, A.A. Adediran, B.A. Makinde-Isola, A.S. Taiwo, E.T. Akinlabi, Characterization of wear and physical properties of pawpaw-Glass fiber hybrid reinforced epoxy composites for structural application, *Fibers* 8 (2020) 44, <https://doi.org/10.3390/fib8070044>.
- [60] K.J. Nagarajan, A.N. Balaji, K. SathickBasha, N.R. Ramanujam, R. AshokKumar, Effect of agro waste α -cellulosic micro filler on mechanical and thermal behavior of epoxy composites, *Int. J. Biol. Macromol.* 152 (2020) 327–339, <https://doi.org/10.1016/j.ijbiomac.2020.02.255>.
- [61] S. Nagappan, S.P. Subramani, S.K. Palaniappan, B. Mysamy, Impact of alkali treatment and fiber length on mechanical properties of new agro waste *Lagenaria Siceraria* fiber reinforced epoxy composites, *J. Nat. Fibers* (2021), <https://doi.org/10.1080/15440478.2021.1932681>.
- [62] T. Iman, S.E. Mohamad, El M. Hamed, Potential of utilizing tomato stalk as raw material for particleboards, *Ain Shams Eng. J.* 9 (2018) 1457–1464, <https://doi.org/10.1016/j.asej.2016.10.003>.
- [63] C. Clemons, D. Caulfield, Natural fibers, in: *Functional Fillers for Plastics*, Wiley VCH, 2005, pp. 213–223.
- [64] G. Nemli, Factors affecting the production of E1 type particleboard, *Turk. J. Agric. For.* 26 (2006) 31–36.
- [65] R.K. Dasari, R.E. Berson, The effect of particle size on hydrolysis reaction rates and rheological properties in cellulosic slurries, *Appl. Biochem. Biotechnol.* 136–140 (2007) 289–299, <https://doi.org/10.1007/s12010-007-9059-x>.
- [66] A. Licari, F. Monlau, A. Solhy, P. Buche, A. Barakat, Comparison of various milling modes combined to the enzymatic hydrolysis of lignocellulosic biomass for bioenergy production: glucose yield and energy efficiency, *Energy* 102 (2016) 335–342, <https://doi.org/10.1016/j.energy.2016.02.083>.
- [67] K. Kucharska, P. Rybarczyk, I. Holowacz, R. Łukajtis, M. Glinka, M. Kamiński, Pretreatment of lignocellulosic materials as substrates for fermentation processes, *Molecules* 23 (2018) 2937, <https://doi.org/10.3390/molecules23112937>.
- [68] H. Rabemanantsoa, S. Saka, Various pretreatments of lignocellulosics, *Biores Technol* 199 (2016) 83–91, <https://doi.org/10.1016/j.biortech.2015.08.029>.
- [69] V. Chaturvedi, P. Verma, An overview of key pretreatment processes employed for bioconversion of lignocellulosic biomass into biofuels and value added products, *3 Biotech* 3 (2013) 415–431, <https://doi.org/10.1007/s13205-013-0167-8>.
- [70] A. Girge, V. Goel, G. Gupta, D. Fuloria, P.R. Pati, A. Sharma, V.K. Mishra, Industrial waste filled polymer composites—a review, *Mater. Today Proc.* 47 (2021) 2852–2863, <https://doi.org/10.1016/j.matpr.2021.03.617>.
- [71] S. Tasnim, F.U.A. Shaikh, Effect of chemical exposure on mechanical properties and microstructure of lightweight polymer composites containing solid waste fillers, *Construct. Build. Mater.* 309 (2021), 125192.
- [72] Z.T. Yao, X.S. Ji, P.K. Sarker, J.H. Tang, L.Q. Ge, M.S. Xia, Y.Q. Xi, A comprehensive review on the applications of coal fly ash, *Earth Sci. Rev.* 141 (2015) 105–121, <https://doi.org/10.1016/j.earscirev.2014.11.016>.
- [73] H.A. Khalid, M.W. Hussin, J. Mirza, F. Ariffin, M.A. Ismail, H.S. Lee, A. Mohamed, R.P. Jaya, Palm oil fuel ash as potential green micro-filler in polymer concrete, *Construct. Build. Mater.* 102 (2016) 950–960, <https://doi.org/10.1016/j.conbuildmat.2015.11.038>.
- [74] N. Ranjbar, C. Kuenzel, Cenospheres: a review, *Fuel* 207 (2017) 1–12, <https://doi.org/10.1016/j.fuel.2017.06.059>.
- [75] M. Gargol, B. Podkościelna, The use of waste materials as fillers in polymer composites -synthesis and thermal properties, *Physicochem. Probl. Miner. Process* 55 (2019) 1549–1556, <https://doi.org/10.5277/ppmp19082>.
- [76] S.G. Pardo, C. Bernal, M.J. Abad, J. Cano, L. Barral Losada, Deformation and fracture behavior of PP/ash composites, *Compos. Interfac.* 16 (2009) 97–114, <https://doi.org/10.1163/156855408X402830>.
- [77] S.G. Pardo, C. Bernal, A. Ares, M.J. Abad, J. Cano, Rheological, thermal, and mechanical characterization of fly ash-thermoplastic composites with different coupling agents, *Polym. Compos.* 31 (2010) 1722–1730, <https://doi.org/10.1002/pc.20962>.

- [78] S. Pardo, C. Bernal, M. Abad, J. Cano, A. Ares, Fracture and thermal behaviour of biomass ash polypropylene composites, *J. Thermoplast. Compos. Mater.* 27 (2014) 481–497, <https://doi.org/10.1177/0892705712452740>.
- [79] M.J. Khan, A.A. Al-Juhani, R. Shawabkeh, A. Ul-Hamid, I.A. Hussein, Chemical modification of waste oil fly ash for improved mechanical and thermal properties of low density polyethylene composites, *J. Polym. Res.* 18 (2011) 2275–2284.
- [80] S. Sengupta, K. Pal, D. Ray, A. Mukhopadhyay, Furfuryl palmitate coated fly ash used as filler in recycled polypropylene matrix composites, *Compos. B Eng.* 42 (2011) 1834–1839, <https://doi.org/10.1016/j.compositesb.2011.06.021>.
- [81] T. Wongwuttanasatian, W. Chaochaiphum, V. Seithanabutara, Valorization of MSW incinerator fly ash for epoxy-based composite for interior light partition application, *Waste Biom. Valoriz.* 13 (2022) 2795–2814, <https://doi.org/10.1007/s12649-022-01684-2>.
- [82] J. Sim, Y. Kang, B.J. Kim, Y.H. Park, Y.C. Lee, Preparation of fly ash/epoxy composites and its effects on mechanical properties, *Polym.* 12 (2020) 79, <https://doi.org/10.3390/polym12010079>.
- [83] M. Barbuta, M. Harja, I. Baran, Comparison of mechanical properties for polymer concrete with different types of filler, *J. Mater. Civ. Eng.* 22 (2010) 696–701.
- [84] R.V. Silva, J. de Brito, C.Q. Lye, R.K. Dhir, The role of glass waste in the production of ceramic-based products and other applications: a review, *J. Clean. Prod.* 167 (2017) 346–364, <https://doi.org/10.1016/j.jclepro.2017.08.185>.
- [85] R. Dilan, B. Edwin, S. Sujuve, A new technology of transforming recycled glass waste to construction components, *Constr. Amd Build. Mat.* 313 (2021), 125538.
- [86] P. Pozzi, R. Taurino, T. Zanasi, F. Andreola, L. Barbieri, I. Lancellotti, New polypropylene/glass composites: effect of glass fibers from cathode ray tubes on thermal and mechanical properties, *Compos. Part A Appl. Sci. Manuf.* 41 (2010) 435–440, <https://doi.org/10.1016/j.compositesa.2009.12.001>.
- [87] Y. Qi, X. Xiao, Y. Lu, J. Shu, J. Wang, M. Che, Cathode ray tubes glass recycling: a review, *Sci. Total Environ.* 259 (2019) 2842–2849.
- [88] R. Mujal-Rosas, J. Orrit-Prat, X. Ramis-Juan, M. Marin-Genesca, A. Rahhali, Study on dielectric, mechanical and thermal properties of polypropylene (PP) composites with ground tyre rubber (GTR), *Polym. Compos.* 20 (2012) 797–808, <https://doi.org/10.1177/096739111202000905>.
- [89] X. Colom, J. Cañavate, F. Carrillo, M. Lis, Acoustic and mechanical properties of recycled polyvinyl chloride/ground tyre rubber composites, *J. Compos. Mater.* 48 (2013) 1061–1069, <https://doi.org/10.1177/0021998313482154>.
- [90] F. Alkadi, J. Lee, J.-S. Yeo, S.-H. Hwang, J.-W. Choi, 3D printing of ground tyre rubber composites, *Int. J. Precis. Eng. Manuf. Technol.* 6 (2019) 211–222, <https://doi.org/10.1007/s40684-019-00023-6>.
- [91] Z. Tang, W. Li, V.W.Y. Tam, C. Xue, Advanced progress in recycling municipal and construction solid wastes for manufacturing sustainable construction materials, *Resour. Conserv. Recycl.* 6 (2020), 100036.
- [92] A. Moustafa, M.A. El Gawady, Mechanical properties of high strength concrete with scrap tyre rubber, *Construct. Build. Mater.* 93 (2015) 249–256, <https://doi.org/10.1016/j.conbuildmat.2015.05.115>.
- [93] N.F. Medina, R. Garcia, I. Hajirasouliha, K. Pilakoutas, M. Guadagnini, S. Raffoul, Composites with recycled rubber aggregates: properties and opportunities in construction, *Construct. Build. Mater.* 188 (2018) 884–897, <https://doi.org/10.1016/j.conbuildmat.2018.08.069>.
- [94] F. Wahid, M. Allan, S. Rafat, M. Priyan, Z. Yan, W.S. Hong, L. Weena, A. Thiru, S. Peter, Recycling of landfill wastes (tyres, plastics and glass) in construction – a review on global waste generation, performance, application and future opportunities, *Resour. Conserv. Recycl.* 173 (2021), 105745, <https://doi.org/10.1016/j.resconrec.2021.105745>.
- [95] X. Colom, J. Cañavate, F. Carrillo, M. Lis, Acoustic and mechanical properties of recycled polyvinyl chloride/ground tyre rubber composites, *J. Compos. Mater.* 48 (2013) 1061–1069, <https://doi.org/10.1177/0021998313482154>.
- [96] M. He, K. Gu, Y. Wang, Z. Li, Z. Shen, S. Liu, J. Wei, Development of high performance thermoplastic composites based on polyurethane and ground tyre rubber by in-situ synthesis, *Resour. Conserv. Recycl.* 173 (2021), 105713, <https://doi.org/10.1016/j.resconrec.2021.105713>.
- [97] S. Yagneswaran, W.J. Storer, N. Tomar, M.N. Chaur, L. Echegoyen, D.W. Smith Jr., Surface-grafting of ground rubber tire by poly acrylic acid via self-initiated free radical polymerization and composites with epoxy thereof, *Polym. Compos.* 34 (2013) 769–777, <https://doi.org/10.1002/pc.22484>.
- [98] E.H. Hernández, J.F. Hernández Gámez, L.F. Cepeda, E.J. Chávez Muñoz, F.S. Corral, S.G. Solís Rosales, G.N. Velázquez, P.G. Morones, D.I. Sánchez Martínez, J. Sulfuric acid treatment of ground tyre rubber and its effect on the mechanical and thermal properties of polypropylene composites, *Appl. Polym. Sci.* 134 (2017), 44858, <https://doi.org/10.1002/app.44864>.
- [99] J. Araujo-Morera, R. Verdugo-Manzanares, S. Gonzalez, R. Verdejo, M.A. Lopez-Manchado, M. Hernandez Santana, On the use of mechano-chemically modified ground tyre rubber (GTR) as recycled and sustainable filler in styrene-butadiene rubber (SBR) composites, *J. Compos. Sci.* 5 (2021) 68, <https://doi.org/10.3390/jcs5030068>.
- [100] I. Fuhrmann, J. Karger-Kocsis, Promising approach to functionalization of ground tyre rubber photochemically induced grafting: short Communication, *Plast., Rubber Compos.* 28 (1999) 500–504.
- [101] A.B. Irez, E. Bayraktar, I. Miskioğlu, Damping and toughening effect of the reinforcements on the epoxy modified recycled devulcanization rubber based composites. In: Thakre, P.R., Singh R.P., Slipper G., (Eds), *Mechanics of Composite, Hybrid and Multifunctional Materials*, Volume vol. 5. Springer International Publishing, New York, pp. 147–158.
- [102] H.T. Nguyen, K. Crittenden, L. Weiss, H. Bardaweel, Recycle of waste tyre rubber in a 3D printed composite with enhanced damping properties, *J. Clean. Prod.* 368 (2022) 133085, <https://doi.org/10.1016/j.jclepro.2022.133085>. Get rights and content.
- [103] P.F. Sommerhuber, J.L. Wenker, S. Rüter, A. Krause, Life cycle assessment of wood-plastic composites: analysing alternative materials and identifying an environmental sound end-of-life option, *Resour. Conserv. Recycl.* 117 (2017) 235–248, <https://doi.org/10.1016/j.resconrec.2016.10.012>.
- [104] O. Väntsi, T. Kärki, Environmental assessment of recycled mineral wool and polypropylene utilized in wood polymer composites, *Resour. Conserv. Recycl.* 104 (2015) 38–48, <https://doi.org/10.1016/j.resconrec.2015.09.009>.
- [105] A. Coelho, J. de Brito, Economic viability analysis of a construction and demolition waste recycling plant in Portugal – part I: location, materials, technology and economic analysis, *J. Clean. Prod.* 39 (2013) 338–352, <https://doi.org/10.1016/j.jclepro.2012.08.024>.
- [106] EEA, <http://www.eea.europa.eu/publications/eu-emission-inventory-report-lrtap>, 2019.
- [107] P. Sormunen, I. Deviatkin, M. Horttanainen, T. Kärki, An evaluation of thermoplastic composite fillers derived from construction and demolition waste based on their economic and environmental characteristics, *J. Clean. Prod.* 280 (2021), 125198, <https://doi.org/10.1016/j.jclepro.2020.125198>. Part 2.