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Plastic Waste Composite Materials: A Sustainable Approach for Waste Management and Resource Utilization

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Abstract: The intense increase in plastic waste highlights the need for sustainable solutions, seizing the opportunity to balance plastics and the environment. This review comprehensively studies the production of composite materials from waste plastic as a valuable resource that also alleviates environmental concerns. This review investigates the vast scope and environmental burden of plastic waste by providing a framework that differentiates the different waste plastics, namely the thermoplastics and thermosets. Particular emphasis is given to various methods of waste plastic processing to form composites by melt blending, compression molding, extrusion, and injection molding. The review identifies various composite plastic reinforcements that incorporate additional polymers as well as natural and synthetic fibers, sand, clay, fly ash, and other recycled and post-consumer resources. This review attempts to examine the interrelationships of waste plastic type and composite reinforcements and the processing and other influencing factors as well the mechanical, thermal, physical, and/or chemical properties of the plastics. This review is intended to be a helpful reference for researchers, engineers, and policymakers focused on the development of safe and sustainable technologies to manage plastic waste (circular economy).

Keywords: *Waste Plastic Recycling, Sustainable Materials, Resource Utilization, Environmental Impact, Circular Economy, and Composite Manufacturing.*

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I. INTRODUCTION

Plastics have captured the attention of engineers, architects and manufacturers with their versatility and inexpensiveness. Sadly, they are not biodegradable which causes a global problem. People have incorporated plastics in their everyday lives. Some materials that are widely used in business and in our homes include packaging materials, office supplies, materials used in transportation and logistics, drugs and pharmaceuticals, and electrical and electronic materials. It can be used for many things in everyday life. It can be used for many things in everyday life. Unfortunately, it is dangerous to the environment. This was a significant problem for everyone to deal with the trash and find a place to keep it. Uncontrolled disposal of plastics can lead to many problems. It causes waste in landfills. It waste in the depths of our rivers, harming the seas. If not managed, it can end up in the marine environment, and get into the food chain, harming animals. There are dangers to the environment caused by this waste. There are also potential dangers to the health of humans, and it may be many years before we can tell the effects on our health.

To manage waste properly, we need to categorize the different types of waste. These include cups, straws and bags among other examples that constitute new pollutants that are called microplastics. It is a problem that is very important to solve.

Figure 1 illustrates the global landscape of plastic waste. The plastic recycling rate worldwide is 15%. Recycling various plastics is a challenge, plastics waste is often contaminated, and many regions lack sufficient recycling infrastructure. Approximately 25% of the remaining plastic waste is incinerated internationally to recover energy. Western Europe, with advanced technology, can burn waste with minimal pollution and converts waste to energy efficiently. 35% of the plastic waste is sent to landfills. In many developing countries, it is the most common method of disposal due to a lack of alternatives and cheaper costs. Landfilling plastic waste creates serious environmental issues, including water and soil contamination. 25% of plastic waste is improperly managed and is due to a lack of disposal infrastructure. This is the most prevalent problem in low-income and middle-income countries.

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The most effective way to combat plastic waste is to reduce the use of plastic. One effective way of doing this is to use more reusable bags and water bottles to prevent the purchase of new bags and bottles and help to limit the disposal of more plastic waste. The future of waste plastic is in recycling, but the key to this is reducing waste.

To prevent plastic waste from leaching into the environment, segregation and delivery to the recycling plants must be operational. There are systems for recycling in various countries worldwide and there must be adherence to those systems. Recycling plastic must be devoid of contaminants including unclean plastics. There are various strategies for forming composite material of plastics such as mixing the waste plastic cans with reinforcing and/or matrix elements. Some methods of composite material formation from waste plastic are: melt blending, compression molding, injection molding, vacuum infusion, filament winding, 3D printing, etc.

Recycled plastic composite materials are essential in reducing environmental damage as they are beneficial and versatile. Composite materials combine plastic with other materials and offer an innovative approach to managing plastic waste. Using throwaway plastics in composite materials reduces the amount of plastic that goes to the landfill and/or ends up polluting the environment. The circular economy cannot come to fruition when there is no means of transforming waste into desirable goods. The pollution of the environment with plastic waste is significant. Using composite materials with plastics that would otherwise be disposed of, reduces the negative impact on the environment. Composite materials of plastics and other materials reduce the impact on the environment more than conventional materials. More than others, composite materials aid in reducing the negative impact on the environment in terms of depletion of natural resources and reducing the impact on the environment in terms of carbon and energy.

Numerous industries worldwide recycle plastic waste to produce composite materials, as illustrated in Table 1. The Trex Company, based in Winchester, Virginia, produces composite decking and railing utilizing wood and recycled PE plastic, while Axion International, based in Zanesville, Ohio, produces composite railroad ties and construction mats, as well as bridge components and marine pilings, using recycled plastic and polymer composites.

One of the options to protect the environment and reduce CO2 emissions is the manufacturing of more ecologically friendly composites using reusable plastic waste. Productive utilization of waste plastics to create composites can help reduce the demand for virgin materials. This is also a positive way to reduce the volume of new plastics and conserve resources. Moreover, recycled plastic composites show enhancement in mechanical characteristics compared to plastics. Strength, stiffness and impact resistance of plastics can all be improved by the inclusion of fibers or nanoparticles as reinforcing agents. They can be used in many applications in consumer products, automotive, aerospace, construction, etc. Also, plastic composites can be made to create a huge variety of products because of the design flexibility and the adaptability of the composites. Waste plastics, when used with different matrix materials and various reinforcing agents, can be employed to make composites that are designed and optimized for a specific use, therefore enhancing the end product. Additionally, in instances that weight is a factor in the design, composites offer a solution.

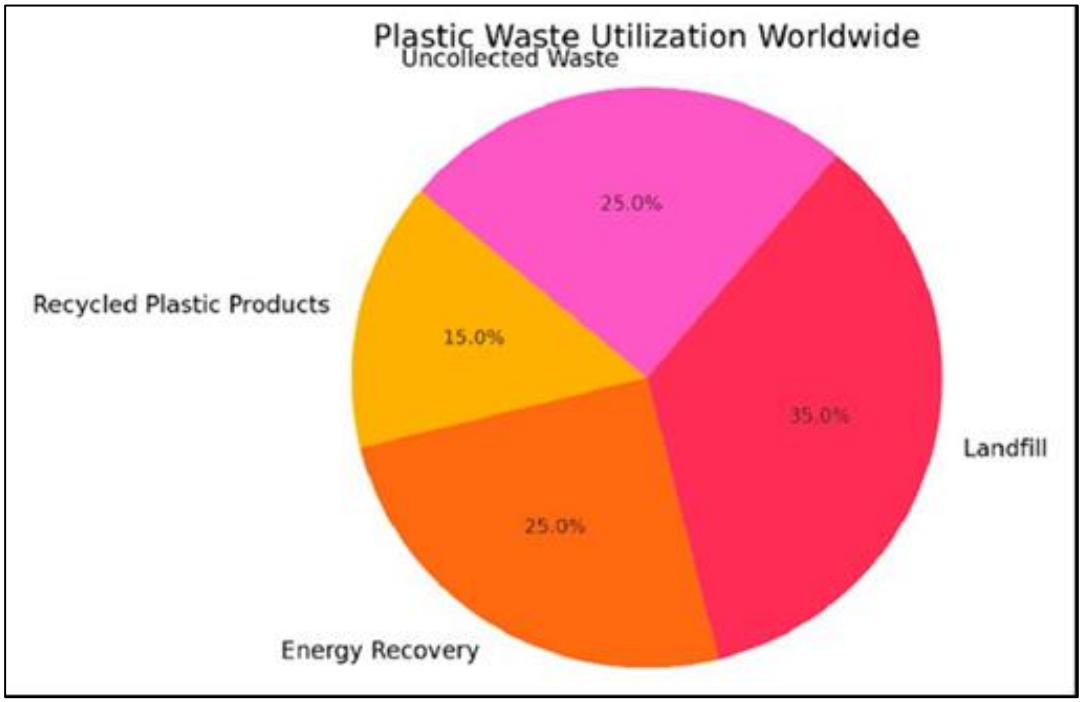

Fig 1 Plastic Waste Utilization Worldwide.

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Table 1 Amount of Plastic Waste Consumed for Composite Material Production in Industries All Over the World.

S.L.	Industry Name	Origin	Amount of Waste Plastic Consumed (Metric Tons) for Composite Production
01	Trex company, inc	USA	181,437
02	UPM ProFi	Finland	10,000
03	Axion International	USA	5000
04	EcoBoard industries ltd	India	5000

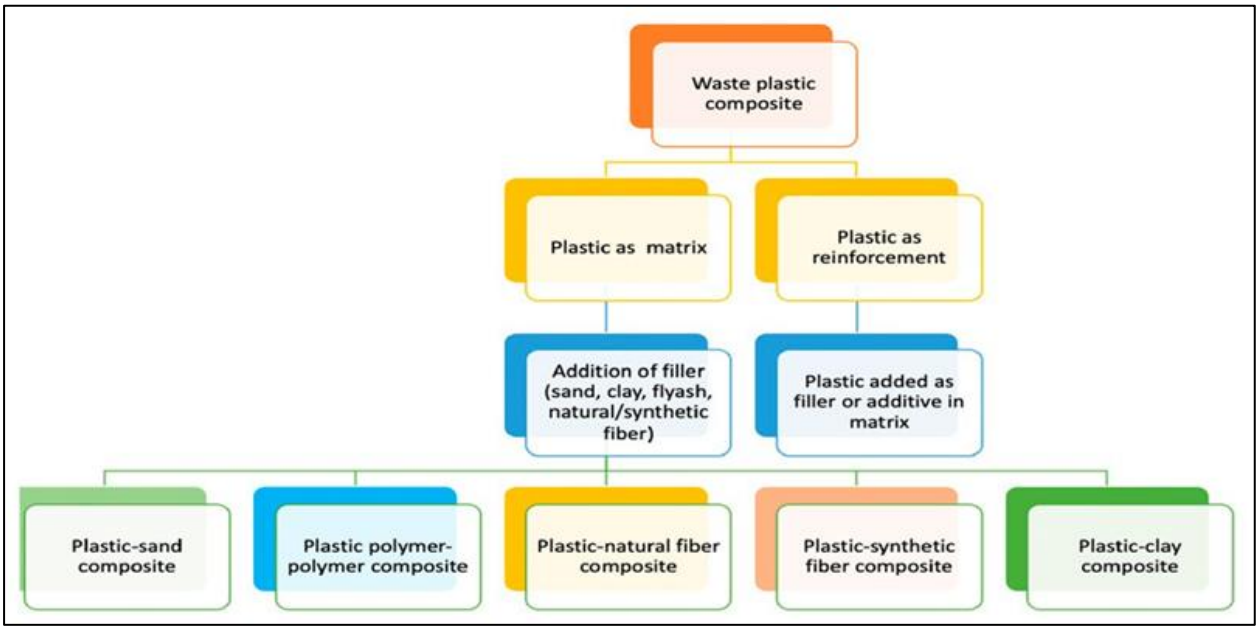

Fig 2 Classification of Waste Plastic Composites where Plastic Acts as Reinforcement or a Matrix.

Weight is an issue.28 Composite parts provide a lightweight, fuel efficient, pollutant reduced, and eco-friendly design alternative in both automotive and aerospace industries.29 Environmentally, composites manufactured from waste plastics are often more durable and have longer life spans as compared to conventional materials. Because these composites weather the UV, moisture, and chemical assault of the environment, they are less likely to fail and do not need to be replaced as often, thus conserving resources and reducing waste. The use of waste plastics in formulating composite materials has led to considerable innovations and numerous new enterprises. The combination of new ideas and the development of composite materials, coupled with improved fabrication, better recycling methods, and a more efficient methodology of material science, have brought about new opportunities for the economy and employment in the field of waste plastic recycling in conjunction with the manufacture of composites.

You can use waste plastic as a base and reinforcement material with other components. Plastic polymer plays the role of a matrix and strengthens the structure by providing a grip for the fibers, maintaining their position. Moreover, it protects the reinforced fibers from the surrounding effects and aids in load transfer between the reinforced fibers. For the purpose of construction engineering, plastic debris is used as a matrix or building block to construct paver blocks, bricks, tiles, and wood-plastic composites. However, Waste plastics can be used as a substitute for fine or coarse aggregates in cement formulations to manufacture cement concrete construction blocks. As shown in Figure 2, are the type of composites used as a matrix or reinforcement. The use of waste plastics as a substitute for hybrids affects the physical properties of the end products. The composites provide the filler or reinforcement with additional strength, stiffness, and various properties.

Plastic composites consist of a plastic matrix and a variety of fillers (sand, clay, natural fibers, and glass). Fillers enhance certain attributes of the composite, including toughness and heat resistance. In the composite, the plastic matrix binds the fillers together. This combination provides cohesion and structural support to the composite. This variety of plastic composites can suit different fields like construction and automotive and consumer goods industries. Depending on the applicational demand, fillers can be modified in the ratio and in the kind.

Cement-free paver blocks were developed by combining plastic waste (LDPE), waste sand, and basalt fiber.33 In this technique, several building blocks were prepared by adding different proportions of basalt fiber (0.1%–1%) to the plastic-sand composites. In total, 144 samples were prepared. This study emphasized the use of cost-effective and eco-friendly solutions. Developing such paver blocks, as a potential solution, promotes sustainable development. The study also explored the use of waste plastics along with commercially available silica sand to make thermoplastic composite floor tiles. In this case, waste plastics acted as binding and filling agents to replace the

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cement (Figure 3).34 In this case, plastic waste was sorted out in terms of color using a computer-based automated color recognition system. The plastic and sand were chopped into smaller pieces (10–15 mm and 150 μm) and mixed in different proportions. The mixture was then melted in order to be poured in a mold of dimensions 150 × 150 × 50 mm. This was done under a pressure of 20.7 MPa.

The study35 explained the mechanical properties of sand blocks that incorporated polyethylene plastic waste. Plastic waste was collected, melted, and mixed with river sand that was sieved through a 4.75 mm mesh. This mixture was placed into molds, compacted with a tamping rod, and then cured. Mechanical tests evaluated the compressive and flexural strengths. The purpose of the study was to evaluate the mechanical properties of the bricks with regards to the plastic waste. Plastic waste was used as a binder for cement-free paver blocks, which consisted of the three groups represented by HDPE, PP/PS, and the remains of the three groups (Figure 4).36 Naturally occurring river sand (3.18 fineness modulus) was sieved as stated in the Indian Standard Code (IS: 2386- Part I-1963). HDPE, PP/PS, and mixed waste plastics were randomly bulked to the sand in the range of 40 to 70%. The samples were designed with a tri-hexagonal shape, in which each hexagonal unit was 60 mm × 60 mm × 60 mm. The setting time of the block was on average 19 to 24 minutes, and all the combined samples were evaluated for compressive strength at 15 to 60°C.

Plastic-bound sand composite development was focused on finding a low-cost recycling option to repurpose waste plastics in developing countries.37 The research used LDPE and HDPE composites to find optimal processing temperatures to achieve higher compressive and flexural strengths (250°C - 325°C). Sand was separated into three fractions of particle size, and two different manufacturing techniques were used. The Heat-Mixing Technique (HMT) required the plastic to be melted and mixed with the sand to cool, while the Oven-Molding Technique (OMT) required layering the plastic with sand to be heated and cooled to form samples. The effects on the plastic bonded sand from the processing temperature, thermoplastic binder type, and particle size and quantity, were all studied. The processing techniques of plastic bonded sand paving tiles, including sorting, melting, mixing, and casting, are shown in Figure 5. Research on sand-plastic composites was focused on developing an optimal compressive strength.38 A design of experiments was used to evaluate a range of combinations of sand and plastic to identify what may be the greatest enhancement of compressive strength. The melt-mixing technique was used in the construction of buildings and other structures from waste sand and plastic composites.39,40 Table 2 shows the available research of sand-plastic composites and their intended use for construction purposes.

II. PLASTIC-POLYMER COMPOSITE

The formation of polymer-polymer composites encompasses the construction of a plastic polymer matrix that is reinforced with plastic particles or fibers. A composite material with improved characteristics is obtained by the combination of the two or more different types of polymers. Polymer-polymer composites were developed by combining waste polyvinyl chloride plastics of water tanks and waste tires with different compositions into a matrix of polyester resin. The study evaluated the effect of this reinforcement in the resulted composite. Waste tires and tanks were grounded into a particle size of 1000 microns by using a grinder of 1800 W at a grinding speed of 2800 r/min. 16 different specimens were designed to evaluate which combinations of the dispersed components of the polymer composites were better to improve the hardness and tensile strength of the polymer composite as compared with polymer composite separated components. Laria et al. (2023) evaluated the mechanical characteristics of poly-ethylene terephthalate with low density (LDPE) and high density (HDPE) plastics. Using a mechanical resistance test, the tensile strength and compressive strength of the recycled material were estimated to be about 60% of the strength of the virgin material. The same methodology was used to recycle plastic materials and transform these materials into different specimen shapes and carry out mechanical tests in accordance with the conventional equipment and test methods. The effect of mixed polymeric composites on their hybrid acoustic was studied using different weight ratios of unsaturated polyesters (UP) together with high density composites of either polyethylene and polystyrene or polymethyl methacrylate.43 Pulsed ultrasonic tests were conducted to determine the time of flight of the ultrasonic waves through hybrid composite materials in which the acoustic velocity and acoustic impedance were derived.

Compared to density of reinforcing material, increasing weight percentage of constituent materials was shown to increase density of the constituents. UP/PMMA + PS at 28% displayed the highest acoustic impedance, therefore superior to ultrasonic wave attenuation UP/PMMA + HDPE. Evaluated was the possibility of using recycled Polyethylene (PET) and Polypropylene (PP) as substitutes to Calcium Carbonate, in the context of pipes transporting sewage and water.44 By replacing originally blended PET/PP at 30% with a commercial waste of 70/30 wt

Fig 3 Flow Diagram Illustrating the Specimen Development Process (CC by 4.0).

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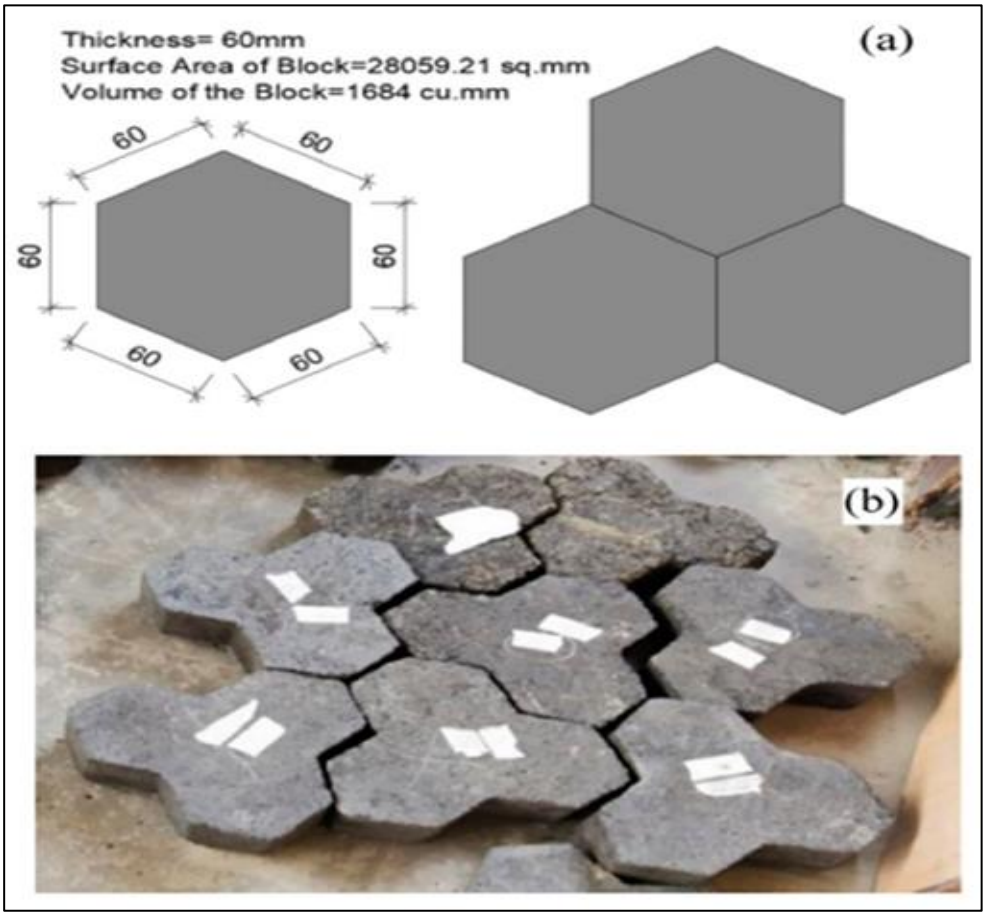

Fig 4 (a) Dimension and (b) Molded Units of Paver Block (CC by 4.0).[36]

Fig 5 Shows How to Create Plastic-Bonded Sand Paving Tiles. First, Leftover LDPE Plastic Shreds are Sorted and Melted. Then, Sand is Combined with the Molten Plastic and the Mixture is Poured into Steel Molds. (CC by 4.0).37

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Percent ratio of PP to PET to study the resulting material's stiffness. The addition of a commercial compatibilizer with 5% maleic anhydride (MAh) was studied. Heat treatment, mechanical properties and morphology of several formulations were studied, and the selected formulation was scaled up to an industrial assessment, resulting in the first time a pipe built with recycled PET and PP was possible to manufacture. Studies focusing on low-density polyethylene and polyethylene terephthalate polymer-polymer coupling microfibrillar plastic composites provided insights on how

Table 2 Sample Collection - Studies Focusing on Plastic-Sand Composites.

Raw Material	Mixing Ratio for Best Output	Processing Method	Dimensions	Application
LDPE, sand, basalt fiber	30:70 LDPE to sand	Compression molding	50 mm × 50 mm × 50 mm	Paver blocks
Waste plastic 10–15 mm pieces (LDPE, HDPE, PET) Silica sand (150 µm)	50:50 HDPE to sand	Static compaction method	150 mm × 150 mm × 50 mm	Floor tiles
PP/PS, HDPE, and all mixed-type	40:60 HDPE to sand	Melt mixing method	Tri-hex with each hexa unit of 60 × 60 (mm)	Paver blocks
Waste plastic (polythene), river sand	Plastic and sand ratios of 1:4	Melt mixing method	(Diameter 6.135 cm and 3.513 cm depth)	Bricks
LDPE and HDPE	65%–80% of sand	Oven molding technique (OMT) and heat-mixing technique (HMT)	50 mm-cubed steel molds	Plastic bonded sand
PET, LDPE, and HDPE	Plastic sand ratios of 1:2	Melt mixing method	23 cm × 10 cm × 8 cm	Plastic sand bricks
LDPE and HDPE	60:40 plastic to sand	Melt blending technique	-	Plastic sand bricks
Molten plastic bags	For bricks, 66.67% plastic and for concrete 50% plastic	Melt mixing method	20 cm × 10 cm ×5 cm	Bricks and concrete blocks

The blending ratio creates a variance in physical and sorption characteristics.45 Microfibrillar composites were produced by blending LDPE and PET at different ratio combinations. The sorption behavior was analyzed in terms of moisture uptake and water absorption at the blend ratios. Mechanical testing was performed to assess the flexural toughness and stiffness of the blend ratios. The work by .46 documented the effect of a compatibilizer on the mechanical properties of blends of recycled PET with polyethylene, polypropylene, and polystyrene. Blends of recycled plastic polymers were prepared with a compatibilizer. The compatibilizer was incorporated to increase the level of compatibilization and improve the interfacial adhesion of the different polymers. Recycled PET was blended with EGMA, a glycidyl methacrylate copolymer, via reactive processing.47 Reactive processing enhanced the chemical interconnection of the two polymers, thereby improving their compatibilization and mechanical properties. Plastic-natural fiber composite. Composites of natural fibers offer a cost-effective solution, as they are derived from renewable resources. It is now widely recognized that these fibers positively impact composites as reinforcing elements. Natural fiber composites in general are characterized by higher elongation, damage tolerance, and lower tensile strength and modulus compared to composite polymeric fibers.48 In waste plastic composites reinforced with natural fibers possessing different levels of integrity, greater mechanical properties are perceived, as seen in Figure 6.

Composite materials were manufactured from the combination of EPS foam waste and natural plant fibers, using a dissolving technique with a mixed organic solvent system.49 NaOH treated (5% w/v) and untreated fibers were used as a fiber reinforcement and combined with different ratios of waste polystyrene to improve the mechanical performance of the waste composite. Green composites of rice husk with recycled HDPE and PET were produced and tested.50 The green composites were tested and results were compared for thermal, physical, and mechanical properties of plain (un-compatibilized) and rHDPE/rPET blended composites. Date palm fibers were treated with NaOH and used as reinforcement for the production of biodegradable composites.51 Treated fibers were cut to different sizes and incorporated as fillers in the polymer matrices for the improvement of the mechanical properties of the composites and to improve the performance of the composite in the area of the micro-failure and the mechanisms associated with it.

This review examines some applications of lignocellulosic biocomposites in architecture and construction and some design and fabrication methods that leverage the natural characteristics and properties of the biocomposites.52 Depending on the application, biocomposite natural fibers can be direct extruded in a thermoplastic composite, or pelletized for subsequent extrusion or injection molding (Figure 7; 1-3). Natural fibers like kenaf, flax, hemp and cotton, which are long, require special compounding methods like comingling. Hot pressing

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provided a good dispersion of polymer in the matrix, allow the fabrication of composite materials with high performance. Finally, lamination, drilling and thermoforming are illustrated (Figure 7; 4-6) to finish components and fabricate their final forms and designs. This was particularly important for architectural applications. A list of the natural fiber and thermoplastic polymer composites is shown in Table 3.

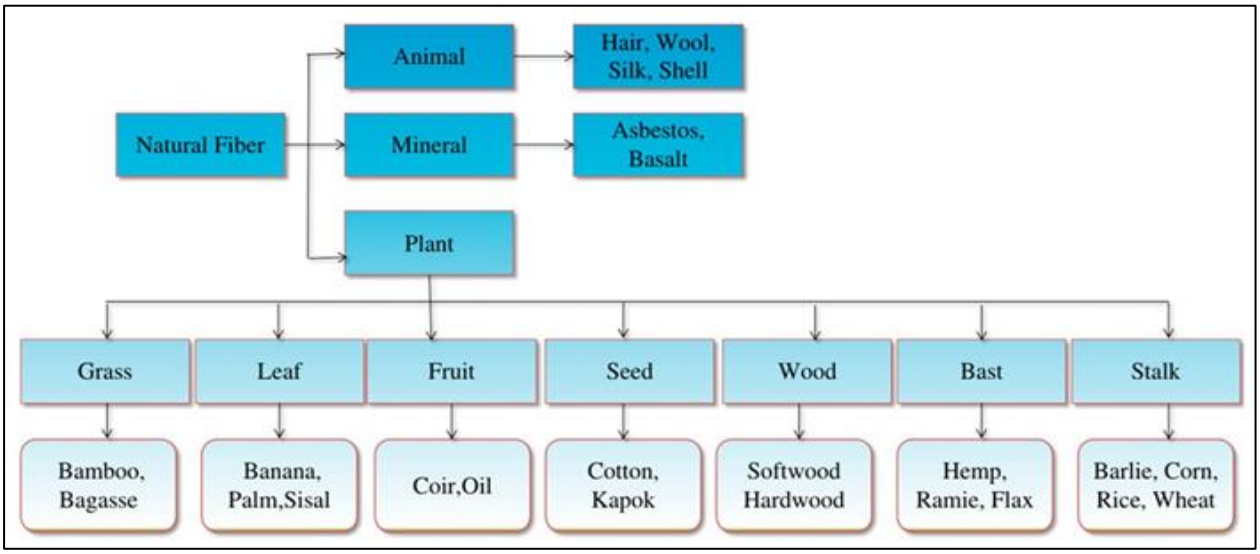

Fig 6 Classifications of Natural Fiber (CC by 4.0) (Amjad et al., 2022).

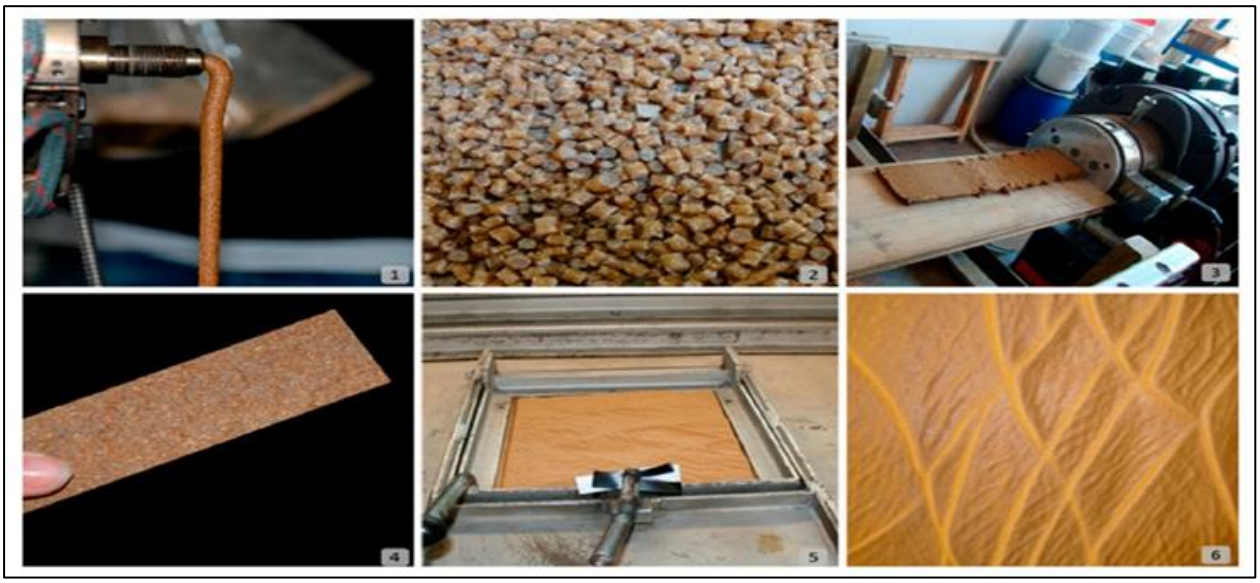
Fig 7 This Diagram Illustrates How Thermoplastic Composites are Produced. The Steps are: (1) Amortization, (2) Granulating, (3) Extrusion, (4) Sliced Panel, (5) The Thermoforming Process, and (6) Thermoformed Final Panel (CC by 4.0)52.

Plastic-synthetic fiber composite. In recent decades, the combination of synthetic fibers and reinforced polymer matrices have achieved increased popularity. This increased popularity is related to the advanced features of these synthetics and the matrices they are combined with. There is the addition of lightweight synthetics, and the improvement of the matrix in relation to stiffness, modulus and tensile strength when compared to matrices that are produced in the traditional manner.56 Synthetic fibers are classified and sub-classified according to their origin and this is shown in Figure 8. The composite materials are able to exhibit outstanding properties on the condition that the processing methods are appropriate together with the selection of the appropriate type of fibers, the appropriate dimensions and orientations, and the type of bonding (which may be chemical or cohesive). Due to the properties of flexibility and the improved thermal, chemical, and electrical resistance, along with fatigue and elasticity when compared to natural fibers, synthetic fibers find their uses in apparel in the aerospace and automotive industries, as well as in indoor and outdoor applications.57–59 Synthetic fibers are classified into organic, inorganic, and other subtypes, as in Figure 8.

Polymer composites bonded with glass fibers combine superior mechanical and chemical characteristics. However, they are more challenging to machine due to reduced tool life and increased disposal problems when compared to

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carbon fiber. (60) The fracture characteristics of a hand-layup manufactured polyester-glass fiber composites were studied. The results demonstrated the composite's ability to endure external stresses without failing or rupturing. (61) The study was designed to fracture the composite and measure the toughness, as well as to observe crack propagation and the failure sequence. Several methods of increased stiffness fabrication for carbon fiber reinforced thermoplastic composites were researched. (62–64) In addition to carbon and glass fibers, other synthetic fibers are used for some applications. For instance, to improve polyolefin composite materials, Kevlar fibers were assembled and synthesized with sequence-defined oligomers. (65) These researchers synthesized oligomers that were rich in phenylalanine and that varied in both the alkyl chain and phenylalanine length. These oligomers were then used as interfacial modifiers to improve the bonding of the Kevlar fibers to the polyolefin matrix. The dip coating method was used to adsorb the oligomers to the Kevlar fibers. In these studies, the parameters that affected the interfacial adhesion in fiber reinforced composites were the focus of the studies. The synthetic fiber-polymer composite is shown in Table 4.

Table 3 Analyzing the Processing of Thermoplastic-Natural Fiber Composites (CC by 4.0).

Plastic (Polymer)	Filler	Chemical Treatment of Filler	Processing Technique	Outcome
Polystyrene	Coconut husk Banana stem	NaOH	Dissolution using organic solvent	Using 6h treated 2% wt of banana stem fiber, tensile strength increased 70%, and impact strength for coir (10 wt% 6h treated) increased 120%. The modified fibers interlocked well with the polymer matrix and adhered effectively
High density polyethylene(HDPE) Polyethylene terephthalate(PET)	Rice husk	-	Melt-blending (Extrusion)	The flexural properties were enhanced with increasing bio-filler concentration. The elasticity of modulus and tensile strength were at an optimum level at 70 wt%
Polyethylene polypropylene	Date palm fiber from the leaf sheath	NaOH	Compression molding	Hardness and impact strength were enhanced to a maximum of 15 wt%. The lowest creep and highest strength were achieved using fiber (10 mm of 20 wt%)
Polyethylene terephthalate High-density, polypropylene	Sawdust from cedrela odorata L	$CaCO_3$	Extrusion	Mechanical strength declined when thermoplastic and wood content became greater than 50 wt%
Polystyrene	Rice husk Sawdust	NaOH	Hand layup	In the sawdust-loaded composite, moderate strengths were attained with an additive level of 15%, a filler size of 100 µm, and a base rate of 4%; in the rice straw-packed composite, the same values were 15%, a filler size of 31 µm, and an alkaline content of 2%

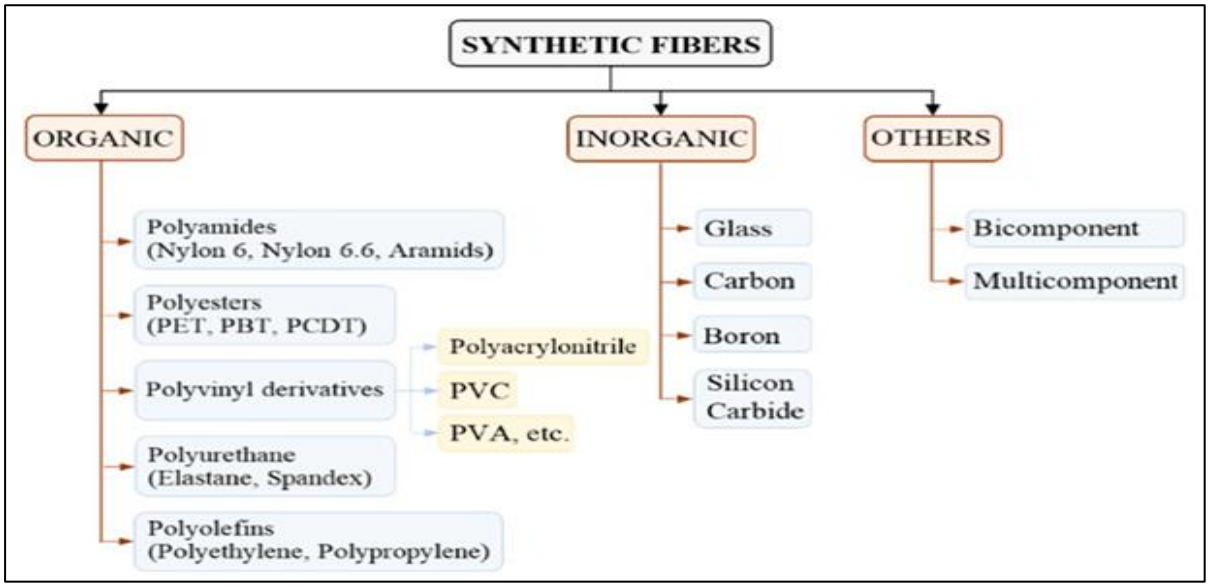

Fig 8 Classifications of Synthetic Fibers (CC by 4.0)[56].

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Plastic-fly ash composite. Fly ash is a collection of light and fine grains that result from the combustion of coal in the thermal power plants after the smoke exhausts.67 Fly ash improves the mechanical strength and the workability of the waste plastic polymers.68,69 Combining waste plastic and fly ash as composite materials for a plastic-fly ash composite for building and construction provides a wide range of applicability and improves the polymeric properties and the economy of the region, thus providing a strong basis for sustainable development.70

Some mechanical68,71 and chemical72 techniques were used to study the properties of fly ash-based composites after modification.

The effect of fly ash particle size in the composites of high density polymers was also studied.53 The fly ash as such was collected, and the bigger particles were removed by sieving before mixing and adding as such in 10% of each of the three fly ash

Table 4 The Fabrication Methods of Synthetic Fiber-Polymer Composites.

Synthetic Fiber	Polymer	Fabrication Method
Carbon fiber	Polypropylene	Microcellular injection molding
PAN-based carbon fiber	Polyphenylene sulphide with polyamide 6	Molding through injection
Kevlar fibers	Polyolefin	Dip coating technique
Chopped strand-based glass fiber	Polyester	Hand lay-up
PAN-based carbon fiber	Polyphenylene sulfide/Polytetrafluoroethylene	Mixing and molding
Woven glass fabrics based on glass fiber	Epoxy resin	Dry hand lay-up

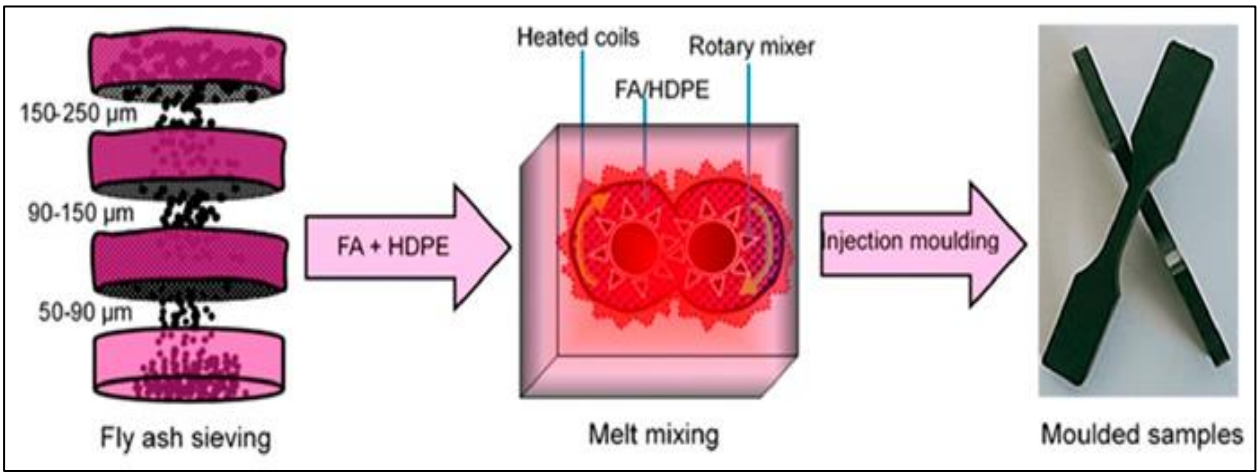

Fig 9 The Fabrication Method of Fly Ash Reinforced Polymer (HDPE) Composite (CC by 4.0)[53].

Type of High-Density Polyethylene After Mixing with Fly Ash at 220°C for 30 minutes (Figure 9). Given the previous studies, which indicated that higher amounts of fly ash may improve the tensile modulus (even at the expense of the material's tensile strength), it was decided to try using 10% fly ash. In this case, 10% fly ash was the optimum value to improve the relevant mechanical properties. Injection molding was performed at 240°C for 10 seconds to obtain dumbbell specimens for tensile testing. To test the tensile properties, plain HDPE and the composite variants underwent the same procedure, and four replicas of each composite type were made (Figure 9). Fly ash was used as the filler in a waste plastic matrix, and flame retardant was added in 5%, 10%, 15%, and 20% loadings. The materials were further processed using a dual screw extruder to assess the extent of the improvement in their properties.72 The materials were used to fabricate composite tiles and assessed their properties. The study focused on investigating the effects of filler loadings on the waste plastic properties of the matrix.

The combination of plastic clay and composite polymers produces advanced materials with highly beneficial properties. Among others, they can have enhanced mechanical, thermal and barrier properties. Many clay particles that have a large surface area and aspect ratio can improve the physical properties of the matrix. Packaging, automotive, and construction materials are just some of the areas where enhanced performance can be customized using these versatile materials.74,75 Many types and amounts of clays and polymers can be manipulated to fine-tune the physical properties of polymer clay matrix composites. Processing methods also allow a great range of morphologies and properties that can be imparted to plastic clay composites.76 The method of synthesis and the application of polymer clay composites is illustrated in Figure 10.

They incorporated Sepiolite nanoparticles into a polypropylene matrix using melt-compounding.76 They adjusted the sepiolite loading to test the effects of differing concentrations in the composites. They then extensively characterized the nanocomposites to test their mechanical properties, thermal stability, and other important properties (Table 5). The effects of clay on the microstructure and properties of injection-molded polypropylene (PP)

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composites was studied.78 Using the melt compounding method, the researchers were able to incorporate multiple levels of montmorillonite into the polypropylene composites and were able to analyze the materials to study changes to their structure and properties. Nano clay with poly-glycidyl methacrylate composites were sonicated to undergo modification.79 The incorporation of the surfactant into the clay layer resulted in the composites exhibiting enhanced thermal stability in comparison with the unmodified polymers. The use of ultrasonication appeared to offer numerous advantages in terms of reaction time, clay dispersion, and yield of the polymer and nano clay composite. Polymer nanocomposites were produced with the dispersion of halloysite nanotubes within a selected polymer matrix.80 They synthesized the nanotubes to have a tubular structure with high aspect ratios in order to provide reinforcement. The focus of the research was to improve the physical properties of the nanocomposites for glass coatings.

Isotactic polypropylene nanocomposites were developed with sepiolite clay minerals.81 Sepiolite was in the form of metallocene, and isotactic polypropylene was polymerized in situ.

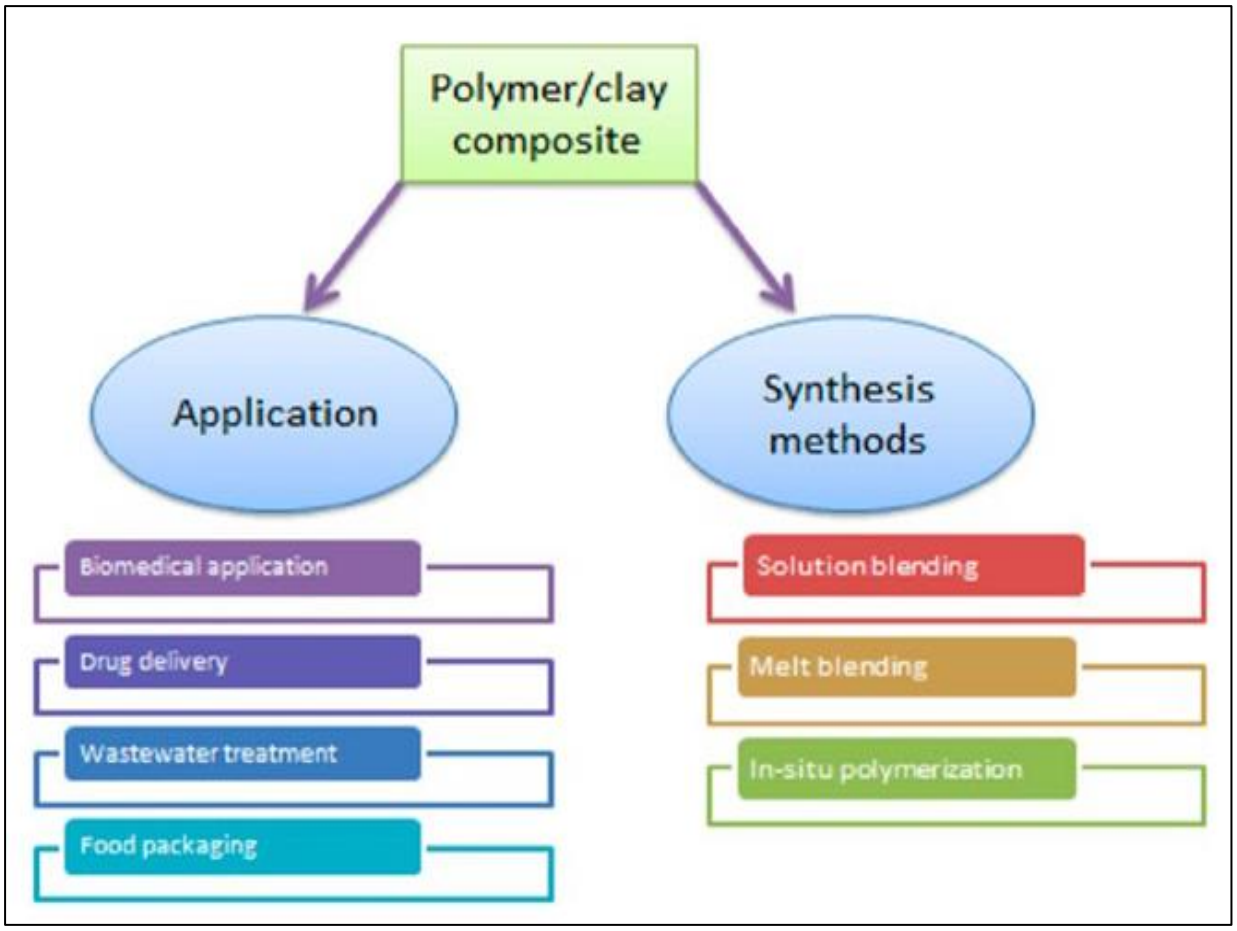

Fig 10 Graphical Presentation of Application and Synthesis Method of Polymer Clay Composite (CC by 4.0).

Table 5 Listing of Different Fabrication Methods of Polymer-Clay Composite.

Polymer	Clay	Method
Polypropylene poly(vinylidene fluoride-hexafluoro propylene)codoped with poly(ethylene oxide)	Sepiolite Zn-based montmorillonite	Melt blending Doctor-blade method
Polypropylene	Montmorillonite	Melt compounding method
Poly-glycidyl methacrylate	Maghnite	Ultrasound-assisted solution blending
poly(methyl methacrylate) (PMMA) Polystyrene (PS)	Halloysite	Ultrasound-assisted solution Blending
Polypropylene	Sepiolite	In situ polymerization
Polystyrene	Vinyl clay	In situ polymerization
Polypropylene	Montmorillonite	In situ polymerization

Technique - The procedure was developed to promote effective bonding between the polymer matrix and sepiolite in order to yield better properties. Table 5 shows alternative processing methods for polymer/clay composites.

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III. PLASTIC COMPOSITES USE PLASTIC AS A REINFORCING MATERIAL

Waste plastic aggregates can be lightweight concrete additives because of waste plastics having low specific gravity. Waste yogurt containers (made from polypropylene) were used as coarse gravel aggregates to make lightweight concrete in hand lay-up methods.84 Concrete samples were made with varying compositions (0% to 25%) of polypropylene plastic. For these samples, water and cement had a 0.5 ratio. Coarse aggregate, sand, and cement were mixed with a ratio of 4:2:1. These samples were left to cure for 28 days. Polystyrene concrete samples were tested for water absorption, density, and, ultimately, compressive strength. Polyvinyl chloride (PVC) waste was utilized as a filler material to substitute fine or coarse aggregates in the environmentally friendly concrete.85 Shredded PVC sheets were crushed by hand and crushed by an electric crusher. The sieved sheets were left with a grading range between coarse and fine aggregate, producing near a specific gravity of 1.3 and a range of ±13.95–32.12 MPa tensile strength when mixed with fine sand and coarse gravel. PVC aggregates of up to 30% were beneficial, but more than that contributed to the deterioration of physical properties.

This paper describes the preparation of self-compacting concrete using plastic waste powder to replace cement and the mechanical properties of the waste.86 In a related work, PET from waste bottles was used to replace fine or coarse aggregates (with size defined by sieve analysis).87 As per the sieve analysis, fine aggregates were taken in the range of 0 to 4.75 mm and coarse gravel in the range of 4.75 to 20 mm. The samples were subjected to 3000C and 6000C to study the developed compressive strengths and the resultant pore formation and loss of strength. Many studies showed that by increasing the plastic waste content in concrete, the compressive strength of the plastic waste concrete also decreased.88–90 The use of finely waste grounded plastic and its subsequent study have shown an improvement in the concrete's workability.91

IV. PHYSICAL AND MECHANICAL PROPERTIES

The use and development of composite materials based on waste plastics is really important to address a number of issues, particularly in the advancement of material science and technology. They consist of waste plastics and other materials, such as wood, glass, and other reinforcing material. The physical and mechanical properties of composite materials are important, as they determine the end-products usability and performance. The physical and mechanical characteristics of the composite material also define the composite's overall sustainability.

Adding fillers92 or coupling agents93 as reinforcing components such as inorganic fillers and fibers improves mechanical properties.94,95 Multiple reports indicated that the mechanical properties of pavement blocks, construction tiles, and wood-plastic composites (WPC) made of recycled plastic waste (the density, tensile strength, compressive strength, and impact strength) are similar to those of end products made using conventional building materials like cement and ceramics. Additionally, the assessment of the recycled plastic's durability (based on indices of porosity and water absorption) is comparable to the durability of traditional materials.96,97 There are many benefits that plastic-sand composite bricks have over conventional bricks, specifically water absorption, compressive strength, and efflorescence.35 Plastic bricks are made by mixing sand, waste plastic, and thermocol in different ratios, and the resulting bricks are then analyzed for their material properties.98 Based on the following properties, the analysis for the selection of ingredients and their ratios, and the procedure for the preparation of the final plastic composite is undertaken.

- *Hardness*

Glass-sand composite bricks are bound by plastic waste with sand and crushed glass fillers. The hardness of the bricks is dependent on the setting time. For cement and concrete, setting time is the time taken for the paste to reduce its plasticity. The hardness of cement-less paver blocks (which were made by using plastic waste as a binding material) was evaluated using a Brinell hardness test under two different loading conditions. The hardness values were found to be between 38.75 and 148.6, and the majority of the plastic waste was found to be soft.36

- *Tensile Strength*

Tensile strength is a very critical mechanical property. It refers to the resistance to pulling apart, and it is the maximum (and breaking) value of tensile (and stretching) stress that can be sustained by the material. The measurement units of the value of tensile strength are in psi (pound per square inch) in the imperial system, or in the metric system, in the units of MPa (megapascals). The strength of the material can be evaluated by the tensile (or tension) test. The tensile test consists of a standard specimen on which an axial load is applied. The load and the (deformation) displacement are recorded. The specimen is subjected to the test until it fractures. The tensile strength is obtained by dividing the value of the maximum (applied) load, by the value of the area of the cross-section of the specimen before the fracturing.

This characteristic is significantly impacted by the type and quantity of reinforcements and fillers added, as well as the type of waste plastic used as the matrix.

PE and PP are used as matrix materials for composites because they are flexible, durable and chemically resistant. The tensile strength of these polymers can be dependent on crystallinity and molecular weight. Crystallinity and molecular weight can be positively correlated to tensile strength of the polymers. An example of this is the comparison of tensile strength of high-density and low-density polyethylene. High-density polyethylene has a greater tensile strength due to a greater level of crystallinity. PET, and more specifically fiber-reinforced polymers, is another common choice for matrix materials for composites. The high stiffness of the aromatic structure of PET makes

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the fibers and composites have a high tensile strength. Recycling PET can weaken the inherent viscosity of the polymer, therefore blending it with virgin PET can be used to retain its high tensile strength. Natural fibers are environmentally friendly and inexpensive, and for this reason are often used as a composite reinforcement. Fibers such as jute, flax and hemp can all be used. The tensile strength of these composites can be affected by the orientation, aspect ratio and fiber-matrix interface. Composites with long hemp fibers that are oriented have shown to have high tensile strength compared to those that are short and randomly oriented. Synthetic fibers such as glass and carbon are also used for reinforcement to increase tensile strength, and due to their high modulus and strength, are very effective. Carbon fiber reinforced polymers, due to their high tensile strength, are applied in many high performance and high strength applications in aerospace and automotive fields. Composites can be made more cost effectively by adding fillers like mica, talc, and calcium carbonate, which also improve stiffness and tensile strength of the composites.

Additionally, these fillers increase the resistance of the composites to heat and can improve tensile strength indirectly by maintaining structural integrity at higher temperatures.105 There can be synergistic effects when inorganic fillers are used in combination with natural or organic fibers—in this case, the toughness of the organic fibers is complemented by the strength and stiffness of the Inorganic fillers. This hybrid approach can optimize the composites' tensile strength and other mechanical properties.106 The tensile strength of the composite materials depends on the nature of the waste plastics and other components, their proportions and the variety of filling materials used.

Sugar cane bagasse was studied to create high-density polyethylene (HDPE) composites. Acetylated sugar cane bagasse was studied and compared to washed bagasse in terms of favorable interactions with HDPE composites. Optimization of favorable interactions was quantified through tensile strength. Tensile strength of HDPE composites with 5% and 10% acetylated cane bagasse was 20.7 MPa and 19.8 MPa, respectively. Washed sugar bagasse with 5% and 10% acetylation had a tensile strength of 20.09 MPa and 19.5 MPa, respectively. The results indicate that the acetylation of sugar cane bagasse improved the favorable interactions through the incorporation of acetylation to HDPE composites. With the addition of 30% bagasse into HDPE, without a coupling agent, tensile strength was recorded at 30.6 MPa. When a coupling agent was utilized, tensile strength increased to 36.1 MPa. The results indicate that a coupling agent optimized the adhesion of the fiber and the matrix. Sisal fiber was incorporated into polypropylene (PP) composites. It was reported that a 20% fiber loading of sisal achieved a tensile strength of 13.6 MPa. When the fiber loading was increased to 40% the tensile strength of the composite decreased to 12.6 MPa. The reduction in tensile strength is attributed to fiber agglomeration. Modifications of sisal fibers and the addition of GMA-SF improved the tensile strength of sisal PP composites to 24.98 MPa. The tensile strength of sisal fiber PP composites was 40.5 MPa and hemp fiber composites were 55.1 MPa. These results indicate that hemp fiber provides better performance in composite manufacturing.

A 30% recycled PET/LDPE composite had a tensile strength of 18 MPa, and this value rose to 27 MPa with 50% PET, confirming that PET has a reinforcing effect.111 Also, blends of PET and PE were examined, and a mixture containing 65% PET and 35% PE was reported to have a tensile strength of 11 MPa.112 The research studied composites of recycled PET resin, and incorporated sand, red mud, silica fume, and fly ash. The composites' tensile strengths were between 10.92 MPa and 12.45 MPa, determined by the amount of PET included.113 A polystyrene (PS)-clay composite had a tensile strength of 19 MPa, and a high-density polyethylene (HDPE)-clay composite had a tensile strength of 21.25 MPa. The results of this research highlighted the reinforcing role of clay on the mechanical properties of both composite materials.114 LDPE composites with alumina

(Al_2O_3) exhibited a tensile strength between 13.8 and 15.5 MPa, and the tensile strength of the composite worsened with higher amounts of alumina.115

Mixed polymer-wood waste composites had a tensile strength between 2.87 and 3.43 MPa, and further enhancement of the strength of the composite is needed.27 Recycled expandable polystyrene composites that included coir and banana stem fibers had a tensile strength between 6.7 and 15.97 MPa. The use of alkali treatment greatly improved the mechanical properties of the composites.4s9 Waste LDPE-fly ash composites had tensile strengths between 10.22 and 10.75 MPa, and the properties showed little to no change with the addition of TPP.72 The review evaluated the literature on recycled PET fiber-reinforced cement and geopolymer composites.

The tensile strengths documented for these materials were between 1.15 and 2.99 MPa, while the performance characteristics were affected by the inclusion of fly ash.

- *Compressive Strength*

The ability of a material to resist breaking under a compressive load is called the compressive strength of that material. This is an important attribute for engineers to estimate the performance of the material under various service conditions. With the increasing percentage of plastic components, the compressive strength increases; however, it decreases by 31.17% when exposed to very high temperatures.116 Compressive strength of these composites is largely dependent upon the composition of the product and the type of waste plastics used as the matrix, type of reinforcement, and type of filler used. Understanding these effects allows for more control over the design of composite materials to exhibit specified mechanical properties for particular applications, including those used in construction, automotive components, and packaging.

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Research has shown that waste plastic-based composite materials demonstrate compressive strength based on the combination and ratio of plastic and matrix materials. Cement bricks were made with 30% recycled HDPE and reached a compressive strength of 13.79 MPa. Given this strength, the cement bricks are suitable for non-load-bearing applications.96 Out of the blocks tested, those containing 25% of mixed waste plastics achieved the highest compressive strength, recording a value of 17.24 MPa. This suggests that using a combination of different types of waste plastics is preferable.117

In sand paver blocks, a combination of 60% recycled HDPE and 40% recycled PP/PS resulted in a strength of 10.25 MPa.36 However, a combination of mixed recycled HDPE (70%) and PP/PS (30%) led to a strength of 20.74 MPa.36 Clearly, in relevant applications, HDPE makes a significant contribution to the strength and the mechanical properties of the paver blocks.

Cement bricks made with 30% recycled HDPE showed an average compressive strength of 13.79 MPa. This strength level indicates that the bricks possess moderate structural integrity and can be used for applications where no structural load is anticipated.95 Compared to the HDPE bricks, cement blocks made with 25% mixed waste plastic showed a compressive strength of 17.24 MPa. This suggests that mixed plastics are more suitable for these types of composites. Sand paver blocks made with recycled HDPE (60%) had a compressive strength of 32.6 MPa, while blocks made with a recycled PP/PS (40%) blend, had a significantly lower strength of 10.25 MPa. Cement bricks made with recycled PET (30%) had a compressive strength of 24.7 MPa, indicating the compatibility of PET with cement. The use of acid-treated fly ash with recycled PET (35%) showed an improvement of the compressive strength of the bricks to 86 MPa.68 Recycled PET fibers used in geopolymer and cement composites reported a range of compressive strengths of 30 to 55 MPa, demonstrating the wide range of versatility of PET fibers.70 On the other hand, recycled PET resin composites reported a range of tensile strengths from 10.32 to 109.62 MPa, indicating their suitability for structural use.113 Finally, recycled PET and PE blends showed a compressive strength of 31 MPa, meaning the combination of different recycled plastics can yield blends with useful mechanical properties for some structural applications.112

As a general trend, studies noticed that some waste-plastic based composites exhibited notable trends in compressive and tensile strength.

The filler and matrix types and their corresponding interactions. The plastic matrix type such as HDPE, PP, PET, or LDPE, plays a major role in determining the mechanical properties of the composite. Pet shows the best reinforcement effects in comparison to the other plastics when considering the increase in tensile and compressive strengths of the composites.

Types of fillers and their matrix interactions. Sisal fibers, bagasse, fly ash, red mud, and silica fume also affect the mechanical properties of the composites. Of the industrial byproducts, fly ash and red mud reinforced the composites with a considerable strength increase when reinforced with PET and HDPE.68,113 Among the natural fibers, sisal and hemp had a variable effect with hemp fibers showing a better effect in the polypropylene matrix compared to the sisal fibers.110

Effects of surface treatment and coupling agents. The inclusion of surface treatment (acetylation, alkali treatment etc.) and coupling agents greatly enhance the adhesion of the fiber to the matrix and in turn improve the tensile strength of the composites. Acetylated bagasse and alkali treated fibers showed a significant increase in strength of the composites compared to their untreated counterparts. For HDPE-bagasse composites, coupling agents were also found to enhance tensile strength by improving fiber-matrix compatibility.

Performance with byproducts. The best documented compressive strengths have been attributed to PET and PE composites that employed fly ash, red mud and silica fume as fillers. These industrial byproducts also aid in improving the mechanical performance of the composite while closing the gap to sustainability by reducing the disposal of industrial wastes.

Fiber content optimization. Increasing fiber content does not always result in higher tensile strength, observed with sisal fiber and wood waste composites. Higher fiber loadings caused worse mechanical properties because of fiber-matrix interaction issues and agglomeration.

Sustainability and recycled content. Research found that recycling plastics into composite materials creates a sustainable substitute to construction materials. Specifically, recycling PET, HDPE, and LDPE into composites. While composites with recycled plastics keep competitive mechanical properties, structural application is limited to integration with cement, geopolymer, or sand matrices.

- *Split Tensile Strength*

Experiments showed a linear relationship in fiber-based composites between filler plastic amounts and tensile strength. Tensile strength is affected by fiber matrix adhesion. However, the tensile modulus is affected by fiber orientation, distribution, and aspect ratio.37 The influence of differing amounts of recycled plastic in Wood-Plastic Composites (WPCs) was studied.118 The study identified the impact on tensile strength and modulus of differing amounts of plastic (100%, 90%, 80%, 70%, 60%, and 50%) represented by PP, HDPE, and LDPE in fiber composites.118

If the aspect ratio of the fillers is optimal, improving the interface between the plastic matrix and fillers can strengthen the composite and increase Young's modulus. The measurement of splitting tensile strength is often performed after 28 days of curing.119 Studies show that a reduction of plastic content in bricks by 20% has a positive

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impact on the splitting tensile strength.35 Further reductions tend to negatively impact the strength of bricks. This is because bonding between the sand and plastic is likely affected as the sand content becomes higher than the plastic.

After 10% SiC filler was mixed with glass-epoxy composite, both tensile strength and modulus improved. With composites without filler, tensile strength was 305 MPa and modulus was 12.6 GPa. After the filler was added strength increased to 404.2 MPa and modulus to 13.1 GPa. Coupling agents can also enhance filler dispersion and reduce water absorption, resulting in increased strength. The addition of molten polypropylene as a coupling agent to wood plastic composites increased tensile strength by 60% and 35% for the recycled HDPE/PP composites with 50% wood flour.

- *Flexural Strength*

Flexural strength is used to determine the ability of a composite to withstand shear and impact forces during processing, transport, installation and use as pavement tiles. The flexural strength of different waste-plastic-based composites varies widely due to the type of matrix/post-processing, fiber, and filler materials. Several studies used recycled PET fiber based composites in geopolymer and cement matrices and in some cases included fly ash. These studies reported flexural strength values of 2.4 MPa for 1% PET fiber in a geopolymer matrix with fly ash and 6.3 MPa for a similar case in a cement matrix. It is also notable that increasing the content of PET fiber to 1.5% of the matrix generally led to a reduction of flexural strength as the fiber-matrix bonding was adversely affected with an increase in fiber content.

Composites of recycled PET resin and sand, red mud, silica fume, and fly ash had a flexural strength of 28.11 to 33.29 MPa.113 The strongest resin sample included 35% PET, proving that PET has to some degree a strengthening effect in relation to flexural strength and strength of the composite, when combined with the right balance of fillers.

Recycled expandable polystyrene composites with alkali-treated coir and banana stem fiber reinforcements were also studied.49 Composites with only coir fiber had better flexural performance with a maximum value of 16.42 MPa, while composites with only banana stem fibers had poorer flexural strengths between 6.55 MPa and 8.64 MPa. This shows that coir fiber, in this case, is a better reinforcing fiber than banana stem fiber.

Investigated blends of recycled PET and PE (HDPE + LDPE) and yielded a flexural strength of 20.19 MPa.112 This shows the mixing of recycled plastics can yield composite materials with mechanical properties which can be deemed sufficient for structural applications. Overall, the studies reviewed testify the positive effect of PET and coir fibers in waste plastic-based composites in relation to flexural strength.

- *Thermal Properties*

The thermal stability of waste plastic-based composite materials is pertinent to their manufacture, performance, and application in various industries. Thermal stability bids an advantage to composites that can sustain their mechanical and physical integrity at elevated temperatures. Degradation of plastic composites is characterized by bond scission, which causes an array of issues such as loss of mass, emissions, discoloration, and a reduction in mechanical strength.122

Composites are made of recycled polymers such as PE and PP due to their better thermal stability. PE and PP being saturated polymers can resist thermal degradation to 250°C and 300°C respectively.123 Similarly, PET composites can also be made to sustain temperatures of 250°C, though degradation may occur without stabilizing additives at higher temperatures.102 Increased thermal stability of composites can be achieved by adding glass, carbon, or wood fibers to the composite as they act as thermal barriers and diminish thermal expansion. Inorganic fillers such as talc, clay, and calcium carbonate also aid in improving thermal stability by increasing heat deflection temperature and char formation.124 Thermogravimetric analysis (TGA) and Differential Scanning Calorimetry (DSC) are the most common methods of evaluating the thermal properties of a composite. TGA analyzes the weight loss of a composite over temperature to assess its decomposition, while DSC monitors the thermal flow over a sample to determine the glass transition temperature and thermal stability of a sample.122 An increase in the natural fibers added to polymer composites improved the thermal resilience of the composites as well.125

Composites also have varying processing temperatures depending on the type of plastic.

PP-based composites are better suited for higher temperature processing than PE-based composites, which begin to degrade at ~200°C.123 For products made from plastic waste, such as plastic-sand bricks, processing temperatures are in the range of 105–115°C,35 and final products are good up to 180°C.97 Composite samples exhibited a sharp increase in compressive strength from 0.73 kN at 15°C to 6.24 kN at 60°C, showing temperature had a significant effect on mechanical behavior.36 Maleic anhydride (MA) was used as a coupling agent to improve adhesion in the composites, and resulted in a 16.3°C improvement in the thermal stability of the polymer matrix.115 TGA showed the thermal degradation of the composites was in the range of 400°C to 500°C. The addition of fibers and fillers, as well as compatibilizers, provides significant improvements to the thermal and mechanical properties of waste plastic-based composites and extends the use of these materials to a variety of high temperature applications.

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V. WATER ABSORPTION AND POROSITY

Water absorption (WA) is an important indicator of the durability of concrete blocks.127 The water absorption test typically performed to assess the porosity of a brick aims to quantify the amount of moisture a brick can absorb under the wet condition. The WA by soaking method presented in IS: 3495(P-2)1992 or IS:1077;1992 is the method adopted for determining the water absorption of the manufactured pavement tiles. In this method, the specimen will be dried to a constant weight (mdry) and immersed in water at 27 ± 4°C (or, 27 ± 2°C). The specimen will be weighed periodically for a duration of 72 hours, or until the weight of the specimen showed a change of 1% in 24 hours or more. The water absorption (WA) is determined by the following equation where msoaked is the final weight of the specimen after soaking.

$$WA = \frac{m_{dry} - m_{soaked}}{m_{dry}} \times 100\%$$

Due to high water absorption, composites are susceptible to fungal and microbial attacks, which affect the durability of the composites.129 It is noted that an acceptable value of water absorption of standard bricks is a maximum of 12%. In the building industry, a high value of water absorption is undesirable and may cause fractures and other defects. However, a very low water absorption is also undesirable.130 The porosity of the recycled plastic-sand composites is very low (<5%), since the strong intermolecular bonding of the plastic matrix reduces water absorption.

Waste plastic matrices have an inverse correlation between quantity and porosity. With sand, as particle size increases, so does water absorption due to capillary action. In ternary composites, like plastic-sand-basalt fiber, water absorption decreases with lower porosity due to the addition of basalt fiber. When sand is replaced with polymer, water absorption also decreases due to greater capillary action. The water absorption of blocks made with recycled material was measured to be 1.08% which is lower than the absorption of conventional blocks which is 3.71%. This also meets the Ethiopian and British Standard range of 2%-5%. Composites with 60 wt% rice hull flour also have the lowest water absorption when compared to other fillers like sand flour, sawdust from wood, and sawdust from particle boards.41 For fiber-composites, limiting water absorption can also improve the composite's mechanical properties and durability.132

VI. EFFLORESCENCE

Efflorescence is the formation of a white crystalline deposit on the surface of a material as a result of the migration of soluble salts, in this case, of calcium and sulfate salts and carbonate salts of magnesium, sodium, and potassium. This phenomenon can be found in masonry and cement-based products and can be observed in some waste plastic-based composites, particularly those with reinforcements or inorganic fillers. This involves the migration of salts in solution which can also lead to surface damage and aesthetic deterioration of the composite. The presence of efflorescence in waste plastic-based composites depends on the materials of the composite, external environmental conditions, and the presence of hygroscopic materials.

Although typically seen as a cosmetic issue, efflorescence can point to moisture-related problems that can result in damage such as cracking and peeling over time.134 A brick's high water absorption, even at roughly 10%, can create high salt solution concentration to enter and migrate through the brick's pores, causing deterioration.135 An efflorescence test according to IS 3495: 1992 was performed on the bricks. No efflorescence was observed on the surface.35 King (2019) considered efflorescence harmless, yet moisture-related deterioration deemed efflorescence unacceptable. For this reason, addressing efflorescence in waste plastic-based composites is necessary to ensure the integrity of the composite and inhibit the risk of structural failure.

VII. MIGRATION OF CARBONATION AND CHLORIDE

Corrosion of concrete structures caused by carbonation and chloride penetration is a leading cause of concrete damage. Wasted plastic-based composite materials lose durability and structural integrity in extreme environments as exemplified in industrial and coastal regions. This is of even greater concern for the given materials, as carbonation and chloride penetrate these materials in extreme settings. Carbonation occurs when the CO2 in the atmosphere interacts with the calcium hydroxide in the pores of concrete. The reaction produces calcium carbonate and water. In an accelerated chamber, with relative humidity of 20%, and CO2 at 10%, carbonation occurred at a rate of 5 – 60 mm/year after 21 days to 32 weeks. It was found that there was little difference in the carbonation rates at 1% and 10% CO2, which was supported by TGA and XRD studies. Binding of chloride and carbonation is a reciprocal process. In standard concrete structures, the cement matrix provides a highly alkaline environment that forms a passive protective layer to the steel reinforcements against corrosion. When chloride ions penetrate concrete, corrosion of the steel reinforcements can occur. The penetration of chloride ions is often evaluated by the silver nitrate (AgNO3) colorimetric method. In this method, AgNO3 is sprayed on the concrete to react with chloride, and the depth of penetration is noted by a colorimetric change.

This method will also fail when the concrete's pH is less than 10 or when carbonation penetration becomes greater than the penetration of chloride ions.144 The composition of these waste plastic-based composites and the working conditions for the application affect the composites' durability in the presence of carbonation and the migration of chloride. Thus, the application of waste plastic-based composites in structural systems calls for

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consideration of the above factors in order to minimize the corrosion of the system and maximize its service life.

VIII. CHALLENGES AND FUTURE OPPORTUNITIES OF COMPOSITE MATERIALS MADE FROM WASTE PLASTICS

The use of composite materials made from waste plastics could help mitigate the environmental problems associated with disposal of waste plastics by providing an environmentally friendly alternative to conventional materials that are also less expensive. There are still a number of challenges that the field is facing. The variability and heterogeneity of waste plastics are an example. Waste plastics can come in different types and have different qualities, making consistent production of composite materials difficult.50 Waste plastics can also come contaminated with debris that can also negatively impact the quality of produced composites. This problem can be alleviated by the development of better sorting and purification techniques.51 Additionally, mechanical properties of composite materials produced from waste plastics can be an issue in that they could be low as compared to virgin plastic materials, while still relatively strong and durable. The value of the materials can be negatively impacted by the subpar properties of the materials as a result of poor selection and low optimization of the manufacturing process.44 The field also suffers from a lack of infrastructure and technology for the effective recycling of composite materials.36 Composite materials made from waste plastics can also face a lack of established practice and market demand due to low confidence and perceptions in the value of the materials. Education in the form of outreach, seminars, and other dissemination of information is necessary to bring about better confidence in the value of the composites made from waste plastics, and to bring about a sustained positive impact on the environment.86 Notwithstanding the challenges, the future of composite materials made from waste plastics is bright.

Research and development can remove current barriers and maximize the opportunities within the current technology. Focus in the following critical areas will streamline the adoptability of this technology:

- *Advanced Recycling Technologies:*
  Innovative recycling technologies designed to selectively separate waste plastics from useful constituents.

- *Characterization of Plastic Waste:*
  Standardized procedures to characterize the quality and consistency of waste plastics.

- *Composite Design:*
  Tailoring the composition and processing of composite materials and their intended use.

- *Improving Waste Plastics Composites:*
  New methods to enhance the mechanical performance of waste plastics composites.

- *Applying Circular Economy Principles:*
  Waste plastics being recycled and reused.

- *Raising Public Awareness:*
  Understanding the concerns regarding the negative environmental impact of waste plastic composites and the advantages of utilizing composite materials derived from waste plastics.80

IX. CONCLUSIONS

Experiments showed a linear relationship in fiber-based composites between filler plastic amounts and tensile strength. Tensile strength is affected by fiber matrix adhesion. However, the tensile modulus is affected by fiber orientation, distribution, and aspect ratio.37 The influence of differing amounts of recycled plastic in Wood-Plastic Composites (WPCs) was studied.118 The study identified the impact on tensile strength and modulus of differing amounts of plastic (100%, 90%, 80%, 70%, 60%, and 50%) represented by PP, HDPE, and LDPE in fiber composites.118

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After 10% SiC filler was mixed with glass-epoxy composite, both tensile strength and modulus improved. With composites without filler, tensile strength was 305 MPa and modulus was 12.6 GPa. After the filler was added strength increased to 404.2 MPa and modulus to 13.1 GPa. Coupling agents can also enhance filler dispersion and reduce water absorption, resulting in increased strength. The addition of molten polypropylene as a coupling agent to wood plastic composites increased tensile strength by 60% and 35% for the recycled HDPE/PP composites with 50% wood flour.

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