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Review

Solid waste recycling and organic particulate hybrid nanocomposite technologies for sustainable infrastructure—A comprehensive review

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Abstract: Solid waste has become a major environmental concern globally in recent years due to the tremendous increase in waste generation. However, these wastes (e.g., plastics and agro-residues) can serve as potential raw materials for the production of value-added products such as composites at low cost. The utilization of these waste materials in the composite industry is a good strategy for maintaining the sustainability of resources with economic and environmental benefits. In this report, the environmental impacts and management strategies of solid waste materials are discussed in detail. The study described the benefits of recycling and reusing solid wastes (i.e., plastic and agro-waste). The report also reviewed the emerging fabrication approaches for natural particulate hybrid nanocomposite materials. The results of this survey reveal that the fabrication techniques employed in manufacturing composite materials could significantly influence the performance of the resulting composite products. Furthermore, some key areas have been identified for further investigation. Therefore, this report is a state-of-the-art review and stands out as a guide for academics and industrialists.

Keywords: solid waste; value-added products; sustainable infrastructure; nanocomposite technologies; organic particulate

1. Introduction

Solid waste management has been a major concern globally in recent years due to the increasing waste generation. Examples of solid waste materials include plastic waste, food waste, chemicals, glass, and metal waste [1], and agro-waste. Solid wastes are known to cause pollution issues that act as threats to human health and the ecosystem [2]. The increasing amount of municipal solid waste (MSW) is ascribed to the rapid socio-economic growth and improvements in the standard of public living in a country like China, as reported [3]. However, the efforts to manage these waste materials are low compared to the quantity of MSW generated [1]. Therefore, efforts should be intensified by employing various waste management strategies, especially sustainable approaches.

Agro-waste such as coconut husk, cotton stalk, corn husk, rice husk, and wood waste is eco-friendly, cheap, nonabrasive, sustainable, and biodegradable. The materials are usually burned or destined for landfills, thereby posing pollution issues [2]. However, several researchers [4–6] have proven the feasibility of using these materials as reinforcements for polymer matrices in the polymer industry. Despite the numerous benefits of these materials, they are still regarded as waste materials and are therefore left to decay or burn after the harvest season. Kang et al. [7] reported that over 20 million tons (dry weight) of cotton stalks are generated in China per year, the majority of which are either burned or left to decay without being fully utilized. The utilization of these biomass materials as reinforcing agents for polymer matrix in the composite industry could be a good strategy for waste management as well as providing additional income to rural farmers.

Petroleum-based plastics are commonly used to produce household materials such as bottles, cups, and pipes due to their lightweight and durability. These plastic materials are estimated to generate about 150 million tons per year as plastic solid waste at the global level [2]. However, this large volume of plastics commonly regarded as household waste could serve as matrices for organic fillers if properly sorted and recycled. The utilization of these plastics in the polymer industry will prevent resource depletion and offer both economic and environmental benefits [2,8] compared to their virgin counterparts.

Nanoclay is gaining attention in the polymer industry as a modifier due to its enhancement properties, such as thermomechanical properties, barrier properties, fire retardancy, and thermomechanical properties [2]. Nanoclay as a layered silicate in the nanoscale diameter range is reported in the literature [6] to significantly improve the performance of plastic materials at a small quantity ($\leqslant$5 wt%) due to its large aspect ratio. Some examples of nanoclays include saponite, hectonite, montmorillonite (MMT), and nontronite.

The mechanical performance of biocomposite products depends on the nature of the components as well as the processing techniques. For example, a good dispersion of fibre/filler in a composite system that will ultimately improve the tensile and flexural properties can be obtained through injection molding [9]. Therefore, choosing an appropriate fabrication technique is critical to the development of improved biocomposite products. The commonly known processing techniques as well as novel approaches reported in the literature are discussed in this review.

Although several solid waste materials and their treatment technologies are reviewed in published papers [1]. Other reviews [10–12] that discussed the fabrication techniques of natural fibre-reinforced composites exist in the literature. However, not all techniques used in natural fibre-reinforced composite production are suitable for natural particulate hybrid nanocomposites. For example, the compression molding manufacturing process is suitable for composites containing long fibre lengths but may not be appropriate for particulate filler-filled reinforced composites. Therefore, a review of the emerging technologies for the production of natural particulate hybrid nanocomposite from plastic waste, nanoclay, and organic filler particles (i.e., from agro-waste) is critical, as the performance of the developed composites is dependent on the manufacturing process employed. This paper seeks to review the recent advances in fabrication technologies involving the use of plastic waste and agro-waste as promising raw materials for the production of natural particulate hybrid nanocomposites for sustainable infrastructural applications. Therefore, the objectives of this work are to:

- Discuss the environmental impacts and management of solid waste materials.
- Discuss solid waste materials (i.e., plastic and agro-waste) as emerging raw materials in the polymer industry.

- Review the emerging fabrication approaches for organic particulate hybrid nanocomposites.

2. Environmental impacts of solid waste materials

Emission of greenhouse gases (GHGs) such as carbon dioxide, methane, volatile organic compounds, nitrous oxide, and sulfur dioxide are caused by inappropriate management of municipal solid waste [13,14]. The atmospheric methane concentration is increasing at a rate of 2% per year, making it one of the major contributors to the greenhouse effect [15]. Methane emissions from landfills comprised 3%–9% of global anthropogenic sources [16]. Despite claims that methane is not harmful to plants, vegetation in areas affected by landfill gas emissions experiences negative effects. When landfill waste decomposes, methane displaces oxygen in the atmosphere, while carbon dioxide leads to a condition where plants experience oxygen deficiency in their root environment [17]. On the contrary, studies have demonstrated that plants can thrive when exposed to carbon dioxide concentrations below 5%, even though the soil typically contains less than 2% of this gas [18]. However, it is important to note that higher concentrations of carbon dioxide, exceeding 20%, are considered phytotoxic and can have detrimental effects on plant growth and health [19]. Landfils elevated carbon dioxide levels can threaten nearby plants, especially their delicate roots, even with sufficient soil oxygen [20]. Approximately 60% of methane and 40% of carbon dioxide (CO_2) emissions from organic materials in waste dumps and landfills occur during anaerobic decomposition [21]. This process also generates trace gases such as carbon monoxide, nitrogen, oxygen, hydrogen, and hydrogen sulfide [22,23] and is regarded as environmentally dangerous [19].

Furthermore, the accumulation of municipal solid waste can indeed cause leachate plumes. Leachate is the liquid that forms when water percolates through waste materials in a landfill or dumpsite. It contains various pollutants and can pose a significant threat to groundwater and surface water if not properly managed. Leachate plumes commonly contain high concentrations of organic carbon, including ammonium and dispersed phenols [24]. Leachate plume generation is affected by different variables such as waste composition, temperature, precipitation, population densities, and amount of moisture [25]. The composition of leachate and the contaminant itself significantly influence pollutant migration. Similar chemical pollutants in leachates, complex mixtures of compounds and pollutants, may behave similarly due to co-contaminant influence [26].

Leachate can seep into the surrounding soil and contaminate groundwater. This can happen due to factors such as inadequate landfill liners, the absence of leachate collection systems, and improper waste disposal practices. Leachate plumes can develop when water-carrying pollutants from the waste site move through the soil, spreading the contamination [27]. Researchers identified two distinct leachate transport routes within the landfill after further investigations [28,29]. The movement of pollutants through defective soil membranes can occur via advection and dispersion, while organic pollutants can move through soil membranes via diffusion. Improper garbage disposal has a growing impact on the environment and human health, especially in developing countries. To mitigate greenhouse gas (GHG) emissions and acidification of ecosystems caused by ammonia release, environmentally friendly municipal solid waste (MSW) management techniques are being implemented.

3. Municipal solid management techniques

Waste management practices that follow the principles of sustainable development and recognize waste as a valuable resource are essential. Municipal solid waste management has gained significant attention due to the production of approximately 450 million tonnes per year [30]. To achieve an effective waste management system, it is necessary to consider specific factors such as waste characteristics, efficient collection systems, appropriate processing infrastructure, proximity of materials for recovery, adherence to emission standards, cost-effectiveness, and community involvement [30,31]. Waste management methods worldwide primarily include landfilling, composting, recycling and reuse, and incineration, as shown in **Figure 1**. The solutions for proper waste treatment are influenced by factors such as population density, income levels, and available infrastructure. Landfilling remains the most used approach, responsible for approximately 40% of global waste disposal [32]. Approximately 19% of waste undergoes recycling and composting for recovery, while 11% is treated through modern incineration methods [33]. Regrettably, a portion of waste is still handled through open dumping and burning practices. The various solid waste management approaches, as well as their merits and limitations, are presented in **Figure 1** and **Table 1**, respectively.

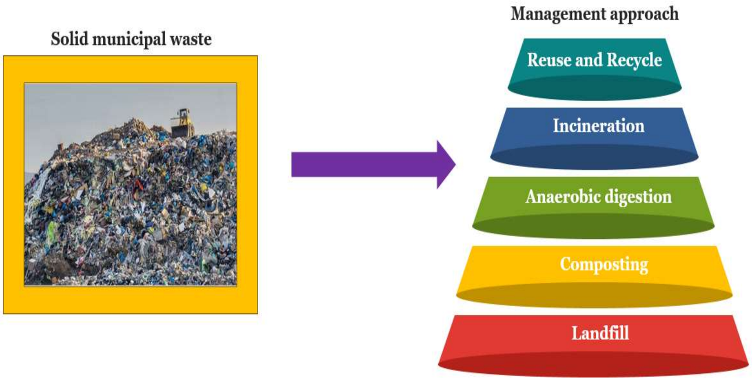

Figure 1. Different management approach for solid municipal waste.

Table 1. Merits and limitations of the different treatment technicities.

Types of technique	Merits	Limitations
Composting	It has cost benefits due to its low operational costs. It can serve as a source of organic manure.	It is suitable for only organic waste and this is a limitation.
Anaerobic digestion	Emission of greenhouse gases is low. Biogas can be utilized for power generation.	It requires high operational costs and maintenance.
Landfilling	It requires low operational costs. Landfill gas can be used for electricity generation. It can be used for any type of waste stream.	It poses the risk of groundwater and soil contamination. It leads to land degradation and reclamation of such land requires huge capital.
incineration	Easy setup and fast treatment. Energy/steam production from the heat generated. Suitable for any type of solid waste.	It is a source of pollution.
Recycling and reuse	It is a sustainable approach with both economic and environmental benefits.	Sorting of waste materials is very cumbersome and therefore, requires lots of effort.

3.1. Landfills

Landfills are traditionally designed to ensure the safe storage and disposal of waste materials [34]. Landfill characteristics are influenced by a range of environmental factors. However, the primary challenge with landfills lies in identifying a suitable location due to the increased disruptions in the physiochemical properties of the soil compared to the surrounding land [35]. Modern engineered landfills utilize a waste control liner system to create a protective barrier separating the waste from the surrounding environment. These landfills are equipped with gas and leachate collection systems to effectively manage these byproducts. After the waste deposition is complete, a final cover is implemented [36]. The management of closed landfills involves the continuous monitoring and regulation of emissions like gas and leachate, as well as the assessment of factors such as surface water, groundwater, soil, and air quality [37]. Additionally, it is crucial to maintain a stable facility for the collection of leachate and waste gas.

The landfills are classified into different categories by the Environmental Protection Agency of the United States.

- Municipal Solid Waste Landfills (MSWLFs): Household, commercial, and nonhazardous materials are among the waste categories that are accepted at these sites. These landfills are subject to operating, closure, and post-closure care requirements, which are governed by the state in which they are located [37,38]. Closure involves implementing a final cover system to minimize liquid infiltration and soil erosion. Post-closure care aims to prevent the release of hazardous constituents by monitoring and maintaining the landfill diligently [39].
- Bioreactor landfill sites: Bioreactor landfills are a type of municipal solid waste landfill (MSWLF) that uses liquid additions to promote waste breakdown by bacteria [40]. This differs from traditional dry landfills. The introduction of liquids and air enhances microbial processes, resulting in increased waste degradation and stabilization [40]. The advantages of bioreactor landfills include accelerated waste decomposition, potential space savings (up to 30% compared to traditional landfills), and cost-effectiveness [41]. However, the increased moisture content may impact the landfill’s structural stability by increasing pore water pressure [40,42]. Proper management is crucial, including liquid addition and other strategies like waste shredding, pH adjustment, nutrient balance, and temperature control. Successful operation requires focused plans to optimize bioprocesses and ensure effective functioning [42].
- Sanitary landfills: Industrial waste landfills are designated areas where non-hazardous industrial waste, including solid waste from manufacturing, is disposed of. These landfills are capable of handling substantial amounts of waste, including construction and demolition waste and hazardous waste [43]. The primary objective of industrial waste landfills is to create a controlled environment that ensures proper waste disposal and minimizes any negative impacts on the ecosystem. They adhere to engineering and sanitary landfill principles, incorporating modern design, stricter regulations, and specific operational procedures. Design specifications for these landfills include the use

of compactors, plastic coverings, double liners, gas, and leachate collection systems, as well as the monitoring of groundwater quality [44].

- Hazardous Waste Landfills: Hazardous waste landfills are specifically designed facilities that prioritize the safe disposal of non-liquid hazardous waste, ensuring no chemical release into the environment [45,46]. These landfills adhere to design standards, including leak detection and collection systems, as well as measures to prevent any potential issues. Closure and post-closure care, such as maintaining a final cover, operating the leachate collection system, and monitoring groundwater quality, are also essential requirements [46,47]. It is important to note that hazardous waste landfills differ from municipal solid waste landfills, as they are subject to separate regulations [48].

Landfills are responsible for the production of methane, nitrogen dioxide, sulfur dioxide, ammonia, carbon monoxide, hydrogen sulfide odor, and particulate matter. These pollutants present a significant hazard [49]. Moreover, the constraints on available land and the recognition of waste as a valuable resource are compelling factors that drive the transition from traditional landfilling practices to more sustainable waste management strategies.

3.2. Composting

Among the various components of municipal solid waste, which encompass domestic waste, agricultural waste, yard debris, and process waste, organic waste, which encompasses domestic waste and agricultural waste materials constitutes the largest proportion of the total solid waste generated [50]. Effectively managing organic solid waste is crucial for achieving sustainable and environmentally friendly waste disposal practices [51]. Composting, as a simple technique for managing organic waste as shown in **Figure 2** [52], involves the controlled decomposition of organic matter by microorganisms such as bacteria, fungi, algae, and protozoa [53]. This process yields compost, which serves as a beneficial soil amendment [54]. The composting processes are influenced by multiple factors based on the composition of the composting mixtures and environmental conditions (temperature, oxygen content, and pH levels) [55,56].

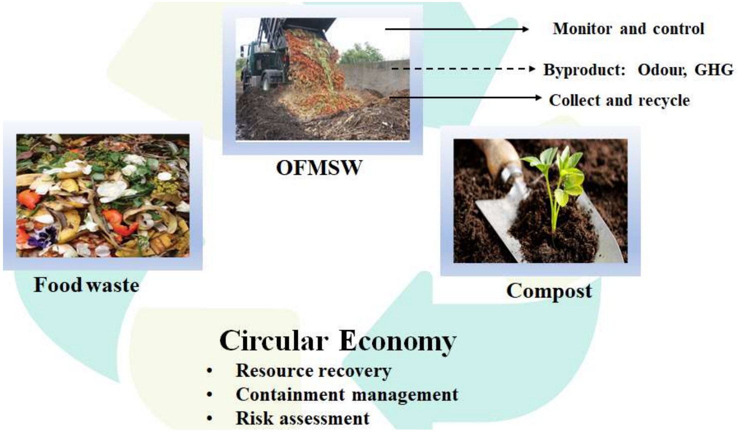

Figure 2. Compositing process of Municipal solid waste [52] with modification.

Composting can be conducted aerobically or anaerobically, depending on oxygen availability. Aerobic composting involves the aerobic microbial oxidation of organic materials, resulting in the production of carbon dioxide, nitrite, and nitrate. Under specific aerobic conditions, biological processes regulate organic matter to generate valuable products [57]. Microorganisms reduce and break down organic molecules in anaerobic environments. The resulting product slightly oxidizes when applied to the land. Municipal solid waste composting provides a reliable source of manure for crop growth. Common aerobic composting techniques include windrow composting and vermicomposting [58]. Composting facilitates the reduction of waste volume, eliminates weeds, and kills harmful bacteria [59]. Composting municipal solid waste enhances soil nutrients, soil organic carbon (SOC), and the biomass and activity of soil microbes. Furthermore, it is essential for controlling the cycles of phosphorus (P), nitrogen (N), and carbon (C) by affecting the activity of important enzymes [60].

Despite the advantages of composting, there are several drawbacks to consider. The challenges include greenhouse gas emissions (methane and nitrogen oxide), nitrogen release as ammonia gas, and potential environmental hazards from contaminants in compost substrates [57,61]. To mitigate these issues, various approaches are being explored, such as implementing different aeration methods, using bulking agents, and optimizing the formulation of the substrate and feedstock to ensure optimal conditions for sustainable composting. The composting sector is experiencing industrialization, characterized by the expansion of operations and the production of superior-quality products. However, compost needs to adhere to specific criteria to guarantee its safety and appropriateness as a biofertilizer for soil. The focus on quality control has led to the establishment of new alliances between composters and other businesses, which encourages creativity in the creation of customized compost materials appropriate for a range of agricultural uses, such as mulching, general purpose farming, and vegetable farming. Even though industrial composting has received a lot of attention, small-scale home composting must also be acknowledged.

3.3. Anaerobic digestion

The process of anaerobic digestion, also known as bio-methanation, breaks down organic molecules in the absence of oxygen, producing methane and carbon dioxide as important byproducts **(Figure 3)**. The resulting residue, referred to as digestate, is highly valuable and can be effectively repurposed as a potent fertilizer or enhancer for soil quality. One of the most impressive aspects of anaerobic digestion is its remarkable capacity to produce a significant quantity of methane, constituting approximately 55%–60% of the overall output. This method is particularly employed for solid waste generated by agriculture-based industries to produce fertilizer and biogas. The primary outcome of bio-methanation is biogas, which comprises 25% of CO_2, 60% of methane, and 15% of other gases like H_2S and NH_3 [62]. This biogas serves as a versatile resource, capable of being utilized as both electricity and cooking fuel. Approximately 2040 W and 2014 W of electricity can be generated from 1 m^3 of biogas through anaerobic digestion [63] and bio-methanation [64] at a conversion efficiency of 35%. Several studies have suggested that the co-digestion of municipal solid waste (MSW) with food waste can enhance biogas production [65]. Purifying biogas generated from anaerobic digestion improves its quality and makes it a viable substitute for natural gas in industrial and household applications. Anaerobic digestion is widely used for energy recovery from high-moisture municipal solid waste (MSW), particularly in developing countries, and is applied in the treatment of animal and plant waste as well as sewage [66]. Therefore, anaerobic digestion is an effective technique for energy recovery.

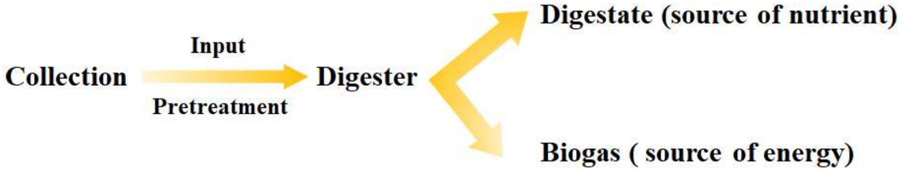

Figure 3. Anaerobic digestion process [67].

3.4. Incineration

The process of incinerating garbage involves burning organic materials at a high temperature to produce fly ash and bottom ash as byproducts. In contrast to bio-methanation, incineration typically occurs at temperatures ranging from 800 °C to 1200 °C in the presence of air and excess oxygen. The waste undergoes multiple steps to transform it into CO_2, water, non-combustible products, and solid residues. To highlight the significance of moisture content, the first step involves removing excess water from the biomass. During the devolatilization process, the biomass is broken down to produce carbon dioxide, water vapor, hydrogen, carbon monoxide, and methane. These organic compounds can be further oxidized to generate heat, while the carbon and hydrogen components produce CO_2 and water [68]. The incineration process can effectively treat all types of waste with a high calorific value and low moisture content.

Due to limited land availability for landfilling, alternative waste disposal methods such as incineration have been adopted. Incineration helps mitigate issues such as land degradation, methane gas production, and leachate generation that are often associated with inadequate landfilling practices. It is particularly efficient in managing non-biodegradable waste with low moisture content [69]. Incineration is a valuable method for both volume reduction and energy recovery, as it can reduce waste volume by 70%–90% while capturing energy for power generation [70].

The drawback of incineration is the significant expenses associated with the technical, and operational aspects of incineration plants, particularly for lower- to middle-income countries that may struggle to afford the establishment and maintenance of such facilities [71,72]. This results in the production of poisonous gases such as NO_x and CO_2 [73]. However, there are technologies readily available to control gaseous emissions and mitigate the environmental impact caused by these gases.

3.5. Reuse and recycle approach

Solid waste management options also consist of recycling and reuse [74]. Recycling is a method of managing waste that entails gathering, treating, and converting waste materials into fresh items. Its goal is to decrease landfill waste, conserve natural resources, and mitigate environmental harm. Recycling enables the recovery and reutilization of materials like paper, plastics, glass, and metals, reducing the necessity for raw material extraction and energy consumption. This waste reduction approach not only aids in waste management but also supports the development of a sustainable and circular economy [75]. Recycle rates are often greater and more effective in developed countries than in underdeveloped ones. This is mostly because there are excellent collecting services and facilities with the necessary equipment for sorting and processing. These recycling facilities are widespread, subject to regulations, and outfitted with cutting-edge technology in industrialized countries. On the other hand, developing nations frequently lack the infrastructure necessary for garbage recycling and treatment, which leads to the open disposal of waste into the environment [76]. The recycling process is commonly carried out informally.

Reusing is a waste management strategy that involves finding new ways to use items or materials instead of throwing them away. It is a sustainable approach that aims to extend the lifespan of products and reduce the amount of waste generated. Reusing helps protect the environment, save energy, and conserve resources. Reuse can take many forms, such as repairing broken items, donating unwanted items to others, or repurposing materials for different purposes. It is a crucial tactic in the hierarchy of waste management because it fosters a more sustainable and circular economy by lowering the demand for new production and consumption [75]. Composting and vermicomposting are popular methods for reusing organic solid waste. The resulting composts and vermicomposts can be used as manure for agricultural purposes. These methods are cost-effective and well-suited for managing solid waste in developing countries, where there is a high proportion of organic waste. Developed countries have witnessed a rise in composting facilities, with certain European countries experiencing composting rates increasing by over 50% between 1995 and 2007 [77]. The implementation of these principles is beneficial in reducing waste generation from various sources, while also mitigating the associated risks to human health and the environment.

4. Solid waste materials as emerging raw materials in the polymer industry

Plastic and agricultural wastes are solid waste materials that are emerging as potential raw materials for the production of composite products in the polymer industry owing to global environmental and resource problems. According to Nassar et al. [78], the efficient utilization of solid wastes leads to the reduction of environmental degradation and waste hazards, which in turn improves the quality of the ecosystem. Meanwhile, Deka et al. [79] have stated that one of the processes to reduce environmental pollution issues is recycling and reusing. Recycling enables the various properties of recycled plastic materials to be improved by combining them with biomass materials. Thus, taking into account the benefits of recycled plastics and agro-residues, these solid waste materials can be used to produce low-cost, sustainable, and eco-friendly composite products, as illustrated in **Figure 4**.

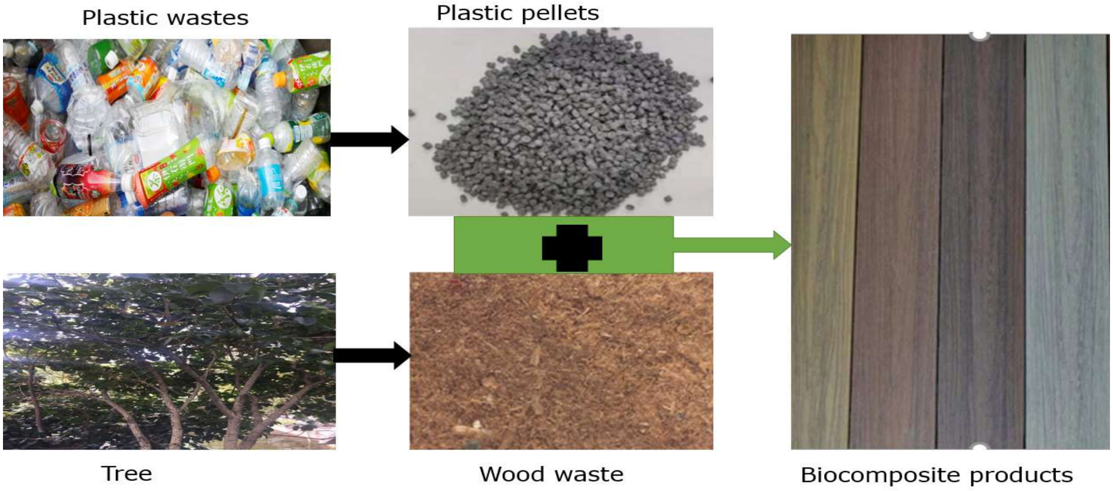

Figure 4. Biocomposite products from solid waste materials.

An investigation by Kazemi et al. [80] revealed that the tensile, flexural, and torsion modulus of the un-compatibilized wood plastic composites (WPCs) were higher than those of the neat polymer due to the stiffness invoked by the wood flour. However, the inclusion of wood filler led to a decrease in the tensile strength, elongation at break, and notched impact strength due to the poor interfacial interactions between the wood flour and the plastic matrix. It was further reported that the addition of compatibilizing agents led to an increase in the tensile strength even as filler loading increased, which was contrary to the case of uncompatibilized ones. The improvement in tensile strength is due to the enhanced interfacial bonding brought about by the reduction of the interfacial tension through the treatment with the compatibilizing agents, as revealed by the scanning electron micrographs (see **Figures 5** and **6**). Overall, the authors have demonstrated the possibility of using wood dust and municipal plastic wastes for the production of wood plastic composites.

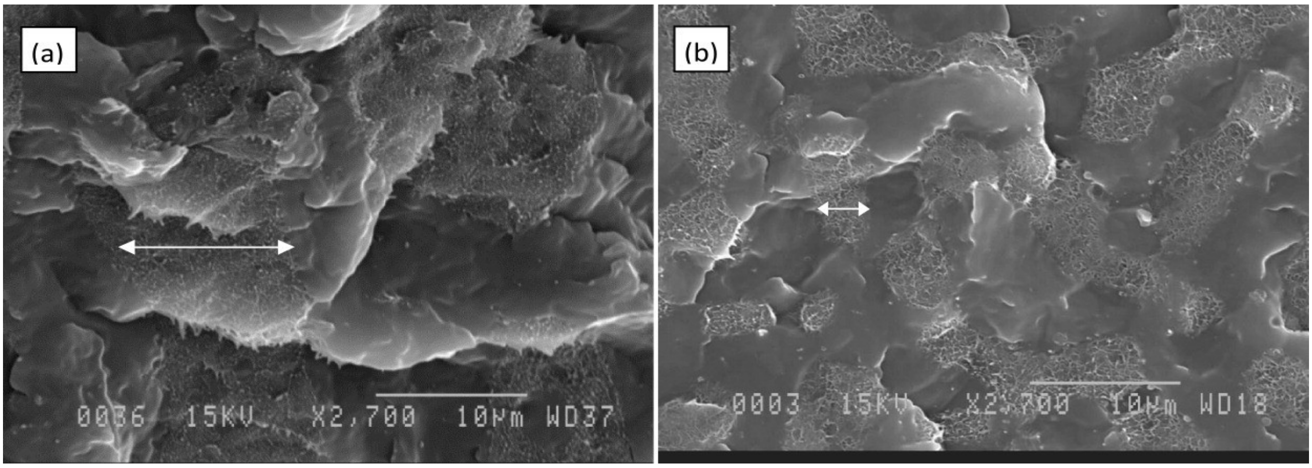

Figure 5. Typical SEM micrographs of the recycled light fraction plastics: **(a)** without compatibilizer and **(b)** with 5 wt% of EOC. The arrows indicate typical domain sizes in SEM micrographs [80].

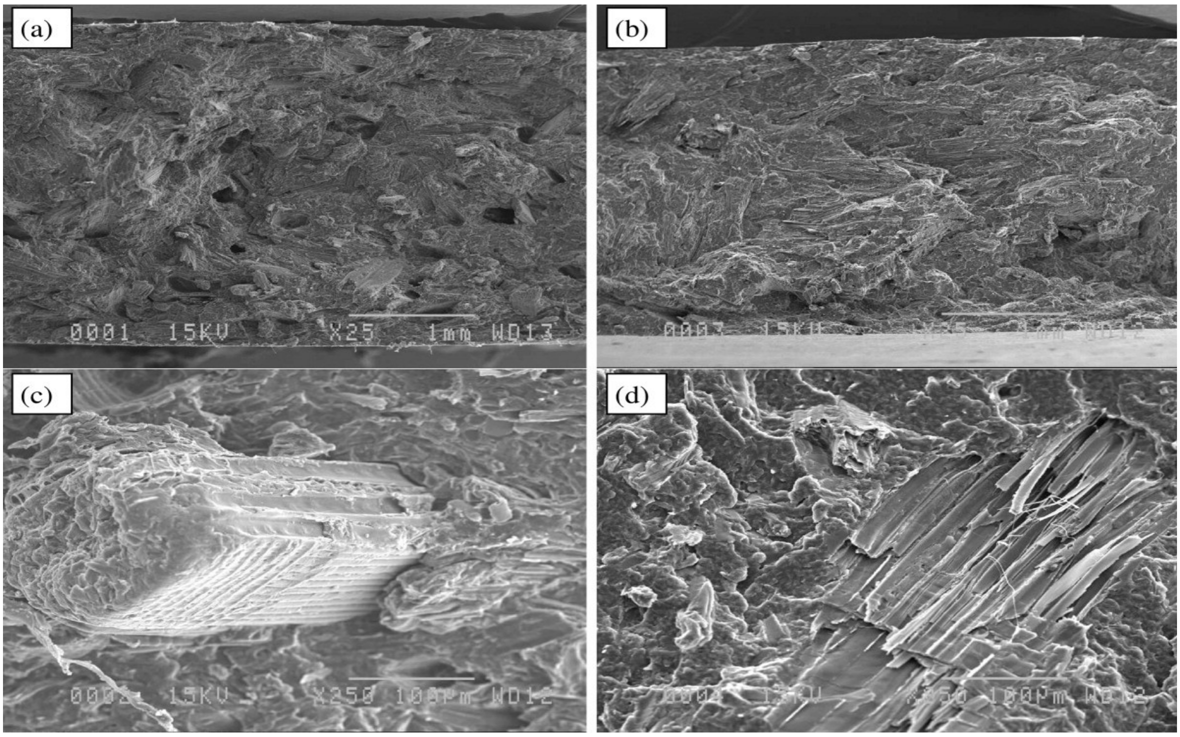

Figure 6. SEM micrograph of composites with 40 wt% wood flour: **(a,c)** without coupling agents and **(b,d)** with additives [5 wt% of EOC and 5 wt% (MAPE/MAPP: 80/20)] at different magnifications [80].

4.1. Agricultural residues as reinforcing agents in composite production

Biomass waste materials are unavoidably generated and are usually destined for landfills or burning, thereby constituting a significant part of the pollution problem. However, the utilization of these materials for the production of value-added products (e.g., biocomposites) can contribute to a safer environment [81] with economic benefits. Literature shows that these cheaply available bioresources are yet to be fully utilized in the research community. These biomass materials, commonly regarded as agro-residues, could potentially serve as raw materials for composite production with sustainable structural applications. Therefore, there should be a continuous effort to utilize these agricultural waste materials as fillers (either in a single or combined form) in the composite industry for the benefit of mankind.

The use of natural fillers (obtained from agro-waste) as reinforcing materials in the polymer matrix stems from the present demand for high-performance green composites [82]. Countries such as China, the USA, the UK, Europe, and other government agencies encourage the use of green composites with several natural sources [83–87]. Due to the global emergency of energy and the dangers of CO_2 emissions, there is an urgent need to develop composite materials that are sustainable and environmentally benign. This has necessitated scientists in the field of green composites to produce new materials from nature itself that allow for the reduction of the carbon emission effect [88–91] and energy demand at the lowest cost of production. As such, the use of green fillers as reinforcement materials is increasingly gaining attention as substitutes for their synthetic counterparts (e.g., glass, carbon, aramid, etc.) in composite material production. The commonly available green fillers include; agro-residue powder (cotton stalk powder, coconut shell powder, rice husks, date seed, cashew nuts powder,), bast fibers (hemp, kenaf, flax, abaca, jute, banana bark, cotton stalk bark), grass fiber (bamboo, vetiver grass, elephant grass, napier grass), and leaf fiber (sisal, pineapple) [82,92–95]. Natural plant-derived fillers, in comparison to other fillers, are generally suitable for reinforcing plastics due to their relatively high specific strength and modulus, lightweight, good biodegradability, environmental benignity, renewability, low cost, low density, and low carbon dioxide emissions, which are very desirable these days [82,86]. Thus, green product-based polymeric matrices have become the emerging innovative products and potential candidates for the replacement of synthetic composites in structural and semi-structural applications like construction, aviation, and automobile industries, as well as in sporting facilities, decking, furniture, and several electronic appliances [82,85,96]. The use of lignocellulose fibres/fillers as reinforcements for plastics will continue to be an important area of research as the demand for biocomposite products is on the increase due to the numerous benefits they possess [97]. However, these natural fillers/fibers have some setbacks that limit their widespread application in the polymer composite industry [82]. These limitations include poor compatibility, poor thermal stability, hydrophilicity, low durability [85], and lower mechanical properties when compared with synthetic fibers/fillers [82]. The weak interfacial properties and poor moisture resistance of the green fillers are the results of the hydrophilicity of the biological organic materials due to the presence of hydroxyl functionalities in them [82], which are incompatible with the polymer matrix being hydrophobic. So, when the natural filler/fibre is incorporated into the polymer matrix, a poor fibre/matrix interfacial bond strength is formed due to the differences in the polarities of the biomass material and the polymer matrix [2]. Furthermore, water or moisture may easily penetrate the inside of the composites through the matrix/filler interface and affect both the short- and long-term properties of the polymer composites [82]. As a consequence, there is a high tendency for polymer-based composites to undergo degradation if used for outdoor applications [98].

Due to the drawbacks mentioned above, Nourbakhsh and Hosseinzadeh [99] suggested two possible ways of improving the mechanical integrity of filler-filled polymer-based composites, namely, by altering the filler's particle size via size reduction and by applying compatibilizing agents. These treatment approaches are discussed in detail in the published literature [2].

4.2. Plastic waste as structural matrices for natural filler/fibre in composite production

Plastics are classified into two main groups, namely, thermoplastics and thermosets [2], which are used in the manufacturing of biocomposite products. However, due to the low degradation temperature (about 220 ℃) of the biomass material, thermoplastics are preferable. Elsheikh et al. [11] suggested that to avoid the disintegration of the cellulose chains of the natural filler/fibre, the processing temperature of the plastic materials should not exceed 200 ℃. Examples of such polymers include high-density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), polystyrene (PS), and low-density polyethylene (LDPE). The waste materials of these plastic products, which contribute to a significant volume of municipal solid waste, can be used as structural matrices in composite manufacturing when sorted and recycled. These plastic wastes, when recycled and reused can offer cost and environmental benefits as well as resource sustainability. Singh et al. [100] stated in their report on recycling plastic solid waste that the production of virgin plastics is energy-demanding and has the capacity to eliminate fossil fuels. Similarly, Kreiger et al. [101] reported that the annual production of virgin plastics (in the form of stored potential energy) requires about 1.3 billion barrels of crude oil, which is estimated to be 4% of the world's oil production. Also, it was noted in the published work [100] that plastics, which constitute a major part of MSW, are increasing daily as new plastic products emerge in the market. This poses a threat to the environment with the consequence of releasing CH_4 and CO_2 (i.e., greenhouse gases). Nevertheless, several environmental advantages can be obtained by using recycled plastic in the production of composite materials, including an extension of the plastic's service life, a reduction in waste, the avoidance of resource depletion, and a contribution to the advancement of waste recycling [8]. Thus, the utilization of recycled plastic waste as a matrix in natural particulate-reinforced polymer composites is a good way to obtain economic and environmental benefits.

The feasibility of using municipal plastic waste materials for the production of low-cost composite products is reported in the literature. For example, Turku et al. [102] investigated the possibility of using recycled plastic waste in the fabrication of wood plastic composites (WPCs). It was reported that the strength of the composites containing recycled plastic waste was inferior to that of the virgin composites. However, the stiffness of the recycled composites was superior to that of the reference. In another study, it was reported that recycled blends of low-density polyethylene (LDPE) and polypropylene (PP) exhibit tensile properties similar to their virgin counterparts, with PP giving more rigidity to the blend and acting as reinforcement in the LDPE matrix [103]. A research study carried out by Schürmann et al. [104] revealed that the impact strength of the blends of high-density polyethylene (HDPE) and isotactic polypropylene (ipp) in a mixing ratio of 60:40 wt% doubled that of pure ipp.

5. Nanoclay as a component of hybrid nanocomposite material

Nanoclays play an essential role in the improvement of the mechanical, thermal, and barrier properties of hybrid nanocomposite materials. The size, shape, filler loading, as well as compatibility with the polymer matrix, are the critical factors that determine the reinforcement property of nanoclay in hybrid nanocomposite products [105]. Therefore, the aforementioned factors should be optimized to obtain maximum performance of the resulting nanomaterials. The feasibility of using nanoclay as a reinforcement for the enhancement of the performance properties of the developed hybrid material is reported [4,6,106]. In the report of Zhong et al. [6], it was stated that a small quantity of nanoclay of approximately 5 wt% is sufficient to greatly improve the performance of the resulting nanocomposite products without affecting the processability and density. Detailed information on nanoclay exists in published reviews [2,105].

6. Fabrication technologies

The use of organic particulate fillers as replacements for their inorganic counterparts is gradually gaining momentum in the scientific community due to their economic and environmental benefits [2]. The performance of the resulting composite products is influenced by the component elements and processing techniques employed. The selection of the type of fabrication technology to be used will be a decision based on a careful evaluation of the various manufacturing methods.

6.1. Adhesive mechanism between the plastics and fillers during the fabrication process

The fabrication process can be defined as the process of manufacturing composite materials by reinforcing polymeric matrices with fillers. The formation of composite products is made possible because, during the manufacturing process, heat is generated, which melts the thermoplastic [2] to become fluidized and then wets the filler particle surfaces [107]. Following wetting, the polymer will spread over the particle surface to form a continuous phase and consolidate. Upon conditioning, good adhesive bond strength at the interface between the polymer and the filler particles is realized.

6.2. Types of processing techniques

There are several processing methods employed in the fabrication of natural particulate hybrid nanocomposite products. These include powder impregnation through compression molding, extrusion followed by injection molding, extrusion followed by compression molding, and solution blending. The various processing technologies and their merits and demerits are herein discussed.

6.2.1. Extrusion followed by injection molding

This method involves two stages, namely, extrusion and injection molding. In the first stage, both the filler and the plastic materials are fed into the hopper of the extrusion machine (e.g., a twin screw extruder) and then pass to the heating barrel, where the melting of the polymer occurs. Upon melting, the plastic material will become fluidized and then wet the filler (e.g., wood waste) particle surfaces. Following wetting, the polymer will spread over the particle surfaces through the mixing occurring in the extruder. After spreading, the polymer will penetrate the porous structure of the filler particles [107] to form a blend that is extruded through the die as extrudates in the form of strands. These strands are then passed through a water bath or air cooling unit. Upon cooling, the interfacial bond strength between the fibre/matrix brought about by mechanical interlocking is strengthened. The cooled strands are then pelletized to form composite granules. The second stage involves the use of an injection molding machine. Injection molding of composite products is a manufacturing process by which a known quantity of mixture that contains molten polymer and fibre/filler is forced into mold cavities [12]. Before injection molding, it is always advisable to dry the composite granules to remove any moisture that might interfere with the mechanical properties of the resulting composite products. So, the dried granules are fed into the hopper of the injection molding machine. Upon reaching the heating barrel, the plastic component will melt and mix sufficiently with the filler by the shear forces of the machine and consolidate. The blend of the mixture will be injected through the mold in the form of a dumbbell shape as an injection molded sample for mechanical testing. According to Liu et al. [9], injection molding will promote good dispersion of the filler particles in the polymer matrix, thereby leading to improvements in the tensile and flexural properties. Mohanty et al. [108] stated that the intimate mixing of fibre/filler and matrix, which promotes interfacial adhesion during the extrusion-injection molding process, is one of the major advantages of the technique. However, the shear forces of the machine can damage fibres with long lengths. Therefore, this method is suitable for the manufacturing of natural particulate filler-reinforced polymer composites.

6.2.2. Extrusion followed by compression molding

This manufacturing process also involves two stages, namely, extrusion and compression molding. The first stage is the extrusion process, which has already been discussed above. The second stage is the formation of composite panels from the resulting granules with the aid of an electrically heated platen press, which was conditioned before mechanical testing. During compression molding, it is believed that the plastic will undergo melting and wet the filler. The plastic will consolidate upon cooling, forming a protective covering for the filler in the composite system. The disadvantage of compression molding is that there is no proper mixing of the filler and matrix. Consequently, hollow features are formed on the developed composite product. During mechanical testing, these voids and holes act as stress concentrations, resulting in poor mechanical properties. According to Ho et al. [12], various minor defects such as residual stress, warpage, voids, fibre breakage, scorching, and sink marks could lead to a reduction in the mechanical performance of the composite material. Thus, to reduce the possibility of flaws appearing, material, process, and geometric parameters should be optimized.

Liu et al. [9] in their work on thermal and mechanical properties of kenaf fiber reinforced biocomposites based on injection and compression molding after extrusion revealed that samples prepared by compression molding after extrusion had the same storage modulus as those of injection molded samples at room temperature (i.e., 25 ℃). However, higher heat of deflection temperature (HDT) and superior notched impact strength were observed with compression molded samples.

6.2.3. Solution blending

In this manufacturing process, a suitable solvent that can dissolve the plastic material and cause the swelling of clay is used, and a homogeneous three-component mixture of an appropriate composition is produced with the aid of heating and mechanical and/or ultrasonic stirring. Then polymer/clay composites are obtained by removing the solvent either by precipitation or evaporation [109,110]. The main disadvantage of this method is that it uses solvents that are not environmentally friendly [79]. However, recovering and reusing such solvents is a good approach to remedying the environmental impact. Several researchers [79,109,110] have demonstrated the feasibility of using solution blending in their investigations.

6.2.4. Powder impregnation through compression molding

In this manufacturing process, natural fibres/fillers are mechanically mixed with cellulosic plastic and liquid plasticizer to form biocomposite products. Mohanty et al. [108] investigated the mechanical performance of composites made from cellulosic acetate plastics and chopped hemp natural fibre. The biocomposites were fabricated using two different approaches, namely, extrusion followed by injection molding and powder impregnation through compression molding. It was reported that biocomposite products fabricated through extrusion followed by injection molding exhibited better flexural strength and modulus properties than those made by powder impregnation through compression molding. The better performance obtained is due to the sufficient shear forces for the intimate mixing of the composite elements. This is contrary to the report of Liu et al. [9], who reported the modulus did not change for both compression- and injection molded samples. Due to this discrepancy, further research work is needed to provide more evidence for researchers in this field. Such studies are ongoing in our laboratory and will be published soon.

7. Applications of natural particulate hybrid nanocomposites

As a class of structural and infrastructural materials, particulate-reinforced composite materials have received wider engineering applications due to their sustainability, ease of preparation, cost, and environmental benefits [2,111,112]. Higher stiffness can be provided by particle fillers due to their large surface area, which is available for effective interactions compared to their fibre counterparts. Natural particulate-filled hybrid nanocomposites have found applications in various sectors, including building, construction, and automobiles [2].

8. Conclusion/future perspective

Plastic waste and agro-residues have been identified as major sources of municipal solid waste in the world today, which requires urgent management attention. The recycling and reuse of these waste materials in the polymer industry is a good management approach that offers economic and environmental benefits. However, compared to the huge amount of waste generated, only a small amount finds its way into the polymer industry, while the majority is either burnt or destined for landfill. Therefore, efforts should be intensified for the full utilization of these waste materials in the engineering fraternity.

Various processing techniques for biocomposite material manufacturing appear in the literature. However, this study has identified extrusion followed by injection molding as the best manufacturing method that could be used to obtain good mechanical performance in natural particulate hybrid nanocomposites due to its ability to promote good interfacial bonding through adequate wetting and mixing as well as good consolidation. The study also identified that a limited amount of research on the mechanical performance of natural particulate hybrid materials based on processing techniques is available. Therefore, more research studies are needed in this area, as we cannot use the research on fibre-reinforced composites based on manufacturing techniques to account for particulate-reinforced composites. This is because the length of the fibre in the injection molding machine is always affected by the shear forces of the instrument; hence, compression molding is preferable. However, this is not the case with particulate fillers.

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Abbreviations

Acrylonitrile butadiene styrene = ABS
Greenhouse gases = GHGs
High-density polyethylene = HDPE
Low-density polyethylene = LDPE
Montmorillonite = MMT
Municipal solid waste = MSW
Municipal Solid Waste Landfills = MSWLFs
OFMSW = Organic food Municipal Solid Waste Landfills
Polypropylene = PP
Polyvinyl chloride = PVC
Polystyrene = PS
Soil organic carbon= SOC
Wood plastic composites = WPCs

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