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Research Article

Agricultural Waste-Based Composite Materials: Recycling Processes, Technical Properties, and Industrial Applications

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ABSTRACT

The transformation of agricultural waste into eco-friendly, lightweight, durable, and biodegradable composite materials supports sustainable production processes and presents new opportunities as alternatives to traditional materials. These composites offer significant advantages, particularly in terms of energy savings, low cost, and minimizing environmental impact. Widely used in industrial applications, these composites contribute to sustainable development goals by serving as insulation materials in construction, interior components and body panels in the automotive industry, biodegradable packaging materials, decorative elements and outdoor furniture in the furniture industry, and plant pots and mulch in agriculture. The broader adoption of agricultural waste-based composites in industrial applications not only offers potential solutions to waste management challenges but also represents a critical step toward enhancing environmental sustainability. This study aims to examine the potential of agricultural waste-based composite materials across various industrial applications. Within this scope, the uses of biodegradable composite materials, recycled from agricultural waste, are detailed across sectors such as construction, automotive, packaging, furniture, and agriculture.

1. INTRODUCTION

The production of composite materials from agricultural waste has garnered significant interest in recent years due to the benefits of waste valorization and the development of sustainable materials. Abundant and often underutilized agricultural residues can be employed as effective reinforcing agents in composite formulations, thereby enhancing the mechanical, thermal, and acoustic properties of the composites. The use of agricultural waste in composite production stems from the growing demand for sustainable materials that can serve as alternatives to traditional materials. Agricultural by-products such as corn stalks, rice husks, and sugar beet pulp are rich in lignocellulosic fibers. Utilizing these materials enables the creation of composites that exhibit improved mechanical properties, thermal insulation, and biodegradability [1]. In comparison to traditional materials, agricultural waste-based composites offer several advantages, such as lower environmental impact due to their renewable and biodegradable nature, as well as a reduction in production costs. These materials also contribute to a circular economy by reducing waste and promoting resource efficiency. The incorporation of such agricultural waste in composite production not only prevents resource waste but also enhances various characteristics of the composites [2]–[4]. For instance, it has been reported that wood-plastic composites (WPC) produced from branches and leaves obtained from the pruning of citrus trees, combined with low-density polyethylene (LDPE), achieve improved compatibility between materials through surface modification with enzymes [3]. It has been reported that this modification enhances the water-repellent properties of the wood-derived fibers, allowing for better adhesion to the plastic matrix. This enzymatic process not only improves the mechanical properties of the composite material but also increases its biodegradability, making it a more environmentally friendly option. The thermal properties of composites produced from agricultural waste have also been extensively studied. One study indicated that due to their low thermal conductivity and lightweight structure, these composites hold significant potential as thermal insulation materials, offering advantages for various applications in the construction and automotive industries [4]. In another study, the mechanical properties of composites made from polyester and corn stalks were evaluated. This research concluded that the incorporation of agricultural fibers into the composite production process significantly enhances the mechanical strength and thermal stability of the resulting materials [2]. Additionally, it has been noted that composites reinforced with pineapple leaf fibers can be utilized in the production of unmanned aerial vehicles (UAVs), as their lightweight and strong characteristics contribute positively to UAV performance [5], [6]. These findings also highlight the versatility of agricultural waste composites in providing effective insulation solutions, particularly in the context of promoting sustainability.

In addition to thermal insulation properties, the acoustic characteristics of agricultural waste composites have been studied, particularly in terms of sound absorption. Koçak et al. (2022) reported that polyurethane composites reinforced with alkali-treated agricultural waste fibers exhibit excellent acoustic properties, making these fibers suitable for noise reduction applications [7]. This characteristic is becoming increasingly important in today's context, where noise pollution poses a growing environmental issue. In addition to their sound-absorbing capabilities, the lightweight and cost-effective nature of these composites makes them a significant alternative to traditional sound insulation materials.

Various methods, such as compression molding, injection molding, and extrusion, can be employed for the production of agricultural waste composites, each exhibiting significant differences [8]. These techniques allow for the customization of composite properties to meet specific application requirements.

Mycelium-based composites represent a novel approach to valorizing agricultural waste through a process where fungal mycelium is cultivated on lignocellulosic substrates to form bio-composite materials. A study examining these types of composites noted that their lightweight and biodegradable structures suggest potential applications in the construction and packaging sectors [9]. The innovative use of biological processes in material production exemplifies the interdisciplinary interaction between biotechnology and materials science. The mechanical properties of composites derived from agricultural waste can be further enhanced by incorporating various additives and treatments. For instance, the addition of agricultural waste fibers as a filler in polylactic acid (PLA) composites improves the material's viscoelastic properties by increasing its degree of crystallinity [10]. These enhancements are of significant importance for applications in sectors such as automotive and aerospace, where there is a demand for high strength-to-weight ratios. Furthermore, the use of agricultural waste as reinforcement not only improves the performance of composites but also reduces production costs, making them more economically viable alternatives compared to traditional materials [11], [12].

The use of bio-based binders such as alginate and starch in the production of composite materials from agricultural by-products enhances the mechanical performance of the composites while also contributing to the preservation of environmental sustainability [13]. This trend towards utilizing renewable resources in composite material production aligns with the principles of a circular economy, which aim to reduce dependence on fossil fuels and promote circular usage.

The environmental benefits of utilizing agricultural waste in composite production are also significant. By repurposing these materials, industries can mitigate waste disposal issues and more easily achieve their sustainability goals [14]. The integration of agricultural waste into composite production promotes resource efficiency and reduces the carbon footprint associated with material manufacturing.

In conclusion, this study has examined the various production processes, properties, and application areas of composites derived from agricultural waste. By highlighting the innovative methods used in their production and the potential benefits they offer across different sectors, a comprehensive perspective has been provided to the literature in this field.

2. SUSTAINABILITY and ENVIRONMENTAL IMPACTS OF AGRICULTURAL WASTE

2.1. *Types and Sources of Agricultural Waste*

Composites produced from agricultural waste have emerged as a significant resource in the quest for sustainable and environmentally friendly alternatives to traditional materials. Various types of agricultural waste, including fibers and by-products, are employed to enhance the mechanical and thermal properties of composites, making them suitable for a wide range of applications. Among the primary types of agricultural waste used in composite material production are lignocellulosic fibers derived from crops such as rice, corn, and wheat. These fibers are renowned for their superior mechanical properties and biodegradability, which render them ideal candidates for reinforcing polymer matrices. Additionally, fruit and vegetable peels, leaves, stems, flowers, and by-products generated during their processing can also be utilized as raw materials in the production of diverse composites. Table 1 provides information on the transformation of various agricultural wastes into materials and products across different industries.

TABLE I
UTILIZATION OF AGRICULTURAL WASTE IN VARIOUS INDUSTRIES

Biomass Waste	Products
Pineapple leaves, sugarcane residues	Animal feed, industrial absorbents, beverage additives, and biocomposites
Wheat straw	Pelletized polypropylene (PP) feedstock, fertilizer, biocomposites
Rice husk	Silica, metal coatings, water-soluble oils, and synthetic lubricants
Sugarcane bagasse	Wood materials, biocomposites, paper and packaging materials, paper goods
Abaca leaves	Fiber crafts, rope, textiles and fabrics, pulp, and specialty papers
Coconut husk	Coconut fiber rope and twine, brooms and brushes, mats, carpets, mattresses, and upholstery, often rubber-coated coconut pads
Sugar factory boiler ash (from bagasse)	Filtration materials and absorbent products
Oil palm fruit residues	Biodegradable packaging materials, construction, pulp and paper, automotive components
Kenaf fibers, jute fibers	Sound insulation systems, thermal insulators, automotive components, electronics, pharmaceuticals
Abaca leaves	Abaca leaf sheath, aerospace, maritime, and electronics
Coconut fibers	Coconut ropes
Banana pseudostems	Banana fibers, biocomposites, pulp, and paper
Flax	Biodegradable bags and covers, energy sports equipment

Biomass, constituting a significant category of agricultural waste, can be derived from various crops and possesses the potential to be processed into lightweight composites [15]. The utilization of excess biomass derived from agricultural waste not only reduces waste volume but also contributes to decreasing dependence on non-renewable resources, thereby promoting ecological sustainability. Composites produced from agricultural waste, such as rice husks and wheat straw, have been found to possess favorable thermal insulation properties, making them suitable for use in construction applications [4]. These findings are consistent with the results of another study that explored the use of rice husks and other agricultural fibers for the development of sustainable thermal insulation bio-composites [9].

2.2. Sustainability and mitigation of environmental impacts

The utilization of agricultural waste in the production of composite materials plays a significant role in mitigating environmental impacts. This practice not only prevents agricultural waste from harming the environment as part of waste management strategies but also reduces dependence on fossil fuel-based materials. The production of agricultural waste-based composites leads to a substantial decrease in carbon footprint and greenhouse gas emissions. Furthermore, the manufacturing processes for these materials consume less water and energy compared to traditional materials. Consequently, composites derived from agricultural waste contribute to the enhancement of environmental sustainability [16], [17].

The use of agricultural waste in composite materials has arisen primarily from the need to reduce environmental pollution and promote sustainability goals. Despite their abundance, agricultural wastes such as rice husks, corn stover, and bagasse is often underutilized. This presents a significant opportunity for recycling and sustainable production processes. For instance, utilizing agricultural waste to reinforce metallic matrix composites not only reduces costs but also contributes to waste reduction. It has been noted that the incorporation of agricultural wastes, such as rice husk granules and corn cob granules, plays a crucial role in this context [18]. Similarly, the use of agricultural waste as a reinforcement material in aluminum matrix composites (AMCs) has been noted to replace traditional reinforcements, thereby reducing environmental impacts and enhancing sustainability [19].

Composites derived from agricultural waste play a vital role in promoting sustainability and supporting the circular economy. These materials are recognized for their suitability for use in various sectors, including automotive, packaging, and construction, offering cost-effectiveness along with superior mechanical properties [15], [20]. Agricultural waste composites contribute to the effective utilization of waste by reducing dependence on non-renewable resources [15], [20], [21]. For instance, various studies have reported that agricultural wastes, such as tomato peels, enhance the properties of biodegradable composite materials and align with the principles of sustainable waste management. Additionally, agricultural waste offers eco-friendly alternatives for 3D printing, contributing to the circular economy [22], [23]. Moreover, the use of by-products such as rice husks in metallic matrix composites has been reported to improve material properties while also reducing pollution [18]. Furthermore, the conversion of agricultural wastes such as cocoa bean shells into biocomposites contributes to sustainable material production by reducing the carbon footprint [20], [24]. This approach is essential for resource efficiency and the reduction of environmental impacts [25]. Table 2 presents the annual production and sources of agricultural waste-based natural fibers [26]. The source of the fibers indicates which part of the plant they are derived from, while the production quantities worldwide are expressed in thousand tons (103 tons).

TABLE II
ANNUAL PRODUCTION OF AGRICULTURAL WASTE-BASED NATURAL FIBERS

Fiber Source	Global Production (10^3 Tons)	Source
Bamboo	10,000	Stem
Oil Palm Fruit	23,500	Fruit
Sugarcane Bagasse	75,000	Stem
Banana	200	Fruit
Coconut Fiber	100	Stem
Wood	1,750,000	Stem
Pineapple	1,200	Leaf
Rice Straw	28,900	Stem
Rice Husk	26,750	Seed
Jute	2,500	Stem
Kenaf	770	Stem
Flax	810	Stem
Sisal	380	Stem
Abaca Fiber	70	Stem
Kapok Fiber	100	Stem

3. THE UTILIZATION OF AGRICULTURAL WASTE IN THE PRODUCTION OF COMPOSITE MATERIALS

The valorization of agricultural waste as composite materials is a significant process for sustainability and involves a comprehensive production line comprising several stages (Figure 1). Initially, suitable agricultural residues must be collected and cleansed of impurities. Following this, the waste undergoes a grinding process to achieve specific dimensions and is subsequently classified to attain the desired granulometric distribution. These steps are critical for rendering the waste suitable for composite material fabrication.

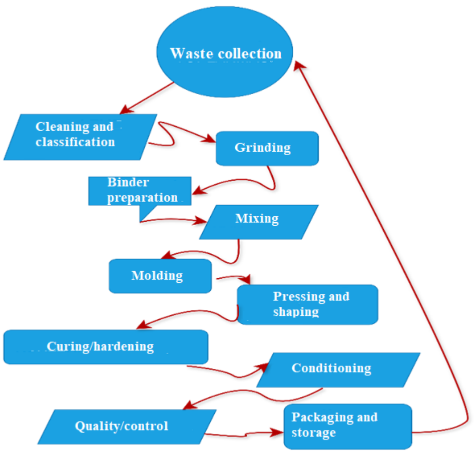

Figure 1. Schematic representation of composite material production from agricultural waste.

The ground agricultural waste must be combined with a binder, or matrix, material. The matrix material determines the final properties of the composite and facilitates the integration of the waste with the matrix [27]. Matrix materials employed in this stage typically include thermoplastics, thermosetting resins, and natural polymers [28]–[30]. Thermoplastics (e.g., polypropylene (PP), polyethylene (PE), and polyvinyl chloride (PVC)) can be melted and reshaped under heat. Thermosetting resins (e.g., epoxy, phenolic resins) are known to provide permanent hardness and strength under high temperature and pressure [31], [32]. Furthermore, natural polymers are also favored in composite production due to their environmentally friendly and biodegradable properties [33]–[35]. The subsequent stage involves the pressing process. Among the pressing methods are:

- Hot pressing, which facilitates the strong bonding of waste materials with the matrix, resulting in a durable composite material.
- Extrusion, employed for the production of continuous lengths of profiles, sheets, and pipes by homogeneously mixing agricultural waste with a polymer matrix.
- Injection molding, an ideal method for the mass production of small products with complex shapes.
- Filament winding, which enables the creation of cylindrical structures and robust composite products by coating agricultural fibers with resin and winding them around a mandrel.

To determine the performance and durability of the composite materials, various testing and analysis methods are employed. Mechanical tests measure the tensile, compressive, flexural, and impact strength of the material, while thermal tests evaluate its stability at elevated temperatures. Microstructural analyses (e.g., scanning electron microscopy (SEM) and X-ray diffraction (XRD)) examine the fiber-matrix interaction and internal structure. Chemical analyses (e.g., Fourier transform infrared spectroscopy (FTIR) and energy-dispersive X-ray spectroscopy (EDX)) assess the chemical composition of the composite material and any potential alterations.

These comprehensive processes enable the transformation of agricultural waste into sustainable and high-performance composite materials, offering significant contributions both environmentally and economically. Table 3 provides information on some agricultural wastes used as reinforcement in composite material production.

TABLE III
UTILIZATION OF AGRICULTURAL WASTE AS REINFORCEMENT IN COMPOSITE MATERIAL PRODUCTION

Waste Type	Matrix	Method	Pros	Cons
Corn Cob	PP, Epoxy, PES	Injection, Compression	Cheap, abundant	Short fibers, low strength
Rice Husk	PLA, Epoxy	Injection, Compression	High area, light	Weak bonding
Wheat Straw	PP, PE	Compression, Extrusion	Light, biodegradable	Hard to mix evenly
Coconut Shell	Epoxy, PES	Compression, Pultrusion	Hard, durable	Hard to process
Sugarcane Bagasse	PP, PLA	Extrusion, Compression	Abundant, cheap	Low fiber quality
Flax Fiber	PA, PP	Pultrusion, Vacuum	Strong, low density	Costly, hard to process
Bamboo Fiber	Epoxy, PES	Pultrusion, Injection	Strong, fast growth	Low density, hard to process
Hazelnut Shell	Epoxy, PU	Compression, Pultrusion	Hard, wear-resistant	Varying quality
Walnut Shell	PES, Epoxy	Injection, Compression	Hard, durable	Hard to process
Apricot Pit Shell	PP, Epoxy	Injection, Compression	Light, recyclable	Low fiber quality

4. PROPERTIES of AGRICULTURAL WASTE BASED COMPOSITES

Agricultural waste-based composites have garnered significant attention due to their technical attributes, often exhibiting advantages such as enhanced mechanical strength, thermal stability, and biodegradability. A study on polyester/corn stalk composites reported that such materials demonstrate excellent water and oxygen barrier properties, rendering them suitable for diverse applications in the construction and automotive industries [2], [36]. Furthermore, research has highlighted the potential of agricultural waste derived composites as effective thermal insulators owing to their low thermal conductivity [4]. This aligns with the findings of [9], which indicated that composites fabricated from rice husk and wood fibers exhibit favorable thermal insulation properties, offering promising results for industrial applicability.

The utilization of agricultural waste in the fabrication of composite materials presents significant potential within the context of recycling, often involving various treatments to enhance the properties of the resultant composites. For instance, a study focusing on epoxy-based polymer matrix composites, incorporating waste materials such as coconut and walnut shells, emphasized the improvement of mechanical properties and the optimization of flexural and physical behavior through the application of Taguchi techniques [37]. Further research on alkali-treated oil palm leaf waste demonstrated its capacity to significantly augment interfacial adhesion in polylactic acid composites, thereby enhancing mechanical performance [38].

4.1. Mechanical Properties

The mechanical properties of agricultural waste-based composites have garnered increasing attention in recent years due to their potential to provide sustainable and environmentally friendly alternatives. Agricultural residues, such as rice husk, corn stalk, walnut shell, hazelnut shell, and coconut shell, are employed as reinforcement materials in composite production. These materials not only enhance mechanical strength but also offer environmental benefits by reducing waste and promoting a circular economy. The integration of these residues into composite matrices contributes to the improvement of mechanical properties, including tensile strength, flexural strength, and impact resistance [39], thereby facilitating their application in diverse industries such as construction, automotive, and consumer goods [9].

Studies have revealed that the mechanical performance of agricultural waste based composites varies depending on the type of waste employed, the matrix material, and the processing techniques implemented [40], [41]. For instance, composites reinforced with rice husk ash have been shown to exhibit superior mechanical properties compared to their counterparts lacking such reinforcement [42]. Specifically, the incorporation of rice husk ash into aluminum matrix composites has been reported to enhance tensile strength and wear resistance, rendering these materials suitable for applications in automotive and structural components [43], [44]. Similarly, the utilization of corn stalk fibers in polyester composites has been shown to contribute to increased mechanical strength, dimensional stability, and thermal resistance, highlighting the remarkable versatility of agricultural waste as a reinforcement material [2].

The optimization of mechanical properties in agricultural waste-based composites can be achieved through various processing techniques. For example, the Taguchi method has been employed to optimize the flexural and physical behavior of epoxy-based composites reinforced with agricultural waste, demonstrating that careful selection of processing parameters significantly improves mechanical performance [37]. Furthermore, alkali treatment has been shown to enhance fiber-matrix interfacial adhesion during the processing of agricultural fibers, yielding composites with superior mechanical properties [7].

4.2. Physical Properties

Agricultural waste based composites, derived from various agricultural byproducts, offer numerous advantages, particularly in the construction, automotive, and packaging sectors, due to their physical properties and environmental sustainability [9], [39]. A primary benefit of these composites lies in their low density and lightweight structure. The utilization of low-density agricultural residues, such as coconut shells, palm leaves, and corn stalks, significantly reduces material weight, facilitating ease of handling and application while simultaneously lowering costs [37], [38]. Despite their lightweight nature, these materials offer sufficient mechanical strength, enabling their effective use in structural and automotive applications. Another notable physical attribute of agricultural waste composites is their excellent thermal insulation capacity. Natural fibers like corn stalk, rice husk ash, and coconut shell, when incorporated into composite matrices, not only enhance mechanical durability but also provide superior thermal insulation, positioning these materials as a sustainable alternative to conventional insulation products [4], [37]. Especially in the context of increasing demand for sustainable building materials, such composites are deemed invaluable for enhancing energy efficiency and mitigating environmental impact [45].

The physical durability of agricultural waste-based composites, notably their resistance to fluctuations in humidity and temperature, is particularly remarkable. Studies have demonstrated the dimensional stability of these materials, confirming their capacity to maintain structural integrity in the face of environmental variations [2], [46], [47]. Furthermore, fiber treatment methods, such as alkali treatment, are reported to enhance fiber-matrix interfacial adhesion, thereby augmenting the composites' physical durability and long-term performance [38], [48]. Agricultural waste, readily integrable with polymer matrices, not only elevates the physical properties of the resultant composites but also fosters environmental sustainability by mitigating reliance on synthetic materials [49], [50]. Table 4 provides a comparative analysis of the mechanical properties of composites derived from various agricultural residues.

The fundamental parameters presented in Table 4, such as density, tensile strength, and Young's modulus, offer valuable insights into the potential applications and durability of these fibers. In particular, the high tensile strength exhibited by sources like oil palm and rice straw enhances their suitability for composite material fabrication. Furthermore, fiber density plays a crucial role in material selection [51], [52]. This table provides a valuable reference for bioengineering and sustainable materials research regarding agricultural waste fibers.

TABLE IV
SELECTED PHYSICAL AND MECHANICAL PROPERTIES OF COMPOSITES FABRICATED FROM VARIOUS AGRICULTURAL WASTE FIBERS.

Fiber Source	Density (g/m³)	Tensile Strength (MPa)	Young's Modulus (GPa)	References
Oil Palm	0.7–1.55	227.5–278.4	2.7–3.2	[53], [54]
Bagasse	0.31–1.25	257.3–290.5	15–18	[55]
Banana	0.65–1.36	51.6–55.2	3.00–3.78	[56], [57]
Coconut	0.67–1.15	173.5–175.0	4.0–6.0	[56], [57]
Pineapple	1.25–1.60	166–175	5.51–6.76	[46]
Rice Straw	0.86–0.87	435–450	24.67-6.33	[58], [59]
Jute	1.3–1.45	300–700	20–50	[60], [61]
Kenaf	0.15–0.55	295–955	23.1–27.1	[62], [63]
Bamboo	0.6–1.1	360.5–590.3	22.2–54.2	[64]
Sisal	1.45–1.5	300–500	10–30	[60], [61]
Abaca	1.42–1.65	879–980	38–45	[61]
Kapok	0.68–1.47	80.3–111.5	4.56–5.12	[65], [66]

As shown in Table 4, agricultural waste materials offer superior mechanical properties compared to traditional materials, such as high tensile strength and Young's modulus. Additionally, their low density provides advantages in terms of reduced weight and ease of transport. Being environmentally friendly and renewable resources, they contribute to sustainability, while their low cost and local availability offer economic benefits. With these characteristics, agricultural waste materials hold great potential as an alternative to traditional materials in the production of construction materials and composites.

4.3. Environmental and Economic Characteristics

The environmental and economic attributes of agricultural waste-based composites offer significant advantages in terms of sustainability and cost-effectiveness. These composites present valuable solutions for waste management, energy conservation, and the mitigation of environmental impact. By repurposing agricultural waste, manufacturers can substantially diminish the environmental footprint associated with waste disposal and raw material extraction. The utilization of agricultural waste in composites not only addresses waste management challenges but also promotes sustainability by providing renewable and biodegradable materials [37], [67]. Moreover, employing locally sourced agricultural waste yields economic benefits through cost savings in material procurement and processing. This renders the production of such composite materials a financially viable option [2].

5. CONTEMPORARY APPLICATIONS of AGRICULTURAL WASTE-BASED COMPOSITES

5.1. Application in the Construction Industry

Agricultural waste-based composites have emerged as a sustainable alternative in the construction industry, offering the potential to address both environmental concerns and the need for innovative building materials. A key application of agricultural waste composites in construction lies in the development of lightweight, high-strength materials. For instance, bio-composites derived from agricultural residues, such as durian peel fibers combined with poly(lactic acid) (PLA), have been shown to exhibit enhanced tensile and thermal properties, rendering them suitable for various structural applications [68]. The incorporation of these natural fibers into composite matrices augments the overall material performance, proving particularly advantageous in applications where weight reduction is critical, such as prefabricated building components [69]. Furthermore, mycelium-based composites, which utilize agricultural waste as a substrate for fungal growth, have demonstrated promising results in construction applications. These composites exhibit excellent mechanical properties and can be molded into diverse forms, making them suitable for use as insulation panels or structural elements [70]. Mycelium's ability to bind agricultural waste into a cohesive material not only provides a sustainable building solution but also contributes to carbon sequestration, mitigating the effects of climate change [71]. The durability and weather resistance of agricultural waste composites are also noteworthy. Studies have revealed that composite materials bonded with methylene diphenyl diisocyanate (MDI) and reinforced with bamboo or other agricultural fibers maintain their structural integrity under natural weathering conditions [72]. This characteristic is paramount for construction materials, which must withstand fluctuating environmental conditions over time. Beyond their mechanical and durability advantages, agricultural waste composites contribute to a circular economy by utilizing materials that would otherwise be considered waste. The use of cocoa pod husks in polypropylene composites, for example, not only offers a sustainable material option but also addresses the issue of agricultural waste accumulation [73]. This approach aligns with the growing trend towards eco-conscious construction practices, where the entire life cycle of materials, from production to disposal, is considered. Moreover, the integration of biocomposites into the construction sector is further bolstered by advancements in additive manufacturing technologies. The ability to 3D print using materials derived from agricultural waste allows for innovative designs tailored to specific structural requirements, opening new avenues for customized building solutions [74]. This technology enhances the versatility of agricultural waste composites, making them an attractive option for modern construction needs.

5.2. Application in the Automotive Industry

The industrial applications of agricultural waste-based composite materials are remarkably diverse, encompassing sectors such as construction, automotive, furniture, packaging, and thermal insulation. The lightweight nature and specific strength of these composites make them particularly appealing for automotive applications, where minimizing vehicle weight is crucial for enhancing fuel efficiency and reducing emissions. In this context, the potential of green materials, including agricultural waste, as reinforcement in aluminum matrix composites, and their role in lightweighting strategies, is underscored [24]. These composites are employed in vehicles to achieve reductions in weight, improvements in fuel economy, and a diminished carbon footprint (Figure 2).

5.3. Applications in the Packaging Industry

The utilization of agricultural waste-based composite materials in the packaging sector has gained significant momentum in recent years, driven by a growing interest in biodegradable and environmentally friendly alternatives. The detrimental environmental impact of conventional plastic packaging materials, and their persistence in the environment for extended periods, has rendered biodegradable composites derived from agricultural waste an attractive solution. These composite materials offer both environmental and economic benefits, particularly in addressing waste management and plastic pollution.

Figure 2. Agricultural waste-based composite components utilized in automotive interiors [75].

The viability of agricultural waste as a packaging material is intrinsically linked to several key advantages inherent in these composite materials. Primarily, their inherent biodegradability ensures environmentally benign decomposition after use, aligning perfectly with the burgeoning demand for biodegradable packaging solutions. For instance, agricultural residues such as corn cobs, wheat straw, rice husks, and coconut shells can be combined with polymer matrices to create biodegradable packaging materials [50]. These materials possess the potential to replace conventional plastic packaging, thereby significantly reducing the environmental footprint of the packaging industry. Furthermore, the use of biopolymer-based composites derived from agricultural waste promotes sustainability by mitigating reliance on non-renewable resources. Agricultural waste, being a recyclable and renewable resource, readily integrates into sustainable production processes. This not only minimizes environmental impact but also facilitates more efficient utilization of local resources [20]. For example, composites produced from combining waste materials like rice husks and corn stalks with biopolymers offer durable, lightweight, and environmentally friendly solutions for the packaging sector (Figure 3). Moreover, biodegradable composites from agricultural waste enhance functional performance within the packaging industry. These materials can exhibit desirable packaging characteristics such as moisture resistance, oxygen barrier properties, and high tensile strength. Biodegradable composites used in food packaging, in particular, provide the necessary barrier properties to maintain product freshness while simultaneously undergoing environmentally benign decomposition at the end of their lifespan [76]. This underscores the considerable environmental sustainability advantage of biodegradable composites over their plastic counterparts.

5.4. Applications in the Furniture Industry

The utilization of agricultural waste-based composites in the furniture industry is attracting increasing attention due to their potential to create sustainable, eco-friendly products while addressing waste management challenges. These composites, often incorporating materials such as wheat straw, pineapple fibers, and mycelium, offer a range of mechanical and aesthetic properties suitable for diverse furniture applications. A significant example of agricultural waste utilization in furniture design is the incorporation of wheat straw into composite materials. Research indicates that composites reinforced with chopped wheat straw can be effectively combined with various plastics, such as polyethylene and polypropylene, to produce materials with enhanced mechanical properties [78]. These composite materials offer a sustainable alternative to traditional wood-based materials, contributing to the mitigation of environmental impacts associated with furniture production. Mycelium-based composite materials, employing fungal growth on agricultural waste substrates, represent another innovative approach in furniture manufacturing. These materials stand out due to their inherent fire-resistant properties and adaptability to specific applications, making them suitable for various furniture designs [79]. Mycelium's ability to bind agricultural waste into a cohesive material enables the creation of lightweight and durable furniture products capable of satisfying the aesthetic and functional demands of modern consumers. Additionally, the use of pineapple leaf fibers in furniture design has been explored as a means of upcycling agricultural waste. Pineapple cultivation generates substantial waste, and research demonstrates that these fibers can be transformed into composite materials exhibiting favorable mechanical properties [80], [81]. Such innovations foster sustainable practices within the furniture industry and contribute to the circular economy by enhancing the value of agricultural by-products. The development of bio-composite boards from straw fibers has also garnered significant interest in the furniture sector. Produced from readily available agricultural waste, these boards find applications in various uses (Figure 4-5), including cabinets and decorative elements [82].

Figure 3. The biodegradable materials in packaging applications [77].

5.5. Applications in Agriculture and Horticulture

Agricultural waste-based composite materials utilized in agriculture and horticulture promote environmental sustainability while offering functional advantages. Composites derived from waste such as rice husks, corn stalks, and coconut shells exhibit organic fertilizer properties and function as soil amendment materials, enhancing water retention capacity. These composites are known to improve soil structure and nutrient content, contributing to healthy plant root development. Furthermore, they offer lightweight and durable materials for horticultural landscaping, providing water-conserving and aesthetically pleasing solutions. The application of agricultural waste-based composites contributes to achieving sustainability goals within this sector, while simultaneously reducing costs and promoting efficient natural resource utilization and waste management.

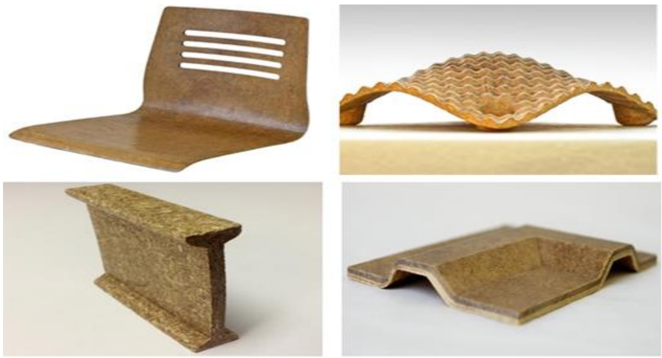

Figure 4. Bio-based wood composites from sugarcane bagasse [83].

The growing demand for biodegradable and sustainable materials has driven research to optimize the properties of these bio-composites and ensure they meet the performance standards required for furniture applications. Furthermore, the integration of waste textile materials into furniture design has emerged as a viable strategy for sustainability. By recycling waste textiles into composite materials, manufacturers can create products that are not only environmentally friendly but also economically viable [84]. This approach highlights the potential for innovation in material sourcing and product design, addressing the dual challenge posed by textile waste and the need for sustainable furniture solutions.

Figure 5. Fiberboard from Rice Straw for Furniture and Furniture Manufacturing [85].

6. CONCLUSIONS

This study has highlighted the significance of agricultural waste-based composite materials from the perspective of environmental sustainability, elucidating their production processes, properties, and potential for industrial applications. Findings demonstrate that these materials, offering advantages such as low cost, lightweight properties, biodegradability, and energy efficiency, can be considered viable sustainable alternatives in sectors including construction, automotive, furniture, packaging, and agriculture. However, certain improvements are necessary to facilitate wider adoption. Specifically, research and development investment is crucial for advancing biodegradable binders and processing technologies, implementing surface modification techniques to enhance fiber-matrix compatibility, and quantifying environmental benefits through life cycle analyses. Furthermore, public policies incentivizing wider adoption of these materials, coupled with industry education on sustainability, will significantly increase sector awareness. The study's conclusions indicate that the efficient utilization of agricultural waste contributes to the circular economy and strengthens industrial sustainability.

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