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Sustainable Polymer Composites from Industrial Wastes

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Abstract

Sustainable polymer composites derived from industrial waste offer a viable solution to resource scarcity and environmental concerns. This review explores the development, properties, and applications of composites incorporating fly ash, slag, agricultural residues, and recycled polymers. Utilizing these waste materials minimizes environmental impact while enhancing mechanical, thermal, and chemical properties. Key processing techniques such as melt blending, extrusion, and additive manufacturing contribute to performance optimization. The review also addresses challenges related to waste compatibility, durability, and large-scale production, proposing effective solutions. Integrating sustainable polymer composites with circular economy principles enables their application in construction, automotive, and packaging industries. Emphasizing the need for further research, this study highlights the potential of these composites to contribute to a more sustainable future.

Keywords: Sustainable polymer composites; Industrial waste; Circular economy; Processing techniques; Mechanical properties

1. INTRODUCTION TO SUSTAINABLE POLYMER COMPOSITES

The concept of sustainable development has provided the foundation for human civilization for centuries, adapting in response to time requirements that would ensure a better tomorrow. An old idea is newly highlighted with increasing attention following the end of the Second World War, because of the visible advances in technology posing a two-fold challenge: on one side meeting human needs and, on the other, minimizing detrimental effects on society, environment, and natural ecosystems. In the present time, rapid increase in human population and related demands for food, products, and other resources have compounded the problem of waste generation. These agricultural, industrial, and household wastes are polluting the environment, causing enormous health hazards, and spoiling the natural aesthetics. Proper management and disposal of these waste materials now carry with them an urgent priority towards providing a clean and healthy environment for the coming generation.

The development of sustainable polymer composites from industrial waste as a raw material has emerged as a significant solution. The utilisation of such innovative materials is poised to contribute to global sustainability, as evidenced by the mitigation of expenses related to virgin resources, the augmentation of waste disposal challenges, and the reduction of their environmental repercussions. The integration of wasted materials, such as fly ash, slag, agricultural residues, and recycled polymers, into polymer matrices has been shown to enhance their mechanical, thermal, and chemical properties, thereby promoting the circular economy. Consequently, these processes have the potential to convert waste into wealth, thereby stimulating

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Table 1. Investigating a variety of industrial waste materials, the main sources of production and their uses according to scientific research.

Type of waste	Source	Potential use in composites
Fly ash	Coal combustion in power plants	Improves mechanical strength, enhances thermal stability, and serves as a filler in construction and road materials [3].
Slag	Steel manufacturing and metal refining	Enhances thermal stability and mechanical properties, suitable for high-temperature applications [4].
Agricultural residues	Crop processing (e.g., rice husk, coir)	Provides lightweight reinforcement, reduces density, and improves biodegradability [5].
Recycled polymers	Plastic recycling (e.g., PET, HDPE)	Reduces reliance on virgin polymers, improves cost-effectiveness, and supports circular economy initiatives [6].
Textile waste (e.g., silk)	Textile industry (natural/synthetic fibers)	Enhances elasticity, tensile strength, and biodegradability; suitable for lightweight automotive parts [7].
Glass fiber waste	Composite recycling	Improves durability and rigidity; used in construction and industrial applications [8].
Coconut fiber (coir)	Coconut husk processing	Increases tensile strength and stiffness; used in structural bio composites for construction [9].
Silica gel waste	Chemical industry	Enhances thermal resistance and rigidity in polymer composites [10].
Rubber waste	End-of-life tires	Improves impact resistance and elasticity; used in automotive parts and flooring materials [11].
Construction debris	Demolition waste	Acts as filler material to reduce costs and enhance mechanical properties in polymer composites [12].
Red mud	Alumina production (bauxite refining)	Enhances flexural strength, thermal stability, and fire resistance; used in geopolymers and polymer composites [13].

innovative material design and applications across various sectors, including construction, automotive, aerospace, packaging, and electronics.

Polymer matrix polymer composites have exceptional properties, such as low-to-high specific stiffness and strength, high impact resistance, high corrosion resistance, and very good thermal behaviour [1]. The incorporation of waste-derived fillers does not only have a positive effect on improving these properties, it also makes production cheaper [2]. Table 1 exemplifies major types of solid industrial wastes that can be effectively used as reinforcements in polymer composites.

Existing environmental issues are thus addressed in parallel to supporting sustainable manufacturing approaches, with the objective of reducing carbon emissions and resource depletion for the associated substances by utilising these materials within polymer composites. This represents a significant advancement in materials science and engineering for our purposes. As the sector engages with sustainability, manufacturers, researchers and policymakers will need to work together towards developing a standardised approach which reflects best practice in maintaining quality standards whilst also delivering on environmental obligations. It is anticipated that such a collaborative initiative will expedite the widespread adoption of sustainable polymer composites in manufacturing contexts. This synergy will serve as a catalyst for innovation and investment, thereby redefining sustainability not as a mere environmental concern, but as an indicator of product performance, without compromising on strength and durability.

1.1. Definition and importance of sustainable polymer composites

A remarkable advancement in the area of material science are the sustainable polymer composites which created by intricately blending natural fibers or waste-based polymers with standard synthetic polymers. This novel combination not only improves the mechanical properties and durability of the materials produced but also responds to the increasing demand for environmentally friendly solutions. By using renewable resources, these composites cut down on fossil fuel use and minimize the carbon footprint of traditional polymer manufacture.

The natural fibers impart lightweight qualities to the composites and also provide excellent tensile strength and stiffness: hemp, flax, or jute are examples of such fibers. The sustainability profile of these polymers is further upped by waste-based polymers from corn-starch or sugarcane. These composites are truly standing at the delicate boundary between high performance and ecological liability, making them suitable in an array of applications including automotive parts, construction materials, and consumer products [14]. As industries are embracing sustainability with vigour, such sustainability polymer composites are poised to be a viable way toward a circular economy, further assisting in creating a balance of technology and conservation [15].

On top of that, deploying sustainable polymer composites across multiple industries not only enhances product performance but also creates a larger impetus towards circular economy practices. The adoption of green composites based on natural fibers and biopolymers is expected to bring a significant reduction in the overall vehicle weight and an improvement in fuel efficiency and lower greenhouse gas emissions within the automotive sector [16]. This transition provides a means by which an industry can simultaneously address pressing environmental regulations and remain competitive. Moreover, collaborative development in this area will gain momentum as manufacturers look for ways to recycle industrial by-products into innovative technologies and products; waste-based (green) composite creation, therefore, serves a dual purpose-as a waste management strategy and an energy-efficient production route [17]. The fundamentally changing environment indicates how research and collaboration become indispensable to provide meaningful advances towards sustainability. This will help the industry to deliver greater values through enhanced product performance and consumer appeal while being a step towards a more sustainable future.

1.2. Overview of industrial waste as a resource

New innovative methods are being rolled out by industries for further improving the sustainability profile of polymer composites as these industries increasingly study the potentials of industrial waste, specifically to be used as a precious raw material resource. For example, by using agricultural waste by-products in these materials, one is able to tend waste yet also have a diverse range of properties within the polymer composite, such as improved thermal stability, biodegradability. Studies conclude that waste-based (green) composites obtained from renewable resources can help minimize the energy consumption for the production process while being competitive in performance against their synthetic counterparts [18]. In addition, the future is opening up with advanced recycling techniques that forge closed-loop systems, where end-of-life products are directly recycled back into high-grade materials [19]. These, on the other hand, support the idea of a circular economy and minimize landfill inputs. Such a progressive shift clearly indicates the importance of collaboration across disciplines, putting together material sciences with environmentalism and industry leadership to develop holistic strategies that integrate ecology with economic viability. This will foster not only innovation but also inspiration to other sectors in implementing sustainable practices as it effectively leads toward a more resilient and environmentally friendly future.

While the demand for sustainable solutions is only sharpening, the industrial sectors are no longer dependent on polymer composites only but finding new avenues in recycling for boosting both properties and sustainability of materials. For example, the automotive industry now accepts waste-based (green) composites that are lightweight and contribute significantly to structural integrity while reducing fuel consumption, allowing for lower greenhouse gas emissions for the entire life-cycle operation without ever going back to fossil fuels [20]. In addition to the above benefits, new processing technologies give the possibility of processing agricultural products into high-performance materials efficiently. High savings in energy usage can be gained during production [21]. This evolution calls for a multi-dimensional strategy linking interface waste management with the best material science and facilitating an environment where eco-friendly practices weave themselves into the fabric of industrial processes. Such strategies will elevate the performance standards of polymer composites, but they will also galvanize a wider societal trend toward a truly circular economy, where waste would be valuable rather than a burden. Growing stainable polymer composites with research focused on improving their properties through innovative practices such as nanomaterials incorporation, which can add enormous enhancements in mechanical strength and thermal stability, have been lightweight, broadening their potential uses in high-performance sectors such as aerospace and automotive industries [22]. Examples include very promising results of incorporating recycled carbon fibers or nanoclays into waste-based (green) composites, addressing not only durability but also their harmonious contribution to sustainability. This development is not only addressing the efficiency of the product but also aligns with world initiatives that target reducing plastic in waste through the encouragement for recycling content use [23]. Hence, in this context, it creates a double benefit: enhanced product function and environmental conscience. Such developments demonstrate the necessity of continuous effort in research and development that shall take optimization of material properties in sustainable polymer composites and strengthening their role in promoting principles of a circular economy.

As the development of sustainable polymer composites matures, life-cycle impacts and end-of-life strategies will need to be developed with biodegradability and recyclability in mind. Not only does the integration of waste-based (green) composites stemming from natural fibers improve the performance of the end product, but it also opens up a more responsible disposal method that decreases environmental burden associated with traditional plastics. The advent of waste-based polymers will eventually extend to materials with even better ability to decompose and, thus, limit persistence in landfills with a potential

Table 2. Comparison of capabilities and challenges in the process of using industrial waste in the production of polymer composites.

Advantages	Challenges
Improved sustainability of final product	Potential processing challenges in industrial scale
Enhanced material properties like durability	Initial research costs
Reduced energy consumption	Limited availability of raw materials
Competitive performance	Biodegradability concerns
Circular economy support	Need for interdisciplinary collaboration

contribution to soil fertility following decomposition [24]. This is lifecycle management in action as products will have been designed with their entire lifespans in mind, thus encouraging the industry to adopt circular economy principles that would make sustainability read into every step-from material sourcing right to end-of-life solutions. In the long run, these comprehensive approaches will enable companies to satisfy the growing consumer appetite in the eco-friendly line while also solving the most pressing global concerns regarding waste and resource depletion (Table 2).

2. OBJECTIVES OF THE LITERATURE REVIEW

This review aims to synthesize current literature on waste-based polymers, particularly their environmental impact and effectiveness of lifecycle management systemic strategies. This review has two main objectives: first, exploring gaps in the current literature on the topic; and second, proposals concerning future research directions that would help broaden and deepen the understanding of waste-based polymers and how such materials can facilitate more sustainable practices in different industrial applications. Ultimately, upcoming findings from different sources into one another will lead to a rich and great appraisal of waste-based polymers in the circular economy and their contribution towards sustainable development goals (Fig. 1).

In addition to the development of waste-based polymers, it will also be necessary to address the role played by consumers that would prompt the usage of polymer composites in an ecologically sustainable manner. And consumer awareness is increasing in order to be able to better access the information about what goes into the products that are consumed, as well as the lifecycle impacts of their products. As consumers become aware of environmental issues, they tend to demand more and more information on the materials used in products and their life-cycle costs. Such a trend

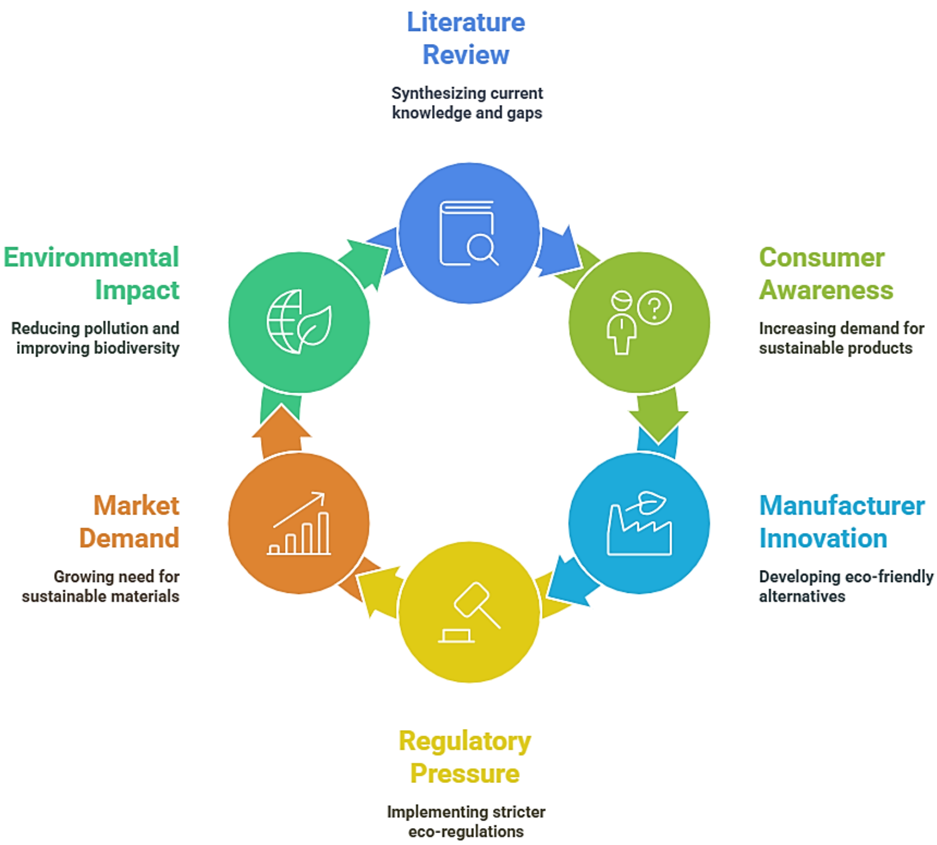

Fig. 1. Circular economy in the process of producing polymers from industrial wastes.

poses pressure on manufacturers to innovate and adopt responsible sourcing with a sustainability-first approach. It is apparent that there are financial advantages derived by companies in using eco-friendly alternatives as projected through the anticipated growth of the global recycled plastic market at US $120 billion by 2030 due to growing demand for valuable applications [25]. As per such provisions, bringing the product offerings in tune with consumers' value and practice can significantly heighten brand loyalty in terms of the market competitiveness of healthy environmentally friendly economies. It is almost certain that as more consumers begin to consider sustainability an actual part of property, the businesses that take an anticipatory stance toward environmental responsibility will usually gain the advantage in any competitive field and develop those relationships into lastingness.

It should be noted that in analysing the shaping of the scene surrounding sustainable polymer composites, consumer behaviour should be analysed alongside a regulatory framework. Several nations of the world are beginning to see stricter regulations to minimize plastic waste while also introducing eco-friendly materials [26]. Such mandates trigger realignment of research and development for innovation of alternatives and encourage both real and competitive environments within which firms expressing high priorities for environmental responsibility can thrive. And, as demands from the market and regulatory pressures start forcing the automotive industry into a lightweight green composite future, further influence is expected on the supply chain dynamics of sourcing renewable resources and boosting recycling efforts [27]. Ultimately, such legislative measures are fundamental in speeding up the transition to the circular economy, as they incorporate sustainable practices into industrial operations across different sectors. Indeed, the effects of such transformations would be felt in the environment through lowered pollution and improved biodiversity, while at the same time boosting the economy with new markets and jobs in green technologies and practices.

The pertinent issues have to be addressed concerning large-scale production and assurance of quality control in line with facilitating the growing momentum towards the pattern of usage in sustainable polymer composites. Thus, modern advanced manufacturing techniques will have to be used together with additively manufactured automated processing in promoting improvements in efficiencies and consistencies of production processes used in the green waste-based composite production process [28]. This promotes industry-wide provisions in meeting increased demand without compromising environmental standards. Equally important is the continued research on the lifecycle environmental effects of these materials and their performance in diverse conditions, as well as possible end-of-life scenarios and compatible recycling pathways in accordance with circular economy principles, as shown by studies that state that using agricultural by-products not only minimizes waste but also leads to improved material properties like thermal stability that could open the way for applications in sectors that require high-performance materials [29]. Thus, there is a need to actively nurture innovation while laying solid production frameworks that optimally utilize sustainable polymer composites in a variety of industrial contexts.

3. HISTORICAL CONTEXT AND DEVELOPMENT

Sustainable-polymer composite is a way forward in material science by enabling new, innovative, and green alternatives to conventional polymers through the use of industrial waste. Such composites are intended to reduce their environmental impact through reduced usage of virgin materials; hence, they aim to address some key situations such as waste and resource depletion. Sustainable polymer composites can be produced by including renewable agricultural by-products and natural fibers together with synthetic polymers. These composites will not only improve the mechanical properties of the material but will also bring the industrial culture along with it, shifting the global population to a circular economy. This new paradigm will make sure waste be converted into sources of riches, creating a range of applications in many industries, such as automotive construction and packaging. Sustainable development in composite development has gained momentum with the increased recognition of industries on the values of sustainability, and will be advanced through collaborations among manufacturers, researchers, and policymakers. In order to ensure quality, safety, and environmental responsibility in industrial units, such collaborations are essential. This study will examine the current status of research on industrial waste-based sustainable polymer composites, which have the potential to transform material design while preserving the environment and financial feasibility. The review will uncover theoretical gaps in the literature and synthesize existing findings, opening the door for further research in this exciting area.

3.1. Evolution of polymer composites from industrial wastes

Over the past decade, the utilization of industrial waste in the development of polymer composites has gained significant attention as a sustainable approach in materials engineering. This shift is primarily driven by the need to mitigate environmental pollution, reduce production costs, and enhance the mechanical and thermal properties of polymer composites. Industrial by-products such as plastic waste, metal slag, fly ash, and construction debris have been investigated as potential reinforcements in polymer matrices, offering an effective solution for waste management while simultaneously improving material properties [18].

Several studies have demonstrated the feasibility of incorporating various industrial residues into polymer composites with quantifiable improvements in mechanical performance. For instance, Teodorescu et al. [30] investigated polypropylene (PP)-based composites reinforced with silico-aluminous industrial waste derived from incinerated medical face masks (aluminosilicate ashes like coal-derived Govora® polyadipate (CGP) with 56.24% SiO_2 and coal-derived volcanic basalt polyadipate (CVBP) with 40.19% SiO_2). Their results showed that incorporating 5 wt.% ash with a particle size below 90 μm increased the modulus of elasticity by 10–14%, while maintaining the tensile strength within a 1.5–6% variation compared to neat PP. Additionally, the impact strength showed minor variations, with a 3% increase in PP–CVBP composites but a 20% reduction in PP–CGP composites [30].

Similarly, Keskisaari et al. [31] examined thermoplastic polymer composites incorporating side-stream materials from the construction and paper industries. Their findings indicated that primary sludge composites exhibited a tensile strength of approximately 22 MPa, nearly equal to the reference material, while the modulus of elasticity was slightly lower. The stone wool and stone dust composites, however, displayed tensile strength reductions of up to 30%, highlighting material-specific performance variations [31].

Girge et al. [32] explored the integration of construction waste, such as red brick dust, into polymer matrices. Their research demonstrated that composites containing 20 wt.% red brick dusts exhibited a flexural modulus of 2.5 GPa and an increase in thermal stability of up to 17% compared to conventional polymer composites. This indicates that such materials can serve as effective reinforcements, providing both mechanical advantages and environmental benefits [32].

Primary examples of industrial waste utilization as fillers in polymer composites include the use of fly ash in epoxy matrices, which enhances compressive strength by approximately 15% and improves thermal stability by 20%. Additionally, incorporating steel slag into polyethylene composites has been shown to increase hardness by 20% while significantly improving wear resistance. Furthermore, waste glass fibers from decommissioned wind turbine blades have been successfully recycled into reinforced thermoplastic composites, preserving up to 85% of their original mechanical properties [20].

Collectively, these studies highlight the potential of industrial waste-derived polymer composites to offer sustainable material solutions. The incorporation of various industrial by-products into polymer matrices not only enhances performance but also supports environmental sustainability by repurposing waste into valuable engineering materials.

3.2. Advancements in recycling and circular economy approaches

New developments in materials science have inevitably stimulated the experimentation of new recycling techniques that can enable closed-loop systems in which composites can be remanufactured into high-quality products, thus reinforcing the principles of the circular economy. For example, mechanical recycling, chemical depolymerisation and solvolysis techniques have shown promising results in terms of recovering the polymer matrix while maintaining structural integrity. This allows a pathway for the reuse of the composites in industrial applications, with reduced use of virgin raw materials and minimized environmental footprint [33].

Furthermore, in terms of valorisation potential, the use of industrial waste as a reinforcing agent in composites is gaining popularity. Previous research studies have shown that fly ash, silica fume and agricultural residues are waste-based fillers that act in combination with the polymer matrix to improve the mechanical and thermal stability of composites. Such reinforcements therefore improve the properties of composites and help to conserve resources by diverting them from landfill [34].

3.3. Performance optimization and industrial applications

To ensure the viability of polymer composites derived from industrial waste, extensive research has been conducted to optimise their mechanical, thermal and chemical properties. Asmatulu et al. [35] investigated nanotechnology-based modifications, such as the incorporation of graphene oxide and nanocellulose, have significantly improved the tensile strength and thermal resistance of recycled polymer composites. In addition, breakthroughs in hybrid composite systems using waste-based and synthetic reinforcements have resulted in materials with improved durability and multi-functionality that are being used for high performance applications in the aerospace, automotive and marine industries [35].

The construction industry has, in turn, gained tremendously from the use of recycled polymer composites in load-bearing structures, insulation panels and reinforced concrete components. According to, the polymer composites with waste-derived fillers showed improved flame retardancy and moisture stability. This renders them suitable for sustainable infrastructure works. In a fashion similar to that, the automotive industry is swiftly adopting green composites for vehicle interior, bumpers and under-hood applications in an effort to reduce weight and thereby enhance fuel efficiency [36].

3.4. Early uses of industrial waste in composites

Improving resilience has been identified as one of the aspects where sustainable polymer composites will be important. For example, waste-based materials incorporated into construction composites not only provide thermal insulation, but also contribute to energy efficiency, so that heating and cooling costs can be a significant part of the savings over the years. Agricultural by-products such as reinforcing materials are beginning to show promise in increasing the durability of these composites through fluctuating environmental conditions and extended lifetimes, opening the door to less frequent replacement. Durability provides a solid argument for improved lifecycle management across the performance and sustainability divide - with close attention being paid to how innovative materials can provide a good response to climate challenges while meeting industry needs. In the end, perhaps the understanding of the changing world associated with sustainable polymer composites will drive further adoption across sectors.

The increasing interest in sustainable polymer composites necessitates their assessment in relation to possible initiatives for local production, with a view to countering social and economic challenges. In this way, a local community can convert some agricultural by-products generated in their farming practices into green composites [37]. The use of these composites serves to reduce waste and to provide local job opportunities in material processing and manufacturing. This localized approach, which intertwines environmental sustainability with social equity, empowers communities to take ownership of their resources and to build what they need. Higher education and training programmes that accompany the use of these materials can nurture a skilled workforce to embrace innovations that further support an economy anchored to resiliency and the global agenda on sustainability. Such approaches offer a perspective on the assessment of sustainable polymer composites as not just another material for industrial use, but as an agent for social change [38].

Moreover, the integration of sustainable polymer composites into local production initiatives has the potential to enhance community resilience in the face of economic fluctuations. By fostering a circular economy model that emphasises regional sourcing and processing of materials, communities can reduce their carbon footprint and create localised supply chains that are less susceptible to global market volatility. This approach aligns with findings that highlight the potential for waste-based (green) composites derived from agricultural by-products to stimulate job creation while simultaneously addressing waste management challenges [39]. Furthermore, as these practices gain traction, they have the potential to inspire similar movements across various sectors, driving innovation and collaboration that further embed sustainability into the fabric of industrial processes. In this way, sustainable polymer composites emerge not just as a solution to environmental issues, but as pivotal elements in building economically vibrant and socially equitable communities [40].

4. SOURCES OF INDUSTRIAL WASTE

Industrial waste generated during the manufacturing and production process constitutes a considerable encumbrance not only to the principle of sustainability but also to the treatment of waste. Among polymer composite applications, potential advantages of industrial waste include improved material properties, reduced production costs, and prevention of issues related to resource conservation and environmental pollution. Nowadays, as industries continue to get more and more greener, combining waste materials into polymer-composite production is proposed as an innovative way of doing things. That option brings a chance through which waste can even be converted into a recycling effort and reused; it offers another way to develop finer composites with improved mechanical, thermal, and functional properties.

Another type of industrial waste takes its origin from various industries, including manufacturing, mining, agriculture, construction, and power. These broad classification types can be broadly classified as solid waste, liquid waste, and gaseous emissions, out of which a large share is considered non-hazardous and amenable to aggregation for composite manufacture applications. Thus, the resource would be exploited to produce eco-advanced composites from polymer matrix systems via the waste industrialism manufacturing technique.

4.1. Types of industrial waste utilized

At the present time, greater significance is being given to sustainability and waste minimization in industrial processes, leading to research on the use of many kinds of industrial wastes in the preparation of polymer composites. Such approach not only reduces immensely the environmental effects linked to waste disposal works but also allows the manufacturers to prepare high-performance composite materials with unique properties by using a variety of waste materials specific to that industry. In this way, the industrial waste that is generally disposed

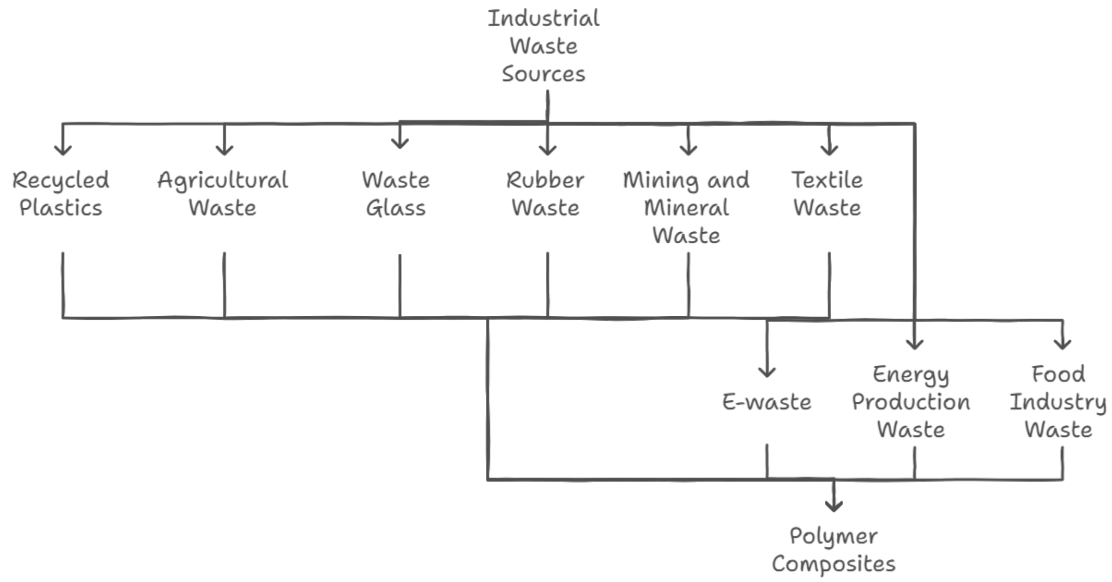

Fig. 2. Utilization of industrial waste in polymer composites.

Table 3. Key properties of industrial waste used in polymer composites.

Type of industrial waste	Key properties	Primary benefits in composites	Ref.
Recycled plastics	Moderate tensile strength (20–40 MPa), degradation over multiple cycles	Reduces landfill waste, conserves fossil fuel resources	[41]
Agricultural waste	Low density (0.9–1.3 g/cm^3), moderate mechanical strength	Enhances sustainability, provides biodegradable reinforcement	[42]
Waste glass	High rigidity (Young's modulus ~70 GPa), thermal stability up to 600 °C	Improves mechanical strength, enhances fire resistance	[43]
Rubber waste	High elasticity (elongation at break > 200%), good vibration damping	Enhances flexibility, improves impact absorption	[44]
Mining and mineral waste	High density (~2.5 g/cm^3), thermal and fire resistance	Reduces weight, improves composite durability	[45]
Textile waste	Moderate tensile strength (30–50 MPa), biodegradable (natural fibers)	Strengthens composites, promotes circular economy	[46]
Electronic waste (e-waste)	Good electrical conductivity, presence of metals like Cu, Al	Enhances electrical and thermal properties	[47]
Energy production waste	High fire resistance, improves thermal insulation	Reduces flammability, enhances material stability	[48]
Food industry waste	Low density (0.8–1.2 g/cm^3), biodegradable	Adds sustainability, useful for packaging applications	[49]

of or incinerated is being considered as a potential feedstock for polymer composites from which strong, affordable, and eco-friendly products are made and spread into the field.

The polymer composites consisting of a polymer matrix reinforced by fibers or particles are well known for their better mechanical properties such as strength, stiffness, and impact resistance. Herein, the use of industrial waste has been proposed for improving these properties in addition to solving environmental problems. Various types of industrial wastes have been used for producing polymer composites, depending on the sectors, ranging, with specific benefits that are obtained in terms of material properties, cost savings, and sustainability (Fig. 2). Main types of industrial waste mostly used in the polymer composite production are showed in Table 3.

4.1.1. *Recycled plastics*

Plastic materials are one of the largest sources of industrial waste, produced massively in diversified industries including packaging, automotive, and consumer goods. Recycled plastics such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) can be processed and used either in composite production as the polymer matrix or as reinforcements. Recycling plastic is beneficial because it reduces landfill loads, conserving fossil fuel resources used for the generation of virgin plastics. The major concern is maintaining the mechanical properties of recycled plastics post-processing since the previous use may have compromised strength and flexibility due to degradation [41].

4.1.2. Agricultural waste

Natural fibers emanating from agricultural by-products, e.g., rice hulls, wheat straws, and corn stalks, are not only rich in natural fibers but are also being recognized as raw materials for polymer composites. Such materials could then provide renewable biodegradable fibers instead of synthetic ones, reducing the environmental implications of composite materials. Agricultural waste fibers are almost always used as reinforcers in polymer matrices to improve mechanical properties, e.g., stiffness and impact resistance. In fact, agricultural wastes are used as raw materials in composite manufacturing to align with the principles of circular economies [42].

4.1.3. Waste glass

Another source of industrial waste that can partially go into making polymer composites is wasted glass, which includes rejected glass containers, windows, and bottles. The glass waste is usually ground into powder and utilized as fillers or reinforcements in composite materials. By the addition of reinforcing glass fiber or particles, the rigidity, thermal stability, and fire resistance of the resultant polymer composites can be considerably enhanced. Glass lends excellent durability and resistance to corrosion; therefore, it can be employed for construction and automotive applications. Compatibility issues between the glass and the polymer matrix remain as key problems that must be overcome to enhance bonding and material properties [43].

4.1.4. Rubber waste

Rubber waste, primarily derived from discarded tires and rubber products, poses a significant environmental challenge due to its non-biodegradability. However, this waste material can be processed and utilized in the production of polymer composites to improve impact resistance, elasticity, and vibration damping. Ground tire rubber, for example, can be used as a filler or reinforcement in automotive parts, footwear, and construction materials. Rubber waste is particularly valuable for enhancing the toughness and flexibility of composites, although it can present processing challenges due to its non-polar nature and tendency to agglomerate in the polymer matrix [44].

4.1.5. Mining and mineral waste

Mining and mineral extraction industries generate large quantities of waste materials, including slag, tailings, and fly ash, that can be utilized in polymer composites. These materials, often rich in minerals such as silica, alumina, and calcium carbonate, are commonly used as fillers to improve the mechanical and thermal properties of the composite. Fly ash, for example, is a fine powder produced during the combustion of coal, and it has been used extensively in construction applications for its ability to improve the fire resistance and reduce the weight of composites. The use of mining waste in polymer composites not only helps in managing these waste materials but also contributes to the reduction of raw material consumption [45].

4.1.6. Textile waste

The textile industry is another significant source of industrial waste, with discarded fibers, fabric scraps, and waste textiles contributing to global waste accumulation. Natural fibers such as cotton, jute, and flax, as well as synthetic fibers like polyester, can be incorporated into polymer composites to enhance their strength, biodegradability, and sustainability. Textile waste fibers are often used as reinforcing agents in composites for automotive parts, building materials, and packaging. In addition to improving mechanical properties, the use of textile waste helps reduce the volume of textile waste that would otherwise end up in landfills [46].

4.1.7. Electronic waste (e-waste)

The rapid expansion of the electronics industry has led to the generation of large amounts of e-waste, which includes discarded electronic devices such as smartphones, computers, and televisions. E-waste contains valuable materials such as metals, plastics, and glass, all of which can be recycled and used in polymer composite production. For example, the plastics from e-waste can be incorporated into composite materials to enhance electrical conductivity, thermal stability, and flame resistance. E-waste also offers the opportunity to recover precious metals like gold, silver, and copper, which can be extracted and reused in other industrial applications [47].

4.1.8. Energy production waste

The energy sector, particularly in fossil fuel-based power generation, produces waste materials such as fly ash, slag,

Fig. 3. Availability factors of waste materials.

and coal combustion residues, which can be repurposed for use in polymer composites. These materials can serve as fillers or reinforcements, improving properties like heat resistance, fire retardancy, and electrical conductivity. Fly ash, for instance, is widely used in the construction industry due to its ability to reduce weight and improve the fire resistance of materials. Additionally, the incorporation of energy production waste into polymer composites helps mitigate the environmental impact of waste disposal in power plants [48].

4.1.9. Food industry waste

The food industry produces a significant amount of organic waste, such as fruit and vegetable peels, seeds, and shells, which can be utilized as natural fiber reinforcements in polymer composites. These fibers not only contribute to the sustainability of composite materials but also provide an additional source of value from by-products that would otherwise be discarded. For example, coconut husk fibers are used to reinforce polymer composites for applications in packaging, construction, and automotive parts [49].

5. AVAILABILITY AND ACCESSIBILITY OF WASTE MATERIALS

The availability and accessibility of waste materials play a crucial role in the development and production of sustainable polymer composites. Various factors influence the supply of these materials, including geographic location, industrial practices, and regulatory frameworks (Fig. 3). Below are key considerations regarding the availability and accessibility of waste materials.

5.1. Geographic distribution

The availability of specific types of industrial waste is often influenced by local industries and agricultural practices. Regions with a strong agricultural base may have abundant agricultural by-products, such as straw and husks, while industrial areas may produce significant amounts of manufacturing scrap and chemical waste [50].

5.2. Industry collaboration

Establishing partnerships between industries can enhance the accessibility of waste materials. For instance, collaborations between agricultural producers and manufacturers can facilitate the collection and processing of agricultural by-products for use in polymer composites. Similarly, construction companies can work with material scientists to repurpose demolition debris [51].

5.3. Regulatory frameworks

Government regulations and policies promoting waste reduction and recycling can significantly impact the availability of waste materials. Incentives for industries to recycle and repurpose waste can increase the supply of materials suitable for sustainable polymer composites. Policies that encourage circular economy practices can foster an environment where waste is viewed as a resource [52].

5.4. Waste management practices

Effective waste management systems are essential for the collection and processing of industrial waste. Regions with robust waste management infrastructure are more likely to have accessible waste streams that can be utilized in the production of sustainable polymer composites. This includes sorting, processing, and distributing waste materials to manufacturers [53].

5.5. Market demand

The growing demand for sustainable products can drive the collection and processing of waste materials. As industries increasingly seek eco-friendly alternatives, the market for sustainable polymer composites can incentivize the development of systems to make waste materials more accessible [54].

5.6. Innovation in recycling technologies

Advancements in recycling technologies can improve the efficiency of recovering valuable materials from waste streams. Techniques that allow for the transformation of complex waste into usable materials can enhance the availability of resources for sustainable polymer composites [55].

5.7. Local sourcing initiatives

Encouraging local sourcing of waste materials can enhance accessibility while reducing transportation costs and carbon footprints. Community-based initiatives that focus on utilizing local agricultural or industrial waste can create a sustainable supply chain that benefits both the environment and local economies [56].

5.8. Education and awareness

Raising awareness about the potential of industrial waste as a resource can encourage industries to adopt more sustainable practices. Educational programs that inform stakeholders about the benefits of utilizing waste materials can lead to increased engagement and collaboration [57].

In summary, the availability and accessibility of waste materials for sustainable polymer composites are influenced by a combination of local resources, industry collaboration, regulatory frameworks, and market demand. By fostering partnerships and innovation, industries can enhance the supply chain for sustainable materials, ultimately contributing to a more circular economy.

6. PROCESSING TECHNIQUES FOR POLYMER COMPOSITES

Polymer composites are materials made by combining a polymer matrix with reinforcing materials such as fibers, particles, or fillers. These composites are valued for their lightweight, high-strength properties, making them suitable for various engineering applications, including automotive, aerospace, and construction. The processing techniques for these composites are critical, as they influence the mechanical, thermal, and electrical properties of the final material.

6.1. Hand lay-up

The hand lay-up process is one of the oldest and simplest methods for manufacturing polymer composites. In this technique, layers of reinforcing fibers are manually placed into a mold, followed by the application of polymer resin, after which the resin cures. This process is particularly beneficial for producing large and complex parts, such as boat hulls and automotive panels. One of the major advantages of hand lay-up is its cost-effectiveness, especially when recycled fibers or particles from industrial waste are incorporated. Additionally, this method allows for the use of natural fibers from agricultural waste, such as flax or hemp, providing a sustainable option for composite production. However, a key limitation lies in the inconsistent distribution of fibers, particularly when irregularly shaped industrial waste particles are included. The manual handling involved can lead to variability in the final product, especially in terms of filler dispersion like fly ash or rubber powder. Despite these challenges, natural fibers from agricultural waste, such as flax and hemp, have been successfully used in hand lay-up composites, reducing the weight of automotive panels while enhancing their environmental sustainability [58].

6.2. Resin transfer moulding

Resin transfer moulding (RTM) involves placing dry fiber reinforcement into a closed mold, with resin injected under pressure to impregnate the fibers. This method offers better control over the fiber-resin ratio and resin distribution compared to manual processes like hand lay-up, making it particularly suited for high-performance composites with complex geometries. The use of industrial waste in RTM provides several advantages, particularly the integration of fine particles like silica fume or fly ash, which improve mechanical properties such as fire resistance and reduce density. RTM allows for a higher-quality finish with more precise control over the material composition. However, incorporating industrial waste can increase the viscosity of the resin, posing challenges during injection. Fine particles, if not properly managed, can clog the system, necessitating careful filtration and dispersion techniques. As an example, fly ash-based RTM composites have been used in aerospace applications to improve both fire resistance and lightweight characteristics, demonstrating the potential of waste-based materials in high-performance sectors [59].

6.3. Compression moulding

Compression moulding is a widely used technique for producing thermosetting polymer composites, where preheated material is placed into a mold and shaped under heat and pressure. This method is highly efficient for large-scale production of composite parts. When industrial waste is integrated into compression molding, it offers the dual benefit of reducing raw material costs and contributing to sustainability. The use of recycled plastics and rubber waste, such as rubber from used tires, is particularly advantageous, as it helps reduce environmental impact while maintaining material performance. Nevertheless, one of the limitations of this process is the potential need for surface treatment of certain industrial waste fillers, such as metal slag or ceramic particles, to enhance compatibility with the polymer matrix. Additionally, uneven distribution of fillers may lead to variability in the final product's mechanical properties. An example of success in this area is the integration of recycled rubber into compression-molded composites, which has been used in impact-resistant flooring materials, showcasing the effective use of waste materials for functional, high-volume applications [60].

6.4. Injection moulding

Injection moulding is a versatile and widely adopted technique for producing thermoplastic composites, where polymer and reinforcement materials are injected into a mold under high pressure. This process allows for precise control over the composite's composition and is particularly suited for mass production. By utilizing recycled plastics from electronic waste (e-waste), injection moulding provides a sustainable solution that also ensures high production rates. The key advantage of this method is its ability to achieve fine control over the material's composition, which is ideal when incorporating industrial waste such as recycled plastics. However, one of the challenges with this process is that recycled materials may degrade at high processing temperatures, potentially compromising the mechanical properties of the final composite. Additionally, fillers like glass powder from waste glass require careful control of particle size to prevent nozzle clogging. As an example, recycled plastics from e-waste have been successfully injection-molded into durable components for consumer electronics, illustrating the potential for large-scale applications of waste-based composites in everyday products [61].

6.5. Extrusion

Extrusion is a continuous production method in which polymer and reinforcement materials are mixed and forced through a die to form shapes such as sheets, rods, or profiles. This technique is ideal for producing continuous composite forms and offers significant advantages when using industrial waste. The use of textile waste fibers, such as those from discarded clothing, in extrusion allows for a sustainable and efficient manufacturing process. Additionally, the incorporation of mineral fillers like fly ash or slag can improve the fire resistance of the extruded composites, making them suitable for construction applications. However, one limitation of this process is the need for precise control over filler loading to maintain consistent viscosity during extrusion. Additionally, adjustments to the processing temperature are required to prevent thermal degradation of recycled fibers. As an example, fly ash-based polymer extrusions have been used to create lightweight building materials, such as panels and roofing sheets, contributing to both material savings and sustainability in construction [62].

6.6. Pultrusion

Pultrusion is a continuous moulding process where reinforcement fibers are drawn through a resin bath and then pulled through a heated die to form long, uniform profiles. This technique is particularly useful for producing high-strength composite profiles for infrastructure applications. The use of recycled glass fibers, such as those derived from wind turbine blades, offers a significant advantage in pultrusion, contributing to both the sustainability of the manufacturing process and the durability of the final product. However, one of the limitations is the variability in the length and quality of recycled fibers, which can affect the mechanical properties of the composite. To mitigate this, chemical treatments may be required to enhance the bonding between the fibers and the polymer matrix. An example of this is the repurposing of wind turbine blade waste into structural pultruded composites, which are used in infrastructure applications like bridges and poles, thus demonstrating how industrial waste can be effectively used in construction materials [63].

6.7. Vacuum assisted resin transfer moulding

Vacuum-assisted resin transfer moulding (VARTM) is similar to RTM but uses vacuum pressure to draw resin into the mold, making it an excellent choice for producing large, complex parts with improved resin impregnation. The integration of industrial waste into this process provides benefits such as the use of lightweight reinforcements like recycled carbon fiber, which can enhance the structural integrity of the final composite while reducing weight. One limitation of VARTM is the tendency for fillers like metal slag to settle unevenly in the resin, which requires careful dispersion techniques. Additionally, this method typically has a longer processing time compared to traditional RTM, which may affect production efficiency. As an example, recycled carbon fiber has been used in wind turbine blades produced by VARTM, enhancing the blades' structural integrity and contributing to the sustainability of renewable energy infrastructure [64].

6.8. 3D printing (additive manufacturing)

Additive manufacturing, or 3D printing, has revolutionized the way polymer composites are produced by building parts layer by layer, offering significant flexibility in design and material usage. This technique is particularly advantageous for sustainable manufacturing, as it allows for the use of recycled plastics from municipal waste. The ability to print customized geometries with minimal material waste is one of the primary benefits of 3D printing. However, a key limitation of this method is the need for consistent feedstock quality, as recycled materials can vary in properties that affect printability. Furthermore, certain industrial waste fillers, such as metal powders, may interfere with print layer adhesion, necessitating careful formulation of the feedstock. An example of successful application is the use of waste-derived polymer composites in 3D-printed architectural components and medical implants, demonstrating the potential of waste materials in creating sustainable, high-performance products [65].

7. CHALLENGES IN PROCESSING AND MATERIAL COMPATIBILITY

Despite the advantages of incorporating industrial waste into polymer composites, several challenges remain in terms of processing and material compatibility (Fig. 4).

7.1. Interfacial bonding issues

A key challenge is ensuring proper bonding between the polymer matrix and the waste-derived filler or reinforcement. Waste materials often have surface characteristics that make them incompatible with the polymer matrix, resulting in poor adhesion and weak composite properties. Surface treatments, such as chemical modifications

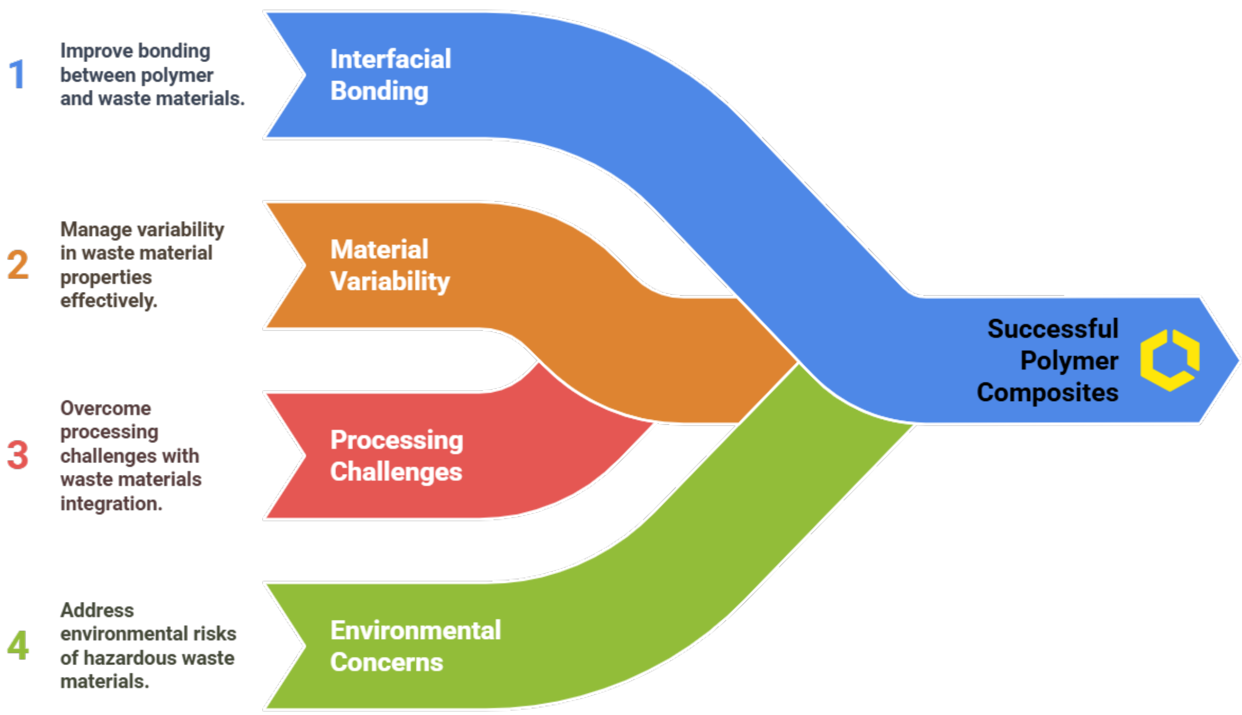

Fig. 4. Challenges and solutions in the process of producing polymer composites from wastes.

Table 4. Methods of surface modification for enhancing interfacial bonding in polymer composites.

Surface modification method	Description	Application in polymer composites
Chemical modification	Involves the application of reactive chemical agents to alter the surface energy and reactivity of waste-derived fillers.	Enhances interfacial bonding by introducing functional groups that improve compatibility with the polymer matrix. Commonly used for waste fillers like metals and ceramics.
Plasma treatment	Plasma treatment activates the surface of materials by generating reactive species that modify the surface properties.	Increases the surface energy of waste materials, improving their adhesion with the polymer matrix by introducing reactive sites. Particularly useful for organic waste materials.
Silane coupling agents	Involves the application of silane-based chemicals to form covalent bonds between inorganic fillers and the polymer matrix.	Silane agents promote stronger interfacial bonding by chemically linking the polymer matrix with inorganic fillers, such as glass fibers and silica-based waste fillers.
Polymer coating	Coating the surface of fillers with a thin layer of polymer that enhances the compatibility with the polymer matrix.	Used to improve compatibility with both natural and synthetic polymer matrices. This technique is effective in integrating waste fibers or particles with the matrix.
Thermal treatment	A process in which the waste material is subjected to elevated temperatures to modify its surface properties, enhancing its bonding capability.	Alters the surface roughness of the filler and creates microstructural changes that promote better adhesion with the polymer, especially useful for high-temperature resistant fillers.

or plasma treatment, can help improve the interfacial bonding [59].

To address these issues effectively, several surface modification methods can be applied to enhance the compatibility between the waste material and the polymer matrix. The Table 4 outlines the key techniques commonly used.

7.2. Variability in waste material properties

Industrial waste materials are often heterogeneous, meaning they can vary significantly in terms of chemical composition, particle size, and other physical properties. This variability makes it difficult to ensure consistent product quality and performance. Therefore, batch-to-batch variation in composite properties must be managed through careful control during processing [66].

7.3. Processing challenges

The presence of waste materials can alter the viscosity, melt flow index, and thermal stability of the polymer matrix. Some waste materials, such as rubber or agricultural by-products, may not easily melt or mix with the polymer, leading to issues during processing. In addition, waste materials can introduce impurities that affect the final product's mechanical or thermal properties [67].

7.4. Environmental and health concerns

Some industrial waste materials, particularly those containing heavy metals or hazardous compounds, can pose environmental and health risks if not properly processed. Ensuring that the waste materials are safe for use in polymer composites requires rigorous testing and regulatory compliance [68].

8. PERFORMANCE CHARACTERISTICS OF SUSTAINABLE POLYMER COMPOSITES

In order for sustainable polymer composites to be considered as real substitutes in any industrial sector, it is necessary to assess the performance characteristics of such materials against stringent mechanical and thermal requirements. The functioning of these materials depends to a large extent on parameters such as tensile strength, impact resistance, thermal stability or durability, which together would determine their performance - their reliability and functional life would ultimately depend on them. Some of these properties are directly related to the ability of the material to withstand mechanical loads, external environmental stresses and temperature fluctuations in order to ensure long-term performance and sustainability. Therefore, it is important to understand and optimise these properties in order to extend the range of applications and to improve the efficiency from a practical point of view.

8.1. Mechanical properties

Understanding the mechanical properties of sustainable polymer composites is essential for evaluating their viability as alternatives to traditional materials. These properties determine how well the composites perform under various stresses and environmental conditions. The mechanical response of polymers is governed not only by the inherent chemical composition of the macromolecules, but also by intricate factors such as cross-linking, branching, weight, plasticizers, crystallinity, additives, fillers, orientation, and the consequences of processing and thermal history of a particular specimen. It has been observed that, when all these parameters are held constant, the material properties of polymers exhibit a significant dependence on the time of testing and the temperature in comparison to metals. This dependency is attributable to the viscoelastic nature of polymers. Consequently, the necessity to enhance the mechanical properties of polymers has given rise to the development of polymer matrix composites.

Singh et al. [62] developed composite materials using a recycled thermoplastic matrix. The study concentrated primarily on the effects of fiber types and the comparison between artificial reinforcements comprising glass fibers and natural reinforcements such as bast, wood, bamboo and date palm leaf fibers. The study comprehensively examined the impact of processing method, fillers, compatibilizer, surface treatment, blending, processing method, processing condition, and processing parameters on the same process. The analysis revealed that the mechanical properties of the fabricated polymer composites are contingent on compatibility, interaction, and interfacial adhesion between the fiber and the matrix. It is evident that the addition of appropriate coupling agents, nanofillers, compatibilizers and their concentration, compatibility, interfacial adhesion and fiber-matrix interaction can further enhance the properties of composites.

In the study conducted by Anozie and Ifeanyi [69], the tensile and flexural mechanical properties of composite materials prepared from agro-waste materials (i.e., oilseed stalk, reed stalk, and corn stalk) were examined. The study's findings indicated that utilising agro-waste as a reinforcement in composite materials resulted in significantly enhanced mechanical properties when compared to those of plastics. The study revealed that the incorporation of oilseed stalk fiber as a reinforcement in composites resulted in a substantial enhancement in mechanical properties, despite the use of corn stalk and reed stalk at all fiber loadings. The findings of this study underscore the significant potential of agro-waste materials as a reinforcement for composite materials, thereby facilitating the attainment of enhanced mechanical properties.

In the study by Pandey et al. [70], a hybrid composite was fabricated by varying the constituent of bio-char and changing the orientation of sisal fiber in the epoxy matrix. The fabricated composites were then tested for different mechanical properties, i.e., tensile, flexural and impact strength. It was concluded that the surface and heat treatment processes result in improved surface adhesion properties. It was observed that samples with sisal fiber orientation in the longitudinal direction exhibited superior material properties in comparison to composites with fiber orientation in the orthogonal direction. Furthermore, it was determined that composites with sisal fiber orientation in the longitudinal direction and bio-char concentrations of 5, 10 and 15 wt.% demonstrated maximum tensile, flexural and impact strength, respectively.

Chun et al. [71] utilised agricultural by-products of the cocoa pod husk (CPH) as fillers in polypropylene composites, developing a green coupling agent (GCA) from coconut oil for filler modification. Both modified and unmodified polymer composites with 0, 10, 20, 30 and 40 filler content (phr) were prepared. The tensile test of the prepared samples was performed on an Instron Testing Machine, model 5569, in accordance with the ASTM D638 standards. It was observed that tensile strength decreased with an increase in filler content (phr). Furthermore, it was also observed that modified polymer composites exhibited superior properties in comparison to their unmodified counterparts.

Different mechanical properties will be accorded to sustainable polymer composites based on their material and processing methods. When combined with natural fibers, the bio-polymer composites perform better than the synthetic ones in the aspects of toughness, increasing the possibility for sustainability among the materials. So composite systems using inorganic polymers can easily replace all conventional polymer applications. These properties are under continued development with special emphasis on achieving the diverse requirements of industries while protecting the environment through sustainable composites.

8.2. Thermal and chemical resistance

The thermal and chemical resistance of a green polymer composite is as mechanical as necessary for functionality in different industries. Waste-derived fillers would therefore enhance mechanical resistance and thermal stability, with the result that such composites can operate at higher temperatures without undergoing a detrimental degradation process. This in turn prolongs their operational life and reliability in extreme application conditions. Inclusion of waste-based polymers improves chemical resistance to a large extent. This feature renders the materials particularly interesting for the automotive and construction industries, where a high level of extremes in operation conditions and performance entail rigorous specification.

Gargol and Podkościelna [4] carried out an investigation into the natural inorganic wastes such as ash and silica gel as fillers in polymer composites synthesized using bisphenol A derivatives glycerolate diacrylate and epoxy resin, Epidian® 5. Composites were prepared in filler content range from 0 to 40% w/w. Thermogravimetric analysis (TG/DTG) showed that fillers improve the thermal stability of samples with those silica-filled exhibiting higher stability than the ash-filled ones. Spectroscopy analysis (ATR/FT-IR) confirmed the presence of characteristic groups such as ether, methyl, methylene, aromatic rings, and SiO_2, confirming the course of polymerization. The study found that such waste inorganic fillers as silica and ash would fit well in polymer composites to improve the thermal behaviour, as well as saving on costs of materials and providing a sustainable way of durable materials.

Badiea et. al. [72] investigated glass-polymer-concrete (GPC) composites whereas considering their mechanical, chemical, and thermal properties unlike traditional concrete. The research showed that the reinforcing properties with glass waste and polymer can be brought with compressive strength of 52.43 MPa at 10% glass powder and 8% polymer blended to the mass of a ternary concrete. Good mechanical, chemical and thermal properties were improved with 10% glass and 8% polymer-being the ideal value. Above this, increasing the amount of filler will have negative effects due to increased porosity and permeation. Chemical improvement is also astonishing, with mass loss reductions of 32% and 37% in dilute sulfuric and nitric acids, respectively. The new composite has a thermal conductivity of 0.73 W/m·K and a water permeability of 3.65%, suggesting that it could be suitable for reliable construction applications.

According to Das et al. [73], waste-derived pyrolyzed biochar was investigated for its effects on the chemical and thermal properties of wood-polypropylene bio composites. Various characterization techniques, namely X-ray diffraction, transmission electron microscopy, and differential scanning calorimetry, revealed the enhancement of free radical availability and thermal conductance of the biochar-containing composites. While biochar particle addition did not interfere with the melting behaviour of the polymer, it acted as nucleation agents, and thus, the crystallization temperature increased. The crystal structure of polypropylene was unaffected, and nuclear magnetic resonance studies confirmed the aromatic nature and amorphous structure of biochar. At greater biochar loadings, particle aggregation became pronounced. The study, hence, indicates the potential application of biochar to improve composite properties and for sustainable management of solid waste.

Ray et al. [74] explored the application of marble dust wastes as fillers in epoxy resin composites, with the addition of epoxy toluene oligomer (ETO) co-matrix. A Fourier transform infrared spectroscopy was used to chemical characterization, and attained thermal and mechanical properties of selected composites were studied via thermogravimetry and tensile testing. Marble waste, which precipitated from wastewater with different coagulants (sepiolite, zeolite, pumice), significantly improved the thermal stability of composites, achieving greater thermal degradation temperatures and char yields above 350 °C. The composites had superior surface hardness and tensile strength relative to pure epoxy. Scanning electron microscopy showed incomplete exclusion of marble particles; higher tensile strength and Young's modulus were observed in composites with sepiolite and pumice coagulants. Hence, the marble waste is able to give enhancement in mechanical and thermal properties of epoxy composites.

Research on polymer composites from industrial waste reveals major improvements in their thermal and chemical properties for extreme applications- even industrial ones. The fillers from waste- such as biochar, glass, ash, silica, and marble dust-enhanced the thermal stability and mechanical resistance of composites. For example, biochar was added to wood-polypropylene composites which managed to enhance the thermal conductance and crystallization temperature without affecting the structure of the polymer crystals. The other example is marble dust, which improves the thermal stability and surface hardness of epoxy composites. Additionally, studies showed that improved thermal behaviour and cost-efficiency were reported when silica and ash were added to bisphenol-based polymers. Moreover, glass-polymer-concrete composites exhibited superb chemical resistance, significantly reducing mass loss when exposed to acid. All this shows that waste-derived fillers can enhance polymers' performance and durability, while waste management and development of newer eco-friendly materials for industries such as construction, automotive and manufacturing can be really sustainable from the aspect of resources, environment, or ecological.

8.3. Environmental degradation and life cycle analysis

With all the growing demand for sustainable polymer composites, consideration should also be given to their end-of-life scenarios, not just to their production and performance. Certainly, the option of recycling these materials has profound ramifications on environmental degradation: shaping a circular economy for waste minimization and conservation of resources [75]. As an example, recent advances in chemical recycling techniques break down composite materials into their fibers and resins, which can be reprocessed into new products without diminishment in quality [76]. Similarly, life cycle analysis (LCA) methodologies determine the environmental implications of each phase of the composite life cycle-from raw material harvesting through manufacturing, use, and finally its disposal. This information will allow manufacturers to decide on their way towards sustainability in a product life-cycle context. This will move the industry closer to true "greenness" in using material towards satisfying consumer demands for responsible resource usage with designing recyclable while integrating LCA conclusions into a development process [77].

9. CASE STUDIES AND APPLICATIONS

9.1. Construction industry: fly ash in composites

Fly ash (FA) is a product of coal pit combustion in power plants, and it has been successfully used in various formulations of concrete. It has been shown from various previous studies that the incorporation of FA improves most mechanical properties of concrete, increases workability, and reduces the entire environmental footprint. For instance, in India, using FA replaced up to 30% of cement in mixes and was acknowledged to result in substantial decrement CO_2 emissions without threatening the integrity of structures. This application shows that industrial waste could be one of the means to produce sustainable building materials [78]. The incorporation of FA composites has been demonstrated to enhance tensile strength, flexural strength, and impact resistance. An optimal range has been identified, varying between 10–20 wt.% for epoxy-based composites and 5–10 wt.% for thermoplastics [79]. The respective composites have been shown to exhibit enhancement in hardness, compressive strength, and reduced ductility [80]. FAs, particularly cenospheres, can reduce the density of composites while improving hardness and strength [81]. A variety of fabrication techniques, including stir casting and hand lay-up, have been employed to produce FA composites [80]. The use of FA in epoxy resin composites over glass fiber reinforcement has also been researched for the potential application in naval structures [82]. In general, FA composites have relatively better mechanical and tribological properties and have the potential of dealing with waste management.

9.2. Automotive sector: recycled plastics in car parts

Replacing new plastics with waste materials in its products is an important step for a major automotive manufacturer, which has chosen to use recycled polyethylene terephthalate (PET) from plastic bottles to make seat cushions, which include interior components such as panels. As well as reducing dependency on virgin plastics, it also contributes to circular economy initiatives by taking waste materials and reusing them. The mechanical performance of recycled PET composites is similar to that of conventional materials, making them suitable for automotive use and demonstrating their sustainability credentials. Recent studies show that recycled PET is suitable for automotive interior applications. In terms of mechanical properties for seat covers, recycled PET fibers provide equivalent results to raw PET. [83]. The blending of post-consumer and post-industrial plastics (Fig. 5) provides a feedstock suitable for interior structural components, with similar performance to raw materials [84]. For foams, polyurethane using up to 50% recycled PET polyols has been shown to have superior mechanical and thermal properties compared to petroleum-based foams [85]. Despite slightly lower tensile and flexural strength, recycled PET composites reinforced with modified kenaf fibers show better impact properties than raw PET composites [86]. All these studies indicate that recycled PET can be an excellent substitute for new plastics in automotive interiors, contributing to sustainable efforts while maintaining or improving material performance.

9.3. Aerospace industry: natural fibers and bio-resins

Recent studies have focused on finding sustainable composites for aircraft interiors made from natural and waste-based materials that promise environmental

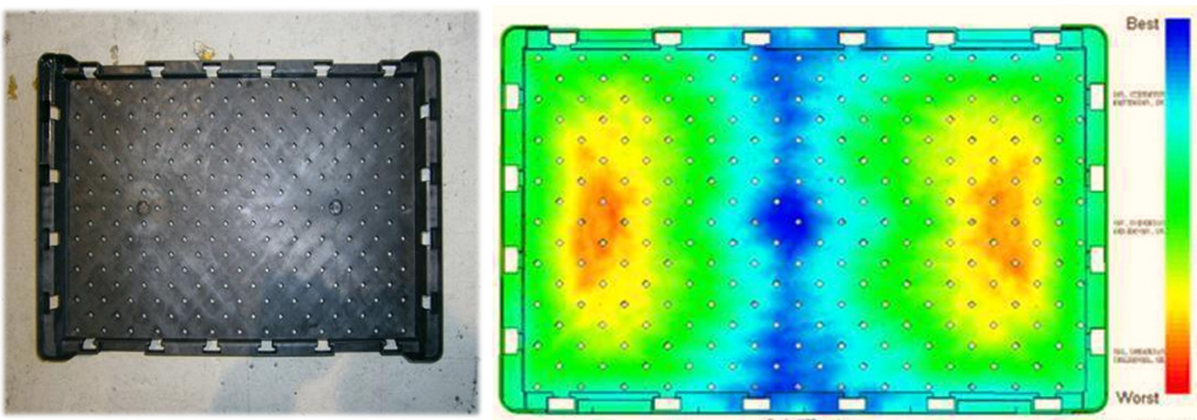

Fig. 5. Interior automotive trim and a tray-base produced from post-consumer recycled plastics by injection moulding process (left) with gate location analysis using Autodesk Moldflow to reveal the best location of injection gates (right). Reproduced from Ref. [84] under the terms of CC BY 3.0 license.

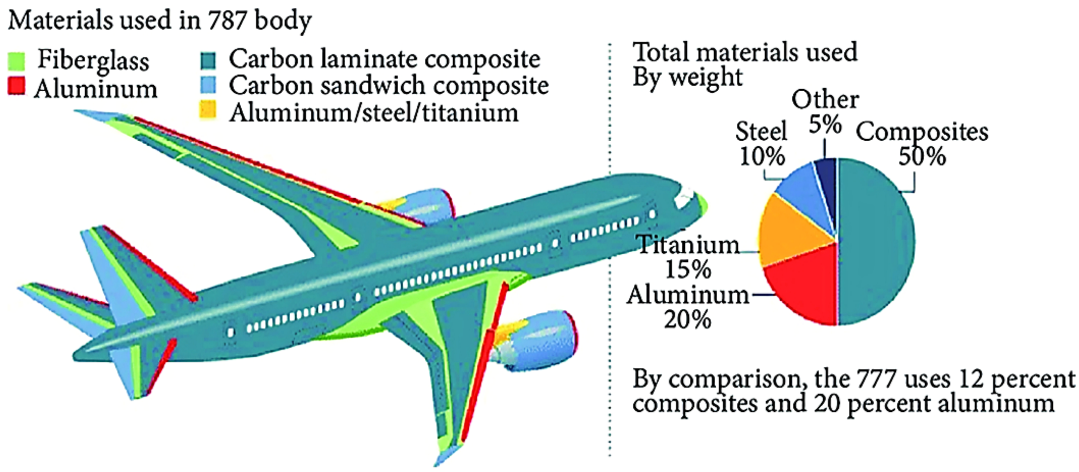

Fig. 6. The high volume of composites usage in the construction of various parts of the aircraft.

Fig. 7. The appearance of corn straw fiber skin (CSFS) and corn straw fiber core (CSFC). Reproduced from Ref. [93] under the terms of CC BY 4.0 license. © 2022 Z. Qi et al.

benefits compared to traditional synthetic fiber composites [87]. One aerospace company has explored the use of agricultural residues, such as flax and hemp fibers, bonded with bio resins to create lightweight composites with improved fuel efficiency and biodegradability. Natural fiber composites made from bast fibers such as kenaf, hemp and flax are being investigated for their environmental properties and aerospace applications [88]. In addition, composites based on waste paper have shown potential as a lightweight, water-resistant and cost-effective alternative. However, challenges remain to further improve the mechanical performance, flammability resistance, and impact resistance of these materials to levels that comply with stringent aerospace regulations [87,89]. Nevertheless, the increasing application of sustainable interior composites in aircraft suggests a growing demand for lightweight components that can provide greater fuel efficiency and reduce environmental impact [89]. The successful combination of these composite materials suggests that sustainable considerations may find their way into high performance industries such as aerospace (Fig. 6).

9.4. Packaging industry: agricultural waste as reinforcement

Between biological polymeric materials from agricultural waste and natural fibers from crop residues, a synergism is created by these materials to their joint performance of mechanical durability and biodegradability [90]. A company specialising in the production of packaging has used the same strategy to produce biodegradable packaging using corn starch and wheat straw fibers. This new development transforms agricultural waste into compostable products with good mechanical strength, replacing conventional plastics. Studies show that composites reinforced with wheat straw, corn stalks and rice hulls have higher hardness, modulus and impact strength, which means they can be used in biodegradable packaging applications [91]. In addition, hybrid bio composites incorporating materials from petrochemical and biomass sources have stimulated innovation in sustainable manufacturing [67]. The use of corn straw fiber complexes (CSFS & CSFC) with bioplastics, such as StrawPlast®, highlights the benefits of such composites in supporting circular economy principles while seeking to reduce environmental impacts [92,93] (Fig. 7).

Fig. 8. Steel slag aggregates from electric arc furnace (left) and recycled slag aggregate (right). Reproduced with permission from Ref. [96] under the terms of CC BY 4.0 license. © 2022 C.D.A. Loureiro et al.

As such, these developments provide users with alternatives to renewable resources while working towards the global goal of sustainability.

9.5. Textile sector: recycled textile waste

The recycling of textile waste into composite materials for automotive applications is gaining traction as an environmentally sustainable solution to the impact on nature perpetrated by the textile and automotive industries. A prominent example is a textile manufacturer that has set the stage for a method of recycling post-consumer textile wastes into composite materials for automotive interiors. After shredding and processing the discarded fabrics, the composites produced by the company show good flexibility and durability. Numerous studies have also addressed potential reinforcement of recycled textile fibers in the composite materials from pre-consumer as well as post-consumer waste [46]. These recycled fiber composites could find application in various matrices including thermoplastic polymers, thermosetting resins, and even concrete, with specific automotive applications in mind [94]. This also helps in weight reduction for the application in car interiors and body parts with the augmented effect of fuel efficiency and reduced CO_2 emission [95]. This further aids in addressing the growing problem of textile waste while also upholding the tenets of the circular economy and fostering eco-friendlier materials for use in automobile production [94].

9.6. Construction and infrastructure: slag in road materials

Steel slag, a by-product of the steel manufacturing process, has gained attention for its potential use as a reinforcement material in polymer composites. New case studies explore the integration of steel slag into polymer matrices, highlighting its benefits, applications, and the environmental impact of utilizing this industrial waste (Fig. 8):

1. Construction materials. Polymer composites reinforced with steel slag can be used in construction applications, such as building materials, flooring, and road surfaces, where enhanced mechanical properties and durability are crucial [97].
2. Infrastructure development. The use of steel slag in polymer composites can contribute to the development of sustainable infrastructure solutions, such as eco-friendly road materials that reduce the environmental footprint of construction projects [98].

9.7. Consumer goods: coconut fiber composites

An Ecuadorian research group dedicated to environmentally sound developments has initiated investigation into the production of innovative bio-composite sandwich wall panels, a project which includes the introduction of eco-friendly panels made from waste-based (green) composites cleverly combining coconut fibers with a polymer matrix (Fig. 9). This remains a novel approach to not only solving the pressing problem of agricultural waste through the valorisation of coconut husks typically discarded but also offers an alternative to wooden products that disturb the balance of the

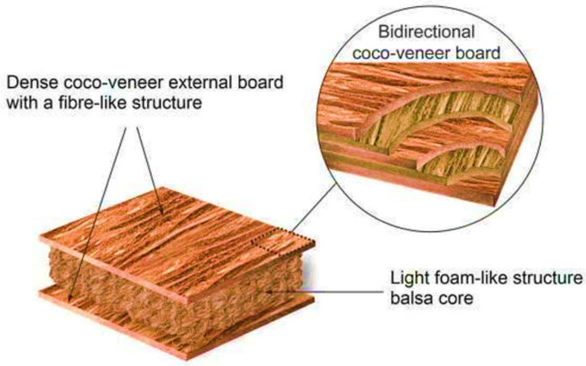

Fig. 9. Sandwich-like structure wall panel made of Ecuadorian balsa lightweight core and coconut bidirectional external veneers. Reproduced from Ref. [99] under the terms of CC BY 3.0 license.

environment and promote the process of deforestation. In this study, the new bio-composite sandwich wall panels with bidirectional coconut-fiber outer veneers and a light core (named Ecuadorian balsa) were designed for environmentally friendly construction appli-cations in seismic regions. The primary aim of this research was to evaluate and analyze the mechanical properties of these panels as alternatives for conventional construction materials such as bricks and concrete. With that in focus, two panels of prototypes (1200 × 600 mm), with a total thickness of 124 mm and 74 mm respectively, went through the process of carrying out mechanical and seismic tests based on ASTM standards. The preliminary results indicate that the proposed panels are two to three times more efficient when it comes to mechanical performance compared to equivalent solid brick or concrete block walls. This bio-system offers great promise as a means of decreasing dependence on conventional materials like steel, concrete, and bricks with a very favourable environmental effect. Further, these panels may also help address the need for the reconstruction of severely earthquake-affected low-rise and mid-rise residential buildings since the 2016 Ecuador earthquake [99].

10. COMPARATIVE ANALYSIS OF DIFFERENT WASTE SOURCES

A comprehensive evaluation of various waste-derived feedstocks is essential for assessing their suitability in sustainable polymer composite production. In this section, we compare recycled waste plastics, agricultural residues, and industrial by-products (e.g., fly ash) in terms of their mechanical/thermal properties, environmental impacts, and economic and processing considerations, supported by numerical data from recent studies. The following summarizes the key quantitative and qualitative attributes for each waste source shown in Table 5.

10.1. Economic problems vs. properties

10.1.1. Waste plastics

Global production of plastics is estimated at approximately 400 million tons per year, with less than 9% being recycled (Organisation for Economic Co-operation and Development Reports) [100]. Most of these wastes flow and import from other parts of the world to China before new ban rules accepted in 2017 (Fig. 10). Recycled plastics such as PET, HDPE, and PP often exhibit tensile strengths in the range of 30–40 MPa and maintain good ductility. However, repeated reprocessing may lead to chain scission and a 10–20% reduction in tensile modulus [101]. In addition, the energy consumption for producing virgin plastics can be 2.5–3 times higher than that for recycled materials. Furthermore, landfill tipping fees for non-recycled plastics can reach around US $60 per ton in some regions (Environmental Protection Agency data), emphasizing the environmental cost if plastics are not properly recycled [102].

10.1.2. Agricultural residues

Agricultural waste—including fruit peels, bagasse (sugarcane residues), rice husks, and wheat straw—is typically rich in 30–60% cellulose, 15–30% hemicellulose, and 10–20% lignin [103]. According to Food and Agriculture Organization estimates, about 20–30% of fruits and vegetables are lost post-harvest, corresponding to an annual global waste volume of approximately 60 million tons [104]. Composites produced from these residues (e.g., rice husk-reinforced polylactic acid) have shown a reduction in greenhouse gas emissions by 20–30% compared to petroleum-based polymers [105]. The initial processing costs for these wastes (e.g., fiber extraction, milling) are relatively low—on the order of US $10–15 per ton—while transportation and handling costs may vary between US $20 and US $30 per ton [106].

10.1.3. Industrial by-products (fly ash)

Fly ash, a by-product of waste-to-energy (WTE) and coal combustion, is characterized by fine particle sizes (over 90% of particles being less than 1000 μm) and high mineral content [107]. Fly ash is available at very low cost, often as a waste product from WTE facilities. In the United States, an estimated 40 million tons of fly ash are produced annually. The cost savings from using fly ash as a filler can be significant—diverting fly ash from landfills saves approximately US $60 per ton, and when used in composites, overall processing costs can be reduced substantially [108]. Studies indicate that incorporating fly ash into matrices like linear low-density polyethylene (LLDPE) can increase the tensile modulus by approximately 10–15% and improve thermal stability (with melting point increases of 5–10 °C). However, due to its tendency to agglomerate and inherent brittleness, fly ash may reduce impact resistance [109]. Moreover, heavy metals—such as lead, sometimes exceeding 5000 ppm—pose environmental risks; consequently, regulatory limits often restrict fly ash content to less than 1.5–2% by weight for applications in direct contact with consumers [110].

10.1.4. Waste glass

Recycled waste glass is predominantly composed of silica, aluminium oxides, and calcium oxides, making it suitable for composite applications due to its hardness and thermal stability. Research indicates that incorporating waste glass into composites can enhance flexural strength by 15–25%

Table 5. Quantitative and qualitative comparison of different waste sources for sustainable polymer composites.

Waste source	Annual production volume	Mechanical properties	Processing & maintenance costs	Environmental impact & savings	Key challenges	Ref.
Waste plastics	~400 million tons (global)	Tensile strength: 30–40 MPa; possible 10–20% drop in modulus upon repeated recycling	Processing costs: US $50–100/ton (advanced sorting, cleaning, stabilization)	Energy savings of 40–50%; prevents ~8 million tons plastic ocean pollution annually	Quality degradation; non-biodegradability; high reprocessing costs	[113] [114]
Agricultural residues	60–100 million tons (fruits and vegetables only)	Moderate strength; lower density; enhanced biodegradability with proper pre-treatment; up to 20–30% reduction in CO_2 emissions when used in PLA composites	Initial processing: US $10–15/ton; transportation: US $20–30/ton	Lower embodied energy; renewable; significant reduction in CO_2 emissions (20–30%)	Heterogeneity; need for effective pre-treatment and fiber extraction	[115] [105]
Industrial by-products (fly ash)	In the US: ~40 million tons; variable globally	Increase in modulus by 10–15%; thermal stability improved (melting point up by 5–10°C); may reduce impact strength	Landfill disposal avoided saves ~US $60/ton; additional processing (compatibilizers): US $5–10/ton	Diverts waste from landfills; reduces disposal costs by up to 70–80%; however, heavy metal concerns (e.g., >5000 ppm lead) limit application	Agglomeration; heavy metal leaching risk; brittleness; additional pre-treatment costs	[116] [81]
Waste glass	~130 million tons globally	Hardness; thermal stability; increases flexural strength by 15–25%; reduces water absorption rates.	Crushing and refining costs are high; reduces raw material costs by ~ US $70/ton.	Reduces CO_2 emissions by up to 35%; prevents landfill accumulation; minimizes resource extraction.	Energy-intensive processing; contamination from coatings or additives in certain glass types.	[117]
Mining and mineral waste	~20–30 billion tons globally (tailings, slags, etc.)	Improves fire resistance by up to 40%; reduces polymer shrinkage; enhances mechanical stability.	Disposal savings ~ US $80/ton; additional processing costs for compatibility ~ US $5–10/ton.	Prevents hazardous tailings accumulation; lowers pollution risks; reduces dependency on virgin minerals.	Heavy metal leaching risks; agglomeration issues; requires advanced treatment technologies.	[118]
Textile waste	~92 million tons annually (USA)	Enhances impact resistance and elasticity when used in composites.	Processing costs ~ US $40–60/ton; energy savings of up to 70% compared to virgin fiber production.	Reduces chemical discharge into water systems; conserves resources; minimizes landfill overflow.	Sorting blended fabrics; maintaining fiber quality during recycling; high transportation costs.	[119]
Electronic waste	~50 million tons annually (EU)	Tensile strengths up to 50 MPa; superior electrical insulation properties in composites.	Metal recovery saves ~ US $150/ton in raw material costs; processing costs vary based on technology.	Prevents heavy metal leaching (e.g., lead, mercury); mitigates health hazards; supports circular economy efforts.	Toxicity risks during dismantling and recycling; high initial investment for advanced technologies.	[120]
Energy production waste	~1 billion tons annually (WORLD)	Enhances flame retardancy and mechanical strength in composites (20–30% increase in flexural modulus).	Landfill diversion saves ~ US $90/ton; additional processing costs depend on material type (~ US $5–15/ton).	Supports circular economy principles; reduces CO_2 emissions from landfills and incineration processes.	Brittle nature of some residues (e.g., bottom ash from blast furnace); contamination with heavy metals or other impurities.	[121]

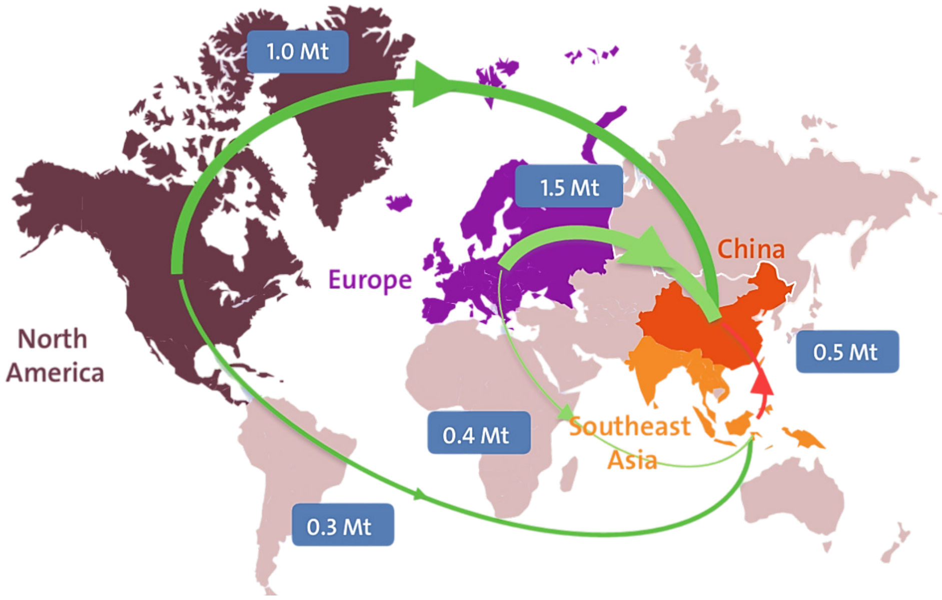

Fig. 10. Main global plastic waste flows before China's ban. Net exports from Europe and North America to Asia in 2017. These flows were already well down on 2016 and continued to evolve in 2018 following the Chinese government's decision to ban imports of post-consumer plastic waste. Source: comtrade.un.org/data [100].

while reducing water absorption rates. However, the energy-intensive processes of crushing and refining glass particles significantly increase processing costs. Despite this, recycling waste glass offers substantial economic benefits, such as reducing raw material costs by around US $70 per ton and alleviating landfill burdens. Furthermore, glass recycling minimizes the depletion of finite resources like silica and mitigates environmental risks associated with hazardous elements in certain types of glass, such as lead in cathode ray tubes (CRTs).

10.1.5. Mining and mineral waste

Mining and mineral waste, including tailings, slags, and spent minerals, presents a sustainable option for reinforcing composites. These materials improve fire resistance in composites by up to 40% and reduce polymer shrinkage. Economically, repurposing mining waste can save up to US $80 per ton in disposal fees while decreasing reliance on virgin minerals. Additionally, utilizing these wastes supports local economies by creating employment opportunities in mining communities, particularly in regions where mining operations are critical to livelihoods.

10.1.6. Textile waste

Textile waste, primarily from polyester, nylon, and cotton, poses a growing challenge due to its accumulation in landfills. When recycled into composites, textile fibers enhance impact resistance and elasticity. While processing textile waste costs between US $40–60 per ton, reusing fibers instead of producing virgin ones can result in energy savings of up to 70%. However, challenges such as sorting blended fabrics and maintaining fiber quality during recycling must be addressed through innovative solutions like chemical recycling or blending old fibers with new ones.

10.1.7. Electronic waste (e-waste)

E-waste contains valuable materials such as thermoset plastics and metals that can be repurposed as composite fillers. For instance, printed circuit board (PCB) waste composites exhibit tensile strengths up to 50 MPa and excellent electrical insulation properties. Recycling e-waste is economically viable due to metal recovery processes that save approximately US $150 per ton in raw material costs while preventing the accumulation of toxic substances like lead and mercury. Moreover, increased eco-investment in e-waste management fosters safer recycling technologies and creates jobs within the circular economy framework.

10.1.8. Energy production waste

Waste from energy production processes—such as bottom ash and desulfurization residues—can enhance the flame retardancy and mechanical strength of polymer composites. Studies show that using these materials increases the flexural modulus of composites by 20–30%, while reducing landfill diversion fees by about US $90 per ton. Additionally, integrating energy production waste into industrial cycles supports circular economy principles by transforming waste into valuable resources.

10.2. Environmental impact

10.2.1. Waste plastics

Recycling waste plastics diverts vast amounts of material from landfills and can lower energy consumption by 40–50% compared to virgin production. Nonetheless, the non-biodegradable nature of these materials remains problematic. For instance, it is estimated that failure to recycle could result in approximately 8 million tons of plastic entering the oceans annually [111].

10.2.2. Agricultural residues

Utilizing agricultural residues in the production of waste-based composites offers considerable environmental benefits. When incorporated into matrices such as polylactic acid, these residues can reduce CO_2 emissions by 20–30% relative to conventional fossil-based polymers. Moreover, converting low-value agricultural waste into high-performance composites minimizes disposal needs, thereby reducing soil and water contamination risks associated with landfilling [69].

10.2.3. Industrial by-products (fly ash)

The use of industrial by-products like fly ash can substantially lower landfill volumes and associated disposal costs. On average, each ton of fly ash diverted from landfills saves about US $60 in tipping fees, and when incorporated into composites, overall transportation and storage costs can be reduced by as much as 70–80%. However, potential leaching of hazardous heavy metals requires rigorous pretreatment to mitigate environmental hazards [112].

10.2.4. Waste glass

Recycling waste glass has significant environmental benefits. By replacing primary raw materials such as silica and limestone, the demand for resource extraction is reduced, leading to a decrease in energy consumption during production. This process also minimizes CO_2 emissions by up to 35%, making it a sustainable alternative for industries like construction and manufacturing. Additionally, waste glass is inert and does not degrade in landfills, meaning recycling prevents long-term environmental contamination [117].

10.2.5. Mining and mineral waste

Mining activities generate substantial environmental challenges, including deforestation, habitat destruction, and pollution of air and water systems. Recycling mining waste, such as tailings and slags, prevents hazardous materials from accumulating in the environment. For instance, acid mine drainage—a common issue—leaches heavy metals into water systems, harming aquatic ecosystems and human health. Repurposing mining waste not only reduces these risks but also lowers greenhouse gas emissions associated with virgin material extraction [118].

10.2.6. Textile waste

Textile waste significantly impacts the environment through landfill overload, water pollution, and greenhouse gas emissions. As textiles decompose in landfills, they release methane—a potent greenhouse gas that contributes to global warming. Additionally, chemical dyes and microplastics from textiles contaminate soil and water sources, endangering aquatic life and human health through the food chain. Recycling textile waste can mitigate these effects by reducing landfill accumulation and conserving water resources [119].

10.2.7. Electronic waste (e-waste)

E-waste poses severe environmental risks due to its toxic components such as lead, mercury, cadmium, and lithium. Improper disposal leads to soil contamination, groundwater pollution, and air toxicity from harmful emissions during incineration. For instance, dismantling cathode ray tubes releases heavy metals into the environment, which can persist for decades. Recycling e-waste not only prevents these hazards but also recovers valuable materials like gold and copper, reducing the need for resource-intensive mining [120].

10.2.8. Energy production waste

Waste from energy production processes—such as fly ash and bottom ash—can be reintegrated into industrial cycles to reduce environmental harm. These materials are often used in cement or polymer composites to enhance durability while minimizing landfill accumulation. This practice supports circular economy efforts by reducing dependency on virgin resources and lowering CO_2 emissions associated with traditional waste disposal methods like landfilling or incineration [121].

11. CONCLUSION

The utilisation of polymer composites manufactured from industrial waste has the potential to effect transformative change in both societal and economic development by addressing certain key emerging environmental challenges. A review of the extant literature clearly

Fig. 11. Future scope of waste utilization processes development in polymer composites production based on lifecycle assessment.

indicates a broad future for an emerging number of wastes, from processed and engineered fly ash, slag, agricultural residues, and recycled plastics, as potential sources for producing high-performance composites. The mechanical and thermal properties of composites could be enhanced in conjunction with a circular economy that combines waste elimination with efficient resource use. Process improvements for extrusion, additive manufacturing, and applications in packaging, automotive, and construction will further enable optimum performance of these composites in a variety of applications. However, barriers remain, such as materials compatibility, scalability of production, and consistency of quality for the technology. It is therefore vital to emphasise the need for public awareness, and to facilitate interaction between scientists, recycling innovators and regulators, in order to gain acceptance for sustainable polymer composites. Increasing consumer awareness is expected to increase the scope of activity in this regard, and further support for development in this direction would be extremely beneficial in realising the full potential of sustainable polymer composites, and in encouraging innovations by stakeholders in the area of coexistence between economic growth and environmental sustainability. The integration of sustainability practices into industrial processes is expected to create a favourable environment for the development of products that can contribute to the preservation of a healthy environment for future generations.

Implications for future research and development

It is reasonable to hypothesise that there will be a variation in the field with regard to future developments in research and development in sustainable polymer composites. Such development will not be possible if a multifaceted approach is not adopted, with emphasis placed on material optimisation, the development of innovative recycling technology, and collaborative multidisciplinary research. There will be a significant focus on the use of waste materials from industries to improve polymer composites for mechanical, thermal, and chemical performance. The type of waste material will have a significant impact on the properties of composites and can serve as a guide for generating specific applications. Furthermore, it will enable advanced recycling processes to convert complicated waste streams to high-quality raw materials and facilitate the construction of closed-loop systems in line with closed-cycle economy principles. Lifecycle assessment (LCA) will take into consideration and evaluate the environmental impact of such composites from raw material origin through processing to end-of-life disposal (Fig. 11). This will provide the basis for future improvements in material input and production methods.

Material scientists, engineers, environmentalists, and industry experts will work together to provide a basis for collaboration and innovation in the standardisation of sustainable composite production. It is important to understand what consumers think about eco-friendly products so that design and marketing strategies can be created that will encourage people to buy them. Similarly, it is important to understand the regulations, as this will provide the necessary insights on how policies can promote sustainability in material use. Using smart technologies in polymer composites could lead to new ideas, such as materials that can check and change their own performance to fit in with the environment. Also, problems with materials that can't be used together because of surface treatments or how they're made will be important for making composites better. Lastly, studies will be done to show how much it will cost and how many jobs it will create in a green economy in the long term. These research results will encourage a balanced approach to economic growth and environmental protection in the area of sustainable polymer composites.

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Устойчивые полимерные композиты из промышленных отходов

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Аннотация. Устойчивые полимерные композиты, полученные из промышленных отходов, представляют собой перспективное решение проблемы нехватки ресурсов и экологических вызовов. В данном обзоре рассматриваются разработка, свойства и области применения композитов, содержащих золу-унос, шлак, сельскохозяйственные остатки и переработанные полимеры. Использование таких отходов снижает негативное воздействие на окружающую среду, одновременно улучшая механические, термические и химические свойства материалов. Ключевые технологические процессы, такие как расплавное смешивание, экструзия и аддитивное производство, способствуют оптимизации характеристик композитов. В обзоре также анализируются проблемы совместимости отходов, долговечности и масштабного производства, предлагая возможные пути их решения. Интеграция устойчивых полимерных композитов в принципы циркулярной экономики открывает перспективы их применения в строительстве, автомобильной промышленности и упаковке. Подчеркивается необходимость дальнейших исследований для раскрытия полного потенциала этих материалов в развитии устойчивого будущего.

Ключевые слова: устойчивые полимерные композиты; промышленные отходы; циркулярная экономика; технологические процессы; механические свойства