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Advancements in green composites: materials science innovations for a sustainable future

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A B S T R A C T

The use of biodegradable polymers and natural fibers in green composites offers sustainable alternatives to traditional materials. Nanotechnology, artificial intelligence, and self-healing mechanisms enhance their performance. AI-based recycling and policy incentives can drive adoption, despite cost and scalability challenges. Advances in manufacturing and circular economy models will be key to future success.

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1. Introduction

As the world grapples with the pressing challenges of climate change and environmental degradation, the quest for maintainable materials has never been more critical [1]. Green composites, which integrate natural fibers with biodegradable matrices, have emerged as a promising solution to reduce reliance on fossil fuels and minimize waste. Fig. 1 illustrates comprehensive data on historical performance and future projections for green composites. In the period between 2010 and 2019, biodegradable polymers and natural fibers were introduced to the green composites market [2, 3]. Global composites market growth declined in 2020 as a result of COVID-19 pandemic, despite innovation, especially with nanotechnology [4, 5]. We also see an increased emphasis in 2023 on the recyclability of materials and the biodegradability of products, as well as advances in nanocomposites [6, 7]. We expect a greater integration of artificial intelligence into manufacturing processes in 2025 as well as an expanded use of AI in the automobile and construction industries[8]. For the selection of materials and process optimization in green composites, emerging technologies such as artificial intelligence (AI) and machine learning algorithms are increasingly being used. The use of AI-driven predictive modeling enables researchers to identify optimal fiber-matrix combinations that maximize mechanical properties while ensuring environmental sustainability [9]. This perspective aims to explore the recent advancements in materials science that are enhancing the performance and applicability of green composites. By importance technological innovations, industry applications, and the contests that lie ahead, we seek to underscore the potential of green composites in fostering a sustainable future.

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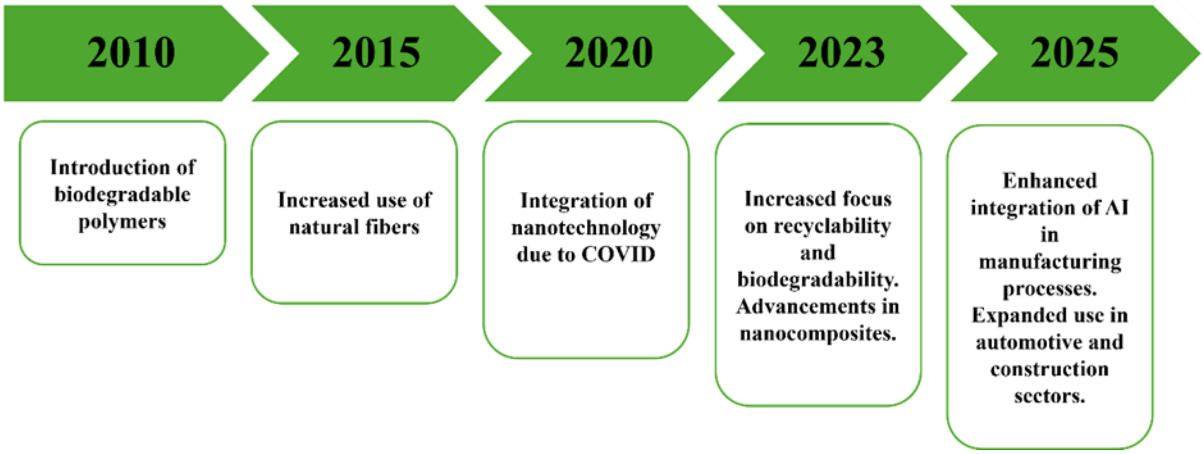

Fig. 1. Advancements in green composites.

2. Understanding Green Composites

Green composites are defined by their composition, typically involving a biodegradable polymer matrix reinforced with natural fibers [10]. This combination not only improves mechanical properties but also reduces the environmental impact associated with traditional synthetic composites [11]. The shift towards these materials is largely driven by the need for defensible answers that minimize carbon footprints and promote recycling and biodegradability [12].

3. Technological Innovations Enhancing Performance

Recent technological novelties in green composites have expressively boosted their presentation, making them more competitive with traditional materials [13]. Key advancements include the use of nanocomposites, which incorporate nanoparticles to improve mechanical and thermal properties, thereby increasing strength and durability [14]. Additionally, advanced biocomposites derived from agricultural waste are being developed to optimize resource utilization while maintaining high performance [15]. Advances in processing techniques, such as improved molding methods and fiber alignment, further contribute to the robustness of these materials. In this field, self-healing mechanisms have also been incorporated into green composites. In industrial applications, self-repairing polymeric matrices are being investigated as a means to enhance durability, longevity, and reduce material waste. The integration of 3D printing technologies allows for precise customization of composite structures, enabling the creation of complex geometries that increase functionality while reducing waste [16]. Collectively, these inventions are propelling green composites into various applications across industries, from automotive to construction, underscoring their potential as sustainable alternatives in material science [17].

4. Applications Across Industries

Green composites are increasingly being adopted across various industries due to their sustainability and performance characteristics [18]. In the automotive sector, manufacturers utilize these materials to create lightweight and durable components, which not only reduce vehicle weight but also improve fuel efficiency and lower carbon emissions [19]. In construction, green composites are employed for insulation, panels, and structural elements, providing an eco-friendly alternative to traditional materials while maintaining structural integrity [20]. The packaging industry is also benefiting from green composites, as they offer biodegradable options that meet consumer demand for sustainable explanations [21]. Additionally, applications in agriculture, such as biodegradable planting pots and films, illustrate the versatility of these materials in addressing environmental encounters while promoting resource productivity [22]. Policy and regulatory frameworks will be crucial to accelerating the adoption of green composites in the future. Biodegradable materials are expected to be promoted by governments worldwide through stricter regulations and incentives, thereby driving an industry-wide transformation into sustainability. Overall, the integration of green composites across these sectors highlights their potential to contribute meaningfully to a sustainable economy [23].

5. Challenges and Future Directions

Despite the advancements in green composites, several important challenges hinder their widespread adoption [13]. Cost competitiveness remains a major barrier, as the production of green composites is often more expensive than traditional materials, limiting their market viability [24]. Additionally, large-scale production poses logistical and technological hurdles that need to be addressed to meet industry demands effectively [25]. There is also a need for market acceptance, as consumers and industries may be hesitant to transition from established materials to newer, eco-friendly alternatives [26]. Furthermore, inadequate infrastructure for recycling and processing these materials can impede their integration into existing supply chains [27]. Recycling waste from green composites into new materials is essential to overcoming these challenges. Waste management processes can be further optimized with AI-driven sorting and recycling technologies, ensuring sustainable goals are met. To overcome these challenges, continued investment in research and development is essential, alongside collaborative efforts among governments, academia, and industry stakeholders. Future directions should focus on enhancing recyclability and biodegradability, as well as leveraging advanced technologies such as artificial intelligence to optimize material properties and processing techniques, ensuring that green composites can play a pivotal role in a sustainable economy [28].

6. Conclusion

The advancements in green composites represent a major step towards achieving sustainability in materials science. As Europe leads the way with funding programs like Horizon Europe, the future looks promising for these innovative materials. With ongoing research focused on enhancing recyclability and biodegradability, green composites are set to play a pivotal role in transitioning towards a more sustainable economy. Artificial intelligence, advanced manufacturing techniques, and sustainable resource management will be key factors in determining how industries integrate these materials into mainstream production in the next decade. The integration of advanced technologies will further develop their potential, making them indispensable in addressing global environmental challenges while meeting industrial needs.

Authors' contribution

Fariba Azamian: Interpretation, Writing—Original Draft Preparation, Writing—Review and Editing**. Mahsa Hojjati**: Conceptualization, Writing—Original Draft Preparation, Writing—Review and Editing**,**

Declaration of competing interest

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