Editorial Corner

Sustainable Composite Products: Industry 4.0 to 5.0

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Natural fibers and their composites have gained significant interest due to growing environmental awareness and sustainability. Primarily, natural fibers, their derivatives, and composites were used for lightweight applications [1]. Furthermore, with advancements in technology and processability, these materials are being utilized in advanced applications such as wearable electronics, biosensors, vibration dampers, aerospace insulation materials, medical scaffolds, and filtration systems.

In the current era, industries are undergoing a shift from Industry 4.0 to Industry 5.0, where the focus is expanding from automation and digitalization to sustainability and human-machine collaboration. In this context, natural fibers extracted from plants have gained significant attention due to their lightweight nature, cost-effectiveness, environmental friendliness, and adequate mechanical properties suitable for both structural and semi-structural applications [2]. Owing to their renewable and biodegradable characteristics, natural fibers serve as ideal reinforcements in sustainable composite materials, leading to their increasing demand across various sectors.

Industry 5.0 places a strong emphasis on eco-conscious innovation, integrating sustainability with smart technologies and bridging the gap between human creativity and advanced automation. Within this framework, the design and manufacture of sustainable composites, particularly those reinforced with natural fibers, have become vital components of next-generation industrial practices aimed at reducing environmental impact.

Traditionally, the fabrication of eco-friendly composites relied on conventional techniques such as hand lay-up, spray-up, extrusion, injection molding, and compression molding. However, recent advancements in manufacturing technologies have enabled more precise, efficient, and automated processes. Modern methods such as additive manufacturing, resin infusion, filament winding, pultrusion, UV curing, microwave irradiation, automated fiber placement (AFP), automated tape laying (ATL), thermoforming, and hybrid manufacturing have significantly expanded the possibilities for producing high-performance natural fiber composites (NFCs) [3]. These advancements not only enhance the structural integrity and functionality of the composites but also align with the sustainability goals of Industry 5.0 by reducing material waste, energy consumption, and production time.

Transitioning to Industry 5.0 introduces a new layer: the emphasis on sustainability, ethics, and human-centric innovation. Here, NFCs stand out as enablers of green manufacturing. Their biodegradability and lower energy consumption directly contribute to reducing the overall environmental impact of composite products. Life Cycle Assessment (LCA) studies show that NFCs exhibit reduced greenhouse gas emissions, lower energy consumption,

and better end-of-life disposal options when compared to conventional fiber composites [4].

Furthermore, NFCs follow the principles of the circular economy. Waste fibers from agriculture or textile industries can be repurposed as reinforcement materials. When reinforced with bio-based or recyclable matrices such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), or recyclable thermoplastics, these composites can be designed for full material recovery and reuse.

Nevertheless, challenges persist. Natural fibers exhibit batch-to-batch variability, hydrophilicity, and limited thermal stability. Advancements in surface treatments, compatibilizers, and nano/macro-reinforcements are essential to enhance fiber-matrix bonding, thermal resistance, and mechanical strength [5]. Similarly, establishing standardized testing protocols and material specifications for NFCs is crucial for their broader industrial adoption.

In Industry 5.0, the manufacturing processes are controlled by robotics, digital systems, and artificial intelligence, aligning with sustainability. This hybrid system advances manufacturing technologies and strategies by enabling precise control over the composite's performance and morphology through tailored fiber orientation, fiber structure, filler dispersion, filler architecture, and matrix selection. The tools of Industry 5.0 support the optimization and customization of composite properties with a strong focus on sustainability, minimizing waste, and reducing energy consumption.

Furthermore, promoting sustainability in Industry 5.0 increasingly relies on the integration of life cycle assessment methodologies. It provides a comprehensive evaluation of the environmental impact of materials, from raw material extraction through processing, usage, and end-of-life disposal or recycling. Incorporating life cycle assessment into the design stage empowers manufacturers to make informed choices regarding fiber types, resin systems, and production routes that minimize ecological burden [6]. Therefore, sustainable composites can be developed with a comprehensive understanding of each phase of their life cycle.

Additionally, from an economic perspective associated with the vision of Industry 5.0, natural fiber composites offer a sustainable pathway for industrial development. By hybridizing intelligent automation with sustainable environmental practices, NFCs demonstrate the role of Industry 5.0 in promoting an industrial evolution that combines economic efficiency with ecological integrity.

The adoption of Industry 5.0 technologies in NFC manufacturing is still emerging, primarily due to limited automation solutions custom-made for sustainable composite materials. Future advancements lie in hybridizing smart systems with material innovation using AI, real-time monitoring, and fiber processing systems to enhance the performance of these composites. Such advancements will provide new potential for developing high-performance, environmentally friendly composites optimized for industrial use.

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