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Bio Based Composites for Engineering Application and Sustainability Perspectives

Nasmi Herlina Sari [a] *, Muhammad Nabil Fadhlurrohman Rivlan [a]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Mataram, Mataram, Indonesia

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Natural fibers such as hemp, flax, kenaf, or jute are commonly combined with bio-derived resins such as polylactic acid (PLA), lignin-based polymers, and soy- Based epoxies to create bio-based composites. Aside from their renewable source, these materials have advantages like biodegradability, lower density, and lesser environmental impact when compared to traditional alternatives. Processing technology advancements, such as compression molding, resin transfer molding (RTM), and additive manufacturing (AM), have increased their relevance for precise components requiring both performance and sustainability. Recent research has also emphasized ways for overcoming bio composites' intrinsic shortcomings, such as unpredictability in fiber quality, moisture sensitivity, and poor interfacial adhesion. Surface modification procedures (alkaline, silane, and enzymatic), nano-filler insertion, and hybridization methods have shown promise in improving tensile, flexural, and thermal performance [1–3]. Nanofillers such as nanoclay, graphene, and cellulose nanocrystals improve stiffness, thermal stability, and multifunctionality [4,5]. Hybrid composites, combining natural fibers with basalt or recycled carbon fibers, expand application potential [6,7]. Collectively, these advances position bio composites as realistic alternatives to conventional synthetic systems in precision engineering [1,3,8,9]. Beyond renewable origins and mechanical performance, bio-based composites are sustainable in terms of environmental impact, energy efficiency, and compatibility with circular economy concepts [7]. For example, PLA-based composites bonded with natural fibers have partial biodegradability, lowering the requirement for landfill or incineration, but thermoplastic-based bio composites can be recycled into secondary goods, increasing resource efficiency.

Despite significant development in bio-based composites for precision engineering, various barriers prevent their widespread implementation. The primary problem is assuring long-term durability against moisture, temperature change, and biological deterioration, as most research rely on short-term laboratory testing. Cost, scalability, and fiber heterogeneity all have an impact on material consistency and reliability. To overcome these issues, standard fiber treatments, better

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* First corresponding author
Email: nasmiherlina336@gmail.com

characterization, and improved resin-fiber compatibility (by green surface modification or molecular-level tuning) are required. Bioplastics derived from lignin, algae, or bacterial polyesters, as well as nano-reinforcements such as graphene, cellulose nanocrystals, and bio-based nanoclays, have shown promise in improving mechanical and functional qualities. Integrating these advancements with digital production, such as additive manufacturing, machine learning-based process optimization, and life-cycle-oriented design, may hasten the transition of bio-composites to mainstream sustainable precision engineering.

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Prof. Dr. Nasmi Herlina Sari, ST., MT

Muhammad Nabil Fadhlurrohman Rivlan