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The emerging role of bio-based nanocomposites in sustainable engineering applications: Current progress and future directions

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Abstract

The growing demand for sustainable materials has advanced bio-based nanocomposites that merge renewable polymers like poly (lactic acid) (PLA) and nanocellulose with nanotechnology to achieve superior mechanical and eco-friendly performance. This paper shows recent advances and the emerging role of novel nanomaterials such as graphene, silica, and nanocellulose, while addressing challenges of compatibility, biodegradation control, and scalable green synthesis. Overcoming these issues through integrated sustainable approaches is vital for expanding their industrial and biomedical applications within a circular and eco-friendly materials framework.

Sustainable development poses a critical challenge that requires innovative approaches balancing environmental, economic, and social aspects. Advances in material science, particularly the emergence of bio-based nanocomposites, provide promising pathways to develop efficient, eco-friendly materials by integrating renewable resources with nanotechnology [1]. These materials offer the dual benefits of maintaining desirable mechanical and functional properties while significantly reducing environmental impact [2].

Biodegradable polymers such as PLA, polyhydroxyalkanoates (PHA), Poly (ε-caprolactone) (PCL), and polyamides (PA), form the foundation of many bio-based nanocomposites. Their capacity to biodegrade and adapt physicochemical properties through targeted processing and modifications enhances their applicability in industrial and medical fields [3, 4]. Incorporation of bio-derived monomers, including sebacic and itaconic acid, and nanoparticles like silica advances the production of green materials with desirable mechanical strength, elasticity, stability, and the potential for scalable manufacturing [5].

Recent advances in the development of PLA-based biocomposites and engineered alloys by incorporating synthetic and natural fibers and fillers will increase product durability and contribute to a low-carbon economy. These composites should maintain long life and balance engineering performance and environmental compatibility for advanced applications [6].

Also, Advances in the fabrication of graphene/PCL nanocomposites have shown that the uniform dispersion of graphene enhances strength, conductivity, and biocompatibility an important step in developing sustainable and efficient materials for tissue engineering and regenerative medicine [7].

Nanocellulose, a bioproduct derived from natural polymers or microbial biodegradation, offers exceptional mechanical strength, optical clarity, thermal stability, and biocompatibility. Its integration within nanocomposites leads to the development of materials with improved performance and sustainability attributes [8].

The combination of nanocellulose with aliphatic polyesters draws attention due to their biodegradability and biocompatibility, although challenges related to the hydrophilic-hydrophobic mismatch between cellulose and polyesters necessitate surface modification strategies [9].

Similarly, research shows that renewable biomaterials such as nanocellulose gels and foams with broad capabilities can be lightweight, low-cost, and sustainable alternatives to metals and ceramics in the construction of scaffolds and extracellular matrices for tissue engineering [10].

Beyond polysaccharides, advanced nanomaterials such as graphene extend the functional capabilities of bio-based composites by enhancing electrical, mechanical, and recycling properties. However, issues like industrial-scale synthesis, cost-

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effectiveness, and environmental compatibility remain significant obstacles requiring holistic strategies [11].

To overcome these limitations, comprehensive methods rooted in green chemistry, life cycle assessment, and recyclable technologies are essential. By aligning these principles, bio-based nanocomposites can transition from research laboratories to industrial and biomedical applications, fostering a robust circular economy. The integration of material innovation with sustainable engineering policies will accelerate this transition, ensuring that bio-based nanocomposites become cornerstone materials in future green technologies [4, 5].

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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