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Nanoscale engineering is one of the most transformative frontiers of modern science and advanced technology. By manipulating matter at dimensions typically between 1-100 nanometers (nm), scientists and engineers are architecting functionality at the level where quantum effects, surface phenomena, and molecular interactions dominate. At this scale, material properties substantially different from the bulk, opening various opportunities in various high-performance applications, including in energy, electronics, healthcare and in infrastructure [1].

The key to Nanoscale engineering is tuning the particle size. Unlike conventional engineering, which primarily focusses on macroscopic structures. On the other hand, nanoscale engineering tailors atomic and molecular arrangements to achieve advanced performance. Several properties such as surface area, surface-to-volume ratios increase exponentially at nano meter scale, making interfacial interactions critical [2]. These enhanced properties of the materials can be incorporated in polymers to achieve remarkable enhancement in properties.

In polymer nanocomposite, the interface governs the overall performance. Unlike micro particle filled composites, where reinforcement depends largely on mechanical interlocking. However, in nanoscale systems, dominated by interfacial phenomena due to their extremely high surface-to-volume ratio. At the nanoscale, a large fraction of polymer chains resides in the interfacial region, and results in several interactions. These interactions include hydrogen bonding/covalent bonding, and/electrostatic forces.

Chain dynamics is the key factor in polymer and nanoscale engineering because the macroscopic performance of polymers ultimately arises from molecular motion. In bulk polymers, properties such as toughness, viscoelasticity, and glass transition temperature are governed by segmental mobility, chain entanglement, and relaxation behavior [3]. When nanoscale structures are introduced, an interphase region is formed where polymer chains experience confinement and strong interfacial interactions [4]. This nanoscale confinement can restrict segmental motion, alter relaxation times, modify free volume, ultimately leading to significant changes in material properties, which are crucial for high-performance applications [5]. However, in the context of sustainability, bio-based polymers such as nanocellulose, nanochitin, and nanostarch are considered as a sustainable solution for nanoscale engineering, combining, high specific surface area, biodegradability and tunable surface chemistry with the ability to effectively modulate polymer chain mobility. Their loading not only enhances mechanical and barrier performance but also supports the development of environmentally stable composites too.

Modern engineering materials are no longer expected to serve for a specific purpose. Polymer and nanoscale engineering together provide a multifunctional approach. Hybrid approach of nano and micro-scale fillers and different nanomaterials combination introduces hierarchical reinforcement, where microscale fillers contribute to bulk stiffness and cost reduction, while nanofillers govern interfacial dynamics and crack resistance, resulting in synergistic improvements in performance. Furthermore, by designing hybrid nanoscale architectures, researchers can integrate reinforcement, conductivity, and flame retardancy, to a single matrix. This hybrid strategy opens more opportunities for advanced applications in aerospace components, flexible electronics, smart coatings, energy storage devices, and next-generation structural materials, where performance, and efficiency coexist within a single system [6, 7]. Although it exhibits high-performance potential in advanced applications, the system faces several critical challenges in practical implementation [8].

Critical challenges associated with nanoscale materials is the manufacturing scalability. Nanoscale fabrication methods, such as chemical vapor deposition is costly and energy-intensive. Bridging the gap between laboratory-scale and scalability requires innovative and cost-effective processing routes, including solution-based self-assembly, and additive manufacturing techniques. Standardization of characterization methods is equally essential to ensure reproducibility and quality control. Despite significant advantages offered by polymer nanocomposites for high-end applications, several challenges remain critically. Uniform nanoscale dispersion is technically demanding and often energy-intensive. Agglomeration reduces efficiency and affects reproducibility. Scalable dispersion methods without compromising nanoscale architecture continues to be a major industrial hurdle. Furthermore, beyond processing and cost considerations, potential environmental and health concerns associated with nanomaterials, especially nanoparticles release during fabrication, usage, and end-of-life disposal pose additional barriers to commercialization [9].

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