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Progress in Sustainable Composite Materials: From Bio-Based to Graphene-Reinforced Systems: A Review

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ABSTRACT
Traditional industries, such as fiber-aerospace, automotive, and defense, are facing challenges related to recyclability, cost-efficiency, and performance under extreme conditions, thereby accelerating the shift toward sustainable composite materials. This study investigates advancements in bio-based, graphene-reinforced, and hybrid composites by focusing on how material selection, processing methods, and analytical approaches impact the structure–property relationships critical to these applications. The research integrates reinforcement sourcing from natural fibres, graphene derivatives, and hybrid fillers with fabrication techniques and experimental design that incorporate reliability analysis and simulation to evaluate damage mechanisms. The results highlight significant trade-offs: chopped carbon fibres with a length of 17 mm enhance tensile and flexural strength by 470% and 350%, respectively; specimen size effects increase splitting tensile strength by 30%, but may reduce the modulus; elevated temperatures impact compressive strength, which can be mitigated by the inclusion of steel fibres; particulate additives decrease ductility, while PTFE enhances toughness. Progress in thermal and electrical performance includes composites exhibiting high resistivity with self-extinguishing behaviour up to 220°C, halogen-free formulations meeting UL-94 V-0 fire safety standards, graphene nanoplatelet–glass fibre composites achieving a 39% improvement, and optimised laminates reaching flexural strengths of 380 MPa. These findings underscore the necessity of balancing mechanical, thermal, and electrical properties to develop sustainable composites for demanding industrial environments.

KEYWORDS: Graphene-Reinforced Composites, Hybrid Composites, Multifunctional Materials, Mechanical Properties.

INTRODUCTION

1.1. Background on emerging materials in materials science: Traditional composite materials typically consist of a polymer, metal, or ceramic matrix reinforced with fibres such as carbon, glass, or aramid fibres, offering improved mechanical, thermal, and environmental properties over conventional materials [1], [2]. However, challenges such as recyclability, cost, and environmental impact have driven the search for advanced materials with further improved properties [1]. However, challenges such as recyclability, cost, and environmental impact have driven the search for advanced materials with further improved properties [1].

The need for advanced materials arises from the limitations of traditional composites, including their environmental footprint and performance under extreme conditions. Advanced composites integrate multifunctional capabilities, such as combining structural strength with energy storage or sensing functions, thereby addressing modern technological demands [1]. Additionally, sustainability and biodegradability issues are driving the development of biobased and hybrid composites that exploit synergistic effects to enhance properties while maintaining eco-friendliness [3], [4].

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Bio-based composites utilise natural fibres, such as sisal, coir, and lignocellulosic fibres, as reinforcements in polymer matrices. These materials are valued for their low weight, low cost, biodegradability, and reduced environmental impact. For example, sisal/coir fibre hybrid composites fabricated via cold pressing have demonstrated promising tensile and flexural strengths suitable for low-cost applications, with environmental advantages owing to lower energy production requirements [3], [5]. Advances in lignocellulosic fibre composites include surface modification techniques and the incorporation of nanocellulose, which considerably improve mechanical properties and thermal stability, facilitating their use in multifunctional and lightweight applications [6].

Graphene-reinforced composites represent another emerging class, leveraging graphene's exceptional mechanical stiffness and strength for reinforcement in polymeric or metal matrices. Graphene incorporation improves the mechanical, thermal, and interfacial properties, even at low filler loadings. Specifically, graphene/aluminum metal matrix composites demonstrate enhanced tensile behaviour driven by the optimised graphene morphology and graphene–metal interface, supported by advanced modelling techniques that elucidate the deformation mechanisms in these composites [7], [8].

Hybrid composites combine natural and synthetic fibres or multiple reinforcement types to mitigate the limitations of individual constituents and harness the synergistic effects on mechanical, thermal, and physical properties. In automotive and other engineering applications, hybrid composites offer lightweight solutions with high strength-to-weight ratios and improved performance characteristics that are unattainable using conventional composites alone. Such material systems enable customised property combinations, including enhanced water absorption resistance and flame retardancy in bio-based variants [3], [4], [9].

Emerging materials in materials science are advancing from traditional fiber-reinforced composites to biobased, graphene-reinforced, and hybrid composites that emphasise sustainability, multifunctionality, and superior mechanical and thermal performance. These developments involve innovative material selection, novel manufacturing techniques, and functional integration, aiming to meet the growing demands for environmentally friendly, lightweight, and smart material systems in a variety of high-performance applications.

These advanced materials include innovative polymers, nanocomposites, bio-based materials, and multifunctional composites that enable enhanced performance and sustainability. 1.2. These advanced materials encompass innovative polymers, nanocomposites, bio-based materials, and multifunctional composites that enable enhanced performance and sustainability.

In terms of applications, emerging materials are increasingly utilised across sectors such as renewable energy, electronics, automotive, aerospace, healthcare, and construction. For instance, advanced polymers and nanomaterials enhance the sensitivity and response times of photodetectors, enabling the development of flexible and wearable devices, as well as next-generation imaging systems [10]. Thermal energy storage materials support sustainable energy systems by improving the efficiency and flexibility in managing thermal resources in industrial processes and green hydrogen production [11]. Multifunctional biochars contribute to water treatment, soil improvement, and waste management, thereby addressing environmental and agricultural challenges [12]. Halogen-free polymers with superior flame retardancy and mechanical properties hold promise for applications in the electronics, transportation, and aerospace sectors [13]. Furthermore, sustainable and recyclable polymers are advancing circular economy principles by enhancing resource efficiency and reducing waste across manufacturing and consumer products [14].

Environmental and sustainability benefits are the core significance of emerging materials. These materials contribute to reducing reliance on fossil fuels by incorporating bio-based feedstocks and biodegradable components, thereby lessening environmental footprints. Sustainable polymers and composites enable improved recyclability, biodegradability, and environmentally friendly manufacturing practices, fostering

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closed-loop material cycles [14, 15]. Lead-free halide double perovskites replace toxic heavy metals with earth-abundant elements, advancing eco-friendly optoelectronics [16]. Emerging technologies, such as clean steel production, carbon capture, and green hydrogen, contribute substantially to mitigating environmental degradation and supporting sustainable development [17]. Review studies emphasise multidisciplinary collaboration and data-driven environmental management as crucial to realising these sustainability benefits [18].

Technological advancements are critical enablers of the evolution and practical adoption of emerging materials. Innovations in synthesis methodologies, additive manufacturing, and nanotechnology allow precise control over material structures and properties, facilitating tailored performance for specific applications [10], [15]. The integration of computational methods, such as AI-based optimisation and digital twins, enhances material design and system efficiency, as exemplified by thermal energy storage and sensing platforms [11], [19]. Advanced material processing techniques improve recycling, reduce waste, and enable multifunctionality, supporting the transition to sustainable material technologies. Additionally, emerging sensors benefit from novel materials and AI integration to enhance environmental monitoring and industrial safety [19].

1.2. Objectives of the study: Studies in materials science typically encompass defining specific research questions or hypotheses, delimiting the scope and limitations of the investigation, and outlining expected contributions to the field.

Specific research questions or hypotheses target knowledge gaps or technological challenges. For example, studies may investigate how certain novel materials improve mechanical properties, sustainability, or multifunctionality compared to traditional materials. Hypotheses might explore the effects of incorporating biobased fibres or nanofillers on composite strength or environmental impact. Research may also address how emerging synthesis or processing methods influence material performance or recyclability.

The scope of such investigations usually defines the material types studied (e.g., bio–composites, graphene–reinforced composites), characterisation techniques employed (mechanical, thermal, interfacial analyses), and specific applications under consideration (e.g., automotive components, energy storage). Limitations can involve material availability, scale of fabrication, environmental factors such as moisture or thermal sensitivity, and challenges in achieving uniform dispersion or interface control. Methodological constraints, including equipment and testing protocols, also define the boundaries within which conclusions are valid.

The expected contributions of these studies include generating a comprehensive understanding of the structure–property relationships of novel materials, demonstrating environmental and technological benefits, and providing data to guide the design and manufacture of advanced composites. Further contributions involve advancing sustainable materials development, improving multifunctional performance, and promoting innovation in materials science theory and applications. Such research supports the industrial adoption of greener, high-performance materials and informs future scientific enquiries.

The articulation of research questions, precise delineation of scope and limitations, and well-defined anticipated impacts are essential for producing meaningful and credible outcomes in material science investigations [20], [21], [22]. The objectives of a study in materials science typically encompass defining specific research questions or hypotheses, delimiting the scope and limitations of the investigation, and outlining the expected contributions to the field.

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MATERIALS AND METHODS

2.1. Material selection and preparation: The selection and preparation of bio-based, graphene, and hybrid composites involves choosing appropriate raw materials, understanding their specifications, and employing suitable fabrication techniques to achieve the desired composite properties.

Bio-based composites typically use natural fibres, such as kenaf, jute, and sisal, along with other lignocellulosic materials, which are valued for their eco-friendliness, biodegradability, and cost-effectiveness. These natural fibres are often combined with synthetic fibres, such as glass or carbon, to form hybrid composites that balance sustainability with enhanced mechanical strength. Such combinations offer synergistic effects in terms of strength, durability, and cost reduction, which are important for applications in the aerospace and automotive sectors [23]. Raw natural fibres are sourced from agricultural or plant materials and are characterised by their fibre dimensions, moisture content, and thermal stability, whereas synthetic fibres provide a consistent mechanical performance [4].

Graphene-based composites utilise graphene and its derivatives (e.g., graphene nanoplatelets) as reinforcements owing to their exceptional mechanical stiffness, thermal, and electrical conductivities, and barrier properties. Raw graphene can be obtained through exfoliation or reduction of graphene oxide with specifications, including flake size, number of layers, and purity levels, that affect composite performance. The dispersion quality of graphene in polymer matrices critically influences the resultant properties [24, 25]. Hybrid graphene fillers are also combined with other nanoparticles like carbon nanotubes or metal oxides to enhance interface interaction and multifunctionality fig.1 [26].

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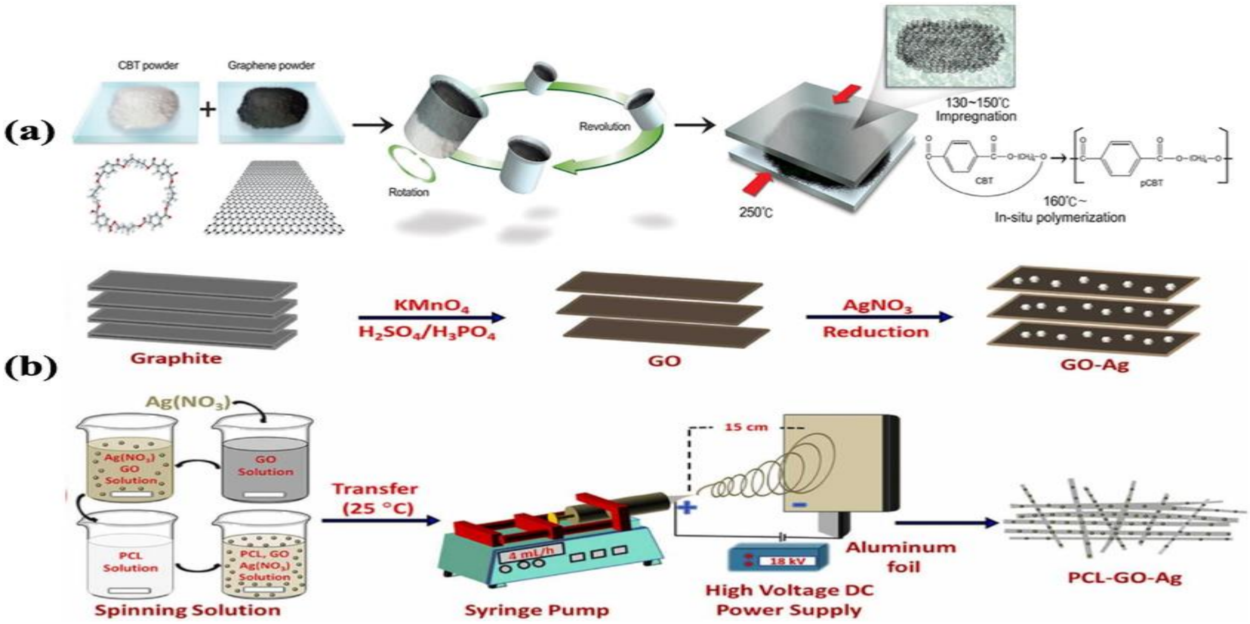

Fig.1 Graphene based hybrid filler polymer Composites

The preparation techniques for these composites vary depending on the material type and desired properties. Bio-based and hybrid composites are commonly fabricated via methods such as cold pressing, hand lay-up, hot pressing, or resin transfer moulding, often with surface treatments (e.g., alkali treatment) to improve fibre–matrix adhesion [5], [23]. The processing parameters typically include applied pressure, curing temperature, and time to optimise mechanical strength and reduce moisture absorption.

Graphene composites are prepared using solution mixing, melt blending, or in situ polymerisation to achieve uniform graphene dispersion and alignment within the matrix, which is essential for enhancing the thermal and electrical conductivities [24, 27]. Advanced homogenisation techniques, such as one-step or two-step mixing, improve the dispersion quality and composite densification, as demonstrated in magnesium oxychloride cement composites doped with graphene nanoplatelets, wherein two-step homogenisation significantly enhanced the mechanical strength and reduced the porosity [28].

The selection and preparation of bio-based, graphene, and hybrid composite materials necessitate tailored sourcing based on fibre or filler characteristics, precise control of processing parameters, such as temperature, pressure, and mixing protocols, and surface or chemical treatment methods to optimise composite performance for targeted applications in various industries.

2.2. Characterisation techniques: Characterisation techniques for composites encompass physical and chemical methods, mechanical testing procedures, and thermal and electrical property analyses to comprehensively evaluate material performance.

Physical and chemical characterisation methods commonly include spectroscopic and microscopic techniques. Raman spectroscopy, X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR) are used to analyse the structure and chemical composition of graphene and its composites, providing information on crystallinity, functional groups, and phase identification [29], [30]. Scanning electron microscopy (SEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM) reveal the morphological details, dispersion quality, and interface characteristics of fillers within the matrix [29, 31]. In addition, energy-dispersive spectroscopy (EDS) complements SEM by analysing elemental composition [32].

Mechanical testing procedures include tensile strength, elongation at break, hardness, and fracture toughness

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measurements. Universal testing machines are utilised to determine mechanical performance metrics and assess the influence of fillers, such as graphene or carbon nanotubes, on matrix reinforcement [29, 33]. Dynamic mechanical analysis (DMA) further studies viscoelastic properties, such as storage and loss moduli, providing insights into damping behaviour and mechanical stability over temperature ranges [31]. Brillouin scattering can be applied for more advanced mechanical characterisation.

Thermal property analysis relies heavily on differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), which assess transitions such as glass transition, melting points, and thermal degradation behaviour. These methods evaluate thermal stability enhancements imparted by nano-reinforcements or hybrid fillers [29], [33], [34]. Rheological studies and thermal conductivity measurements further elucidate the matrix–filler interaction and heat transfer capabilities.

The evaluation of the electrical properties includes dielectric strength, surface and volume resistivity, and conductivity measurements, which are particularly important for composites incorporating graphene or carbon nanotubes, in which improved electrical performance is anticipated. For example, silicone composites are characterised for their partial discharge resistance and tracking behaviour to evaluate high-voltage insulation properties [33, 35].

A comprehensive characterisation protocol for composites integrates structural analysis by spectroscopic and microscopic techniques, mechanical testing for strength and durability, and thermal and electrical analyses to assess stability and functionality. This multi-dimensional approach guides the understanding and optimisation of advanced composite materials for diverse applications.

2.3. Experimental design: The experimental design for composite material research involves well-defined fabrication processes tailored to different composite types, systematic investigation of variables with appropriate control measures, and implementation of replication and randomisation strategies to ensure validity and reliability.

The fabrication processes vary depending on the type of composite. Bio-based composites are often fabricated using techniques such as cold pressing, hot pressing, hand lay-up, and resin transfer moulding. Hybrid composites, which combine bio-based and synthetic fibres, may require customised fabrication methods to optimise fibre–matrix compatibility and mechanical properties. Graphene-reinforced composites commonly utilise preparation techniques such as solution mixing, melt blending, in situ polymerisation, or electrochemical deposition to achieve uniform graphene dispersion in polymer or metal matrices [23, 24, 35]. The variables typically investigated include the type and concentration of reinforcing material, processing parameters (pressure, temperature, and curing time), dispersion quality, fibre orientation, and interfacial adhesion treatments. Control measures involve maintaining consistent raw material specifications, environmental conditions during fabrication, and standardised measurement procedures. Proper characterisation of these variables enables the assessment of their impact on the mechanical, thermal, and electrical properties of composites.

Replication is employed by preparing multiple specimens per condition to address variability and enhance statistical power. Randomisation strategies are critical for controlling biases and confounding factors in experimental runs. These may include randomising the phase order, assignment of fabrication batches, or sample testing sequences. Randomisation improves internal validity by mitigating systematic errors, whereas replication aids in identifying inherent natural variability and improves the generalisability of the results [36], [37], [38].

Together, rigorous control of fabrication variables, replication, and thoughtful randomisation ensure experimental robustness, credible interpretation, and reproducibility of composite materials research findings.

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2.4. Data analysis methods: Data analysis in composite research employs advanced statistical techniques, specialised software tools, and rigorous validation and reliability assessment approaches to ensure robust interpretation and credible conclusions.

Statistical methods include confirmatory composite analysis (CCA), a structural equation modelling technique for assessing composite variables where conventional factor analysis falls short, especially in human development-related composites [39]. Reliability-based design optimisation integrates hybrid and sequential optimisation approaches that combine deterministic and stochastic evaluations to optimise composite structures under uncertainties in material properties and loading [40]. The reliability analysis incorporates homogenisation, stochastic finite element analysis, and structural reliability methods to capture uncertainty propagation from the micro to macro scales, thereby providing accurate failure predictions [41].

Software used for data processing spans finite element analysis packages that enable meso-level draping and failure simulations of textile composites, facilitating the detailed modelling of deformation and failure phenomena [42]. Data quality verification routines apply filtering, reconstruction, and inference techniques to ensure fidelity in large datasets, such as in photovoltaic performance monitoring, and mitigate errors from missing or invalid data [43]. Additionally, advanced wavenumber estimation algorithms quantify composite delamination damage from guided wavefield experimental data, demonstrating a hybrid evaluation [44].

Validation and reliability assessments involve systematic verification and validation processes that focus on progressive damage and failure analysis methods. This includes selecting representative standard test articles to interrogate key failure modes and ensuring that computational simulations match the observed physical behaviour [45]. Dependability modelling in software systems related to composites utilises UML-based approaches to evaluate reliability, availability, and maintainability, highlighting the importance of early verification [46]. A critical review of composite delamination mechanisms emphasises the understanding of failure stability and crack growth and the incorporation of viscous–plastic effects for realistic reliability analysis [47].

RESULTS

3.1. Mechanical performance: The mechanical performance of composite materials is typically evaluated based on key mechanical properties, such as tensile, compressive, and flexural strengths, modulus of elasticity, elongation at break, impact resistance, and fatigue behaviour.

Tensile strength represents the maximum stress that a material can withstand when stretched or pulled before failure. For example, composites reinforced with chopped carbon fibres have demonstrated improvements in tensile strength of up to 470% compared to neat polymer matrices, optimised around certain fibre lengths (~17 mm) [48]. Glass fiber-reinforced polymers (GFRP) have demonstrated size-dependent reductions in tensile strength with increased diameters, highlighting the significance of specimen dimensions in tensile property evaluation [49]. The incorporation of polyvinyl alcohol (PVA) fibres increased the tensile strength and toughness owing to fibre bridging effects, with the splitting tensile strength increasing by over 30% [50].

Compressive strength measures the capability to resist deformation under compressive loads. High-temperature studies of fiber-reinforced reactive powder concrete have shown a decrease in compressive strength with increasing temperature; however, steel fibre reinforcements mitigated this reduction [51]. Ultra-high-performance concrete (UHPC) exhibits a similar complex compressive strength behaviour modelled by bilinear and trilinear equations reflecting strength fluctuations under different conditions [52].

The flexural strength reflects the resistance to bending and is notably improved by fibre reinforcement. Carbon fiber-reinforced composites exhibited up to a 350% increase in flexural strength with longer fibre lengths, which is linked to an enhanced fibre–matrix contact area [48]. Magnesium hydroxide flame retardants altered the flexural properties of polyethylene composites, peaking at specific filler contents before plateauing [53].

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PVA fibres in concrete significantly enhanced the flexural strength and deformation resistance, as shown in Fig. 2 [50].

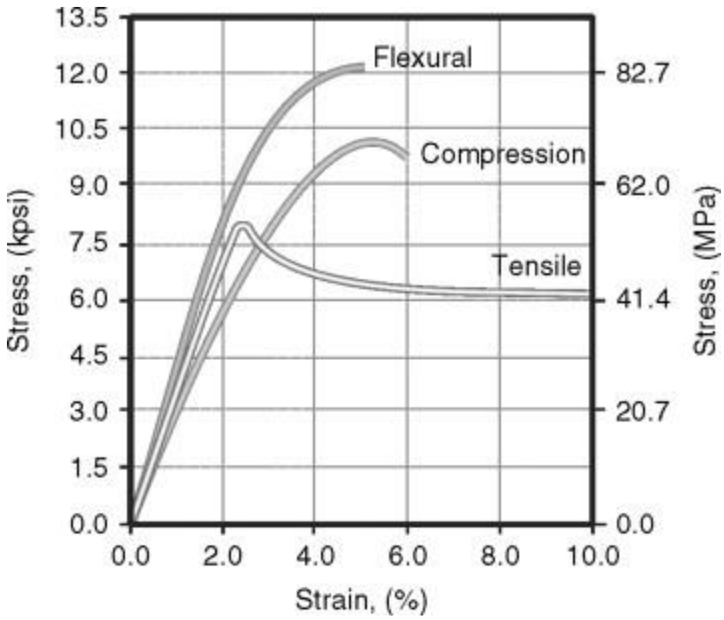

Fig. 2 Mechanical properties of PVA

The modulus of elasticity, which indicates material stiffness, usually increases with fibre or filler addition; however, it may decrease under certain modifications, such as PVA fiber-induced porosity [50]. Carbon fibre reinforcement considerably increased both the tensile and flexural moduli, whereas the impact on the compressive modulus was adverse [48]. Steel fibres enhanced the elastic modulus of concrete, even under elevated temperatures [51].

The elongation at the break indicates ductility and decreases with increasing silver particle fillers in polypropylene composites, indicative of the onset of brittle behaviour [54]. In contrast, composites with longer carbon fibres exhibit higher plastic deformation and elongation owing to fibre entanglement [48].

Impact resistance is crucial for toughness assessment. The incorporation of silver powder fillers sharply decreases the Izod impact strength at low concentrations [54]. The incorporation of PTFE in polymer composites enhances toughness, despite a decrease in tensile strength [55]. Fiber-reinforced concretes exhibit improved toughness and impact resistance, particularly with PVA and steel fibres [50, 51].

Although less frequently investigated, the fatigue behaviour in aluminum composites can be improved by nanoscale fillers, such as silicon carbide, thereby enhancing wear resistance and fatigue life [56]. The introduction of fibres and fillers generally contributes to the retardation of crack initiation and propagation, thereby improving fatigue resistance.

3.2. Thermal and electrical properties: Composites exhibit critical thermal and electrical properties that make them suitable for advanced applications such as thermal conductivity and stability, electrical conductivity and resistivity, flame retardancy, and fire resistance.

The thermal conductivity and stability of composites can be enhanced by the incorporation of thermally conductive fillers, such as hexagonal boron nitride (hBN), aluminum nitride (AlN), and three-dimensional (3D) porous boron nitride frameworks. For instance, polyamide 6 (PA6) composites with hBN and phosphorus–nitrogen (P–N) flame retardants exhibit improved thermal conductivity and better thermal stability than neat PA6. HBN creates a flaky framework within the char residue during combustion, increasing its strength and compactness, which also suppresses melt dripping behaviour upon burning [57]. High

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compressive moduli are ideal for thermal insulation with flame-retardant properties [58]. Freeze–cast metal–organic framework (MOF)–polyvinyl alcohol (PVA) aerogel composites (MOF@PVA) also achieve excellent thermal insulation (~0.04 W/m·K) and self-extinguishing flame retardancy, retaining these features even at elevated temperatures (220 °C) [59].

The electrical conductivity and resistivity of composites depend on the nature and distribution of conductive or insulating fillers. The incorporation of hBN leads to composite materials with very high volume resistivity (~ 1015 Ω·cm), meeting electrical insulation requirements while enhancing thermal management [57]. Emerging materials, such as MXene-based polymer nanocomposites, have shown great promise in combining electrical conductivity and flame retardancy for applications such as electronic devices and batteries [60]. Ceramizable silicone composites with carbon fibre fillers improve the mechanical properties of the resultant ceramic structure and support flame retardancy while maintaining electrical network integrity during fires [61].

Advancements in the flame retardancy and fire resistance of polymer composites have been achieved by integrating flame-retardant additives that promote char formation and reduce the combustion heat release. Lignin-based flame retardants chemically grafted with phosphorus, nitrogen, and copper significantly improve the thermal stability and reduce the heat release rates in wood–plastic composites [62]. Polyamide 6 composites with halogen-free flame retardants and thermally conductive fillers, such as AlN and BN, successfully meet the UL-94 V-0 rating and exhibit limiting oxygen index (LOI) values exceeding 29%, aided by highly integrated char layers that form during combustion [63]. Enhancing the synergistic effects of expandable graphite and melamine improves the char quality, flame retardancy, and thermal stability of polyamide 11 composites [64]. Additional ceramic–inorganic hybrid composites, such as ceramizable silicone-based systems, enable the formation of ceramic protective layers that enhance the flame resistance in electrical cable applications [61].

3.3. Comparative analysis: A comparative analysis of composite materials reveals distinct performance differences among various composite types, significant benchmarks against traditional materials, and notable synergistic effects in hybrid composites.

Performance comparisons have demonstrated that hybrid composites, which combine different reinforcement types, outperform single-fibre composites in terms of their mechanical and functional properties. For example, polypropylene (PP) composites hybridised with graphene nanoplatelets (GnPs) and glass fibres (GFs) display a significant synergistic effect, with tensile and flexural strengths increasing by approximately 52% and 39%, respectively, compared to biphasic composites. This hybridisation enhances load transfer via chemically or electrostatically assembled hierarchical structures while optimising matrix crystallinity and creating thermally conductive pathways [65]. Similarly, epoxy-based hybrids with coir fibres, glass sheets, and charcoal have demonstrated improved tensile and flexural properties, with alternating layers of coir and glass fibres yielding superior mechanical performance, underscoring the role of hybrid fibre configurations [66].

In composites incorporating Kevlar, carbon, and glass fibres, specific stacking sequences in hybrid laminates have demonstrated optimal flexural strength (up to 380 MPa), high hardness (59 BHN), and impact strength (80 kJ/m ^{2}), outperforming corresponding non-hybrid composites with single fibre types. The positive hybrid effect improves not only mechanical performance but also cost-efficiency ratios, making them promising candidates for engineering applications [67]. Bio-inspired nanohierarchical hybrids, with covalently bonded nanoscale graphene nanoplatelets on microscale glass fibres, exhibited remarkable improvements in tensile modulus, strength, and impact strength of 54%, 37%, and 75%, respectively, demonstrating the efficacy of multiscale interfacial engineering [68].

Benchmarking these composites against traditional materials highlights their enhanced multifunctionality and weight savings. Graphene hybrid fillers impart superior mechanical strength, electrical conductivity, and

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thermal management capabilities compared to conventional composites, thereby fulfilling industry demands in the aerospace, automotive, electronics, and energy sectors [69]. Natural fibre-reinforced hybrid composites serve as sustainable alternatives to petrochemical composites, offering improved mechanical and thermal properties; however, challenges remain in terms of moisture management and heat stability [4].

Synergistic effects in hybrid composites arise from optimised filler dispersion, interfacial interactions, and complementary properties of diverse reinforcements. Hybrid nanocomposites containing graphene nanoplatelets and carbon nanotubes exhibit electrical conductivity superior to that of either filler alone, enabled by increased tunnelling junctions in the percolated network, as supported by Monte Carlo simulation models [70]. Studies have also shown that the incorporation of multiscale carbon-based fillers in bio-based polymers enhances electromagnetic interference shielding through synergistic filler–matrix adhesion and fibre retention [71]. Reviews have identified that combining organic–inorganic, nano–micro, and bio-based fillers maximises mechanical, thermal, and electrical properties beyond what is achievable with single fillers, indicating broad opportunities and challenges in mastering hybrid composite design [72], [73].

Comparative analyses conclusively demonstrated that hybrid composites provide enhanced performance through synergistic reinforcement effects, outperforming monolithic composites and traditional materials in terms of strength, durability, thermal management, and multifunctionality. Strategic hybridisation, interfacial engineering, and filler selection remain key to unlocking these benefits across industrial sectors.

DISCUSSION

4.1. By examining these property–structure correlations, one can identify the mechanisms driving a material's performance, such as atomic arrangements, bonding characteristics, and microstructural elements that govern mechanical, thermal, or electronic responses. By examining these property-structure correlations, one can identify the mechanisms driving the material's performance, such as atomic arrangements, bonding characteristics, or microstructural elements that govern mechanical, thermal, or electronic responses. Comparing the findings with existing literature and theoretical models further contextualises the results and validates observed trends or highlights novel deviations. Comparing the findings with existing literature and theoretical models further contextualises the results, validating observed trends or highlighting novel deviations. This comparative approach not only reinforces the credibility of the study, but also situates it within broader scientific discourse, offering pathways for future research and potential applications.

4.2. Implications for materials science: The interpretation of the results requires an in-depth examination of the intricate relationships between material properties and their corresponding structural characteristics, emphasising how specific features at the atomic, molecular, or microstructural levels influence the overall behaviour of the material. By analysing these property–structure relationships, it becomes possible to uncover the fundamental mechanisms responsible for the observed performance, such as the nature of chemical bonding, crystallographic orientation, phase distribution, or defect structures. These mechanisms elucidate how and why certain responses, including mechanical strength, thermal conductivity, or electronic properties, manifest under varying environmental or operational conditions. Furthermore, situating these findings within the context of existing literature and theoretical frameworks allows for a critical comparison that either corroborates established models or reveals novel phenomena that challenge current understanding. Ultimately, this comprehensive interpretation fosters a deeper scientific insight into the material system, enabling targeted improvements and innovations. Ultimately, this comprehensive interpretation fosters a deeper scientific insight into the material system, enabling targeted improvements and innovations.

The implications for material science emerging from this study underscore notable progress in the development of composite materials, particularly through the strategic manipulation of structural components to achieve superior integration of desired properties. These advancements pave the way for innovative applications across diverse sectors, including aerospace, automotive, electronics, and energy, where enhanced mechanical resilience, reduced weight, improved thermal management, and multifunctional capabilities are

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increasingly demanded. The tailored design approaches demonstrated herein suggest promising routes for creating materials with customised performance profiles suited to specific operational challenges. However, the transition from laboratory-scale success to widespread practical implementation faces several challenges, including the scalability of synthesis and fabrication techniques, the economic feasibility of production, and the durability of these materials under prolonged and variable service conditions. Additionally, potential limitations related to environmental impact, recyclability, and compatibility with existing manufacturing infrastructure must be carefully addressed. Recognising and overcoming these obstacles is crucial to fully exploit the potential of next-generation composite materials and to foster their adoption in real-world applications, thereby driving the frontier of material science innovation.

4.3. Environmental and sustainability aspects: The environmental and sustainability aspects of emerging composite materials are critical considerations that encompass a comprehensive life cycle assessment, biodegradability and recyclability potential, as well as energy efficiency throughout the production and usage phases. This holistic approach highlights areas where environmental burdens can be minimised, such as reducing greenhouse gas emissions, lowering resource consumption, and mitigating waste generation. Biodegradability and recyclability are increasingly prioritised to address growing concerns regarding material waste and environmental pollution. Biodegradability and recyclability are increasingly prioritised to address growing concerns regarding material waste and environmental pollution. However, challenges remain in balancing performance requirements with environmental compatibility, as some high-performance composites may incorporate non-degradable or difficult-to-recycle constituents. Energy efficiency is another pivotal factor, as the production of composites often involves energy-intensive processes, such as polymerisation, curing, and fabrication. Energy efficiency is another pivotal factor, as the production of composites often involves energy-intensive processes, such as polymerisation, curing, and fabrication. Collectively, these environmental and sustainability considerations align with global efforts toward greener materials and manufacturing and influence the future design strategies and commercial viability of composite technologies, emphasising the need for continued research into eco-friendly materials and sustainable production methods.Acknowledgements References Tables Collectively, these environmental and sustainability considerations align with global efforts toward greener materials and manufacturing and influence the future design strategies and commercial viability of composite technologies, emphasising the need for continued research into eco-friendly materials and sustainable production methods.

4.4. Despite considerable progress, significant uncertainties remain regarding the fundamental interactions at multiple scales, including atomic, microstructural, and macroscopic levels, which influence the performance and reliability of composites. Investigating these interactions through advanced characterisation techniques and multiscale modelling can uncover new mechanisms that govern material behaviour, thereby enabling the design of composites with enhanced and predictable properties. Investigating these interactions through advanced characterisation techniques and multiscale modelling can uncover new mechanisms that govern material behaviour, thereby enabling the design of composites with enhanced and predictable properties. Additionally, research should explore novel material combinations and hybrid structures that integrate multifunctionality, such as self-healing, sensing, or adaptive responses, expanding the functional scope beyond traditional mechanical or thermal attributes.

Potential improvements in material design and processing are pivotal for translating laboratory innovations into scalable technologies. This includes refining synthesis methods to achieve greater control over the microstructure, phase distribution, and interfacial bonding, which are critical for optimising composite performance. Process innovations, such as additive manufacturing, advanced curing techniques, and environmentally friendly fabrication routes, can enhance precision, reproducibility, and sustainability. Furthermore, tailoring processing parameters to balance cost, efficiency, and material quality is essential for commercial viability. Emphasis on developing standardised protocols for quality assessment and performance evaluation will support consistent benchmarking and accelerate technology adoption.

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Expanding production and commercialisation prospects presents both challenges and opportunities that future research must strategically address. Overcoming barriers related to manufacturing scalability involves optimising raw material sourcing, process throughput, and integration with existing industrial workflows. Economic analyses and life cycle assessments are crucial to ensure that scale-up efforts align with cost-effectiveness and environmental sustainability goals. Collaborative efforts between academia, industry, and regulatory bodies can facilitate the development of certification standards and market acceptance pathways. Additionally, exploring niche markets and application-driven customisation can create early adoption opportunities that validate composite technologies and generate momentum for broader commercial deployment. Overall, a coordinated research agenda focusing on these areas will be instrumental in bridging the gap between experimental breakthroughs and real-world impact, fostering the next generation of composite materials with transformative potential.

CONCLUSION

This study surveys the shift in materials science from traditional fiber-reinforced composites (polymer/metal/ceramic matrices with carbon, glass, or aramid fibers) toward emerging bio-based, graphene-reinforced, and hybrid composites driven by persistent limitations in conventional systems—especially recyclability, cost, environmental footprint, and performance demands under extreme conditions—and by the need for multifunctionality (e.g., coupling structural capability with sensing or energy-related functions). It positions bio-based composites (e.g., sisal, coir, and lignocellulosic fibers) as lightweight, low-cost, and biodegradable options whose performance can be improved via surface modification and nanocellulose, and highlights graphene reinforcements (including graphene nanoplatelets) as effective at low loadings for enhancing mechanical, thermal, and interfacial behavior, exemplified by improved tensile response in graphene/aluminum systems attributed to graphene morphology and interface quality supported by modeling. Hybrid composites—combining natural and synthetic fibers and/or multiple fillers—are emphasized for synergistic property gains and application-specific tailoring (automotive, aerospace, electronics, energy), including improved water resistance and flame retardancy in bio-based variants. The study outlines material selection and preparation routes (cold/hot pressing, hand lay-up, resin transfer molding with fiber treatments for adhesion; solution mixing, melt blending, in situ polymerization for graphene dispersion; and homogenization strategies where two-step protocols can reduce porosity and raise strength), and describes a comprehensive characterization toolkit spanning Raman/XRD/FTIR; SEM/TEM/AFM/EDS; tensile, compressive, flexural, hardness, fracture, DMA and advanced mechanical probes; DSC/TGA and thermal conductivity; and electrical insulation/conductivity metrics relevant to high-voltage and functional composites. Experimental design principles focus on controlling reinforcement type/content, processing parameters, dispersion, orientation, and interfacial treatments, with replication and randomization to reduce bias; data analysis emphasizes reliability-based and multiscale methods, computational simulation (including finite element modeling), data-quality verification, nondestructive evaluation, and verification/validatiotowardsnst key failure modes such as delamination and progressive damage. Reported performance trends show that reinforcement type, length, and loading govern trade-offs among strength, stiffness, ductility, impact, and fatigue: chopped carbon fiber additions can raise tensile strength up to ~470% and flexural strength up to ~350% with an optimum around ~17 mm fiber length; GFRP tensile strength can decrease with increasing specimen diameter; PVA fibers can increase splitting tensile strength by >30% via bridging but may reduce modulus through porosity; high temperatures reduce compressive strength in fiber-reinforced reactive powder concrete though steel fibers mitigate losses; certain particulate fillers (e.g., silver powder) can sharply reduce elongation at break and Izod impact strength, while PTFE can improve toughness despite tensile losses; and nanomodellingllers (e.g., SiC in aluminum) can enhance wear and fatigue life. Thermal/electrical and fire-safety advances are linked to engineered fillers and char structures: PA6 with hBN plus phosphorus–nitrogen retardants improves thermal conductivity and stability, forms robust char that suppresses melt-dripping, and can maintain very high volume resistivity (~10^15 Ω·cm); porous BN skeletons in bismaleimide resins achieve ~1.53 W/m·K at 12.5 wt% with improved flame retardancy; insulating aerogel composites (polybenzoxazine: 0.031–0.069 W/m·K; MOF@PVA: ~0.04 W/m·K) combine low conductivity with self-extinguishing behavior even around 220 °C; and multiple halogen-free strategies (e.g., lignin-derived

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P/N/Cu systems, expandable graphite–melamine synergy, ceramizable silicone composites) promote protective char/ceramic layers, enabling UL-94 V-0 performance and LOI >29% in relevant formulations. Comparative analyses consistently identify hybridization and interfacial engineering as central to outperforming single-reinforcement and traditional materials: PP composites hybridized with graphene nanoplatelets and glass fibers show ~52% higher tensile and ~39% higher flexural strength than biphasic counterparts via hierarchical structures, crystallinity optimmodelling and thermally conductive networks; layered coir/glass/charcoal epoxy systems and optimized Kevlar–carbon–glass stacking sequences can reach flexural strength up to ~380 MPa with high hardness (~59 BHN) and impact strength (~80 kJ/m^2); and bio-inspired glass fiber–graphene nanohierarchies improve tensile modulus/strength/impact by ~54%/37%/75%. The discussion frames these outcomes through property–structure relationships and mechanisms (bonding, crystallography, phase distribution, defects, and interfaces), underscoring broad industrial relevance alongside practical constraints such as moisture/thermal sensitivity in natural fibers, dispersion and interface control for nanofillers, scalability and cost, durability in service, and compatibility with existing manufacturing. Sustainability is treated as a design requirement addressed through life cycle assessment, improved recyclability/biodegradability, reduced energy intensity in production, and lightweighting/thermal-management benefits in use, while future research priorities include deeper multiscale understanding, multifunctional hybrid architectures (e.g., sensing/self-healing), standardized quality/benchmarking protocols, greener processing routes including additive manufacturing, and coordinated scale-up strategies supported by economic and environmental evaluation to accelerate commercialization and societal impact.

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