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Tribological and mechanical performance of epoxy composites reinforced with iron sand and carbon fillers: A Systematic review with experimental perspective

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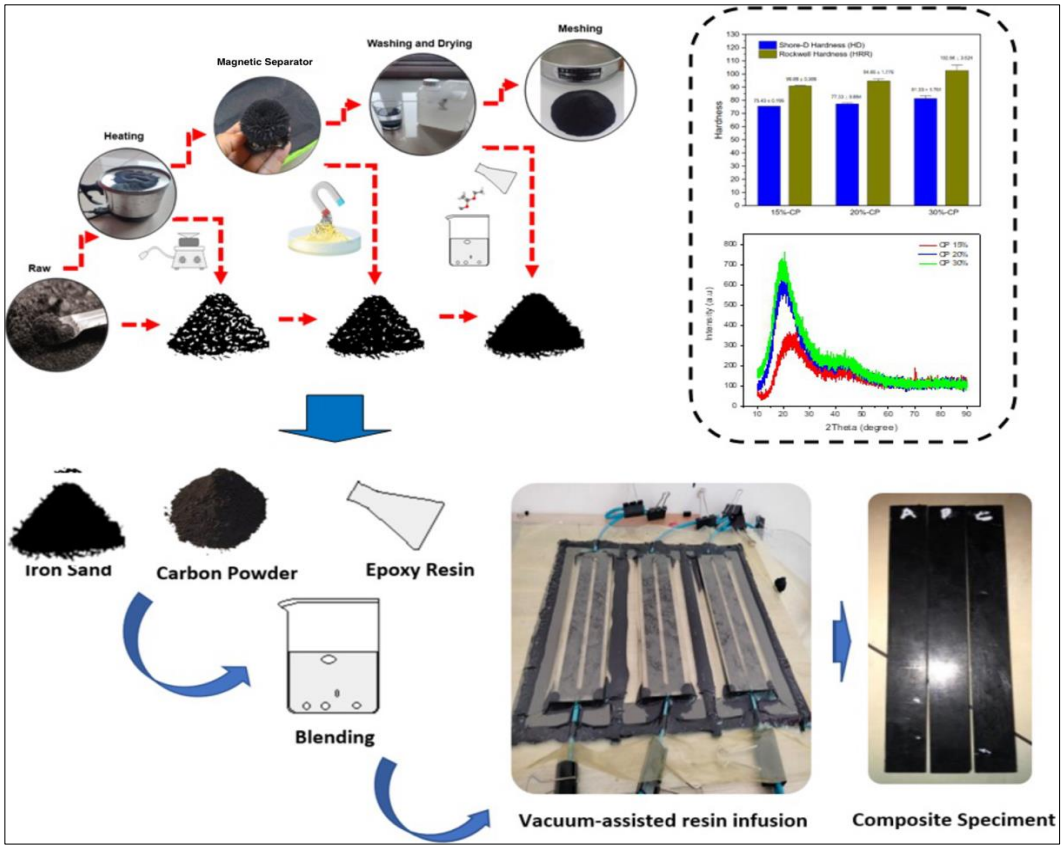

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Highlights:

- Epoxy composites reinforced with iron sand and carbon fillers show a clear trade-off between wear resistance and flexural performance.
- Intermediate carbon loading commonly provides the best balance between particle dispersion, hardness, and flexural strength.
- Excessive carbon loading improves wear resistance but often promotes agglomeration, porosity, and brittle fracture.
- XRD, FTIR, and SEM should be interpreted cautiously because apparent structural ordering, chemical assignment, and interfacial quality are strongly method-dependent.
- Future work should address durability, fatigue, thermal cycling, conductive functionality, and scalable dispersion strategies.

Abstract

Epoxy composites are widely used in structural and tribological applications because they combine good adhesion, corrosion resistance, and mechanical stability with relatively simple processing. Their main limitation is inadequate wear resistance under sustained sliding or abrasive contact. A growing body of literature therefore explores the incorporation of mineral fillers and carbon-based additives to improve both tribological and mechanical performance. This review critically examines epoxy composites reinforced with mineral iron sand and carbon fillers, with emphasis on processing routes, microstructural evolution, interfacial behavior, wear response, hardness, and flexural properties. The review also places this material system within the broader context of polymer composites used in automotive, aerospace, gears, electronics, and tribological components. Across the literature, iron-rich fillers mainly improve stiffness, hardness, and load-bearing ability, whereas carbon fillers reduce friction and facilitate the formation of lubricating transfer layers. However, the benefits are non-linear. Intermediate carbon loading often yields the best compromise between wear resistance and flexural strength, while excessive loading tends to increase agglomeration, porosity, and stress concentration. The review further re-examines common interpretations of XRD, FTIR, and SEM results and highlights important methodological limitations. Finally, it identifies research gaps related to long-term durability, fatigue, thermal cycling, surface treatment of carbon particles, and data-driven optimization of filler content for engineering applications.

Keywords: Epoxy composite; Iron sand; Carbon filler; Wear behavior; Flexural strength; Interfacial adhesion

1. Introduction

Polymer composites are increasingly used in transportation, mechanical systems, electronics, biomedical devices, tooling, and structural engineering because they offer low density, corrosion resistance, design flexibility, and tunable functional performance [1], [2], [3]. In tribological applications, polymer matrices are attractive because they are easier to process than metallic systems and can be tailored through filler design. However, neat polymers often suffer from low hardness, high wear rate, thermal softening, and unstable friction under service conditions. These limitations have motivated the widespread development of filler-modified polymer composites for gears, bearings, bushings, sliding seals, structural panels, and multifunctional lightweight components [4], [5], [6].

Different polymer matrices address these challenges in different ways. PTFE is well known for very low friction, but it often requires fillers to overcome poor wear resistance [7]. PETG has been studied for lightweight structural and additively manufactured components where durability and impact resistance are important [8]. Epoxy remains one of the most important thermoset matrices because it combines good stiffness, strong adhesion, dimensional stability, and chemical resistance with compatibility across many reinforcement strategies [9], [10], [11]. For this reason, epoxy-based composites continue to attract attention in applications that require both structural support and resistance to sliding or abrasive damage [12], [13], [14], [15].

Several strategies have been proposed to improve the tribological and mechanical performance of epoxy. Mineral fillers increase hardness and load-bearing capacity, while carbonaceous fillers can reduce friction, enhance wear resistance, and modify interfacial stress transfer [16], [17], [18], [19], [20], [21], [22], [23]. Among mineral fillers, iron-rich particulates are particularly interesting because of their hardness, magnetic mineral content, industrial availability, and compatibility with cost-sensitive composite production routes [24]. Among carbon fillers, graphite, carbon black, carbon fiber, graphene-derived fillers, and CNTs are widely studied because they can function as solid lubricants, crack-deflection agents, or interfacial modifiers depending on their morphology and concentration [25], [26], [27].

The combined use of iron sand and carbon fillers in epoxy is especially attractive because it can create a dual-function system. The iron-rich phase can improve stiffness, hardness, and resistance to deformation, whereas the carbon phase can reduce friction and support the formation of a protective transfer layer during sliding. Even so, the response is not linear. In many particulate-filled polymer systems, increasing filler content beyond an optimum level raises viscosity, weakens wetting, promotes agglomeration, and increases local stress concentration, all of which can reduce mechanical reliability even when wear resistance improves [25], [28], [29].

Despite this promise, the literature on iron sand/carbon/epoxy systems remains fragmented. Many papers report useful data, but they are often discussed in isolation, and broad reviews on epoxy composites rarely focus on this specific combination of mineral and carbon reinforcement. In addition, some published discussions overinterpret apparent crystallinity from XRD or assign FTIR peaks too confidently without adequate chemical support.

Therefore, this review critically examines the tribological and mechanical behavior of epoxy composites reinforced with iron sand and carbon fillers. Unlike earlier descriptive summaries, the present review integrates material selection, processing, wear behavior, mechanical response, SEM-based interfacial evidence, and the limitations of XRD/FTIR interpretation in a single framework. It also identifies the main research gaps that must be addressed before these composites can be more confidently scaled for automotive, structural, marine, and multifunctional engineering applications.

2. Mineral Iron Sand as a Reinforcement

Mineral iron sand is widely recognized for its distinctive properties, which can improve the performance of epoxy composites, particularly when it is used as a reinforcement material. Its relatively high density and strength contribute to the overall mechanical stability of the composites. In addition, its ability to enhance thermal and electrical conductivity makes it especially suitable for applications that require efficient heat dissipation and electromagnetic shielding [30].

Iron sand is a type of sand that is rich in iron-bearing minerals, predominantly magnetite (Fe_3O_4), and is commonly found in coastal areas. In Pacitan Regency, East Java, iron sand is formed through weathering and sedimentation processes in which iron-rich rocks are eroded and transported by river flow and ocean waves. This sand is characterized by a dark color, which indicates a high concentration of iron minerals [31]. The chemical composition of iron sand in this region includes major elements such as iron (Fe), aluminum (Al), silicon (Si), calcium (Ca), and titanium (Ti), with iron as the dominant element, mainly present as Fe_2O_3.

In addition, the sand contains smaller amounts of other minerals, including quartz, pyroxene, and rutile. The iron-bearing fraction of these iron sand deposits is dominated by titanomagnetic minerals and consists of particles with diameters ranging from 0.074 to 0.075 mm for fine grains and 3 to 5 mm for coarse grains. Owing to its high iron (Fe) content, iron sand is widely used as a raw material in steel production. Moreover, iron sand contains magnetic minerals such as magnetite (Fe_3O_4), hematite (α-Fe_2O_3), and maghemite (γ-Fe_2O_3), which support a wide range of applications. Magnetite (Fe_3O_4), for example, has been used in magnetic recording media, high-density digital recording disks, magnetic fluids, data storage devices, magnetic resonance imaging (MRI), drug delivery systems, surface plasmon resonance (SPR) biosensors, microwave devices, and magnetic sensors. The chemical composition of iron sand from Pacitan Regency is summarized in **Figure 1**.

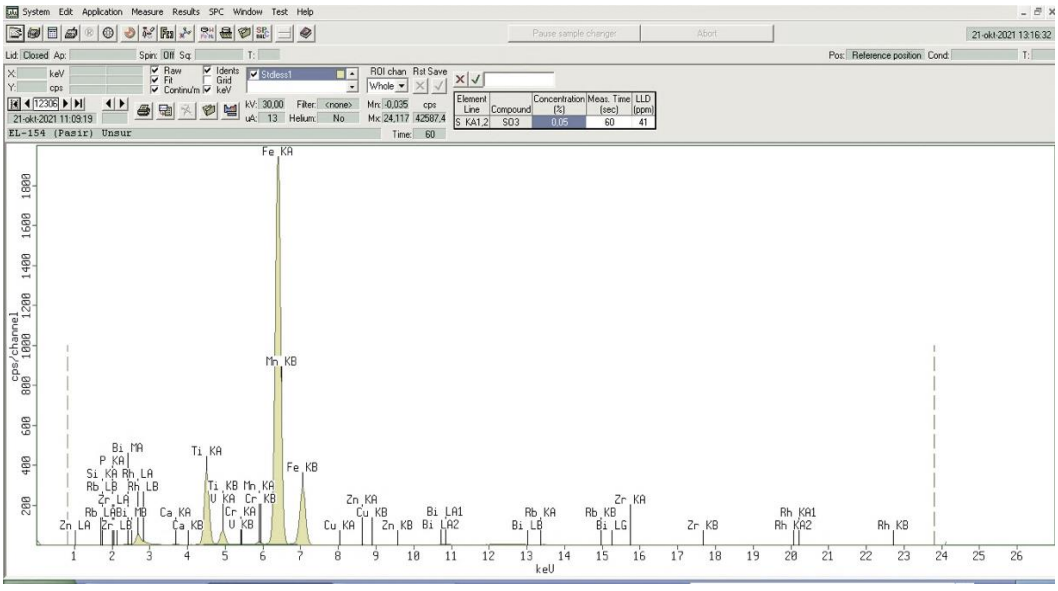

Figure 1. Chemical composition of iron sand

The chemical composition of iron sand from Pacitan Regency, shown in **Figure 1**, indicates substantial potential for industrial applications. With an iron (Fe) content of 83.01%, the material is a promising raw material for steel production, in which iron is the principal constituent. The high titanium content (14.3%) also suggests possible applications in high-strength materials for the aerospace and automotive sectors. Trace elements such as vanadium (0.54%), chromium (0.04%), and manganese (0.53%) further increase its value for the production of specialized steel alloys with improved strength, heat resistance, and corrosion resistance. The presence of silicon (0.6%) and calcium (0.26%) also indicates potential use in the cement industry, where these elements can contribute to material strength and durability. In addition, elements such as copper, zinc, and zirconium broaden the potential applications of this iron sand in magnetic materials, electronics, and other advanced technology industries. Overall, iron sand from Pacitan Regency demonstrates broad industrial potential, particularly for steel production, specialized alloys, and other high-value applications.

Figure 2 illustrates the separation process of iron sand used as a composite reinforcement material and highlights each purification stage, from raw sand collection to final particle refinement. Iron sand powder was collected from the south coast of Pacitan District, Indonesia, and subjected to a systematic multistage purification process to ensure its suitability for composite fabrication. The process began with an initial washing step, in which the raw iron sand was thoroughly cleaned with water to remove surface impurities. The material was then dried on a hot plate at 40 °C for 2 h to remove residual moisture. In the second stage, the dried sand was separated using a permanent magnet to isolate the iron-rich fraction from non-magnetic materials. This step was followed by an additional washing process using distilled water to further remove any remaining contaminants. Finally, the purified iron sand was dried and sieved through an 80-mesh screen to obtain a uniform particle size distribution, thereby improving its compatibility as a reinforcing material in epoxy composites. This rigorous processing procedure ensured the consistency and quality of the iron sand powder, which is essential for achieving reliable and reproducible composite properties.

Figure 2.
Separation process for mineral iron sand [32]

3. Carbon Powder Fillers

Carbon-based fillers have attracted considerable attention in tribological applications because of their unique properties, which can enhance the performance of a wide range of materials. Common carbon-based fillers include graphite, carbon nanotubes (CNTs), amorphous carbon, and carbon black, each of which offers distinct advantages (**Table 1**). Graphite, for example, is widely known for its excellent lubricating properties. Its layered structure allows easy shear between adjacent layers, thereby significantly reducing the coefficient of friction in sliding applications [33]. Studies have shown that the incorporation of graphite into polyether ether ketone (PEEK) composites effectively reduces friction and improves wear resistance [34].

In addition, the size of graphite particles can influence the mechanical and tribological properties of the composite. Finer particles often result in better performance because of their larger surface area and more uniform dispersion within the matrix [35]. Carbon nanotubes (CNTs), which are known for their exceptional mechanical strength and thermal conductivity, can reduce friction and wear through a unique "roller-bearing" effect that helps distribute loads during sliding contact [36]. Previous studies have highlighted the effectiveness of CNT incorporation in phenolic laminates, showing substantial improvements in interlaminar shear strength and tribological performance, particularly under water-lubricated conditions [37].

Amorphous carbon materials, such as diamond-like carbon (DLC), are also valued for their exceptional hardness and wear resistance. Studies have demonstrated that DLC coatings on substrates can significantly improve tribological performance by reducing adhesive and hysteresis losses, especially in high-friction applications [38]. Carbon black, which is widely used in rubber and polymer composites, is known to improve mechanical properties and wear resistance. However, its effectiveness depends strongly on careful optimization of filler concentration [39]. Excessive carbon black content may lead to particle agglomeration, which can adversely affect the tribological properties and processability of the material [40]. Therefore, optimizing filler concentration is essential to maximize the beneficial effects of carbon black while minimizing its potential disadvantages [41]. Overall, carbon-based fillers play an important role in improving tribological performance across various applications, and ongoing research continues to explore innovative ways to exploit their unique properties.

Table 1. Physical properties of different types of carbon fillers [42]

Carbon	COC	Carbon black	Carbon fiber	Graphite	Expanded graphite
	TOPAS® 8007	ENSACO® 250	AKSACA®	TIMREX® KS75	TIMREX® BNB90
Density (g/cm³)	1.02	0.17	1.7-2.0	2.24	
Tg (°C)	78				
MVR (ml/10 min)	32				
Surface area (m²/g)		65			
Particle size μ (d_{90})		45	D:8; L:3	55.8	85.2
OAN (ml/100 mg)		190		84	150

4. Fabrication of Iron Sand/Carbon Powder/Epoxy Composite Specimens via VARI

Vacuum-Assisted Resin Infusion (VARI) is widely recognized as an effective closed-mold process for manufacturing polymer composites because it provides better control of resin flow, more uniform impregnation, and lower void content than many conventional open-mold techniques. In this process, vacuum pressure drives resin transport through the reinforcement or particulate bed, thereby improving consolidation and promoting more consistent composite quality (**Figure 3**). Previous studies have shown that vacuum-driven infusion plays an important role in reducing entrapped air and enhancing the mechanical performance of the final composite [33]. More broadly, the quality of composites produced by VARI depends not only on vacuum conditions, but also on the resin system, reinforcement type, filler loading, and mold design. The literature indicates that high-performance matrices such as epoxy, when combined with suitable reinforcement architectures, can improve both mechanical and thermal performance, while the closed-mold configuration can also enhance surface quality and reduce porosity in fabricated parts [34], [37].

Within the broader literature on epoxy composite processing, VARI is considered attractive because it is relatively economical, scalable, and more effective in controlling volatile emissions than open-mold fabrication methods [43], [44]. These advantages are particularly relevant for particulate-filled epoxy systems, in which uniform filler distribution and effective matrix wetting are essential for achieving reproducible mechanical and tribological properties. However, the successful application of VARI to particle-filled systems still requires careful control of slurry viscosity, filler dispersion, resin infiltration pathways, and vacuum stability, because excessive filler loading may hinder resin flow and increase the risk of local agglomeration or incomplete impregnation.

To support the discussion of specimen fabrication, **Table 2** summarizes selected studies related to VARI, VARIM, and VARTM processing of epoxy-based composites containing iron-rich or carbon-based fillers. Although studies specifically addressing iron sand/carbon powder/epoxy composites fabricated by VARI remain limited, the available literature consistently shows that

vacuum-assisted infusion can improve composite quality by reducing void formation, promoting better consolidation, and enhancing filler-matrix interaction.

Table 2. Summary of selected studies related to VARI/VARIM/VARTM processing of epoxy-based composites

Study	Material system	Process	Key finding	Relevance to the present review	Ref.
Apriliani *et al*.	Iron sand/carbon powder/epoxy	Closed-mold VARI-based fabrication	Carbon powder improved wear resistance and selected mechanical properties	Most directly relevant to the iron sand/carbon powder/epoxy system	[32]
Zheng *et al*.	Carbonyl iron powder/epoxy composite	VARI	Surface treatment improved interfacial bonding and mechanical properties	Supports the use of iron-based fillers in VARI-processed epoxy composites	[45]
Malhotra *et al*.	MWCNT/glass fabric/epoxy	VARIM	Low filler loading improved tensile, flexural, fatigue, and wear properties	Demonstrates the importance of optimum filler loading	[46]
Shelly	Nanoclay/glass fiber/epoxy	VARIM	Excess filler caused agglomeration and reduced composite performance	Highlights the need for proper dispersion control	[47]
Shen *et al*.	Epoxy composite laminates	Enhanced VARTM	Reduced porosity and improved tensile performance	Confirms the benefit of vacuum control for composite quality	[48]
Wang *et al*.	Fiber-reinforced epoxy composites	Automated vacuum infusion	Stable pressure control reduced voids and improved laminate quality	Supports the importance of controlled infusion conditions	[49]

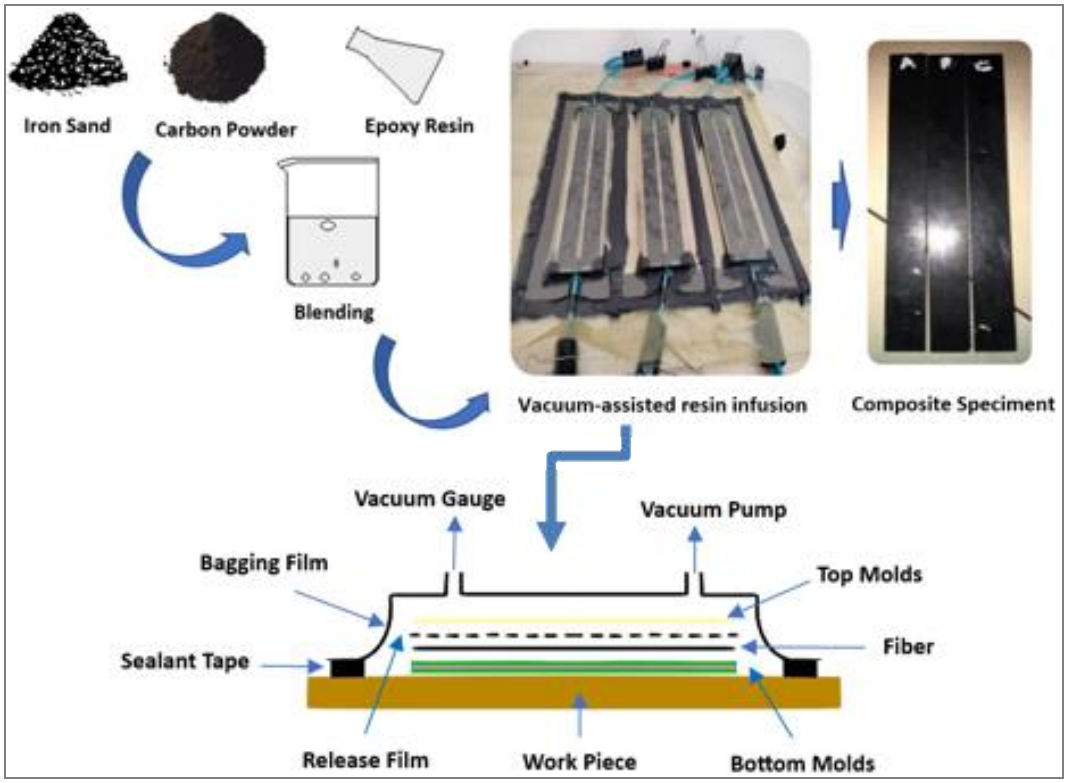

Figure 3. VARI Method with iron sand, carbon powder, and epoxy matrix

For iron sand/carbon powder/epoxy systems, the available literature generally follows a similar fabrication sequence consisting of raw material preparation, filler and matrix proportioning, mold filling, vacuum-assisted compaction, and post-curing. A representative example was reported by Apriliani *et al*. [32], who fabricated iron sand/carbon powder/epoxy composites using a closed-mold VARI approach. In that study, iron sand, carbon powder, and epoxy were weighed according to predetermined formulation variations, and the prepared mixture was introduced into molds designed in accordance with the relevant ASTM specimen dimensions. After molding, the composites were dried for 24 h and then oven-cured at 40 °C for 2 h. This sequence is consistent

with general practice in VARI-based epoxy composite fabrication, in which vacuum pressure is applied to improve material compaction, reduce air entrapment, and enhance matrix distribution throughout the mold cavity.

During fabrication, the mold is sealed with a vacuum bag so that the resulting pressure differential promotes more uniform consolidation and helps minimize internal voids. This characteristic explains why VARI is often selected for epoxy-based composites intended for mechanical and tribological evaluation. Although specific processing details vary across studies, the overall evidence suggests that VARI is a suitable manufacturing route for iron sand/carbon powder/epoxy composites because it combines relatively simple equipment requirements with improved control over porosity and filler-matrix distribution.

As shown in **Table 2**, the effectiveness of VARI-based fabrication depends not only on the application of vacuum pressure, but also on filler loading, particle dispersion, resin flow behavior, and process stability. Several studies indicate that moderate filler addition can improve mechanical and tribological performance, whereas excessive filler loading may increase agglomeration, hinder resin infiltration, and reduce composite quality. These findings are directly relevant to iron sand/carbon powder/epoxy composites, in which homogeneous filler distribution and stable vacuum-assisted impregnation are essential for obtaining reproducible physical, mechanical, and tribological properties.

Nevertheless, the literature also indicates that process optimization remains necessary, particularly for systems with increasing carbon content, because excessive solid loading may reduce flowability and compromise dispersion quality. Therefore, in the context of this review, VARI should be regarded not merely as a fabrication method used in a single study, but as a relevant processing strategy whose effectiveness depends on the interaction among vacuum conditions, formulation design, particle dispersion, and post-curing parameters.

5. Impact of Carbon Filler on Tribological Performance

Tribological evaluation is essential for understanding the degradation behavior of composite materials under sliding or abrasive contact. In polymer-based composites, wear behavior is commonly assessed using the pin-on-disc test because this method provides controlled contact conditions for comparing friction and material loss among different formulations. As summarized in **Table 3**, the available literature generally indicates that the incorporation of carbon-based fillers, including CNTs and carbon powder, can improve tribological performance by reducing the wear rate and lowering the coefficient of friction. These improvements are commonly attributed to the lubricating nature of carbon, its ability to increase surface hardness, and its role in promoting the formation of a more stable transfer layer during sliding contact [32], [50].

Table 3. Summary of tribological results of carbon-based filler-reinforced polymer composites

Materials	Conditions	Friction coefficients	Wear rates
Polyetheretherketone/CNT [51]	1.0 wt% CNT (10 N, 5 Hz, 10,000 cycles)	~0.087 ± 0.003	~1.23 × 10^{-4} mm^3/Nm
Polyimide/MWCNT-NH2 [52]	0.7 wt% MWCNT-NH2 (5 N, 300 r/min, 30 min)	~0.310	~2.234 × 10^{-4} mm^3/Nm
Epoxy/amino-MWCNT [53]	0.5 wt% MWCNT (40 N, 40 min)	~0.314	~0.953 × 10^{-4} g/min
Epoxy/CNT/ZnS [54]	1.25 wt% CNT/ZnS (0.5 N, 20 min)	~0.13	~0.6 × 10^{-4} mm^3/Nm
Epoxy-CNT/GO/MoS2 [55]	1.25 wt% CNT, 1.25 wt% GO, 1.25 wt% MoS2 (4 N, 20 min)	~0.042	~3.44 × 10^{-5} mm^3/Nm
Epoxy/MWCNT/nanosilica [56]	0.45 wt% MWCNT, 0.45 wt% nanosilica (20 N, 0.2 m/s, 800 m)	~0.51	~0.95 × 10^{-13} m^3/Nm
Epoxy-polyamide blend/MWCNT [57]	0.5 wt% MWCNT (40 N, 20 min)	~0.10	~0.058 × 10^{-6} gm/cm^3
Polyacrylonitrile-methylmethacrylate/CNT [58]	1.5 wt% CNT (50 N, 0.431 m/s, 60 min)	~0.36	~5.82 × 10^{-4} mm^3/Nm

A representative study by Apriliani *et al*. [32] evaluated the wear behavior of iron sand/epoxy composites modified with carbon powder using a pin-on-disc method in accordance with ASTM G99. The study reported a clear reduction in specific wear with increasing carbon powder content, from 1.81 × 10^{-6} mm^2/kg for the 15%-CP composite to 1.58 × 10^{-6} mm^2/kg for the 20%-CP

composite, followed by a further decrease to approximately 8.63 × 10^{-7} mm^2/kg for the 30%-CP composite. These results indicate that higher carbon loading improved the wear resistance of the composite surface under the tested conditions. From a review perspective, this finding is important not only because it provides numerical evidence of reduced wear, but also because it reflects a broader trend reported in the tribology literature on carbon-containing polymer composites, in which carbonaceous fillers commonly act as friction-reducing and wear-resistant phases [59], [60].

The beneficial effect of carbon powder on wear performance can be explained by several complementary mechanisms (**Figure 4**). First, carbon particles can fill voids within the composite and contribute to a denser microstructure, thereby reducing the likelihood of local surface failure during sliding. Second, the intrinsic hardness and abrasion resistance of carbon-containing particles can improve resistance to surface damage. Third, carbon may act as a solid-lubricating phase, thereby reducing direct asperity contact and limiting friction-induced damage at the sliding interface [61], [62]. As a result, composites containing carbon powder often exhibit lower material loss than unmodified or low-carbon formulations.

The influence of carbon addition is not limited to wear rate alone. Several studies have also shown that carbon-based fillers can reduce the coefficient of friction in epoxy-based composite systems. Asawthnarayan *et al*. [50], for example, reported that carbon addition reduced the coefficient of friction in glass-epoxy composites, while Alajmi *et al*. [59] observed a substantial reduction associated with the lubricating behavior of graphite-containing epoxy materials. Bu *et al*. [60] similarly reported that carbon/epoxy composites exhibited lower friction and wear because of the self-lubricating behavior of the carbon phase. Taken together, these studies support the broader interpretation that carbon powder can improve tribological performance not only by increasing wear resistance, but also by stabilizing sliding behavior through friction reduction.

Even so, the tribological benefit of carbon addition should not be interpreted as strictly linear under all conditions. The literature suggests that the magnitude of improvement depends on filler dispersion, filler concentration, interfacial bonding, test load, counterface condition, and sliding environment. Moderate carbon loading may improve wear resistance while preserving structural integrity, whereas excessive loading can promote agglomeration, increase local stress concentration, and reduce matrix continuity. Thus, although high carbon content may further reduce wear in some cases, it may also introduce microstructural defects that negatively affect other mechanical properties.

Overall, the literature supports the conclusion that carbon powder is an effective modifier for improving the tribological behavior of iron sand/epoxy composites. Its contribution is best understood as a combination of microstructural densification, friction reduction, and surface protection during sliding. Therefore, in the context of this review, the main significance of carbon powder lies not only in lowering wear, but also in helping to create a more durable tribological surface, provided that the filler content and dispersion are properly controlled.

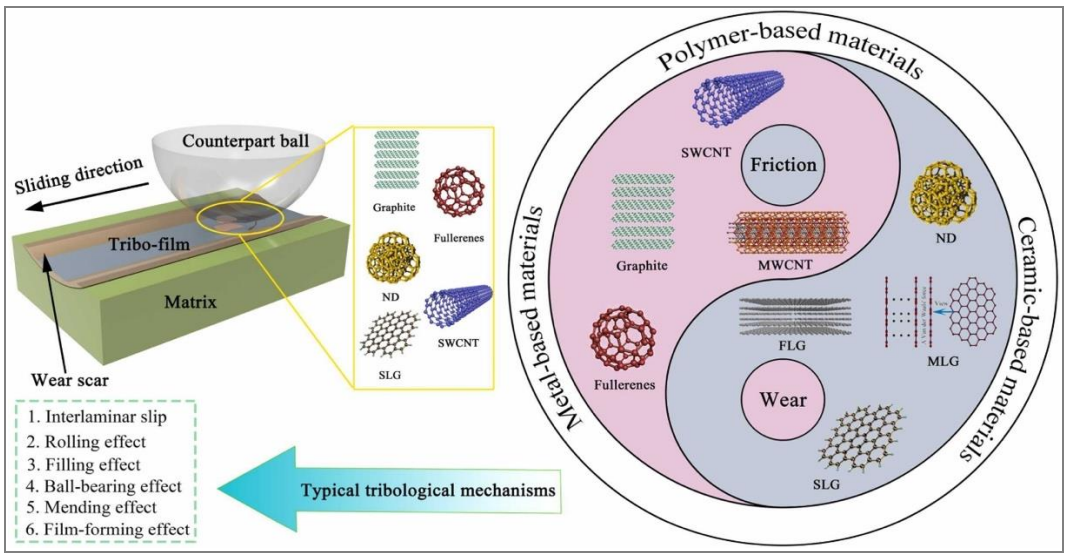

Figure 4. Schematic representation of the effect of carbon powder on the tribological performance of polymer composites [63]

6. Mechanical Performance of Composites Carbon Fillers

The available evidence consistently shows that carbon fillers are a promising reinforcing phase for improving the mechanical performance of polymer-based composites, particularly hard-

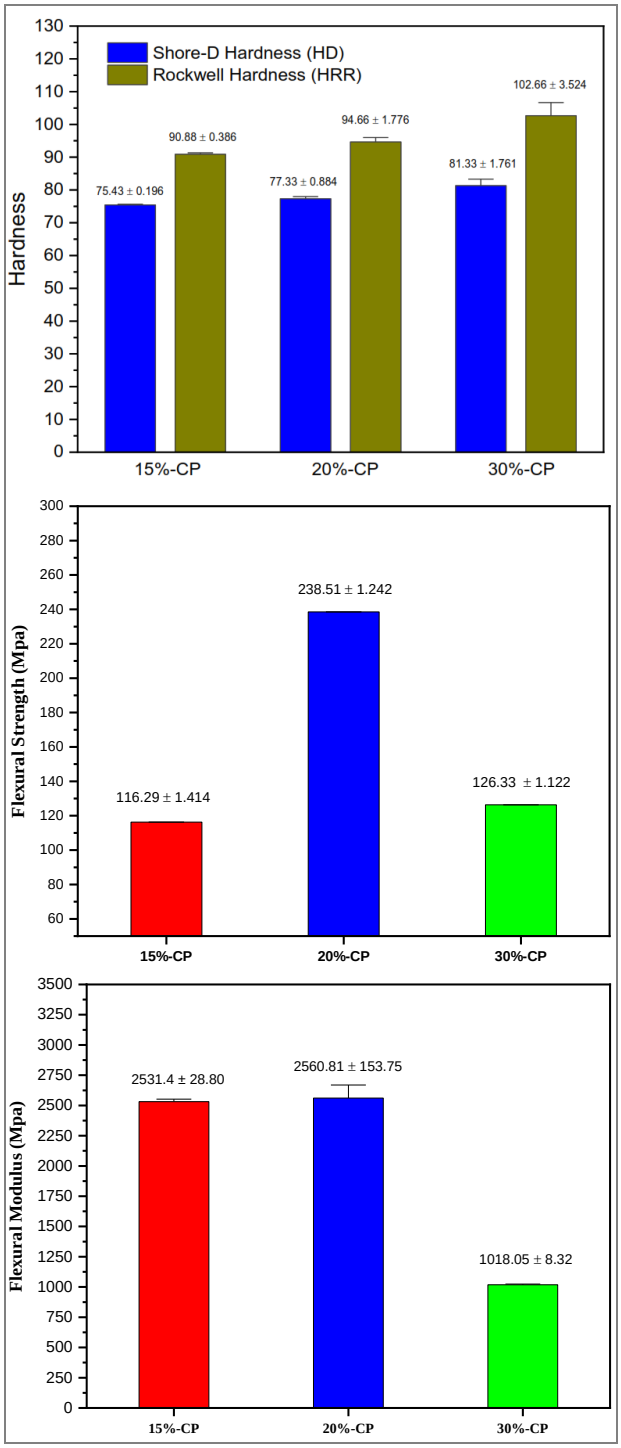

Figure 5. Mechanical performance of composites carbon fillers

ness, flexural strength, and flexural modulus. However, a synthesis of the existing studies confirms that these effects are neither universal nor linear. Instead, they are strongly influenced by filler fraction, dispersion homogeneity, particle size, and the quality of the interfacial bonding between the filler and the matrix. In most studies, increasing the carbon filler content is associated with higher hardness through mechanisms such as void filling, void reduction, increased density, and the formation of a more rigid structure [64], [65], [66]. In the iron sand–epoxy system, Apriliani *et al*. [32] also confirmed that carbon powder plays an important role in optimizing the mechanical properties of the composite.

Among the various mechanical parameters, hardness is the response most consistently reported to increase after the addition of carbon fillers (**Figure 5**). At carbon powder contents of 15%, 20%, and 30%, the hardness values were 75.43 HD, 77.33 HD, and 81.33 HD, respectively, indicating an increasing trend with increasing filler fraction. This finding supports the view that carbon fillers contribute to greater material compactness and microstructural stability, particularly when particle dispersion is homogeneous [64], [65], [67]. SEM-based micromorphological evidence also shows a more uniform structure, while other studies have reported higher Brinell hardness than that of neat epoxy [68]. This consistency is further supported by Szeluga *et al*. [68] and Bal [69], both of whom reported a significant increase in hardness after carbon addition. Therefore, based on the literature synthesis, hardness can be regarded as the most stable mechanical indicator for reflecting the effectiveness of carbon fillers [32], [70].

In contrast, the effect of carbon fillers on flexural performance shows a more complex pattern and tends to follow the concept of an optimum filler content. Several studies have shown that carbon fillers can improve flexural strength and flexural modulus when the filler content falls within an appropriate range and interfacial interactions are effective, allowing efficient stress transfer from the matrix to the filler [71], [72]. However, at higher filler fractions, flexural performance tends to decline because of particle agglomeration, non-uniform stress distribution, and weakened interfacial adhesion [73]. In the system examined in this study, LCP showed a flexural strength of 116.29 MPa and a flexural modulus of 2531.4 MPa, MCP produced the highest values, namely 238.51 MPa and 2560.81 MPa, whereas HCP decreased to 126.33 MPa and 1018.05 MPa. This pattern indicates that 20 wt% is the optimum condition, while further filler addition beyond this point reduces performance because of degradation of microstructural integrity.

This trend is consistent with reports from other studies. Sari *et al*. [74] showed that a certain filler content produced higher flexural strength than lower filler contents. In contrast, Wirawan *et al*. [73] emphasized that the hydrophilic nature of carbon powder can reduce the wetting effectiveness of epoxy, which is relatively hydrophobic, thereby weakening interfacial bonding and reducing mechanical properties. Nevertheless, several studies have still shown that carbon fillers can improve flexural performance when particle dispersion and physicochemical interfacial interactions are adequately controlled. Yue *et al*. [71], Abdul Khalil *et al*. [75], and Chandramohan [76] each reported that carbon fillers contributed to improved flexural performance through stronger matrix–filler bonding and more efficient stress transfer. Thus, unlike hardness, the flexural response is more sensitive to microstructural variation and interfacial compatibility.

7. Crystallinity and Structural Properties of Carbon-Reinforced Iron Sand/Epoxy Composites

Developing advanced composite materials generally requires optimization of the constituent components to achieve the desired mechanical and structural properties. One such material, the carbon-reinforced iron sand/epoxy composite, has attracted considerable attention because of its potential applications in various industries. The incorporation of carbon powder into the composite matrix affects its crystallinity, structural integrity, and overall performance. This chapter presents an X-ray diffraction (XRD) analysis of these composites, with particular emphasis on the relationship between carbon content and crystallinity. The XRD results, together with scanning electron microscopy (SEM) observations, provide important insights into the crystalline and amorphous characteristics of the material, which are essential for understanding its mechanical behavior and potential industrial applications.

The X-ray diffraction (XRD) analysis of the carbon-reinforced iron sand/epoxy composite is presented in **Figure 6**. The diffractogram reveals notable differences in crystalline structure among the composite specimens. Specifically, the low carbon powder (LCP) specimen exhibited an amorphous peak in the 2θ range of 20°–60° with an intensity of 762. In comparison, the medium carbon powder (MCP) specimen displayed a peak at 2θ = 21.080° with an intensity of 663, whereas the high carbon powder (HCP) specimen showed a peak at 2θ = 22.340° with an intensity of 366. These results indicate that the HCP composite had the lowest peak intensity, which is likely attributable to the non-uniform distribution of carbon within the composite. This uneven distribution may have weakened the interfacial bonding between the carbon particles and the epoxy resin, thereby affecting the overall crystallinity of the material [77], [78].

The amorphous nature of the composites is further supported by the broad peaks, which are characteristic of materials lacking a well-defined crystalline structure. All specimens exhibited broad diffraction peaks, indicating the presence of amorphous carbon in the composites [65], [79]. Notably, the HCP specimen produced the broadest peaks and exhibited the lowest crystallinity among the three specimens, suggesting a greater degree of amorphousness than in the LCP and MCP composites. In addition, the XRD peaks generally shifted to the right as the carbon content increased. This shift may be attributed to the introduction of amorphous carbon, which caused overlapping diffraction peaks within the composite structure. The crystallinity index values for the low carbon powder (LCP), medium carbon powder (MCP), and high carbon powder (HCP) composites were 46.92%, 59.45%, and 45.08%, respectively. This variation in crystallinity is closely related to the amount of carbon powder incorporated into the composite. The MCP composite, which contained 20 wt% carbon powder, exhibited the highest crystallinity index, indicating a more ordered crystal structure than the other specimens. In contrast, the HCP composite, which contained 30 wt% carbon powder, showed a decrease in crystallinity, likely because excess carbon promoted the formation of more amorphous regions within the composite.

These findings indicate that carbon powder content significantly affects the structural and mechanical properties of the composite [80]. Higher diffraction intensity in XRD patterns is generally associated with a greater proportion of crystalline regions within the material. In particular, the MCP composite containing 20 wt% carbon powder exhibited a substantially higher crystallinity index than the HCP composite containing 30 wt%. This suggests that excessive carbon content can lead to a more amorphous structure, characterized by disordered atomic arrangements and the absence of a well-defined crystalline pattern. Therefore, maintaining an optimal carbon content is essential to obtain the desired crystalline structure and, consequently, favorable mechanical properties in the composite. Based on these results, the MCP composite

containing 20 wt% carbon powder appears to be the most suitable for practical applications, as it provides a balanced combination of crystallinity and mechanical performance.

Several studies have examined the relationship between carbon content and crystalline structure. For example, Bee *et al*. [81] reported that the removal of organic constituents and the reduction of carbonate content during high-temperature processing can enhance the crystallinity of hydroxyapatite. Their findings suggest that careful control of material composition can optimize crystalline structure. Similarly, Guo *et al*. [82] found that increasing the carbon fiber content in composites improved crystallinity and reduced moisture absorption. This indicates that carbon fibers not only act as reinforcing agents but also contribute to a more ordered structural arrangement within the polymer matrix. These findings highlight the dual role of carbon as both a reinforcing material and a promoter of improved crystallinity in composite systems.

Çavdar *et al*. [83] noted that although carbon can improve thermal and mechanical properties when used appropriately, excessive amounts may inhibit crystallinity and thereby adversely affect the mechanical properties of composites. They emphasized that achieving an optimal carbon concentration is crucial for maintaining favorable thermal and mechanical performance in polymer composites. This conclusion is consistent with the findings of Wang *et al*. [84], who reported that increasing carbon fiber content was generally associated with reduced crystallinity in semi-crystalline polymers. These observations suggest that the relationship between carbon content and structural integrity is complex and must be carefully controlled during composite processing. Overall, these studies support the conclusion that there is a limit to the beneficial addition of carbon. Exceeding this threshold may compromise the mechanical properties of the composite, highlighting the importance of precise control during material synthesis.

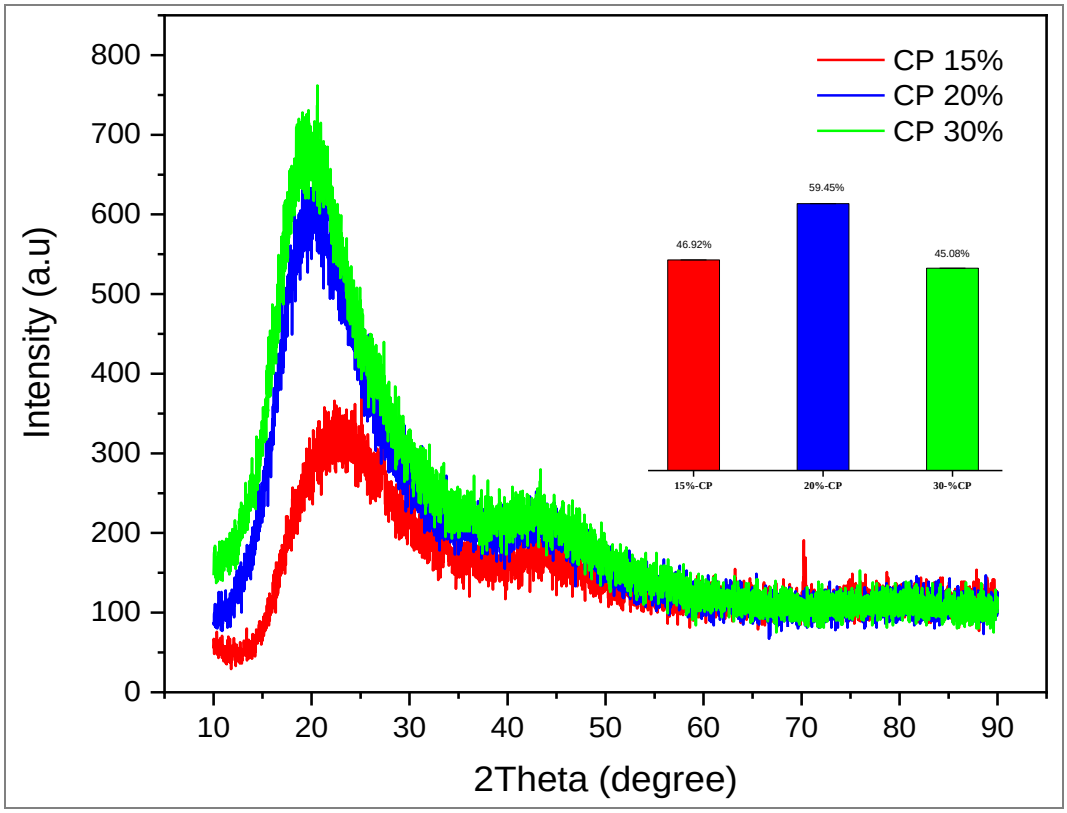

Figure 6. X-ray diffraction (XRD) analysis

8. FTIR Analysis of Iron Sand/Epoxy Composite Modified with Carbon Powder

Fourier Transform Infrared Spectroscopy (FTIR) is an important analytical technique for identifying functional groups and examining molecular interactions in composite materials. In this study, FTIR was used to characterize the chemical bonding and structural changes in iron sand/epoxy composites modified with different amounts of carbon powder. The FTIR spectra provide valuable information on the chemical and structural modifications resulting from the incorporation of carbon powder at different weight percentages (wt.%).

As shown in **Figure 7**, the FTIR spectra of the composites exhibit similar peak patterns at different carbon powder contents (15wt%, 20wt%, and 30wt%). Although the spectra are generally similar for all samples, the main difference is observed in the absorption intensity. This variation indicates that the fundamental chemical structure of the composite remains largely unchanged, while the concentration or contribution of specific functional groups varies with increasing carbon powder content. The absorption peak at 653 cm^{-1} corresponds to C–H bending vibrations, whereas the peak at 775 cm^{-1} is associated with aromatic C=C stretching. The presence of epoxy groups is confirmed by peaks in the range of 1051–1301 cm^{-1}, which correspond to C–O bond stretching [85], [86]. The peak at 1124 cm^{-1} is also attributed to C–O stretching of the epoxy group [87]. The absorption band at 2310 cm^{-1} is assigned to C=O stretching, while the peak at 1517 cm^{-1} corresponds to aromatic C=C bonds, suggesting the presence of graphite as a major bonding component [77]. In addition, aldehyde groups were identified at 2717 cm^{-1}, and aromatic C–H stretching bands were observed at 2964 cm^{-1}, indicating the interaction between the carbon powder and the epoxy matrix [88].

The FTIR spectra confirm the presence of key functional groups, including epoxy, aromatic C=C, and C–O stretching, all of which play important roles in determining the structural integrity of the composite. The changes in peak intensity observed with increasing carbon powder content suggest stronger interactions between the epoxy matrix and the carbon powder. Furthermore, the presence of aromatic C–H and C=O functional groups indicates the formation of a stable composite structure, which may contribute to the mechanical and chemical stability of the material. The peaks associated with C–O stretching in the epoxy resin suggest that the incorporation of carbon powder does not significantly alter the main chemical backbone of the composite. However, it may still influence the composite's mechanical properties. Moreover, the presence of graphite-like bonds at 1517 cm^{-1} confirms the contribution of carbon powder to the overall composite structure, which may enhance its electrical conductivity and thermal stability.

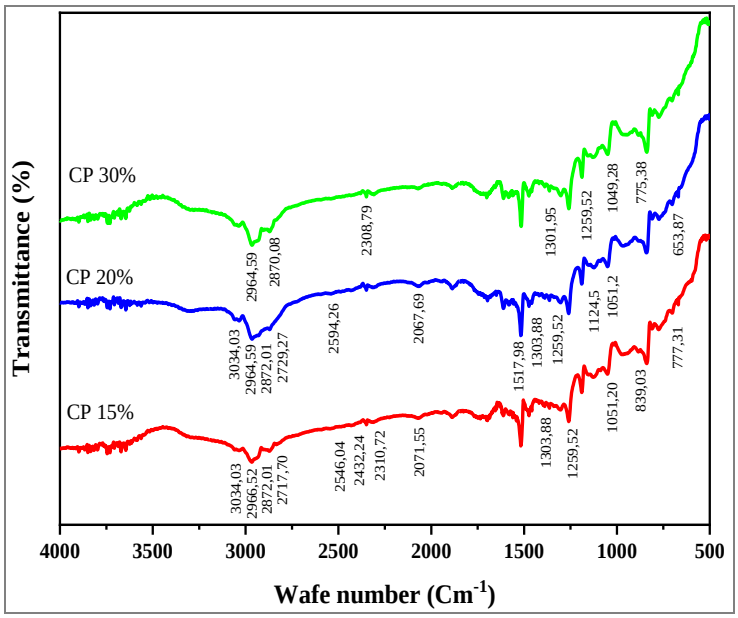

Figure 7. FTIR Spectra of iron sand/epoxy composite modified with carbon powder

9. Scanning Electron Microscopy (SEM) Analysis of Composite Carbon Fillers

Scanning Electron Microscopy (SEM) is widely used to assess dispersion, agglomeration, porosity, and interfacial adhesion in particulate epoxy composites. In iron sand/epoxy systems modified with carbon powder, SEM is especially important because mechanical and tribological performance depends not only on filler content, but also on the distribution of iron-rich and carbonaceous phases within the epoxy matrix. Previous studies indicate that uniform dispersion and strong matrix–filler adhesion improve stress transfer and reduce local stress concentration, whereas clustering, interfacial defects, and porosity are associated with brittle behavior and property deterioration [22], [89].

This interpretation is consistent with the framework illustrated in **Figure 8**, which describes the transition from a two-phase nanocomposite, where fillers are dispersed only in the resin, to a three-phase composite architecture, where the modified resin contributes to improved composite-level performance. In such systems, fillers act as matrix modifiers that improve compressive resistance, toughness, load transfer, and damage tolerance. Although the iron sand/carbon/epoxy system differs from carbon-fiber-reinforced laminates, the same principle applies: carbon-based fillers can modify both the epoxy phase and the interfacial region, thereby affecting structural

integrity and tribological behavior, provided that dispersion and filler loading are properly controlled [90].

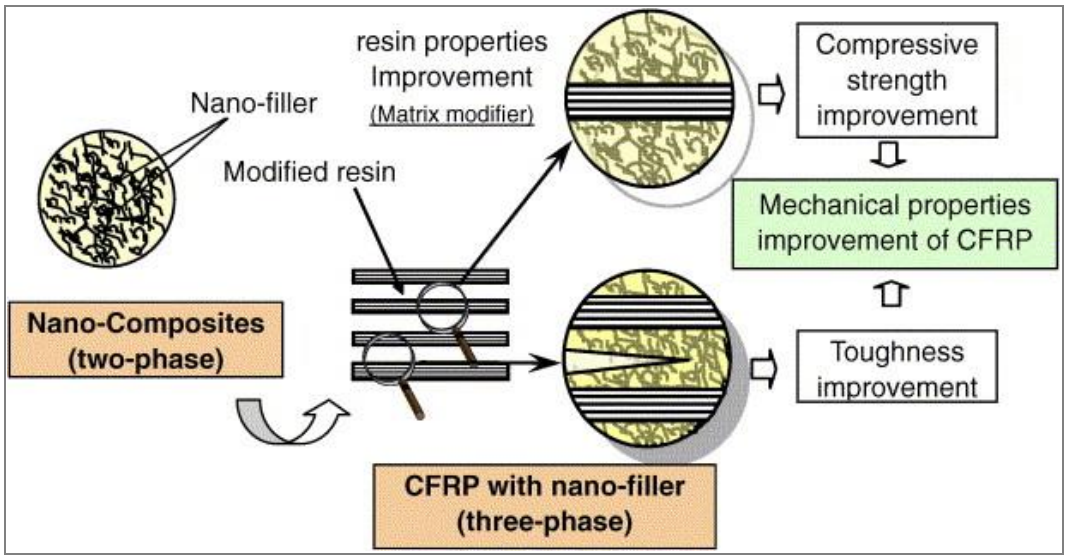

Figure 8. Schematic illustration of mechanical properties improvement in carbon fiber reinforced polymer (CFRP) via nano-filler incorporation, showing the transition from two-phase nano-composites to three-phase systems

Across the literature, a consistent SEM-based trend can be identified. As illustrated by the SEM micrographs in **Figure 9**, which show the interaction among iron sand, epoxy, and carbon powder at magnifications of 250× and 10,000×, low carbon loading generally preserves matrix continuity and relatively good filler dispersion, although microcracks or isolated defects may still appear. At intermediate loading, the microstructure tends to become denser and more homogeneous, with better matrix–particle interaction. By contrast, excessive carbon loading often promotes agglomeration, non-uniform particle packing, and void formation because high surface energy favors clustering and limits effective wetting by the epoxy matrix [91]. These observations are consistent with the broader composite literature, which identifies interfacial quality and dispersion state as key factors governing mechanical reliability [92], [93], [94].

For iron sand/carbon powder/epoxy composites, the available SEM evidence supports this general pattern. Low-carbon formulations often show relatively good dispersion and a continuous epoxy-rich phase, but visible microcracks may still be present, indicating that apparent dispersion alone does not guarantee optimum flexural performance. Intermediate-carbon formulations are more commonly associated with the most favorable morphology, characterized by a denser structure, more homogeneous particle distribution, and a better-developed interface between iron sand, carbon powder, and epoxy [22]. Such features are generally linked to improved stress redistribution, lower defect sensitivity, and greater resistance to crack initiation [95]. Stronger matrix–filler bonding further enhances load transfer and reduces the likelihood of interfacial debonding, while lower porosity and fewer microdefects help suppress crack propagation [92], [93], [94], [96], [97], [98]. This explains why intermediate filler loading is often associated with superior flexural performance compared with either insufficient or excessive filler addition [99], [100].

By contrast, high-carbon formulations illustrate the microstructural limitations of excessive filler addition. SEM observations commonly show particle clustering, reduced matrix homogeneity, and more pronounced pore formation at high carbon loading [40]. Because carbonaceous particles tend to aggregate at high concentration, such morphologies disrupt stress transfer, generate internal heterogeneity, and create voided regions that act as crack initiation sites [101]. As a result, high-carbon systems are generally more susceptible to brittle fracture and reduced structural integrity. However, the literature also shows that high carbon loading may still improve surface-dominated properties such as hardness and wear resistance, because carbon particles enhance local surface durability and resistance to abrasion or erosion [62], [64]. Thus, the SEM morphology of high-carbon formulations reflects a trade-off in which tribological gains may occur at the expense of flexural strength and fracture resistance.

Overall, the SEM literature indicates that the performance of carbon-modified iron sand/epoxy composites is governed by the balance among filler loading, dispersion quality, porosity, and interfacial adhesion. Low filler loading may preserve matrix continuity but still permit microcrack formation, intermediate loading often provides the most coherent and mechanically

efficient morphology, and excessive loading tends to induce agglomeration, porosity, and brittle behavior [102], [103]. Accordingly, SEM should be regarded not merely as a descriptive tool, but as an important link between processing, microstructural organization, and macroscopic mechanical and tribological performance. Future studies should focus on quantitative SEM-based defect analysis, improved particle surface treatment, and scalable dispersion strategies that suppress agglomeration while preserving the functional benefits of carbon addition [104], [105].

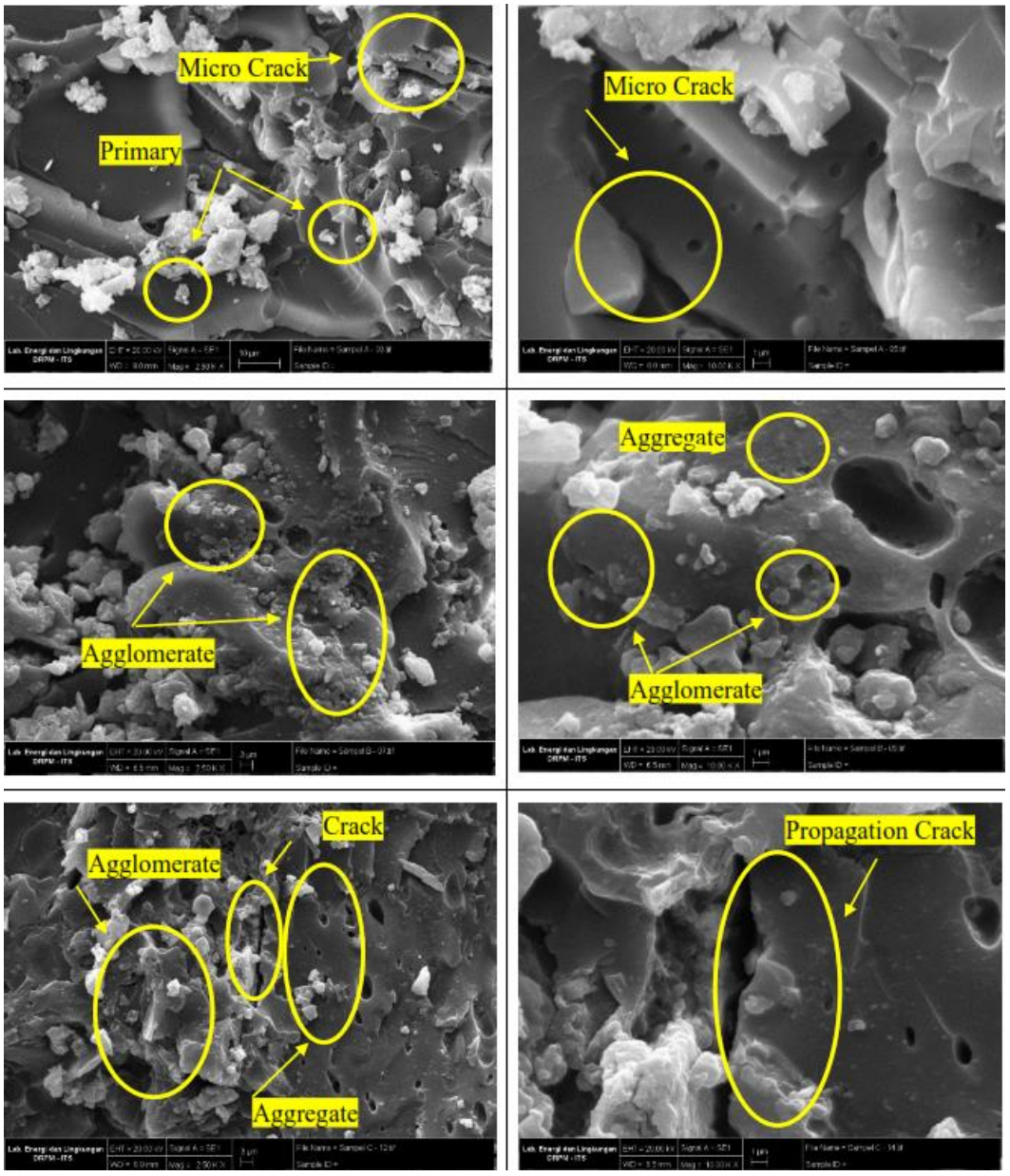

Figure 9. SEM micrographs of the iron sand/epoxy composite modified with carbon powder, showing the interaction among iron sand, epoxy, and carbon powder

10. Enhancing Fiber-Matrix Bonding with Carbon Powder

The interaction between the constituent components of fiber-reinforced composites, particularly the fibers and the matrix, plays a critical role in determining the overall mechanical performance of the composite. A strong interfacial bond is essential for efficient load transfer from the matrix to the reinforcing fibers, enabling the composite to withstand mechanical stresses effectively. In fiber-reinforced polymer composites, the adhesion between the fibers and the matrix governs key properties such as tensile strength, flexural strength, and impact resistance. Poor interfacial bonding can lead to stress concentration, delamination, and fiber pull-out, ultimately reducing the structural integrity of the composite.

Sulistyo *et al*. [106] investigated the effect of incorporating carbon powder (CAP) into natural fiber-epoxy composites, as illustrated in **Figure 10**. The study showed that the interface among alkali-treated lignocellulosic fiber (ALF), carbon powder (CAP), and epoxy (EP) was significantly

improved by the addition of CAP. Carbon powder adhered to the fiber surface and filled the voids between the fiber and the matrix, thereby enhancing the overall interfacial integrity. This mechanism produced a more cohesive composite structure by reducing weak interfacial regions that could otherwise act as failure initiation sites. The effectiveness of CAP in improving interfacial adhesion was attributed to its ability to promote a mechanical interlocking mechanism. During drying and curing, CAP became embedded within the microvoids and surface irregularities of the fiber, resulting in a more stable and tightly bonded interface.

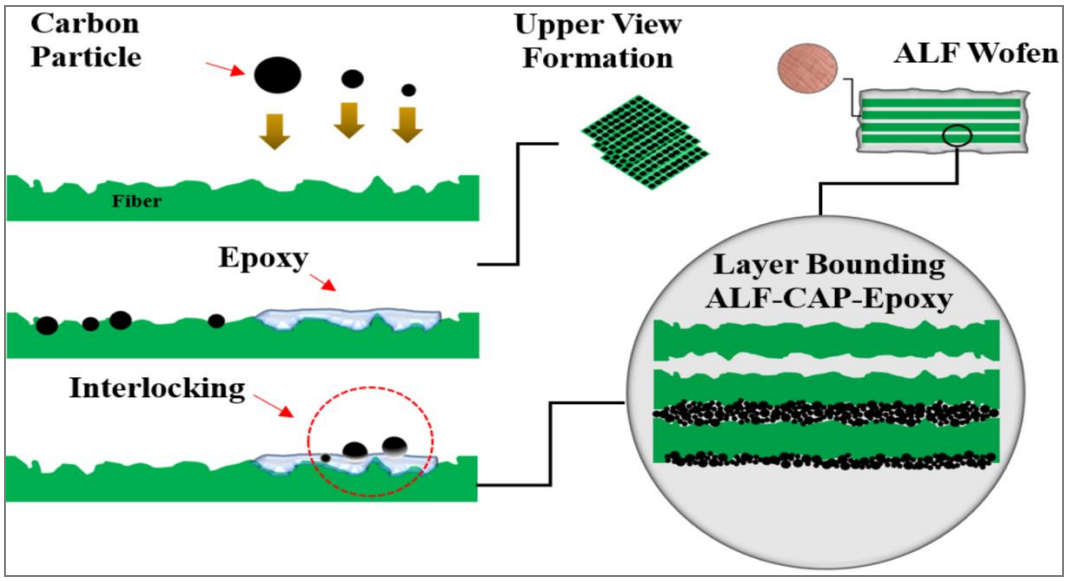

Figure 10. Illustration of fiber-matrix bonding with carbon powder [106]

The improved fiber-matrix interaction facilitated by carbon powder contributes substantially to the mechanical properties of the composite, particularly its longitudinal tensile strength. The efficiency of stress transfer between the matrix and the reinforcement directly affects the tensile strength of a composite. When the interfacial bond is strong, applied loads are distributed efficiently to the fibers, allowing them to carry most of the stress while reducing the likelihood of premature failure in the matrix phase. In contrast, weak interfacial bonding causes stress localization, which may lead to fiber pull-out or interfacial debonding and, consequently, inferior mechanical performance [107].

Moreover, the presence of carbon powder at the fiber-matrix interface may influence other important properties, such as toughness and fatigue resistance. The interlocking effect not only strengthens the bond but also helps absorb and dissipate energy under dynamic loading, thereby increasing the composite's resistance to crack propagation [108]. In addition, carbon powder may act as a secondary reinforcement, further enhancing the stiffness and durability of the composite. However, achieving an optimal distribution of carbon powder within the composite remains essential, because excessive amounts may cause particle agglomeration, which can adversely affect structural uniformity and mechanical performance [109]. In conclusion, the addition of carbon powder plays an important role in enhancing interfacial bonding within the composite system. By filling voids and improving adhesion between the fibers and the matrix, carbon powder filler strengthens the composite microstructure and leads to improved tensile strength and overall mechanical performance [110]. The interlocking mechanism formed during drying and curing further stabilizes the fiber-matrix interface, ensuring efficient stress transfer and reducing the likelihood of failure under mechanical loading [111].

The literature indicates that the performance of filled polymers is strongly governed by the matrix type, filler morphology, filler loading, and the manufacturing route employed. Accordingly, a comparative evaluation of various composite systems is essential to clarify the position and relevance of the iron sand/carbon/epoxy system discussed in this review. **Table 4** summarizes representative studies directly related to polymer composites for both tribological and structural applications.

11. Applications and Industrial Relevance

Iron sand/carbon/epoxy composites are promising for lightweight tribological components, sliding pads, low-speed wear elements, structural covers, and multifunctional parts that require

moderate mechanical stiffness together with enhanced wear resistance. More broadly, polymer- and epoxy-based tribological composites have been investigated for gears, bushings, shafts, surface coatings, and related machine elements, supporting the extension of this material design strategy to automotive interiors, protective panels, marine secondary structures, and other wear-sensitive mechanical applications [3], [4], [7], [112]. The main attraction of iron sand/carbon/epoxy systems lies in the integration of a relatively low-cost mineral reinforcement with a carbon-based friction-reducing phase within a single matrix. This hybrid formulation is particularly attractive when the design objective is not maximum load-bearing capacity, but rather a balanced combination of dimensional stability, surface durability, and moderate structural performance.

Table 4. Representative literature on polymer matrices, fillers, and performance trends relevant to tribological and structural composites

System	Matrix	Reinforcement / modifier	Main reported benefit	Main reported limitation	Ref.
Polymer composite applications review	Various polymers	Various fibers and fillers	Broad engineering applicability of polymer composites	Performance depends strongly on processing and interphase control	[3]
Hybrid biocomposites	Epoxy, vinyl ester, polyimide	Natural/hybrid reinforcement	Matrix selection strongly affects comparative performance	Interfacial compatibility remains critical	[4]
Polymer gears review	Engineering polymers	Filler- and design-dependent	Useful for lightweight transmission systems	Wear, thermal effects, and life prediction remain limiting	[113]
PTFE composites	PTFE	Mica and MAO	Strong wear improvement and lower friction	Mechanical balance depends on filler content and tribofilm formation	[7]
PETG components	PETG	Process-parameter controlled	Good durability for lightweight printed parts	Performance strongly depends on manufacturing conditions	[8]
Graphite/CNT-filled epoxy	Epoxy	Graphite and/or CNTs	Lower friction and improved wear resistance	Dispersion difficulty and concentration sensitivity	[26]
Carbon black-filled epoxy	Epoxy	Carbon black	Improved interfacial bonding and deformation behavior	Agglomeration at excessive loading	[22]
Iron powder-filled glass/epoxy	Epoxy laminate	Iron powder	Improved structural response in some conditions	Environmental stability and processing sensitivity	[114]
Graphite-filled epoxy	Epoxy	Graphite	Reduced coefficient of friction	Mechanical benefit depends on filler fraction and bonding	[59]
Carbon nanocage-filled epoxy	Epoxy	Carbon nanocages	Low friction and wear	Processing and cost considerations	[60]
Biomass-based carbon black epoxy	Epoxy	Carbon black	Improved flexural and thermal response at suitable loading	Overloading can reduce property balance	[76]
Iron sand + carbon powder	Epoxy	Iron sand + carbon powder	Combined hardness, wear, and microstructural tuning	Agglomeration and brittle behavior at high carbon loading	[32]

Despite this potential, large-scale industrial implementation remains dependent on the resolution of several important challenges (**Figure 11**). First, particulate settling and batch-to-batch reproducibility must be controlled more rigorously, because sedimentation and filler migration are well-recognized processing limitations in particle-filled polymer systems, especially in casting- and liquid-resin-based manufacturing routes [115], [116]. Second, the nominal cost advantage of natural iron sand may be reduced if purification, grading, magnetic separation, drying, or surface modification becomes excessively complex or economically impractical for stable industrial production. Third, tribological behavior measured under simplified laboratory contact conditions cannot be assumed to translate directly to service environments involving temperature cycling, wet or saline exposure, impact, and vibration-assisted loading. These conditions may progressively degrade the matrix, weaken the interfacial region, and alter the dominant wear mechanisms over

time [117]. Finally, carbon-filler selection must remain application-specific. A formulation optimized for low friction or transfer-film formation may not provide the best flexural durability, fracture resistance, or long-term environmental stability, because filler content, morphology, and dispersion state influence tribological and structural responses in different ways [26], [59], [75].

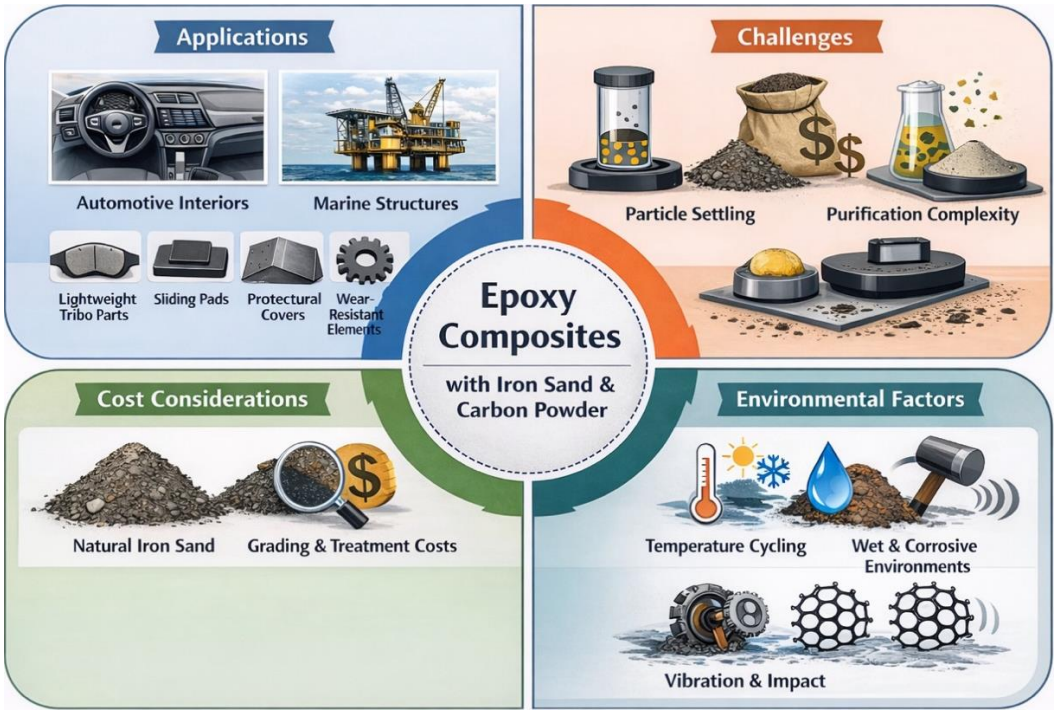

Figure 11. Applications and industrial relevance

12. Conclusion

This critical review demonstrates that iron sand/carbon/epoxy composites represent a promising material system for applications that require a balance between tribological performance and structural reliability. Across the reviewed literature, iron-rich particles primarily enhance hardness and load-bearing capacity, whereas carbon fillers reduce friction and improve wear resistance through solid-lubrication effects and transfer-layer formation. However, these benefits are strongly non-linear and depend not only on filler content, but also on dispersion quality, interfacial adhesion, and processing conditions.

A consistent finding throughout the literature is the trade-off between tribological improvement and mechanical integrity. Higher carbon loading generally leads to lower wear and friction, yet excessive addition frequently promotes agglomeration, porosity, poor wetting, and stress concentration, which ultimately compromise flexural performance and increase the likelihood of brittle failure. In contrast, intermediate carbon loading appears to provide the most favorable overall balance, as it better preserves microstructural uniformity and matrix–filler interaction while still delivering meaningful improvements in hardness and wear behavior. This indicates that the most effective design strategy is not the maximization of a single property, but the optimization of multiple competing responses.

The review also highlights the need for more rigorous interpretation of characterization results. XRD-based claims regarding changes in crystallinity should be treated with caution, since the diffraction response reflects the combined contributions of crystalline iron oxides, disordered carbon phases, and the predominantly amorphous epoxy matrix rather than a simple change in matrix crystallinity alone. Similarly, FTIR analysis more reliably confirms compositional retention and chemical backbone stability than the formation of specific new interfacial bonds. SEM observations consistently support the importance of filler dispersion and interfacial cohesion, although the available evidence remains largely qualitative and rarely quantifies agglomeration, porosity, or interphase quality in a rigorous manner.

Overall, iron sand/carbon/epoxy composites offer a cost-conscious and technically attractive pathway for wear-sensitive engineering applications requiring moderate structural performance. Nevertheless, the current evidence base remains limited by insufficient durability assessment, restricted service-condition testing, and incomplete understanding of processing reproducibility

and long-term interfacial stability. Future research should therefore focus on scalable dispersion control, targeted interphase engineering, durability and environmental exposure testing, and data-driven multi-objective optimization of filler loading to enable more reliable translation of this material system into practical engineering applications.

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Authors' Declaration

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Generative AI statement - The authors used ChatGPT (OpenAI) during the preparation of this manuscript solely to improve language, clarity, and readability and to assist in creating the conceptual illustration shown in Figure 11. All AI-generated content was carefully reviewed, verified, and revised by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the manuscript.

Additional information – No additional information from the authors.

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