

A comprehensive review of silicon-based composite materials for wind and hydropower applications: Properties, performance, and industrialization barriers

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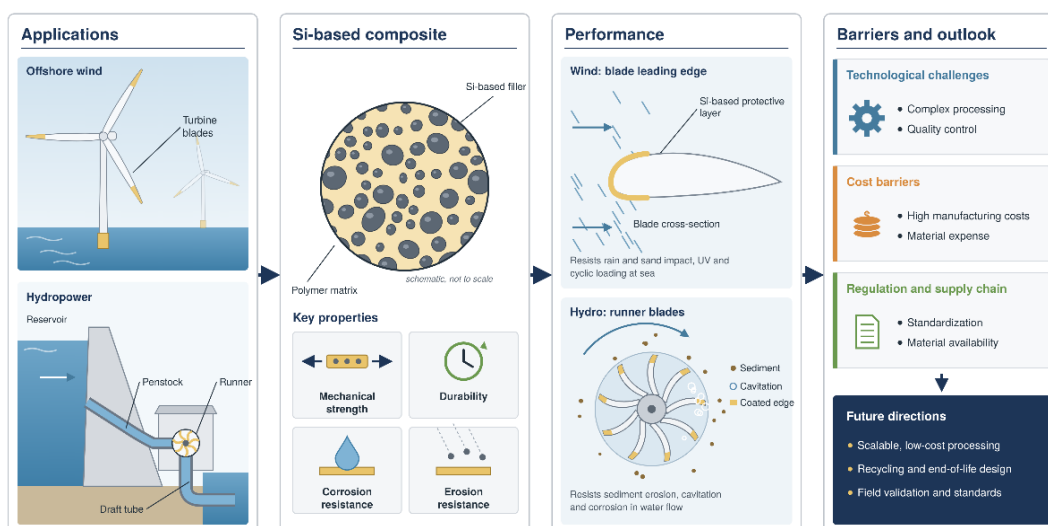
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Highlights:

- Silicon-based composites offer durable options for wind and hydropower systems.
- SiC and Si₃N₄ provide high thermal, wear, and corrosion resistance.
- Silicone-based composites suit seals, coatings, damping, and functional layers.
- CVI, PIP, and hybrid routes govern performance, cost, and scalability.
- Industrial adoption depends on scale-up, quality control, cost, and market fit.

Abstract

Silicon-based composites (SBC) are gaining popularity as sophisticated materials for renewable energy systems that operate under harsh mechanical, thermal, and environmental conditions. This research presents a critical and comparative evaluation of SBC for wind and hydropower applications by combining quantitative performance data, component-level viability, and industrialization problems such as scalability and cost considerations. Reinforcement topologies ranging from particle and short fibers to continuous, along with essential processing techniques such as chemical vapor infiltration, melt infiltration, polymer infiltration and pyrolysis, and new additives. The fundamental mechanical, thermal, tribological, and chemical durability qualities are examined in terms of the predominant deformation, damage, and degradation mechanisms. The

performance of SBC under actual service conditions—such as cyclic loading, erosion-corrosion, cavitation, and harsh environments—is examined and compared to traditional glass- and carbon-fiber-reinforced polymer composites. Aside from technical features, the review is unusual in that it includes industrialization and commercialization views, identifying scale-up impediments, quality control issues, and technology-market misalignments that prevent acceptance. To connect material-level advantages with system-level benefits, business model archetypes and risk-sharing techniques are thoroughly evaluated. This study frames silicon-based composites as high-performance materials for next-generation wind and hydroelectric infrastructure, as well as strategic directions for accelerating their industrial application.

Keywords: Silicon-based composites; Wind energy; Hydropower; Industrialization barriers; Business models

1. Introduction

Wind and hydropower have emerged as cornerstone technologies in the global shift to low-carbon energy because of their maturity, scalability, and extended service life. However, the shift to larger turbines, offshore constructions, and high-head hydropower systems has resulted in much higher material performance requirements [1], [2], [3]. Under these conditions, material constraints have emerged as a major impediment to increasing system efficiency, dependability, and lifespan cost.

Turbine blades, drivetrain parts, bearings, and structural supports in wind energy systems are subjected to a variety of cyclic stress, fatigue, temperature changes, and harsh climatic conditions [4], [5]. Conventional materials such as glass fiber-reinforced plastics, carbon fiber composites, and metallic alloys have permitted the wind industry's fast growth over the last few decades [6], [7], [8], [9], [10]. Nonetheless, these materials have ongoing issues relating to long-term fatigue resistance, wear, erosion, and supply chain constraints, especially as turbine sizes grow. Recent research has shown that material degradation and repair-related downtime significantly increase operational costs, emphasizing the need for alternative material options with increased durability and reliability [11], [12], [13].

Hydropower systems present a distinct but equally complex operational environment. Turbine frames, guide shafts, seals, and other wet components have been shown to perform under persistent exposure to high-velocity water flow, pressure variations, cavitation, erosion, and corrosion [5], [14]. Metallic materials used in hydropower facilities are known to need frequent repair or replacement, resulting in extended outages and significant maintenance expenses. Although sophisticated surface coatings and alloys have been created to address these concerns, their effectiveness has been shown to be limited under extended service conditions [9], [15], [16]. As a result, there has been increasing interest in advanced composite materials that can provide enhanced resilience to wear and environmental deterioration while retaining structural integrity.

Silicon-based composite (SBC) materials, notably those made from silicon carbide SiC, silicon nitride (Si₃N₄), and other silicon-containing matrices, have emerged as viable options for high-performance renewable energy applications [16], [17]. These materials have a distinct mix of high specific strength, outstanding thermal and chemical properties, and superior resistance to wear and corrosion [18], [19]. These characteristics have been widely used in high-performance industries such as aerospace, automotive, electronics, and energy applications due to their ability to perform under demanding conditions, where dependability in severe environments is vital [18], [20], [21], [22]. Applying these benefits to wind and hydroelectric systems has the potential to result in longer service life, lower maintenance requirements, and higher system availability. Despite its inherent advantages, the use of SBC in renewable energy projects is still limited. Ceramic-based composites exhibit low damage tolerance and sensitivity to defects, along with high processing cost, whereas silicone-based systems are limited by lower mechanical strength, restricting their use to non-structural applications [20], [23]. Overall, their industrial use remains selective and application-driven, depending on specific performance requirements. Despite their broad industrial relevance, their application in renewable energy systems such as wind and hydropower remains relatively underexplored.

The extant literature focuses on fundamental material characterization and experimental demonstrations, with relatively few researches addressing performance under realistic operating settings or the constraints of industrial-scale manufacture [24], [25]. Material qualities reported in research frequently vary greatly due to changes in processing processes, microstructural control, and testing methodologies, rendering direct comparisons impossible [26]. Furthermore,

conventional manufacturing methods for SBC, including chemical vapor infiltration, polymer infiltration, and pyrolysis, have been linked to high production costs, limited throughput, and significant capital investment [21], [27]. These factors, taken together, impede the move from experimental validation to broad industrial adoption. Another underexplored area of present evaluations is the commercialization and transfer of technology of innovative materials. Successful adoption of renewable energy systems is determined not just by technical performance, but also by alignment with market requirements, regulatory frameworks, qualification standards, and risk-sharing arrangements. The absence of established validation methodologies, uncertainty in long-term dependability, and mismatches between technology readiness and business strategy continue to impede the industrial adoption of SBC beyond pilot or niche applications [25], [28].

Therefore, this review presents a comprehensive evaluation of silicon-based composites (SBC) for wind and hydropower applications, spanning the gap between material research and industrial implementation. Despite the expanding quantity of literature on SBC, previous studies frequently focus on individual material systems or specific applications, rather than presenting a holistic perspective that links material features to practical implementation. In particular, less emphasis has been paid to integrating material performance with industrialization problems and application practicality in renewable energy systems. In this context, the present review provides a comprehensive and critical comparison of SiC, Si₃N₄, and silicone-based composites, with emphasis on their performance characteristics, limitations, and suitability for wind and hydropower applications. Unlike traditional reviews, this work combines quantitative comparison, component-level application analysis, and industrial considerations, including cost and commercialization barriers. As a result, the main contribution of this study is to bridge the gap between material-level understanding and real-world engineering implementation, offering a more application-oriented and industry-relevant perspective. Furthermore, this organized approach enables the assessment to uncover not just performance benefits but also constraints, inconsistencies, and practical application boundaries, resulting in more actionable findings for future research and industry use.

2. Silicon-Based Composite (SBC)

2.1. Material and Classifications

SBC are ceramic and polymer matrix systems designed to improve mechanical, thermal, and functional performance [29], [30]. They are generally classed as silicon carbide-, silicon nitride-, or silicone/siloxane-based composites depending on their main matrix phase. This matrix-based classification allows for a clear relationship between processing pathways, microstructural design, and particular application performance [25], [30].

2.1.1. Silicon carbide-based composites

Silicon carbide (SiC)-based composites are one of the most thoroughly researched silicon-based material systems because of its excellent mix of high strength-to-weight ratio, thermal endurance, chemical inertness, and resistance to corrosion and wear [16], [25], [26], [31], [32], [33], [34]. These characteristics stem from Si-C's strong covalent bonding, which contributes intrinsic stiffness and strength, while tailored composite topologies alleviate the inherent brittleness of monolithic SiC. Recent research shows that tailoring reinforcement structure—such as whiskers, fibers, or woven preforms—plays a critical role in controlling crack propagation behavior and load transfer efficiency, allowing for improved fracture resistance and mechanical performance under demanding service conditions [16], [17], [21], [32].

SiC-based composites are typically manufactured utilizing chemical vapor infiltration (CVI), polymer infiltration and pyrolysis (PIP), or a hybrid CVI-PIP technique to obtain high densification and controlled microstructures. CVI allows for the fabrication of high-purity SiC matrices with higher thermal and chemical stability, but it is often coupled with lengthy processing periods and expensive production costs [32], [35]. In comparison, PIP provides greater processing versatility and cost efficiency but frequently results in residual porosity that must be properly handled [36], [37].

Over the last five years, research has shown that optimizing infiltration cycles, using modified polymer precursors, and deliberately engineering fiber-matrix interfacial layers improves densification, oxidation resistance, and mechanical strength of SiC composites, extending their

applicability to turbine components, thermally protected systems, and next-generation aerospace structures [17], [25], [38]. To better understand the mechanical response and reinforcement-driven strengthening mechanisms of silicon carbide-based composites, **Figure 1** depicts a conceptual framework that connects tensile characterization to microstructural damage evolution. The representative tensile testing configuration (**Figure 1a**) demonstrates the importance of uniaxial loading in assessing the intrinsic tensile behavior of brittle and almost-brittle SiC-reinforced materials, where reliable stress transfer and controlled breakdown are required to

evaluate structural applicability. The related schematic stress-strain response (**Figure 1b**) highlights SiC reinforcements' improved energy absorption and postponed catastrophic failure when compared to unreinforced matrices [21].

At the microstructural level, **Figure 1c** and **Figure 1d** show the primary toughening mechanisms that drive SiC-based composites' increased mechanical performance. Elongated SiC reinforcements cause crack deflection and bridging, which efficiently redistribute stresses and minimize crack driving forces, whereas interfacial debonding and whisker pull-out lead to further energy dissipation during fracture [21], [32]. These mechanisms, which have been consistently described in recent investigations across various matrix systems, provide a transportable mechanistic foundation for understanding strength and toughness increase in SiC-based composites.

The fracture-tip stress-field study proposed by Xuqin Li *et al.* [25], as shown in **Figure 2**, clarifies the crack deflection mechanism even more. **Figure 2a** shows that the fracture-tip stress field has two components: σ_{zz} , which drives crack opening, and σ_{rr} , which promotes interfacial tugging and debonding. As seen in **Figure 2b**, the maximum parallel stress is approximately one-fifth of the vertical stress, implying that interfacial cracking becomes energetically beneficial when the interface strength is less than around 20% of the matrix strength. This mechanistic insight emphasizes the crucial role of interface engineering in limiting crack propagation and increasing toughness in SiC-based composite materials.

Figure 1. Illustration of mechanical characterization and reinforcement-driven toughening mechanisms in silicon carbide-based composites: (a) Representative tensile testing configuration for brittle and quasi-brittle composite systems; (b) Schematic stress-strain (or load-displacement) response; (c) Crack deflection and bridging induced by SiC reinforcements; (d) Interfacial debonding and whisker pull-out mechanisms contributing to energy dissipation during fracture. The figure is conceptually inspired by experimental observations reported in Lan *et al.* [21]

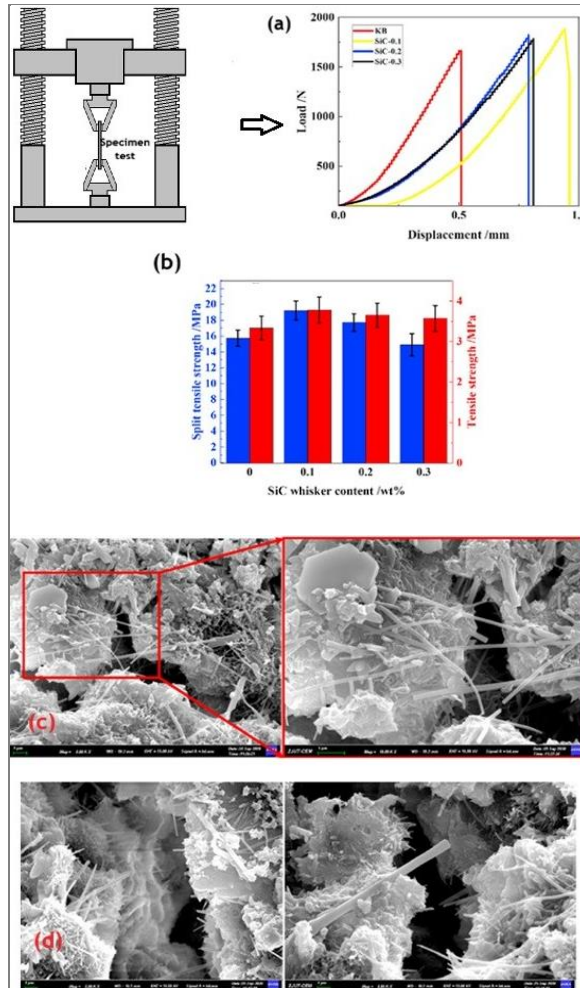
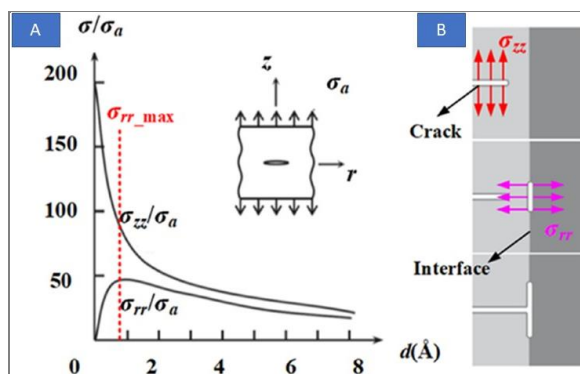


Figure 2. Crack deflection mechanism: (a) Stress field at the crack tip; (b) Crack deflection process [25]



2.1.2. Silicon nitride-based composites

Silicon nitride (Si_3N_4)-based composites are highly regarded for their excellent fracture toughness, thermal shock resistance, wear resistance, and endurance under extreme thermo-mechanical conditions. Si_3N_4 's anisotropic grain shape leads to fracture deflection and grain-bridging mechanisms, which are enhanced by tailored secondary phases and tailored interfaces [39], [40]. **Figure 3a** shows how elongated Si_3N_4 grains and intergranular phases modify fracture pathways and redistribute stresses, making composites ideal for applications demanding high

structural dependability, thermal management, and tribological durability. Recent advancements in processing technology have considerably increased the property envelope of silicon nitride composites [39]. Spark plasma sintering (SPS), as shown schematically in Figure 3b, allows for rapid densification at lower temperatures while maintaining fine-grained and well-controlled microstructures [40]. Coëffe Desvaux *et al.* [40] found that SPS-processed silicon (oxy-) nitride/boron nitride composites have tunable thermophysical properties. The incorporation of boron nitride (BN) phases improves thermal shock resistance and generates anisotropic heat transport while maintaining mechanical integrity. These findings emphasize the significance of phase architecture and processing control in combining thermal conductivity and mechanical performance.

Beyond completely ceramic systems, silicon nitride has been effectively used into hybrid and polymer-based composites to add new functional properties. Du *et al.* [41] found that sodium alginate-Si₃N₄-PVA composites have better damping behavior and mechanical stability through synergistic relationships among ceramic reinforcement and viscoelastic polymer systems. This study demonstrates Si₃N₄'s adaptability as a multifunctional reinforcement that can operate beyond traditional load-bearing functions.

Silicon nitride-containing composites outperform in lubricated and hostile environments, thanks to the high hardness and chemical resilience of Si₃N₄ phases. This stabilizes transfer layers and reduces abrasive wear [42]. Furthermore, recent breakthroughs in chemical processing have resulted in significant increases in thermal transfer qualities. Yin *et al.* [43] demonstrated that ammonia-assisted manufacturing in reaction-bonded silicon nitride eliminates oxygen-related defects while promoting continuous nitride networks, resulting in significantly increased thermal conductivity. Si₃N₄-based composites show promise for advanced structural components that require mechanical robustness, tribological durability, and effective heat dissipation.

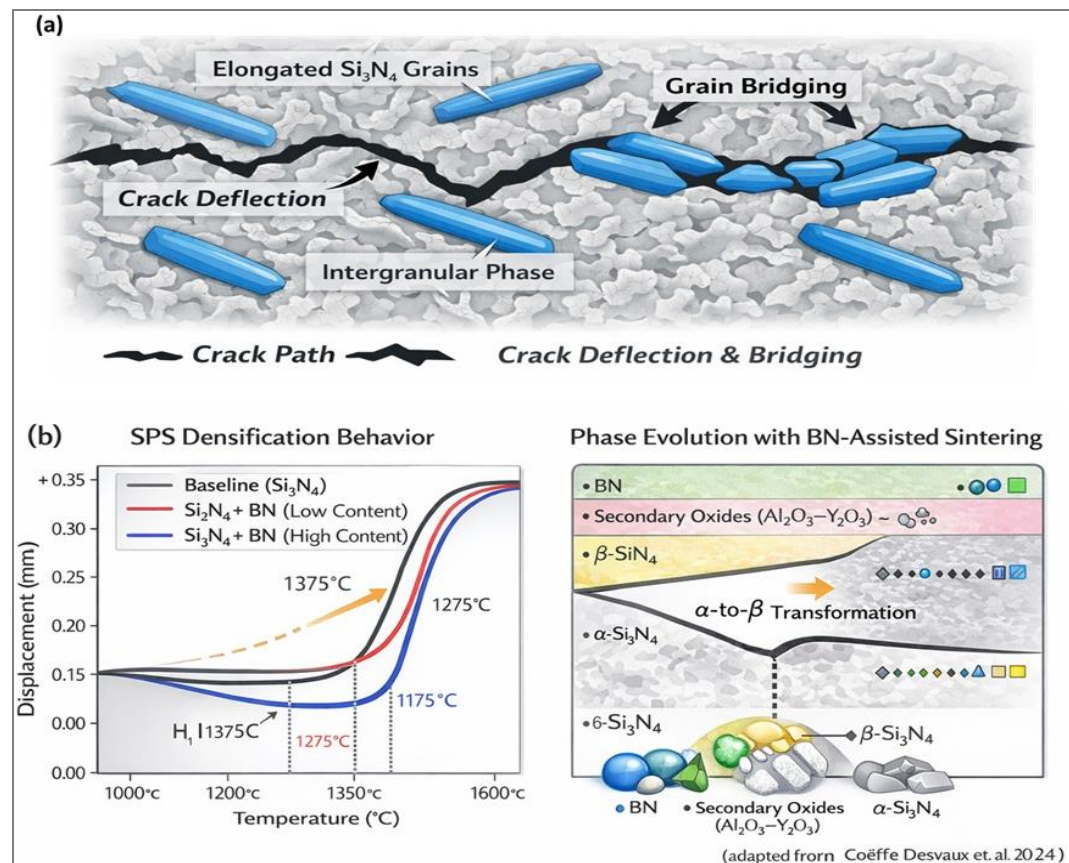


Figure 3.
(a) Schematic microstructure of elongated Si₃N₄ grains and crack deflection mechanisms (conceptually inspired by Yin *et al.* [43]);
(b) Illustration of spark plasma sintering (SPS) for Si₃N₄-based composites; (adapted from Coëffe Desvaux *et al.* [40])

2.1.3. Silicone- and siloxane-based composites

Composites made of silicone and siloxane constitute a flexible family of silicon-based materials with adjustable surface chemistry, low glass transition temperatures, good thermal stability, and flexible Si–O backbones [42], [44]. These characteristics make siloxane composites ideal for functional, soft-structural, and new energy-related applications because they allow for exact control over elasticity, wettability, damping conductivity, and environmental resistance.

Unlike ceramic-based systems, molecular network structure, crosslink density, and interfacial chemistry—rather than traditional load-bearing reinforcement—are the main factors influencing performance optimization in siloxane composites. The significance of amphiphilic siloxane design in attaining multifunctionality and interoperability with additive manufacturing (AM) technologies is highlighted by recent advancements [45], [46]. In order to facilitate the creation of intricate embedded-channel architectures with excellent mechanical integrity and fluid compatibility, Wong *et al.* [47] used hydrophilic silicone-based inks made from amphiphilic siloxane oligomers for vat photopolymerization. While the siloxane backbone preserves bulk elasticity, nanoscale phase segregation encourages the migration of hydrophilic segments to surfaces, as illustrated in Figure 4a. Optimized crosslink density and filler dispersion produced biomimetic elasticity and high dimensional integrity in stereolithography-printable silicone-derived elastic composite hydrogels [47].

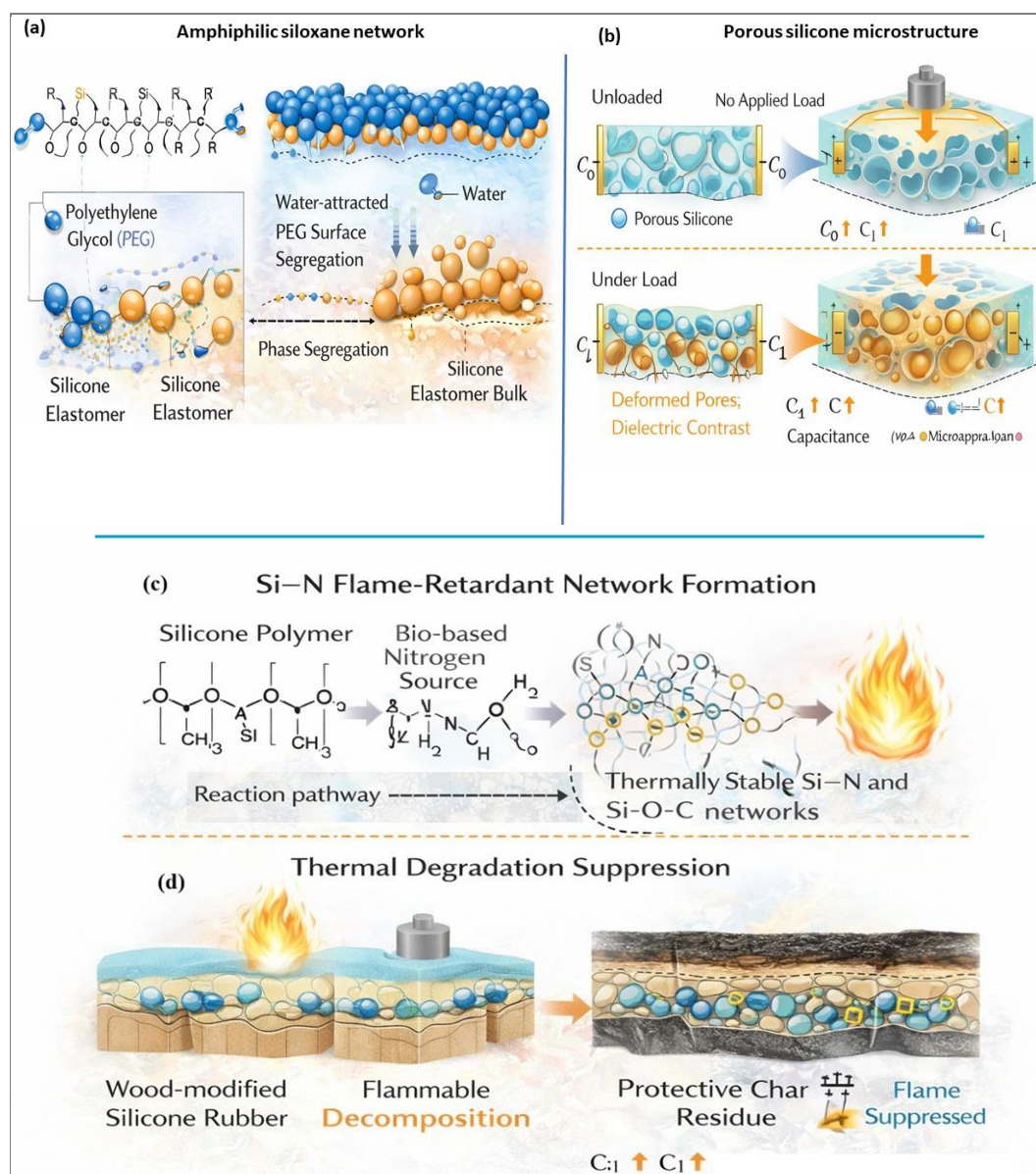


Figure 4.
(a) Schematic illustration of molecular architecture and phase segregation in amphiphilic siloxane networks (adapted from Wong *et al.* [47]);
(b) Simplified schematic of porous silicone microstructure and piezocapacitive sensing mechanism (adapted from Racles *et al.* [48]);
(c) Reaction pathway for the formation of bio-based Si-N flame-retardant networks in silicone systems (adapted from Li *et al.* [49]);
(d) Schematic representation of thermal degradation suppression

Beyond additive manufacturing, controlled microstructural design has allowed siloxane composites to be developed for increased sensing and durability capabilities Athanasios Goulas. According to Racles *et al.* [48], during mechanical loading, emulsion-templated porous silicone composites showed noticeable piezocapacitive reactions due to reversible pore deformation and dielectric contrast (Figure 4b). Concurrently, thermal stability and fire resistance have been demonstrated to be greatly improved by chemical network engineering. According to Li *et al.* [49], bio-based Si-N flame-retardant curing systems encourage the creation of thermally stable Si-N and Si-O-C crosslinked networks (Figure 4c), preventing volatile leakage and facilitating the development of protective char layers when exposed to heat (Figure 4d). When taken as a whole,

these investigations demonstrate a distinct structure–processing–performance connection in siloxane-based composites, connecting molecular architecture to stability in AM, sensing capabilities, and long-term environmental durability [50], [51]. All of these results point to silicone- and siloxane-based composites as a unique paradigm for reinforcement in silicon-based material structures, where functionality is attained not only by high stiffness or strength but also by network structure, interfacial chemistry, and controlled porosity. In renewable energy systems, where conformity, environmental resilience, and multifunctionality are crucial, these characteristics are especially pertinent for hybrid structural–functional components, dampening layers, protective coatings, and adaptable interfaces [52], [53], [54], [55].

2.1.4. Critical comparative analysis of silicon-based composite systems

SBC systems exhibit distinct performance characteristics that strongly influence their suitability for engineering applications. SiC-based composites provide high strength and stiffness (≈ 200 – 600 MPa) together with excellent thermal stability above 1200°C , making them well suited for load-bearing and high-temperature environments. However, these advantages are offset by inherent brittleness, sensitivity to defects, and complex processing routes that increase manufacturing cost and time [56].

Building on this, Si_3N_4 -based materials offer a more balanced performance profile, combining moderate-to-high strength with improved fracture toughness (5 – 10 $\text{MPa}\cdot\text{m}^{1/2}$) and superior thermal shock resistance. These characteristics enhance their reliability under fluctuating thermal and mechanical conditions, although their properties remain highly dependent on processing parameters, which can lead to variability in performance [57]. In contrast, silicone- and siloxane-based composites operate in a different regime, where lower mechanical strength (<100 MPa) is compensated by superior flexibility, damping capacity, and environmental resistance. As a result, these materials are more suitable for functional applications such as coatings, seals, and vibration control rather than structural use [58]. These distinctions become more evident when considering durability: ceramic-based systems generally provide superior high-temperature and oxidation resistance, whereas polymer-based systems perform better under cyclic deformation but are more vulnerable to UV and moisture degradation [59]. These performance differences and associated trade-offs are quantitatively summarized in Table 1. The table compiles representative quantitative ranges of mechanical, thermal, and durability-related properties for SiC-, Si_3N_4 -, and silicone-based systems, enabling a direct evaluation of their relative performance.

Rather than presenting separate tables for each material category, this unified approach provides a more concise and systematic comparison, highlighting both performance advantages and limitations across material systems. This also supports a more structured interpretation of their suitability for different engineering applications.

Table 1.
Comparative properties
of silicon-based
composite systems [56],
[57], [59]

Property	SiC-Based Composites	Si_3N_4 -Based Composites	Silicone/Siloxane-Based Composites	GFRP (Reference)	CFRP (Reference)
Tensile Strength (MPa)	200–600	300–800	<100	200–1000	600–1500
Fracture Toughness ($\text{MPa}\cdot\text{m}^{1/2}$)	2–5	5–10	– (ductile)	10–40	20–60
Elastic Modulus (GPa)	150–400	200–320	0.001–0.01	20–50	70–200
Service Temperature ($^\circ\text{C}$)	>1200	1000–1400	<300	<200	<300
Fatigue Resistance	Moderate–High	High	High (viscoelastic)	Moderate	High
Thermal Shock Resistance	Moderate	High	Excellent	Low–Moderate	Low
Processing Complexity	Very High	High (sintering)	Low–Moderate	Low	Moderate
Manufacturing Cost	Very High	High	Low–Moderate	Low	High
Typical Applications	Coatings, high-temp parts	Bearings, thermal parts	Seals, damping layers	Blades, structures	High-performance blades

From Table 1 Ceramic-based systems such as SiC and Si_3N_4 demonstrate clear advantages in high-temperature capability, maintaining structural integrity beyond 1000°C , which is significantly higher than the typical operational limits of polymer-based composites ($<300^\circ\text{C}$). This distinction is particularly relevant for applications involving thermal and oxidative loading conditions. From a mechanical standpoint, although SiC- and Si_3N_4 -based composites can achieve strength levels comparable to or exceeding GFRP, they generally exhibit lower fracture tolerance, reflecting their inherent brittleness. In contrast, CFRP systems maintain a more favorable balance between

strength and toughness, which contributes to their widespread use in structural applications. Moreover, silicone- and siloxane-based composites, while mechanically less robust, provide functional advantages through flexibility and damping behavior, which are not achievable with ceramic or conventional fiber-reinforced composites. This highlights their complementary rather than competing role in engineering systems. Overall, these comparisons indicate that silicon-based composites are not direct replacements for GFRP or CFRP, but instead offer performance advantages under specific thermal, environmental, or functional conditions, as summarized in [Table 1](#). Despite their promising properties, silicon-based composites present several inherent limitations that constrain their widespread application. A key challenge is their brittleness and low fracture tolerance, particularly in ceramic-based systems such as SiC and Si₃N₄, which makes them sensitive to flaws and defects introduced during processing or service. In addition, high processing cost and long manufacturing cycles, especially for techniques such as CVI and PIP, significantly limit scalability and industrial adoption. These challenges are further compounded by the complexity of repair and maintenance, as damage in ceramic matrix composites is often difficult to detect and restore compared to conventional polymer-based composites. Furthermore, performance can be affected by microstructural defects, including residual porosity and interfacial inconsistencies, which may reduce mechanical reliability under cyclic loading conditions. While silicone-based systems offer improved flexibility, they are limited by lower mechanical strength and thermal resistance, restricting their use to non-structural or functional applications.

2.2. Reinforcement Architectures and Design Concepts

The mechanical response, thermal resistance, and long-term dependability of SBC are all significantly influenced by the reinforcement design. Discrete reinforcements (whiskers and particles), short fibers, unidirectional continuous fibers, and multidimensional textile architectures, such as two- and three-dimensional (2D/3D) woven, braided, or needled structures, can be used to broadly categorize reinforcement systems [\[60\]](#), [\[61\]](#). Different load-transfer methods and damage-tolerance features are introduced by each architecture, allowing for customized performance under challenging service conditions.

Continuous fiber reinforcements with regulated orientation are especially useful for dispersing applied stresses and preventing catastrophic brittle failure in ceramic matrix composites like SiC/SiC and silicon nitride-based systems [\[41\]](#), [\[43\]](#), [\[62\]](#). According to recent research, 2D weaving structures outperform unidirectional laminates in terms of in-plane strength and fracture resistance, while 3D architectures improve through-thickness characteristics by reducing interlaminar cracking and delamination. These architectures are particularly well-suited for high-temperature and energy-related applications because the intrinsic fiber interlocking in 3D braided or needle-shaped composites greatly enhances tolerance to damage and structural integrity under mixed thermo-mechanical stress, cyclic fatigue, and impact conditions.

In addition to geometric arrangement, interfacial engineering and property gradients over length scales are becoming more and more important in contemporary reinforcement design. Fiber-matrix bonding strength is carefully controlled by customized interphase layers, such as pyrolytic carbon, BN, or multilayer hybrid coatings [\[10\]](#), [\[35\]](#), [\[54\]](#), [\[62\]](#), [\[63\]](#). These designed interphases boost fracture toughness and energy dissipation while sacrificing thermal stability by promoting non-catastrophic failure modes such as controlled fiber debonding, fiber pull-out, and crack deflection by adjusting interfacial shear resistance [\[21\]](#), [\[64\]](#). Optimized interphase designs are essential for preserving mechanical dependability in oxidizing and thermally demanding settings, according to experimental data from recent studies. Moreover, multiscale reinforcing techniques have become a successful means of concurrently enhancing functional performance, toughness, and strength. Hierarchical load sharing and crack-arrest methods spanning various length scales are made possible by the incorporation of micro- or nano-scale fillers, such as SiC nanoparticles, whiskers, or layered ceramics, within fiber-reinforced matrices. It is known that hybrid architectures can maintain oxidation resistance and thermal conductivity while improving fatigue endurance and crack resistance [\[54\]](#), [\[65\]](#). For next-generation SBC aimed for extreme-environment components, renewable energy systems, and aerospace structures, multiscale reinforcement designs thus offer a reliable and adaptable design paradigm.

2.3. Processing Routes

SBC are processed in a way that preserves the inherent mechanical and thermal benefits of silicon-based matrices while achieving high density, controlled microstructures, and stable fiber–

matrix interfaces as shown in [Table 2](#). Strong covalent bonding significantly limits mass dispersion in SiC- and Si₃N₄-based systems, making traditional pressure less sintering inefficient [66]. Consequently, sophisticated approaches based on in situ chemical processes, precursor conversion, and infiltration have taken center stage.

2.3.1. Chemical Vapor Infiltration (CVI)

Because CVI can create high-purity matrices with exceptional thermal and oxidative durability, it continues to be a key processing method for high-performance silicon-based ceramic matrix composites, especially SiCf/SiC systems [62], [67]. According to recent research, sophisticated CVI variations greatly reduce traditional drawbacks such residual porosity and lengthy processing periods. According to D'Ambrosio *et al.* [62], microwave-assisted CVI using multiple-frequency solid-state sources significantly improves infiltration uniformity and speeds up deposition kinetics, resulting in increased densification without compromising fiber integrity [62].

Controlled heat gradients are essential for stabilizing infiltration fronts and preventing premature pore closure, which allows for more uniform matrix formation throughout complicated preforms, according to complementary computational and experimental investigations [68]. [Figure 5a](#), which is based on the CVI infiltration front evolution shown in Vignoles *et al.* [68], provides a schematic summary of these mechanisms. The application of CVI has been further broadened by its integration with architected preforms made by AM. In triply periodic minimal surface (TPMS) SiC preforms made by powder bed fusion and binder jetting, Pelanconi *et al.* [42] showed that CVI densification is feasible and revealed that pore topology significantly affects early-stage infiltration rates and matrix continuity. Comparably, research on pyrocarbon deposition during CVI shows that temperature, residence duration, and gas composition control carbon texture and interfacial bonding, which in turn influence load transfer and tolerance to damage in composite joints components [35], [67], [69], [70]. [Figure 5b](#) depicts the microstructural evolution of CVI-derived matrices and interphases.

Furthermore, because it can create high-purity matrices with superior thermal and oxidative stability, CVI is still a key processing method for high-performance silicon-based ceramic matrix composites, especially SiC/SiC systems. Gaseous precursors break down and deposit solid ceramic phases inside a porous fiber preform during CVI, allowing for precise microstructural control and conformal matrix formation. Nevertheless, delayed densification kinetics and residual porosity result from the intrinsically diffusion-limited character of gas transport. Advanced CVI techniques can significantly reduce these restrictions, according to recent research. According to Aydın *et al.* [4], because of improved gas–solid interactions and volumetric heating effects, microwave-assisted CVI employing multifrequency solid-state excitation greatly speeds up densification while enhancing matrix uniformity. In a similar vein, Vignoles *et al.* [68] explained how thermal gradients stabilize infiltration fronts by demonstrating that optimal temperature fields encourage uniform matrix deposition and prevent premature pore closure. Pelanconi *et al.* [42] showed that CVI infiltration of TPMS SiC structures created via powder bed fusion and binder jetting allows for controlled early-stage matrix growth while maintaining complex geometries, further extending the applicability of CVI through its integration with architected preforms produced by AM. Systematic studies into deposition temperature, gas composition, and pressure have shown that CVI-deposited interphases and pyrocarbon layers are extremely sensitive to process parameters at the microscale, which directly affect texture, anisotropy, and load-transfer behavior [54], [67]. These results highlight how crucial CVI process management is for customizing interfacial mechanics and structural dependability, especially in z-pinned designs and complicated joints [64].

2.3.2. Polymer Infiltration and Pyrolysis (PIP)

PIP offers a complementary route characterized by high geometric flexibility and cost efficiency, particularly suitable for complex-shaped components. In PIP, liquid preceramic polymers are infiltrated into porous preforms and subsequently converted into ceramic matrices through pyrolysis. Compared to CVI, PIP enables faster infiltration and greater compositional tunability but is challenged by volumetric shrinkage and residual porosity induced during polymer-to-ceramic conversion. Recent advances emphasize gradient and multi-cycle PIP strategies to overcome volumetric shrinkage and residual porosity. Zhang *et al.* [71] demonstrated that graded concentration PIP significantly improves densification efficiency in SiCf/SiC composites by promoting uniform polymer distribution and reducing internal stress accumulation during pyrolysis. When combined with AM, PIP enables the conversion of polymer-derived preforms into dense ceramic architectures with tailored compositions. Pelanconi *et al.* [37], [72] showed that

selective laser sintering or powder bed fusion of polymer templates followed by PIP yields complex SiC and SiCN(O) structures with competitive mechanical strength and thermal stability.

More recently, the incorporation of crystalline Si_3N_4 fillers into PIP-derived ceramic architectures was shown to improve both mechanical strength and thermal stability by promoting load-bearing ceramic networks and suppressing microcrack propagation during pyrolysis [42]. These developments highlight PIP as a versatile platform for producing architected SBC when combined with precise control of precursor chemistry, filler content, and infiltration sequencing. The PIP densification pathway and shrinkage compensation mechanism are schematically depicted in Figure 5c.

Figure 5.

(a) Schematic evolution of infiltration fronts during CVI under controlled thermal gradients (adapted from Vignoles *et al.* [68]);
(b) Microstructural development of CVI-derived pyrocarbon/SiC matrices as a function of process parameters (adapted from Kumar *et al.* [67]);
(c) Polymer infiltration and pyrolysis (PIP) densification pathway illustrating shrinkage compensation and multi-cycle infiltration (adapted from Pelanconi *et al.* [37])

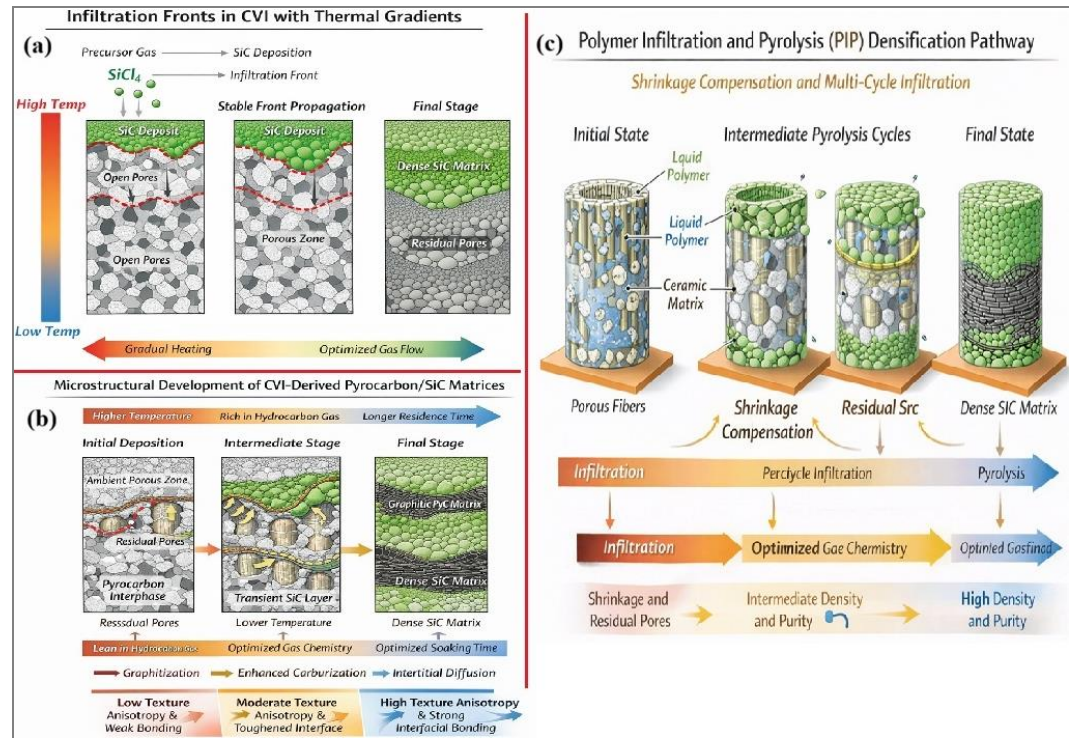


Table 2.

Comparative summary of processing methods for silicon-based composites [37], [66], [68], [73]

Processing Method	Principle	Processing Time	Densification Level	Cost	Advantages	Limitations	Scalability	Typical Applications
CVI (Chemical Vapor Infiltration)	Gas-phase precursor infiltrates porous preform and deposits matrix	Very long (days–weeks)	High (low residual porosity)	Very high	High purity, excellent high-temperature performance, good matrix uniformity	Slow process, high cost, limited throughput	Low–moderate	Aerospace components, high-temperature structures
PIP (Polymer Infiltration and Pyrolysis)	Polymer precursor infiltrates and converts to ceramic via pyrolysis	Moderate–long (multiple cycles)	Moderate (residual porosity)	High	Lower cost than CVI, relatively flexible processing, good shape complexity	Shrinkage, microcracking, multiple cycles required	Moderate	Coatings, structural components with moderate load
MI (Melt Infiltration)	Molten silicon infiltrates porous carbon preform to form SiC matrix	Short	High	Moderate–high	Fast densification, high density, good mechanical strength	Residual free silicon, limited thermal stability in some environments	High	Structural components, wear-resistant parts
Sol-gel / Slurry Infiltration	Liquid-phase precursor infiltrates and forms ceramic via drying and sintering	Short–moderate	Low–moderate	Low	Low cost, simple processing, scalable	High shrinkage, lower mechanical properties	High	Coatings, low-load components
Additive Manufacturing (AM)	Layer-by-layer fabrication using preceramic polymers or powders	Variable	Moderate	High (currently)	Complex geometries, design flexibility, material efficiency	Limited maturity, defects, post-processing required	Emerging	Complex-shaped components, prototypes

2.3.3. Melt Infiltration (MI)

By infiltrating molten silicon or metal alloys into porous preforms, melt infiltration (MI) offers a quick and cost-effective densification method that is followed by in situ reaction or solidification. Infiltration depth, solidification rate, and pore morphology all significantly influence matrix continuity and residual stress generation, according to recent numerical studies [74], [75]. Further experimental research on reactive melt infiltration of carbon substrates showed that gas-phase SiC production is essential for regulating microstructural homogeneity and reaction kinetics [61], [76]. Remaining free silicon or secondary phases may jeopardize high-temperature stability even when MI allows near-full densification in brief processing durations. As a result, hybrid approaches that combine PIP or CVI with MI are being used more frequently to balance long-term performance, microstructural control, and densification efficiency.

High-performance metal-matrix and bimetal composites with specific mechanical and thermal properties, such as Ti/Mg bimetallic lattice structures with improved energy absorption [75] and H13 tool steel-copper composites for thermal management uses [75], have been successfully created by combining MI with AM outside of ceramic systems. Despite being carried out in metallic systems, these investigations offer transferable knowledge on solidification behavior, capillary-driven flow, and infiltration kinetics that is directly applicable to silicon-based composite manufacturing.

2.3.4. Additive and hybrid manufacturing approaches

A revolutionary method for creating SBC with intricate geometries and well-designed microstructures is AM. Silicon-containing preforms or precursor-derived matrices can be printed using methods like direct ink writing, stereolithography, and binder jetting. These are then transformed into ceramic phases using pyrolysis, CVI, or infiltration-assisted densification [37], [68], [77]. Unprecedented design freedom, decreased material waste, and the capacity to combine structural, thermal, and functional properties into a single component are the main benefits of additive approaches. However, recent literature has focused a lot of emphasis on hybrid manufacturing systems that combine traditional densification techniques with additive fabrication. These methods enable for spatial control over densities, anisotropy, and functional gradients by using additively built porous structures as customized preforms that then go through CVI or PIP densification. It has been demonstrated that such integration produces SBS with enhanced damage tolerance, regulated thermal conductivity, and high specific strength. These developments make additive-hybrid processing a crucial enabler for high-temperature energy systems, thermal management components, and next-generation lightweight constructions [38]. In order to overcome the inherent limits of individual procedures, recent research clearly shows a tendency toward hybrid processing pathways that include CVI, PIP, melt infiltration, and AM [66], [78]. In order to achieve SBC with optimal microstructure–property combinations for demanding applications in aerospace, energy, and severe environments, such hybrid techniques allow hierarchical control over densification, interfacial chemistry, and design.

3. Properties of SBC

Fundamental properties determine the applicability of SBC in advanced structural and functional systems, with mechanical performance playing a central role in sustaining static and cyclic loads under extreme thermal and environmental conditions. This mechanical response is governed by the interplay between matrix chemistry, reinforcement architecture, interfacial integrity, and processing-induced microstructural features.

3.1. Mechanical Properties

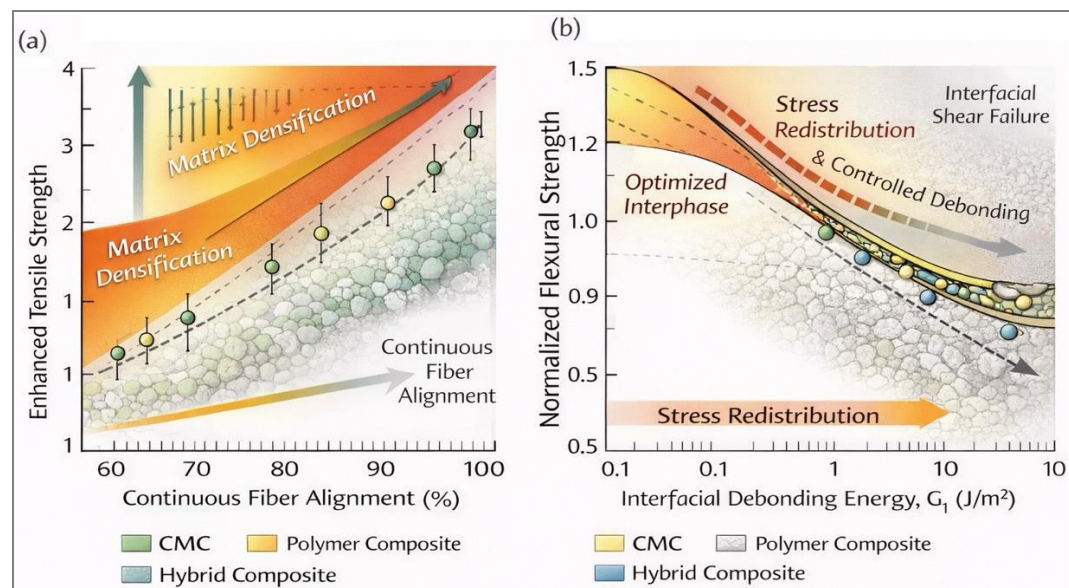
3.1.1. Strength

The effectiveness of load transfer from the matrix to the reinforcement, which is regulated by interfacial bonding quality and microstructural uniformity, is the main factor determining the strength of SBC. Flexural and tensile strengths typically rise with increased matrix densification and continuous fiber alignment along the loading direction in ceramic matrix composites, such as SiC/SiC and Si₃N₄-based systems [42], [62]. Fibers are the main load-bearing components, as schematically shown in Figure 6a, and the matrix allows stress transfer and redistribution, which postpones the onset of critical cracks.

According to recent research, strength can be increased without compromising damage tolerance by carefully optimizing the fiber–matrix interphase. For example, as schematically illustrated in Figure 6b, interphase engineering with compliant or chemically compatible interlayers enhances stress accommodation and suppresses early interfacial failure. In their thorough analysis of the shear and tensile failure mechanisms in SiC-based ceramic matrix composites, Li *et al.* [25] emphasized the crucial significance that regulated crack deflection and interfacial debonding play in maintaining high tensile strength under challenging loading circumstances. The universality of interfacial strengthening mechanisms is further supported by complementary evidence from polymer- and hybrid-based systems: in Kevlar–glass hybrid composites [42] and hemp fiber–epoxy structures [79], the addition of silicon carbide fillers was demonstrated to significantly improve interfacial adhesion and load transfer efficiency, resulting in quantifiable improvements in tensile and flexural strength.

Moreover, critical flaw size and residual porosity continue to be the principal factors limiting strength, especially at high temperatures. Silicon-based matrix modification techniques can reduce strength degradation in harsh environments, according to recent studies. According to Elshorbagi *et al.* [27], substituting silicon-based matrices for traditional polymer matrices significantly enhances post-fire mechanical performance and thermal stability, maintaining structural integrity during thermal exposure. Similar to this, flexible silicon rubber-based composites created by Elshorbagi *et al.* [27] show improved mechanical resilience while retaining lightweight properties, demonstrating how silicon-containing phases support strength retention in a variety of composite classes. Highly densified, microstructurally homogeneous SBC regularly demonstrate better tensile and flexural strength, supporting their competitiveness for extreme-environment structural applications, according to experimental data collected over the last five years.

Figure 6.
Strength-governing
mechanisms in silicon-
based composites:
(a) Effect of fiber and
matrix optimization;
(b) Effect of
engineered fiber
matrix interface.
(adapted from
Lakshmaiya *et al.* [79])



3.1.2. Toughness

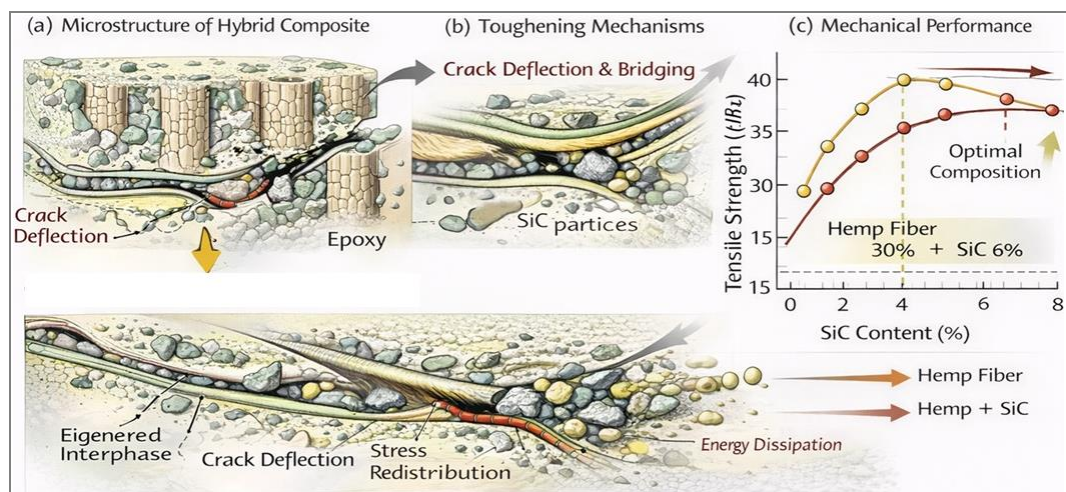
One key characteristic that sets SBC apart from monolithic ceramics—which are intrinsically brittle and prone to catastrophic failure—is fracture toughness. A hierarchy of energy-dissipation mechanisms, such as fracture deflection, crack bridging, controlled interfacial debonding, and fiber pull-out, are triggered during crack propagation in SBC to improve toughness. The material can absorb far more fracture energy before failing thanks to these mechanisms, which successfully lower the crack driving force and encourage stable, non-catastrophic fracture behavior. Extensive experiments on SiC/SiC and Si₃N₄-based composites consistently show that the activation of these extrinsic toughening mechanisms is directly associated with the change from brittle to pseudo-ductile fracture behavior [27], [71].

Recent developments demonstrate how interfacial design and reinforcing architecture have a significant impact on the fracture toughness of SBC. Because they permit regulated debonding and frictional sliding while maintaining global structural integrity, interfaces with intermediate bonding strength are very beneficial. In SiC-based ceramic matrix composites, Li *et al.* [25] methodically shown that tailored interphases allow progressive crack propagation controlled by fiber bridging and pull-out, resulting in notable increases in work-of-fracture. Simultaneously, it

has been demonstrated that multiscale reinforcement techniques, which combine continuous fibers with micro- or nano-scale fillers, further improve toughness by suppressing unstable crack growth and causing crack path tortuosity across multiple length scales [65], [79].

Together, these results demonstrate that the primary design lever for attaining high fracture toughness in contemporary SBC is microstructural engineering rather than intrinsic material strength alone. **Figure 7** illustrates the relationship between microstructure, toughening mechanisms, and mechanical performance in hybrid composites. As shown in **Figure 7a**, the incorporation of SiC particles within the polymer matrix modifies the microstructure by introducing heterogeneous interfaces that influence crack propagation behavior. Instead of propagating linearly, cracks are deflected along the fiber–matrix and particle interfaces, increasing the fracture path and energy required for failure. This behavior is further explained in **Figure 7b**, where multiple toughening mechanisms, including crack deflection, crack bridging, and stress redistribution, contribute to improved damage tolerance. The presence of an engineered interphase enhances load transfer while enabling controlled energy dissipation, which delays crack growth under mechanical loading [65]. The effect of these mechanisms on macroscopic performance is reflected in **Figure 7c**, where tensile strength increases with SiC content up to an optimal composition. Beyond this point, excessive particle addition leads to diminishing returns, likely due to particle agglomeration and stress concentration effects. This trend highlights the importance of balancing reinforcement content to achieve optimal mechanical performance. Overall, the figure demonstrates that microstructural design and interface engineering play a critical role in governing the mechanical behavior of hybrid composites, particularly through the activation of multiple synergistic toughening mechanisms.

Figure 7. Illustration of toughening mechanisms in hybrid hemp fiber–SiC–epoxy composites; (a) Microstructural interaction among fibers, SiC particles, and matrix; (b) Crack deflection, bridging, and interfacial stress redistribution mechanisms enhancing energy dissipation; (c) Schematic mechanical performance trends as a function of SiC content, adapted from Lakshmaiya et al. [79]



3.1.3. Fatigue

When silicon-based composites are exposed to cyclic mechanical and thermo-mechanical loading, as is the case in aerospace, automotive, and energy applications, fatigue behavior is a crucial performance metric. In contrast to ductile metals, where fatigue is primarily controlled by plastic deformation and dislocation movement, microcracks, interfacial degradation, and damage accumulation at reinforcement–matrix boundaries are the main causes of fatigue in ceramics and ceramic matrix composites (CMCs). Fatigue damage develops in fiber-reinforced systems by a combination of matrix cracking, interface breakdown, fiber bridging, and gradual microstructural degradation, all of which have an impact on fatigue life and load transfer efficiency. The amount and distribution of SiC particles have a significant impact on fatigue strength and life, according to studies on hybrid metal matrix composites supplemented with SiC. By improving load redistribution and postponing the formation of critical strain bands under repeated loading, the addition of fly ash and SiC particles to hybrid Al 5083 metal matrix composites increased fatigue strength and prolonged fatigue life, underscoring the function of ceramic reinforcement in reducing fatigue-related damage processes [65].

The importance of interface quality and reinforcement in fatigue behavior is further supported by research on polymer matrix composites. Studies on SiC / carbon fiber / epoxy composites show that enhanced interfacial adhesion through surface modification and filler incorporation lowers localized stress concentrations and modifies wear and fatigue mechanisms in comparison to unreinforced matrices, even though the primary focus is on mechanical and

tribological properties [80]. According to Hu and Zhang [80], composites containing properly distributed and surface-modified SiC particles had behavior typical of both abrasive and fatigue wear, suggesting a complicated interaction between microstructural characteristics and cyclic damage resistance. When combined with results from the literature on ceramic matrix composites, these investigations highlight the fact that fatigue resistance in SBC is a design-dependent characteristic rather than an intrinsic constant. The onset and propagation of fatigue cracks can be considerably delayed by improving interfacial stability, strengthening phase distribution, and maximizing matrix–reinforcement bonding. This leads to slower stiffness degradation and a longer fatigue life. Therefore, engineering approaches that prioritize reinforced interfaces and regulated microstructural architecture provide a practical means of enhancing fatigue performance in SBC for demanding structural contexts.

3.2. Thermal and Environmental Stability

In sophisticated structural and energy applications, SBC's thermal and environmental resilience is a major benefit. Strong Si–C and Si–N covalent bonds give ceramic matrix systems like SiC/SiC and Si₃N₄ composites their high melting temperatures, minimal thermal expansion, and exceptional phase stability at high service temperatures. By functioning as an efficient diffusion barrier that considerably slows oxidation kinetics, the formation of a dense and adherent SiO₂-based oxide scale in oxidizing environments further improves durability and permits sustained operation above 1200–1400 °C—well beyond the limitations of conventional metallic materials. This thermal stability is closely linked to interfacial chemistry and microstructural development, according to recent research. The potential of designed interphases to improve thermal dependability in hybrid ceramic–metal systems was highlighted by Thabethe *et al.* [81], who showed that controlled thermal annealing can maintain reaction layers at Cr–SiC interfaces under vacuum, inhibiting excessive carbide breakdown.

Silicon-based components support environmental durability and thermal control in multifunctional systems in addition to intrinsic matrix stability. According to Senthil Kumar *et al.* [54], SiC and BN nanoparticle reinforcements greatly increase phase-change materials' thermal conductivity and heat storage efficiency. These findings are pertinent to composite systems that need both structural integrity and thermal control. Though recent studies on SiCf/SiC composites show that dense microstructures and chemically stable fiber–matrix interphases significantly reduce oxidation rates and strength loss even in aggressive wet-oxygen environments, environmental resistance under oxidizing and wet conditions remains a crucial challenge [80]. Hu and Zhang *et al.* [80] further demonstrated that the creation of thermally stable, silicon-rich char layers in FRP systems significantly improves post-fire mechanical retention when silicon-based matrices are substituted for typical polymer matrices. Together, these results show that SBC's thermal and environmental performance is a system-level result controlled by oxide scale stability, microstructural densification, and interfacial reactions, making these materials excellent options for long-term use in energy, aerospace, and fire-resistant structural applications.

3.3. Tribological, Erosion, and Wear Resistance

Because SBC have strong covalent bonds, high intrinsic hardness, and outstanding thermal and chemical stability, they have great tribological, erosion, and wear resistance. Wear mechanisms in SiC- and Si₃N₄-based systems are usually controlled by a mix of oxidative, abrasive, and mild adhesive wear. The creation of silica-based tribo-oxide layers during sliding or erosive contact is one of these materials' main advantages. These layers function as self-lubricating films that lower friction coefficients and prevent significant material removal, especially in harsh environments and at high temperatures. Recent experimental research has shown that adding SiC reinforcements greatly improves tribological performance in a variety of matrix systems. According to Hu and Zhang [80], SiC/carbon fiber/epoxy composites show much lower wear rates and friction coefficients when compared to unreinforced polymer systems. This is explained by the stabilization of transfer films at the sliding interface and the load-bearing function of SiC particles. These results demonstrate that, even in reasonably compliant polymer-based composites, SiC reinforcements efficiently redistribute contact stresses and reduce matrix deformation. Ceramic matrix composites directly benefit from similar reinforcement-induced advantages, which are further enhanced by harder matrices.

Improving tribological durability has also been demonstrated to be significantly influenced by surface engineering and coating techniques. In a comparison of SiC coatings applied by chemical

vapor deposition (CVD) and atmospheric plasma spraying on carbon/carbon composites, Qi *et al.* [82] showed that CVD-derived SiC coatings have better wear resistance and lower friction coefficients because of their higher density, smoother surfaces, and stronger interfacial bonding. These findings emphasize how crucial microstructural continuity and defect minimization are for regulating wear and erosion resistance, especially in applications involving high temperatures or speeds. Furthermore, surface microstructural manipulation has been a successful strategy for customizing tribological behavior. Polishing, grinding, and laser surface treatment of SiC ceramics dramatically change surface roughness, subsurface damage, and tribo-chemical activity, resulting in different wear and friction responses, as demonstrated by [80]. In particular, laser-modified SiC surfaces showed increased wear resistance because of improved development of protective tribo-layers and localized microstructural refinement. These findings demonstrate that surface condition and near-surface microstructure have a significant impact on tribological performance, which is not only determined by bulk material parameters.

SBC with homogenous reinforcement distributions and fine-grained, highly densified microstructures show improved resistance to particle impingement from an erosion standpoint. Hard ceramic phases reduce the onset and propagation of cracks at the surface and efficiently dissipate impact energy. By preventing microfracture and material spallation under repeated particle impact, multiscale reinforcement designs and improved interfacial bonding further increase erosion tolerance. All of these results point to SBC as extremely durable tribological materials whose wear, erosion, and friction resistance may be methodically adjusted by surface engineering, microstructural control, and reinforcement choice. Because of these qualities, they are especially well suited for bearings, seals, sliding parts, and erosion-prone components in sophisticated transportation systems, energy conversion, and aerospace, where long-term dependability under extreme mechanical and thermal conditions is crucial.

3.4. Corrosion and Chemical Durability

For SBC to function in harsh environments such oxidizing atmospheres, corrosive gases, and reactive liquid media, corrosion and chemical durability are essential characteristics. The exceptional resistance of these materials to chemical assault is fundamentally based on the strong chemical stability of Si–C and Si–N covalent connections and the in-situ development of a silica-based (SiO₂) passive layer [34], [83]. By preventing the inward migration of reactive species like oxygen, water vapor, and corrosive ions, this passive layer functions as an efficient kinetic barrier, greatly lowering degradation rates in both high-temperature and aqueous environments [80], [84]. The corrosion resistance of SBC is significantly influenced by microstructural integrity and phase composition, according to recent research conducted over the last five years. It has been demonstrated that the presence of free silicon, interconnected porosity, or irregular secondary phases accelerates chemical degradation by enabling localized penetration of reactive species, especially in humid, hydrothermal, or alkaline environments. Highly densified composites, on the other hand, with continuous ceramic matrices and chemically stable fiber–matrix interfaces, are more resilient to acids, bases, molten salts, and high-temperature corrosive gases. They also retain surface stability and mechanical integrity over long exposure times [81].

Additionally, compositional management and interfacial engineering have become important methods for improving chemical durability. The development of dense, adherent silica layers with enhanced self-healing capacity is encouraged by optimized interphases and protective surface modifications, which further reduce corrosion kinetics under cyclic thermal and chemical loading. Together, these results highlight the crucial role that compositional optimization and microstructural design play in extending the long-term chemical durability of SBC, strengthening their suitability for demanding applications in energy conversion systems, chemical processing, and harsh environmental conditions.

4. Performance in Wind Energy Applications

Materials with high specific strength, resistance to fatigue, environmental resilience, and long-term reliability are necessary for the upscaling of contemporary wind turbines. In place of traditional GFRP and CFRP, SBC such as SiC/SiC, Si₃N₄-based ceramic matrix systems, and reinforced silicone-based polymers have shown promise [85], [86], [87], [88]. They are highly suited for future wind turbines with larger components and longer service lifetimes because of their strong covalent bonding [89], [90], which offers inherent resistance to thermal and environmental degradation, and tailored reinforcement structures that improve damage tolerance. The application discussion

has been refined to explicitly link each class of silicon-based composites to specific component-level uses in wind and hydropower systems, as summarized in **Table 3**. SiC-based composites are mainly suited for wear- and temperature-critical components (e.g., coatings and seals), Si_3N_4 for bearing and tribological applications, and silicone-based systems for functional layers such as sealing and damping.

4.1. Operational Conditions and Performance Requirements

Cyclic aerodynamic loading, stochastic wind fluctuations, and coupled bending and torsion loads are only a few of the extremely variable and multiaxial operating situations that wind turbine components must deal with. Particularly at offshore or desert facilities, these mechanical pressures are layered on top of environmental stressors such as daily and seasonal temperature fluctuations, excessive humidity, UV radiation, and exposure to airborne abrasive particles [91]. The adoption of environmentally resilient composite systems is also required since wind turbine blades and ancillary components must survive a wide range of environmental conditions that directly challenge long-term material durability and strength [81].

The tendency toward larger rotors and taller towers exacerbates these issues by raising absolute stress values and the total number of load cycles collected over the turbine's lifetime. Fatigue performance becomes a key design criterion in such situations, since components are anticipated to withstand tens to hundreds of millions of load cycles without catastrophic deterioration. Composite systems with customized reinforcement and curing strategies have superior fatigue resistance in wind turbine blades, as demonstrated by predictive fatigue modeling and life analysis that takes into account cyclic load variations and material structure [4], [81].

In this context, new composite materials provide a unique blend of high specific strength, fatigue durability, and environmental resistance, which supports their widespread use in demanding wind energy applications. SBC, in particular, benefit from strong Si-C, Si-N, and Si-O covalent bonding, which provides inherent resistance to heat cycling, oxidation, and chemical degradation. Engineered reinforcement architectures effectively reduce stress concentrations and delay damage accumulation. These characteristics, taken together, make SBC intriguing candidates for next-generation wind turbine components that must be reliable over long periods of time under complicated mechanical and climatic circumstances [55]. **Table 3** presents a comparison of the performance parameters of conventional GFRP and CFRP systems to SBC under wind turbine operating circumstances.

Table 3.
Comparative assessment
of conventional fiber-
reinforced polymers and
silicon-based composites
for wind energy
applications

Property / Requirement	GFRP	CFRP	Silicon-Based Composites (SiC/SiC, Si_3N_4 -based, Silicone-based)	Refs.
Density / weight efficiency	Low–moderate	Very low	Moderate (CMCs) to low (silicone-based)	[92]
Static strength	Moderate	High	High (CMCs); moderate (silicone-based)	[25]
Fatigue resistance	Moderate	High	High under thermo-mechanical cycling	[4], [25], [93]
Damage tolerance	Moderate	Moderate–low (brittle failure)	High via crack deflection and fiber bridging	[25]
Thermal stability	Limited (<120–180 °C)	Limited	Excellent (>1200 °C for CMCs)	[27], [94]
Environmental resistance (UV, moisture, oxidation)	Moderate	Moderate	High due to Si–C / Si–N / Si–O bonds	[4], [94]
Damping capability	Low	Low	Moderate–high (silicone-based)	[95]
Wear / erosion resistance	Low	Moderate	High (SiC, Si_3N_4 systems)	[82], [96]
Manufacturing maturity	Very high	High	Moderate (emerging for wind energy)	[93]
Cost	Low	High	High (CMCs); moderate (silicone-based)	[27]
Typical wind turbine applications	Blades, nacelles	Spar caps, blades	Bearings, seals, coatings, hybrid components	[94]
Long-term reliability in harsh environments	Moderate	Moderate	High	[27], [94]

4.2. Structural Components in Wind Turbines

Composite materials are essential in modern wind turbines, where they are used in a variety of structural and functional components such as rotor blades, bearing housings, nacelle coverings,

surface protection systems, insulation, and thermal management elements [89], [97]. The constant increase in turbine size and rated power places strong demands on materials, particularly high specific strength, fatigue durability, and sustained environmental stability [98]. In this context, SBC—which include silicone polymer matrices and also ceramic-based systems—have emerged as intriguing alternatives to standard fiber-reinforced polymers for some turbine components.

In rotor blade applications, materials having a high strength-to-weight ratio are critical for increasing aerodynamic efficiency while reducing inertial loads and gravity fatigue stresses [99]. Silicon-modified polymer composites and hybrid systems with silicon-based phases improve fatigue resistance and environmental durability without increasing density. This leads to longer blade service life under cyclic aerodynamic loading [4], [100]. Furthermore, silicon-containing matrices are more resistant to moisture ingress and ultraviolet deterioration than typical epoxy systems, which is especially useful for offshore and coastal wind farms [27].

Aside from basic load-bearing constructions, silicone and siloxane-based composites are frequently used in functional components including seals, barrier coatings, vibration-damping layers, and electric or thermal insulation. Silicone-based polymers' inherent flexibility, chemical inertness, and thermal stability provide efficient protection against humidity, abrasive particles, salt spray, and UV radiation while maintaining performance across a wide temperature range [80], [82]. Recent research indicates that silicon-based protective coatings and encapsulation materials may significantly decrease wear, corrosion, and service frequency in drivetrain and nacelle subsystems, improving overall turbine reliability in harsh operating conditions [27], [101]. The use of silicon-based composite materials in both structural and operational wind turbine components results in a synergistic balance of mechanical performance, environmental resistance, and longevity. These characteristics contribute to their increasing use in next-generation wind energy systems, especially in applications needing durability under combined mechanical, thermal, and climatic loading.

4.3. Fatigue Performance

Fatigue behavior is an important predictor of wind turbine service life, as essential functional and structural parts are subjected to millions of cyclic load cycles caused by fluctuating aerodynamic forces, gravitational loading, and operating start-stop events [90], [102]. Fatigue resistance in SBC is determined by damage accumulation mechanisms such as microcrack initiation in the matrix, slow interfacial degradation, and stress redistribution within the reinforcing architecture [99], [103]. Unlike monolithic materials, the presence of tailored reinforcements allows for effective energy dissipation and crack-growth inhibition, leading to a more damage-tolerant fatigue behavior.

Recent research shows that SBC with tailored fiber topologies and designed fiber-matrix interphases have dramatically better fatigue stability under cyclic loading [103], [104]. Controlled interfacial bonding encourages stable debonding and fracture deflection, reducing crack coalescence and postponing catastrophic failure [25]. Furthermore, homogenous microstructures and high matrix densification diminish stress concentrations caused by residual porosity, which is known to promote fatigue fracture initiation in composite systems. Environmental and thermal stability contribute to SBC's better fatigue performance in wind energy applications. The intrinsic resilience of silicon-containing matrices to moisture intrusion, UV radiation, and thermal fluctuations reduces environmentally induced degradation mechanisms that often reduce fatigue life in traditional polymer composites [27]. Furthermore, many works continue to focus on material qualities without sufficiently considering reliability under service circumstances and application-specific needs. In numerous cases, variations in reported behavior suggest that performance is heavily influenced by system setup rather than basic material features. This emphasizes the need for more uniform evaluation and application-oriented research to ensure reliable implementation.

5. Performance in Hydropower Applications

Hydropower components are subjected to harsh circumstances such as high velocity flow, fluctuating pressures, and abrasive aquatic environments, resulting in linked erosion, corrosion, and cyclic loading. SBC have emerged as possible substitutes for metallic alloys because to their improved wear resistance, chemical stability, and fatigue durability. Recent studies show that SiC- and Si₃N₄-based composites and silicon-containing protective coatings exhibit enhanced resistance to erosion-corrosion synergy under hydraulic loading, caused by strong covalent bonding, high hardness, and stable phases that delay surface and subsurface damage [94], [96]. These

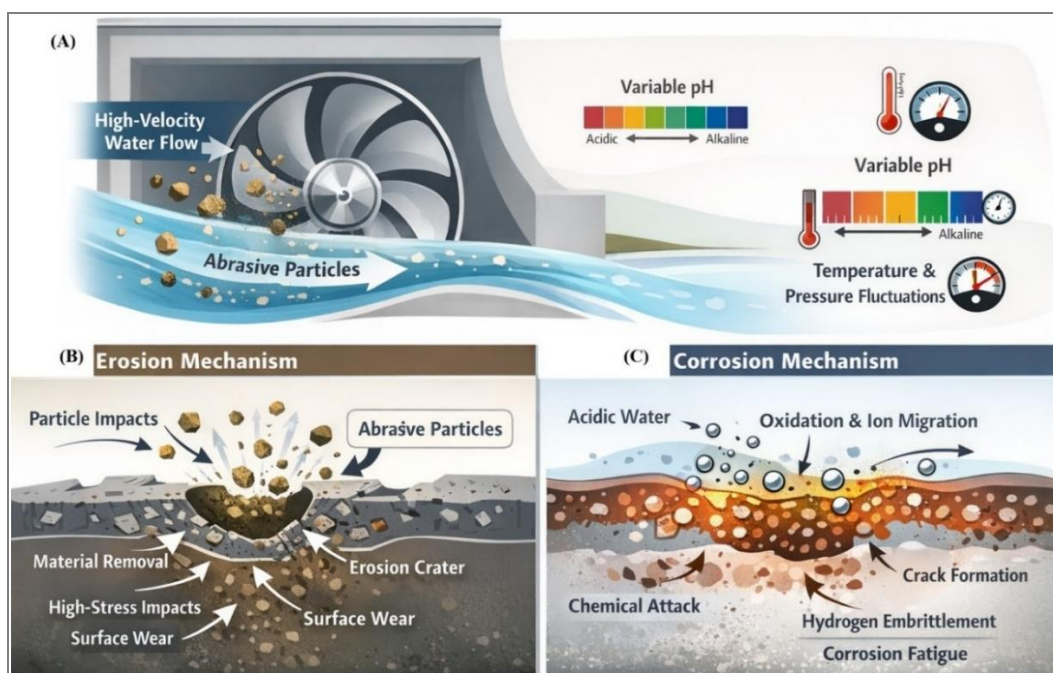
characteristics contribute to their usefulness for long-term, low-maintenance hydroelectric applications.

5.1. Service Environments and Material Demands

Turbine runners, guide vanes, and flow-channel linings are all exposed to abrasive, chemically changing aqueous environments that cause mechanical loading, particle erosion, and surface degradation [102], [103]. As a result, materials must be strong, resistant to erosion and wear, and chemically stable over time in both freshwater and mineral-rich environments. Recent studies show that SiC- and Si₃N₄-based composites maintain structural integrity under aggressive hydraulic conditions because of strong Si-C and Si-N linkages and dense microstructures that restrict fluid ingress and prevent surface-initiated damage [25], [82]. Furthermore, silicon-based polymer and ceramic coatings lower erosion rates by creating stable tribo-oxide layers in high-velocity flow [80], [105]. These characteristics encourage the use of SBC in current hydropower systems to increase service life, improve dependability, and reduce maintenance requirements.

The degradation of hydropower components is influenced by the interaction of mechanical erosion and electrochemical corrosion. As shown in Figure 8, abrasive particle impacts cause surface material loss and micro-crater development (Figure 8a), whereas pH, temperature, and pressure changes enhance corrosion-assisted crack initiation (Figure 8b). Their linked contact continuously destroys protective layers and exposes new material, hastening damage buildup (Figure 8c). SBC reduce this process by combining high hardness, strong covalent bonding, and the development of chemically stable silica-based surface layers, which together decrease erosion-corrosion synergy and improve durability in harsh hydraulic conditions.

Figure 8. Erosion–corrosion mechanisms in hydropower components: (a) Schematic illustration of erosion damage induced by high-velocity water flow containing abrasive particles, leading to surface wear, material removal, and erosion crater formation; (b) Corrosion mechanisms driven by variable pH, temperature, and pressure conditions, including oxidation, ion migration, hydrogen-assisted embrittlement, and crack initiation; (c) Synergistic erosion–corrosion interaction



5.2. Cavitation, Erosion, and Corrosion Resistance

Cavitation is one of the most severe degradation mechanisms impacting hydropower components, resulting from the cyclic production and collapse of vapor bubbles on material surfaces under fluctuating pressure fields. The collapse of these bubbles generates localized shock waves and high-velocity microjets, which cause surface pitting, microcrack initiation, and rapid material loss. SBC have better cavitation resistance due to their high hardness, designed fracture toughness, and ability to dissipate impact energy via customized microstructures and reinforcement-matrix interfaces [25], [94].

Solid-particle erosion and electrochemical corrosion, in addition to cavitation, work together to accelerate surface degradation in sediment-laden, chemically hostile water conditions. SiC- and Si₃N₄-based materials outperform typical steels by resisting plastic deformation and inhibiting erosion-induced fracture propagation [96], [106]. Furthermore, silicon-containing matrices and coatings stimulate the production of silica-rich passive layers, which restrict oxygen and ion diffusion, reducing corrosion kinetics under changing pH and temperature conditions [27], [81].

Recent research has found that silicone- and siloxane-derived coatings used on metallic hydropower parts significantly reduce combined erosion-corrosion rates by acting as compliant, chemically stable layers that absorb impact energy and inhibit surface fracture [81], [82], [94]. This combination of mechanical strength and chemical passivation underlines the growing interest in SBC for long-term hydropower applications.

5.3. Practical Limitations under Real Operating Conditions

Despite their promising performance, large-scale adoption of SBC in hydropower applications is limited by a number of practical constraints. The expense of raw materials and improved manufacturing or coating methods, especially for SiC- and Si₃N₄-based systems needing high-temperature processing or controlled atmospheres, is a major problem [81], [94]. When applied to big hydropower components such as turbine runners and guide vanes, these cost factors become even more relevant. Another significant issue is the difficulty of evenly applying silicon-based composite coatings to large and geometrically complicated metallic surfaces. Inadequate coating thickness control, residual porosity, or interfacial flaws can operate as stress concentrators, speeding up failure when paired with cavitation, erosion, and corrosion loading [82], [96], [107]. Furthermore, the mismatch in thermal expansion coefficients and elastic characteristics between SBC and metallic substrates can cause residual stresses, increasing the risk of interfacial debonding or lamination during long-term cyclic operation [27].

According to recent research, addressing these constraints needs system-level optimization rather than material substitution alone. Hybrid design solutions, which combine silicon-based composite coatings with traditional metallic substrates, have shown enhanced damage tolerance by balancing surface protection and structural compliance [81], [94]. In parallel, innovations in deposition processes, graded interlayers, and in-situ repair methodologies are being investigated in order to improve coating adhesion, reduce residual stresses, and increase service life under real-world operating conditions [82], [96]. Overall, while practical hurdles persist, continuous advancements in processing technology and a better knowledge of degradation mechanisms are gradually lowering these barriers. These advancements make SBC more viable solutions for increasing the efficiency, durability, and reliability of future hydropower systems operating in harsh settings [27], [94].

6. Industrialization Barriers and Scale-Up Challenges

Despite their shown efficacy in harsh energy and environmental circumstances, SBC encounter considerable obstacles when transitioning from laboratory research to industrial application. Key limitations include restricted manufacturing scalability, high production costs, stringent quality-control requirements, and unresolved concerns with big component joining, repair, and long-term maintenance. Recent research shows that complex processing routes, small processing windows, and high defect sensitivity limit repeatability and yield at the industrial scale [62], [72]. Overcoming these constraints necessitates integrated process optimization, standardization, and cost-effective manufacturing strategies, rather than material-level breakthroughs alone. As shown schematically in Figure 9, successful scale-up is dependent on addressing energy-intensive production bottlenecks (Figure 9a), balancing flaw tolerance with long-term reliability (Figure 9b), evaluating lifecycle cost-performance trade-offs relative to GFRP and CFRP systems (Figure 9c), and determining viable commercialization pathways from laboratory development to field deployment (Figure 9d). These elements together demonstrate that industrial adoption is dependent on coordinated developments in processing, quality assurance, techno-economic assessment, and business model innovation.

6.1. Manufacturing Scalability and Cost Constraints

Manufacturing scalability is a significant obstacle in the industrialization of SBC, especially for ceramic matrix systems such as SiC/SiC and Si₃N₄. Traditional fabrication routes, such as CVI and PIP, are inherently time-consuming and energy-intensive due to slow mass transport, repeated infiltration cycles, and high-temperature treatments required to achieve adequate densification and microstructural uniformity [68], [108]. These variables significantly raise manufacturing costs and impede throughput for large or complicated components.

Recent improvements suggest that hybrid processing algorithms offer intriguing solutions to overcome these restrictions. The combination of CVI-PIP or PIP-melt infiltration has been found to

expedite densification while enhancing matrix continuity and oxidation resistance, lowering total processing time and cost [37], [94]. In parallel, combining AM techniques (such as powder bed fusion or stereolithography) with subsequent infiltration processes allows for near-net-shape fabrication and reduced material waste, increasing the economic viability of complex geometries [72]. As shown in Figure 9a, energy-intensive CVI, PIP, and melt infiltration pathways continue to contribute to long processing cycles and cost increases, restricting large-scale manufacturing. However, ensuring consistent quality among large-scale components remains difficult. Variations in infiltration depth, residual porosity, and thermal gradients can result in regional heterogeneity in mechanical and thermal properties, jeopardizing reliability. As a result, more optimization of process control, continuous surveillance, and energy-efficient manufacturing equipment is required to create scalable, cost-competitive manufacturing. These innovations are commonly regarded as necessary for increasing the industrial competitiveness and market penetration of SBC materials in energy and infrastructural applications.

6.2. Quality Control, Reproducibility, and Defect Tolerance

Because SBC are highly sensitive to processing-induced flaws and microstructural variability, quality control and reproducibility remain significant issues in industrial-scale manufacture. Small variations in porosity, fiber distribution, phase transition thickness, or residual stresses in SiC/SiC and Si₃N₄-based systems can cause significant scatter in mechanical, thermal, and fatigue properties [109], [110], [111]. This complicates process standardization and increases the risk of premature failure under cyclic or thermomechanical loading. Defect development is directly related to infiltration non-uniformity, inadequate densification, and thermal gradients during processing, with residual porosity and microcracks serving as preferential sites for oxidation, moisture ingress, and crack initiation [67], [68].

Recent research emphasizes the integration of advanced process monitoring and non-destructive evaluation techniques, such as X-ray computed tomography, ultrasonic inspection, and acoustic emission analysis, for early defect detection as well as quality assurance at scale [72], [112], [113], [114]. Defect-tolerant design techniques, such as designed fiber-matrix interphases, three-dimensional reinforcement designs, and multiscale toughening, have also been proven to reduce sensitivity to local flaws by redistributing stresses and preventing crack propagation. As shown in Figure 9b, combining robust quality-control frameworks and defect-tolerant material design is critical for achieving reliable, reproducible performance and enabling large-scale industrial deployment of SBC [25], [71].

Figure 9.

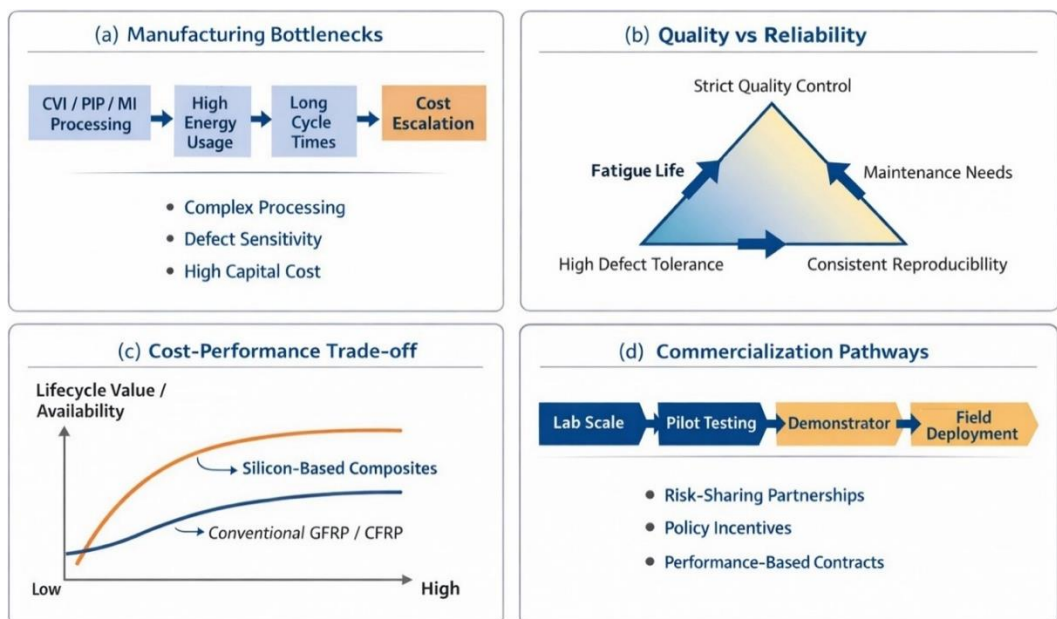
Industrialization and commercialization framework for with silicon-based composites for energy applications:

(a) Manufacturing bottlenecks arising from energy-intensive infiltration processes;

(b) Trade-offs between quality control, defect tolerance, and long-term reliability;

(c) Lifecycle-oriented cost-performance relationships relative to conventional GFRP and CFRP systems;

(d) Representative commercialization pathways from laboratory development to field deployment



6.3. Business Models for the Commercialization of BSC

The commercialization of SBC relies not only on technical performance but on alignment with market needs and business models. In wind and hydropower sectors, adoption is often hindered because conventional cost-focused procurement fails to capture long-term benefits such as

durability, reduced maintenance, and extended service life. Recent studies show that without lifecycle- and performance-based business models, high-performance materials struggle to achieve broad market uptake [115], [116]. The transition from laboratory-scale materials to industrial applications requires consideration of both technical and economic constraints.

6.3.1. Technology–market misalignment

Misalignment between technology and market remains a recurrent impediment to the commercialization of innovative materials for renewable energy systems. Material development efforts frequently prioritize maximizing mechanical, thermal, or environmental performance, while market adoption decisions in the wind and hydropower industries are primarily influenced by capital expenditure, operational performance, certification standards, and investment risk. As a result, materials with greater initial prices, such as SBC, face resistance despite superior long-term performance.

According to recent evaluations, traditional cost models based solely on initial material price do not adequately represent the benefits of high-performance composites, such as increased service life, decreased downtime, and lower maintenance frequency [25], [115]. In wind and hydropower applications, wherein components are required to work reliably for decades, such short-term cost criteria consistently undervalue materials that improve lifespan performance. This discrepancy emphasizes the importance of using evaluation frameworks based on total cost of ownership (TCO), lifetime cost analysis (LCCA), and performance-based contracts to allow for sensible material selection. Technology-market alignment can be improved by reframing SBC as enablers of long-term system reliability and risk reduction rather than cost-intensive materials. New research reveals that incorporating material performance measures into financial and operational decision-making greatly increases adoption potential, especially in capital-intensive renewable energy infrastructures [117], [118]. As a result, overcoming technology-market misalignment is required before SBC's technological maturity can be translated into commercial success.

6.3.2. SBC in wind and hydropower

The capacity of SBC to preserve mechanical integrity and environmental stability during harsh operating circumstances, such as those seen in wind turbines and hydropower systems, is its primary value proposition. Superior resistance to fatigue, erosion, cavitation, corrosion, and thermal degradation directly translates into longer service life and less frequent maintenance. These performance attributes are critical for large-scale energy infrastructures, particularly in remote, offshore, or high-load installations in which maintenance interventions are costly and economically complex [94], [115].

Recent studies conducted over the last five years consistently show that, while SBC have higher initial material and processing costs than conventional metallic or polymeric systems, their cumulative economic benefits become clear when evaluated using lifecycle performance metrics rather than upfront cost alone. Reduced downtime, longer inspection and replacement intervals, and improved tolerance to harsh environmental conditions all contributed to a lower total cost of ownership (TCO) over long operational horizons [27], [118]. As a result, the economic case for SBC is most compelling when failure-related risks, system downtime penalties, and long-term dependability are explicitly considered. As a result, SBC are best positioned as performance-enabling materials that improve system-level efficiency and risk resilience, rather than direct cost-driven alternatives for traditional materials. This placement is especially important for safety-critical and valuable parts in wind and hydropower systems, where material failure can cause disproportionate economic losses and operational disruptions. When SBC are valued in terms of lifecycle performance, reliability assurance, and risk mitigation, their contribution to sustainable and profitable renewable energy infrastructures is more accurately represented.

The application of SBC in wind and hydropower systems is more realistic at the component level rather than as full structural replacements. SiC-based composites are well suited for coatings and wear-resistant surfaces due to their high hardness and oxidation resistance, while Si₃N₄-based materials are more appropriate for bearings and tribological components requiring thermal stability and reliability under cyclic loading. In contrast, silicone- and siloxane-based composites are primarily applicable in seals, coatings, and vibration damping layers, where flexibility and environmental resistance are critical. Despite these advantages, their use in large structural components (e.g., turbine blades) remains limited due to high cost, processing complexity, and lower fracture tolerance compared to conventional composites such as GFRP and CFRP. Therefore,

their most feasible role lies in targeted subcomponents, where performance benefits can justify the higher cost.

6.3.3. Commercialization and business model

While SBC demonstrate promising performance characteristics, their commercialization in wind and hydropower applications remains constrained by several industrial and economic challenges. Beyond material-level advantages, successful deployment depends on the ability to scale production, meet certification requirements, and establish reliable supply chains.

One of the primary limitations lies in the relatively low technology readiness level (TRL) of advanced ceramic matrix composites for large-scale structural applications. Although laboratory and pilot-scale studies show strong performance, scaling these materials to industrial production remains challenging due to process complexity and limited reproducibility. Manufacturing scalability is particularly constrained by processing techniques such as CVI and PIP, which are inherently time- and energy-intensive. These limitations reduce production efficiency and significantly increase costs compared to conventional composites such as GFRP and CFRP. In addition, certification and standardization represent critical barriers. The adoption of new materials in wind and hydropower systems requires extensive validation under long-term mechanical and environmental loading conditions. The lack of well-established certification frameworks for silicon-based composites further delays their industrial implementation. Supply chain readiness is another key factor, as the availability of high-quality precursor materials, reinforcement fibers, and specialized processing facilities remains limited. This constraint is further amplified by the need for skilled manufacturing expertise. From an economic perspective, the high initial cost of silicon-based composites remains a major barrier to adoption. However, their potential advantages in terms of durability, reduced maintenance, and extended service life may offer lifecycle cost benefits, depending on the specific application. Overall, these challenges indicate that commercialization is not solely a function of material performance, but also depends on advances in scalable processing, certification pathways, and cost-effective manufacturing strategies.

Instead of traditional volume-based adoption, SBC in renewable energy systems are often commercialized through a performance-driven and staged market entrance strategy. Early deployment is most viable in high-value and failure-critical applications, such as offshore wind turbines and high-velocity hydropower components, where extended service life, increased reliability, and lower maintenance costs can economically justify higher initial costs [118]. Several business model archetypes have been recognized as effective accelerators of market penetration. Performance-based purchasing, in which suppliers are compensated based on lifecycle enhancements like availability or maintenance reduction, integrates long-term material value into procurement decisions and shifts the emphasis from capital cost to lifecycle performance [118], [119], [120], [121], [122], [123]. In simultaneous, hybrid material integration—deploying SBC selectively in critical areas while retaining conventional materials elsewhere—provides a pragmatic path to reduce cost and technical risk while allowing for incremental validation under real-world operating conditions [27], [61]. Furthermore, technology licensing and co-development collaborations among material developers, OEMs, and energy operators are crucial for lowering scale-up risks and accelerating field validation. Such collaborative methods allow for cost sharing, access to long-term operational data, and early alignment of material capabilities with system-level requirements, all of which are critical in regulatory- and investment-constrained renewable energy markets.

6.3.4. Cost structure and investment risk

The cost structure of SBC is mostly determined by energy-intensive manufacturing techniques, high-purity precursor materials, and demanding quality-control requirements to assure microstructural uniformity and fault tolerance [53], [69], [124], [125], [126]. Densification processes based on CVI or PIP, as well as advanced coating or infiltration techniques, dramatically increase capital expenditure and operational expenses as compared to standard composite systems [127], [128], [129], [130]. These variables add to the initial investment risk, especially in renewable energy industries where cost sensitivity and competitive margins remain strong. In addition to production costs, market uncertainties—such as changing demand, protracted qualification cycles, and conservative certification procedures in the wind and hydropower industries—increase financial risk for material suppliers and system integrators.

Recent evaluations of advanced materials deployment in energy infrastructure show that delays in return on investment and uncertainties in large-scale adoption are frequently more significant impediments than technological feasibility [131], [132]. From a lifecycle perspective, SBC provide better long-term value due to lower maintenance and longer service life, despite higher initial costs, as shown schematically in Figure 9c. To address these issues, new research emphasizes the relevance of risk-sharing systems and creative funding structures in advancing the commercialization of materials with outstanding performance. Strategic partnerships among material suppliers, turbine manufacturers, and energy operators, as well as performance-based contracts and long-term service agreements, have been shown to effectively distribute investment risk while retaining lifecycle performance benefits [118]. Furthermore, policy-driven innovation encouragement, pilot-scale demonstration programs, and public-private collaboration frameworks are crucial for lowering entry barriers and boosting market trust. SBC can increase their economic competitiveness by combining techno-economic assessment with adaptive business models that consider lifecycle value rather than just upfront cost.

Adoption of SBC is directly related to their lifespan value rather than its initial cost. While production costs remain high, their opposition to wear, corrosion, and heat deterioration can reduce maintenance frequency and increase service intervals, especially in demanding operating conditions. These advantages, however, are limited to specific applications. Because of established manufacturing techniques, conventional materials like as GFRP and CFRP are still more cost-effective for big structural components. SBCs, on the other hand, are more justified in high-performance subcomponents, where durability and reliability can balance the larger initial expenditure.

7. Conclusions

This review demonstrates that silicon-based composites (SBCs) offer strong potential for wind and hydropower applications, particularly in environments requiring high thermal stability, wear resistance, and long-term durability. However, their practical implementation remains constrained by challenges related to processing complexity, cost, and material reliability, which must be addressed for broader adoption.

The performance of SBCs is governed by the interplay between processing methods, microstructural control, and application-specific requirements, leading to inherent trade-offs between performance, manufacturability, and cost. As a result, their effective use is highly dependent on context-specific integration, rather than generalized material substitution.

From an application perspective, the most feasible pathway lies in the selective use of SBCs in performance-critical components, where their advantages can be maximized while minimizing economic and technical limitations. This targeted approach provides a more realistic route toward industrial implementation. Looking forward, further progress requires improved damage tolerance, defect control, and scalable processing techniques, along with the development of standardized evaluation and certification frameworks. Strengthening the alignment between material development and application needs will be essential to bridge the gap between laboratory-scale research and reliable industrial deployment.

Nomenclature

CVI	: Chemical Vapor Infiltration	Si₃N₄	: Silicon Nitride
PIP	: Polymer Infiltration and Pyrolysis	GFRP	: Glass Fiber Reinforced Polymer
CMC	: Ceramic Matrix Composite	CFRP	: Carbon Fiber Reinforced Polymer
SiC	: Silicon Carbide	TRL	: Technology Readiness Level

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