International Journal of Multidisciplinary Innovative Research
Volume 6, Number 3 (July' 2026) pp. 70–95
DOI: https://doi.org/10.66566/ijmir/2026.v6n3.08
ISSN: 2583-0228
https://www.ijmir.org

Received: 15 Apr' 2026 | Revised: 07 June' 2026 | Accepted: 12 June' 2026 | Published: 01 July' 2026

*Review Article*

OPEN ACCESS

# A Review on Basalt Fibers and Their Composite Systems: Challenges, Limitations, and Applications

Anirudh Kumar[1], Satendra Pal Singh[2], R. M. Mehra[3], Yogendra Kumar Mishra[4] and Sanjeev Kumar Sharma[5*]

*[1,5]Biomaterials and Sensor Laboratory, Department of Physics, Ch. Charan Singh University, Meerut, India.*
*[2]Department of Physics, SSV College (Affiliated to C.C.S. University), Hapur, Uttar Pradesh, India.*
*[3]Faculty of Engineering, Sharda University, Knowledge Park III, Greater Noida, Uttar Pradesh, India.*
*[4]Smart Materials, NanoSYD, Mads Clausen Institute, University of Southern Denmark, Sønderborg, Denmark.*

*Email: anirudhkumar@ccsuniversity.ac.in, spsphysics76@gmail.com, rm.mehra@ennobleip.com, mishra@mci.sdu.dk, sksharma18@ccsuniversity.ac.in**

***Abstract:*** *Basalt-fibers (BFs), derived from natural basalt rock, are emerging as a cost-effective, mid-performance reinforcement material for fiber-reinforced polymer composites (FRPs), offering a balance between glass fibers (GFs) and carbon fibers (CFs). Compared to GFs, BFs demonstrate superior mechanical properties, thermal stability, and chemical resistance, enabling reliable performance in harsh environments. While not matching the specific stiffness and strength of CFs, BFs composites show enhanced tensile, flexural, impact, and damping properties over GFs composites, with durability approaching that of aramid fibers (AFs). Performance can be further improved through fiber surface treatments and hybridization. Economically and environmentally, the production of BFs benefits from abundant raw materials and lower energy requirements, resulting in a reduced environmental footprint. These attributes make BFRPs well-suited for structural applications in civil infrastructure, marine, automotive, and fire-resistant systems.*

***Keywords:*** *Basalt Fiber (BF), Fiber-reinforced Polymer Composites (FRPs), Mechanical Properties, Thermal Stability, Durability, Environmental Impact.*

## INTRODUCTION

The global pursuit of sustainable, lightweight, and high-performance materials has greatly sped up the development of advanced fiber-reinforced composites (FRCs). These materials, made up of high-strength fibers embedded in polymeric, metallic, or ceramic matrices, provide superior specific strength and stiffness, design flexibility, and resistance to tough service environments [1]. As a result, FRCs are increasingly used in aerospace, automotive, civil infrastructure, marine, and renewable energy sectors, where they improve structural efficiency and lower environmental impact [2]. Usually, glass fibers (GFs) and carbon fibers (CFs) have dominated the composite market because of their well-established processing methods, high availability, and known performance. GFs are popular due to their low cost and balanced mechanical properties; however, they show limited stiffness, reduced thermal stability, and vulnerability to chemical degradation in harsh environments [3, 4]. On the other hand, CFs offer excellent tensile strength, stiffness, and fatigue resistance, but their wider adoption is limited by high manufacturing costs, energy-intensive production, and recyclability issues [5, 6]. Aramid fibers (AFs) constitute an important class of high-performance reinforcements distinguished by their exceptional toughness, impact resistance, and energy absorption capabilities. Despite these advantages, their broader utilization is constrained by inherent drawbacks, including relatively low compressive strength, pronounced susceptibility to ultraviolet (UV) degradation, and elevated production costs compared to other synthetic fibers [7].

In response to these constraints, basalt fiber (BFs) has emerged as a comparatively recent addition to the spectrum of structural reinforcements, attracting significant scientific and industrial interest for its advantageous combination of mechanical efficiency, thermal stability, chemical resistance, and sustainability [8, 9]. BFs produced by the direct melt-extrusion of naturally occurring basalt rock at ~1450-1500 °C, BFs offer a simplified, additive-free manufacturing process that circumvents many of the chemical treatments, precursor preparation, and energy-intensive steps associated with GFs and CFs production [10]. From a performance perspective, BFs occupy a transitional position between glass GFs and CFs. They exhibit superior tensile strength, elastic modulus, and chemical resistance compared with GFs, as well as markedly improved thermal and moisture stability. Although they do not achieve the extreme stiffness and strength characteristic of high-grade CFs, their favourable performance-to-cost ratio, combined with environmental compatibility and large-scale availability, establishes BFs as attractive reinforcements for mid to high-performance structural applications [11, 12]. In addition, their exceptional durability in alkaline, saline, and elevated-temperature environments enables deployment in demanding service conditions such as marine infrastructure, offshore platforms, and concrete reinforcement, where GFs are particularly vulnerable to rapid degradation [13].

In recent years, FRCs have gained recognition as next-generation structural materials, distinguished by their tailored mechanical properties, superior thermal stability, and outstanding environmental durability [14]. Hybridization of BFs, GFs, CFs, AFs, or natural fibers with polymeric materials has emerged as an effective approach to tailor stiffness, toughness, impact performance, and fatigue resistance while optimizing material costs. For instance, BF-GF hybrids improve thermal and chemical stability at minimal cost increments. BF-CF hybrids reduce the economic barrier to carbon-intensive applications while enhancing stiffness. BF-AFs hybrids integrate toughness with improved compressive and thermal resistance [15-18]. The incorporation of BF into natural-fiber composites also contributes to eco-friendly solutions with enhanced mechanical reliability. Beyond mechanical performance, BF offers functional advantages such as fire resistance, acoustic damping, and thermal insulation, thereby broadening its multifunctional utility. Advances in surface modification and interfacial engineering, including plasma treatments, silane coupling agents, and nanoparticle grafting, continue to improve the fiber-matrix bonding of BFRCs, thereby enhancing their overall structural efficiency [19-21].

In this context, a systematic comparison of BFs with other reinforcing fibers, as well as an evaluation of their role in hybrid composite architectures, is critical. Understanding the interrelationship between processing, microstructure, and performance will accelerate the translation of basalt-based composites from laboratory research to industrial adoption. This chapter consolidates the current state-of-the-art on BFs and their composites, with emphasis on material processing, mechanical and thermo-chemical behaviour, hybridization strategies, durability, environmental impact, and economic feasibility. The discussion highlights both opportunities and challenges, offering insights into how BFs can contribute to the next generation of sustainable, lightweight, and high-performance structural materials.

## RAW MATERIAL AND MANUFACTURING OF REINFORCED FIBER MATERIALS

### *Glass fiber (GFs)*

GFs are high-performance reinforcement materials produced by melting and extruding precisely formulated glass compositions. The raw materials for GFs typically include silica ($SiO_2$) as the primary component, combined with controlled amounts of alumina ($Al_2O_3$), calcium oxide (CaO), boron oxide ($B_2O_3$), magnesium oxide (MgO), and various other modifiers and stabilizers depending on the desired fiber properties [22]. These raw materials, in proper ingredients, are melted at high temperatures (~1400–1600 °C), forming a homogeneous molten glass that is subsequently extruded through fine bushings to produce continuous filaments with diameters typically ranging from 5 to 25 µm. This process is executed with stringent process controls, including precise temperature regulation, viscosity management, and environmental isolation, ensuring uniform fiber diameter and consistent mechanical and chemical properties [23, 24].

Among the various GF types, E-glass (electrical-grade glass) is the most commonly used due to its low cost, good electrical insulation characteristics, moderate mechanical properties, and compatibility with a wide range of matrix systems. E-glass typically contains around 50-60% of silica ( $SiO_2$), 12-16% alumina ($Al_2O_3$), and moderate amounts of CaO and $B_2O_3$, the latter of which enhances melt fluidity and fiber-forming behaviour [25]. In contrast, S-glass (structural glass)-originally developed for military and aerospace applications-offers significantly higher tensile strength, elastic modulus, and temperature resistance, attributed to its higher alumina and silica content and the near elimination of boron oxides. However, these enhancements come at a higher production cost due to more demanding raw material purity, increased melting temperatures, and tighter compositional tolerances required to achieve the desired structural performance [23, 26].

The process for the manufacturing of GFs is highly mature and extensively optimised, enabling reproducible large-scale production with minimal sample-to-sample variability. Real-time viscosity monitoring, online filament-diameter control, and automated bushing improved the quality and throughput of the GFs [27]. The GFs represent a well-established class of reinforcement materials due to their tailored high process reliability and cost-effective properties, particularly for E-glass. In contrast to E-glass, S-glass offers superior mechanical performance for high-end structural applications, while higher production costs limit its application to specialized industries [26, 28].

### *Carbon fibers (CFs)*

CFs are advanced state-of-the-art materials with a micro-graphite crystal structure known for their light weight, high tensile strength, and chemical resistance, enabling their extensive use in aeronautical and aerospace, healthcare, and defense applications. CFs' reinforcement materials are manufactured through a multi-stage thermal conversion process in which organic precursors, such as polyacrylonitrile (PAN), mesophase pitch, or regenerated cellulose, are progressively stabilized, carbonized, and in some cases graphitized [29]. During this manufacturing process, the molecular structure of the precursor is transformed into highly oriented, carbon-rich filaments with exceptional mechanical and thermal properties. Each step is critical for controlling the fiber’s microstructure and performance characteristics. During the stabilization process, the linear PAN chains undergo cyclization and oxidation, transforming into a thermally stable structure. Subsequently, the carbonization process, which removes non-carbon elements such as hydrogen, nitrogen, and oxygen, results in a CFs structure. Finally, the graphitization process aligns the graphene-like layers into more ordered structures, dramatically increasing modulus and thermal conductivity. The resulting CFs exhibit exceptional tensile strength, chemical resistance, and stiffness, depending on the types of precursors and processing conditions [30]. PAN-based CFs dominate commercial markets due to their balance of strength, processability, and cost, while pitch-based fibers can achieve ultra-high modulus and high thermal/electrical conductivity [29].

However, the complexity and higher energy intensity involved in manufacturing CFs, particularly the long residence times in inert atmospheres, precise temperature control, and equipment for handling corrosive and high-temperature environments, make it significantly more expensive in comparison to GFs production. Additionally, precursor costs, fiber yield, and processing speed heavily influence the economic viability of CF composites. As a result, while CFs offer superior mechanical and functional properties, their cost-performance ratio limits widespread adoption to high-end structural applications [31, 32].

*Aramid fibers (AFs)*

AFs reinforced materials are high-impact resistant materials produced using high-performance synthetic fibers belonging to the aromatic polyamide family, most notably para-aramids such as Kevlar and Twaron. These fibers are manufactured through a solution-spinning process, where a liquid-crystalline polymer, formed by polymerising monomers such as para-phenylenediamine and terephthaloyl chloride, is extruded through fine spinnerets into a coagulation bath to form solid filaments [33]. The fibers are then drawn to align their molecular chains, heat-set to stabilise their structure, and subsequently surface-treated to enhance adhesion to polymer matrices. When used to fabricate composites, AFs are typically incorporated through processes such as hand lay-up, prepreg/autoclave curing, resin transfer molding, filament winding, or compression molding [34, 35]. The resulting AFs-reinforced polymer composites (AFRPs) exhibit outstanding specific tensile strength, high stiffness, excellent impact resistance, and superior energy-absorption capability, along with exceptional thermal stability, flame resistance, low density, and electrical insulation. However, they are vulnerable to UV degradation and long-term moisture exposure. These combined properties make AFRPs ideal for applications in ballistic protection, aerospace structures, advanced automotive components, ropes and cables, protective gear, and other high-performance engineering systems [33]. Their molecular structure, featuring rigid aromatic rings and amide linkages, leads to high crystallinity and strong directional bonding, which enhances their thermal stability, flame resistance, and dimensional stability under load. Importantly, AFs do not melt but rather degrade at high temperatures, which allows them to retain structural integrity in extreme environments [7]. Additionally, AFs are sensitive to ultraviolet (UV) radiation, which can lead to photo-oxidative degradation and loss of mechanical properties over time. They are also vulnerable to strong acids and bases, and their surface chemistry is relatively inert, making fiber-matrix adhesion in composite systems more challenging without specialized surface treatments or coupling agents [34]. Despite these limitations, AFs are widely valued for their extraordinary toughness, damage tolerance, and energy absorption capabilities, outperforming both glass and CFs in applications involving dynamic loading, impact, and vibration. They also exhibit excellent fatigue resistance and low creep, further enhancing their durability in cyclic loading conditions. Continued research aims to improve their UV resistance, interfacial bonding, and compressive properties through nano-reinforcements, hybridization, and chemical surface modifications[36, 37].

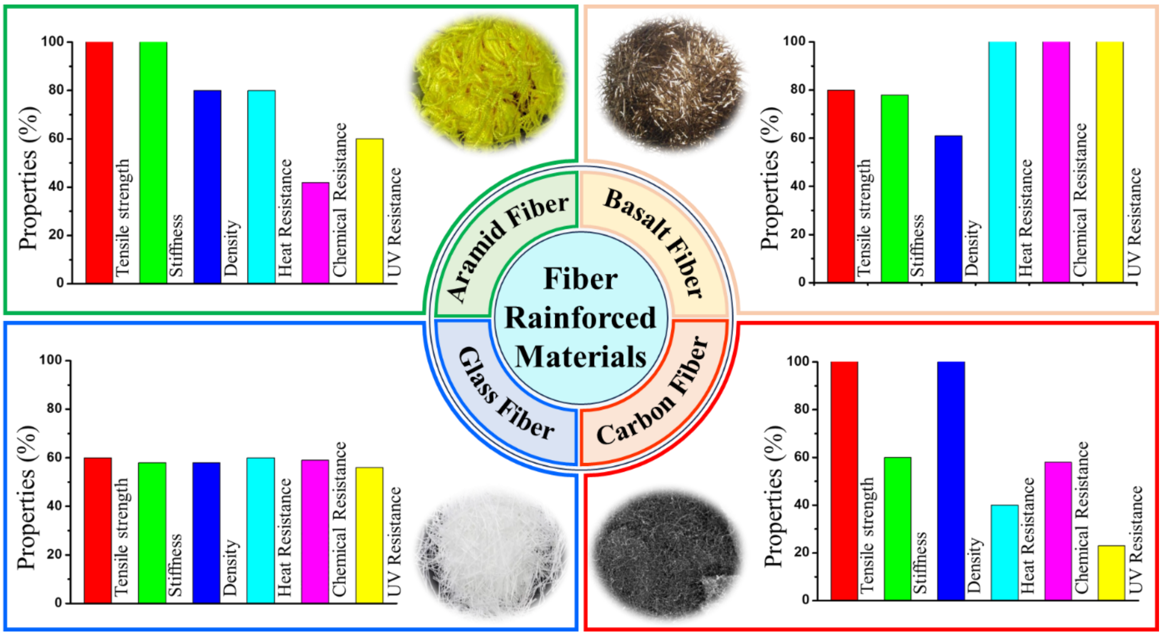


**Figure 1: Comparison of the properties of the basalt fiber (BFs) with glass fiber (GFs), Aramid Fiber (Afs), and carbon fiber (CFs).**

*Basalt Fiber (BFs)*

BFs is a golden brown color advanced inorganic fiber produced by melting naturally occurring basalt rock at high temperatures, typically ranging between 1,350-1,800 °C, followed by extruding the molten material through platinum-rhodium bushings to form continuous filaments [20, 38]. Unlike the production of GFs, which relies on a carefully engineered mix of raw materials such as silica sand, limestone, alumina, borates, and other oxides, BFs production benefits from its single-component feedstock, eliminating the need for additive formulations and pre-melting batch control. This significantly simplifies the manufacturing process and reduces the potential for compositional variability introduced during blending, although it shifts the burden of consistency to the natural variability of the basalt source itself [39]. The chemical composition of BFs typically mirrors that of volcanic basalt rocks, rich in $SiO_2$ (45–55%), $Al_2O_3$, CaO, $Fe_2O_3$, MgO, $Na_2O$, and $K_2O$, with minor trace elements. This oxide mix lends BFs many of the desirable mechanical and thermal properties of traditional E-glass and S-glass fibers, including high tensile strength, thermal stability, chemical resistance, and good insulating properties. However, unlike synthetic systems, the $Fe_2O_3$ and alkali contents are often higher, which can influence the fiber's electromagnetic properties, corrosion resistance, and thermal behavior-attributes of importance in high-temperature and structural applications [40, 41].

In terms of processing advantages, BFs have a lower overall energy footprint than fibers such as carbon fiber, which require energy-intensive precursor synthesis (e.g., polyacrylonitrile, or PAN), stabilization, and graphitization. Moreover, it does not involve the toxic emissions or complex chemical routes often associated with polymer-based fibers or aramid production [42-

44]. The direct melt-and-draw process improves both environmental sustainability and cost-effectiveness, making BFs an attractive candidate for construction, automotive, aerospace, and fire-resistant applications. However, quality control remains a major challenge due to the inherent variability in basalt rock composition, which depends on the deposit's geological origin. Small variations in mineral content or crystallinity can lead to significant differences in fiber spinnability, viscosity, filament uniformity, and mechanical performance. As a result, large-scale commercialization and application of BFs require stringent characterization and sorting of raw materials, or blending strategies to homogenize feedstock quality [45-47]. Research is ongoing to develop predictive models and real-time monitoring systems to ensure consistent fiber performance in industrial-scale operations. BFs represent a promising class of reinforcement material with sustainable processing pathways, competitive mechanical and thermal properties, and broad industrial applicability. However, further advancements in raw material standardization and process control are essential to fully unlock its potential as a cost-effective and environmentally favourable alternative to conventional GFs and CFs. **Fig. 1** shows the properties of BFs, with the comparison of GFs, AFs and CFs, which clearly exhibit the advantages of BFs over other fiber-reinforced materials.

## MICROSTRUCTURE AND SURFACE CHEMISTRY OF BFs

BFs, often described as "green materials without pollution for the 21st century," have attracted significant global attention owing to their superior mechanical performance. The microstructure and surface chemistry of BF are critical determinants of its mechanical performance, chemical durability, and compatibility with polymer matrices in composite applications. BFs are amorphous to partially crystalline inorganic silicate fibers, formed by the rapid quenching of molten basalt rock, which consists of a naturally occurring multicomponent oxide system rich in $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, MgO, $Na_2O$, and $K_2O$, among others [48]. Due to the rapid cooling during fiber drawing, the resulting microstructure is predominantly non-crystalline (glassy), though localized regions of nanocrystalline phases (e.g., magnetite or plagioclase-type structures) may form depending on the cooling rate and composition of the source basalt. The lack of long-range atomic order imparts isotropic mechanical and thermal behavior, while the presence of iron and magnesium oxides can influence magnetic, dielectric, and oxidation characteristics [49]. The SEM images in Figure 2(a-c) show clear differences in the surfaces of BFs after ethanol cleaning and heat treatment (400 °C for 4 h). The untreated fibers contain visible dust and impurities, as shown in Figure 2(a), whereas the ethanol-washed fibers are cleaner and retain only the original sizing layer (Figure 2 b). Heat-treated fibers display uniformly smooth surfaces, confirming the complete removal of dust and impurities, as shown in Figure 2(c). The average fiber diameter remains essentially unchanged after desizing, indicating that the treatment does not significantly affect fiber thickness. While minor variations in diameter can occur along the length of a single fiber, the more pronounced differences are those observed between individual fiber specimens [50].

At the microscopic level, BFs exhibit a smooth, glassy surface morphology, which contributes to their low surface reactivity and relatively poor interfacial bonding with organic matrices, even without surface treatment. However, the surface chemistry is complex due to the heterogeneous distribution of oxides, particularly transition-metal oxides such as $Fe_2O_3$ and $TiO_2$, which may form localized sites with altered surface polarity or catalytic activity [52]. The fiber surface contains silanol (Si-OH) groups, though typically at lower concentrations than in E-glass fibers, resulting in lower inherent hydrophilicity. These silanol groups are critical for chemical functionalization, particularly in silane coupling reactions, which are commonly used to enhance interfacial adhesion in composite systems.

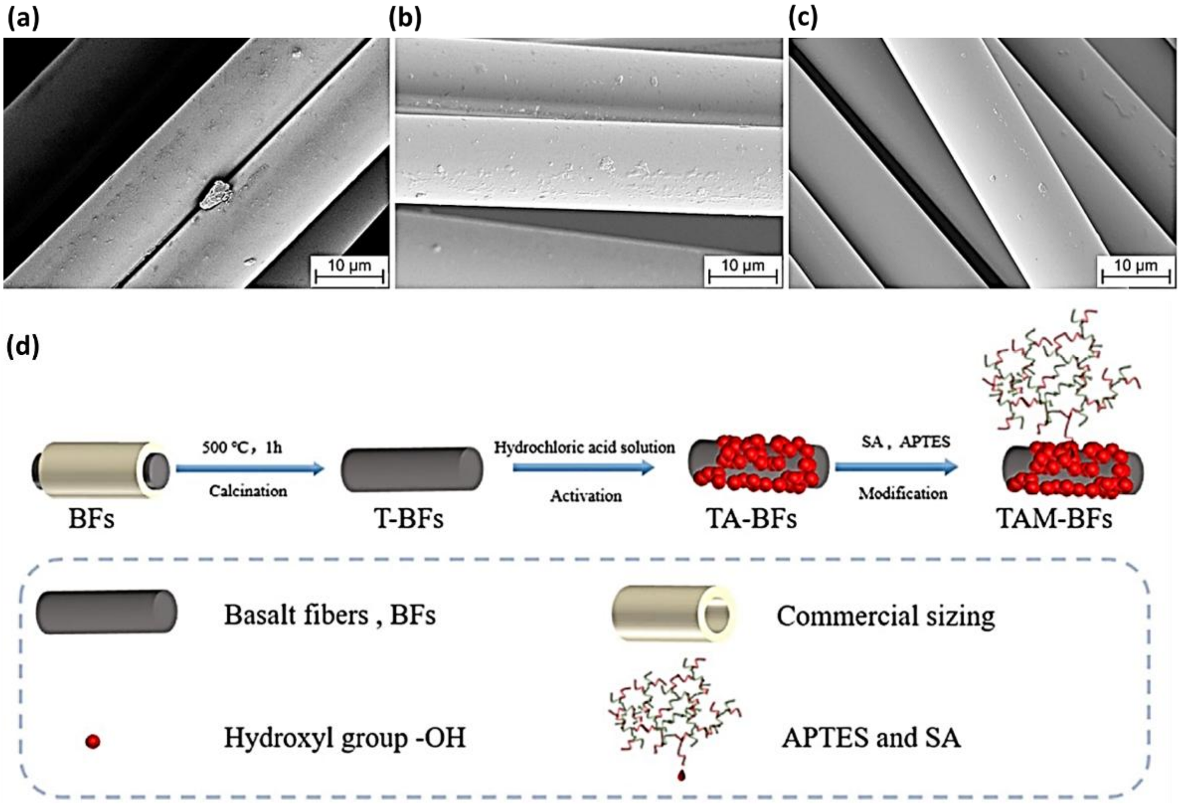


**Figure 2: Microscopic SEM image of (a) as prepared, (b) cleaned with ethanol, (c) heat-treated BFs (Reproduced with permission of [50], Copyright © 2025, Elsevier Ltd.) and (d) the acidic treatments used to functionalize BF surfaces, beginning with high-temperature desizing followed by HCl activation and subsequent 3-aminopropyltrimethoxysilane (APTES) and succinic anhydride (SA) grafting (Reproduced with permission of [51], Copyright © 2024, Springer Nature).**

Techniques such as plasma activation, acid etching, and silanization are frequently employed to increase surface roughness and introduce functional groups that enhance fiber-matrix adhesion. Continued advancements in surface modification and microstructural optimization are further improving the performance of BFs-reinforced composites used in structural, thermal, and corrosive operating environments.

Moreover, the presence of alkali and alkaline-earth oxides (e.g. $Na_2O$, $K_2O$, CaO) near the surface can serve as potential leaching sites under aggressive environmental conditions (e.g., alkaline or acidic media), thereby influencing long-term durability and chemical resistance [51, 53-55]. Figure 2(d) presents the acidic treatments used to functionalize BF surfaces, beginning with high-temperature desizing, followed by HCl activation and subsequent grafting with 3-aminopropyltrimethoxysilane (APTES) and succinic anhydride (SA). The thermally treated and acid-activated fibers (TA-BFs) served as the base material for silane modification. APTES and SA grafting reduced surface defects and wettability of BFs while noticeably improving their tensile strength, thermal stability, and functional surface characteristics [51]. These enhancements significantly expand the potential uses of the modified fibers in advanced composites. Acid treatments using solutions such as HCl or NaOH increase the surface roughness of BFs and generate additional hydroxyl groups, leading to a more compact and stronger fiber-matrix interface. These surface modifications also increase the mesoporous volume in the mortar, which helps reduce or, in some cases, fully negate the negative impact of untreated fiber addition on compressive strength.

## PROPERTIES OF BFs

### *Mechanical Properties*

BFs (BFs) have emerged as an increasingly important reinforcement material in advanced composite systems due to their favorable balance of mechanical strength, thermal stability, chemical durability, and economic viability compared with conventional fiber types. Produced through the melting and extrusion of naturally occurring basalt rock, these fibers form a dense, defect-resistant silicate network rich in Fe-Mg-Ca-Al components, enabling tensile strengths of approximately 2.8 to 4.8 GPa and elastic moduli of 85 to 110 GPa. These values exceed those of E-glass and closely approach the performance of more specialized S-glass, while still benefiting from lower energy demands in production [8, 56, 57]. Their intermediate elongation at break (around 2.7-3.2%) results in a balanced stiffness ductility profile that enhances impact resistance and crack-arrest behaviour, contrasting with the inherently brittle failure of CFs. The microstructural uniformity and reduced pore content of BFs contribute to improved fatigue life and reduced vulnerability to stress-corrosion cracking across varied environmental conditions [58, 59]. Additionally, their high softening temperature and superior thermal resistance maintained beyond 600-700 °C, allow BFs to retain structural capability in high-heat or fire-critical applications where glass, aramid, and polymer-based fibers usually degrade. Despite these strengths, the chemically inert and smooth surface of untreated BFs can restrict effective bonding with polymer matrices, prompting extensive research into advanced surface modification methods, including silane coupling, plasma processing, nano-scale coating, and biomimetic functionalization [60-62]. Such treatments significantly improve interfacial shear strength, load-transfer efficiency, and composite damage tolerance by enhancing adhesion and promoting controlled crack-deflection mechanisms. Consequently, BFs-reinforced composites are increasingly recognized as a sustainable and competitive alternative to traditional reinforcements, with ongoing innovations in surface engineering, hybrid composite architectures, and multifunctional material design further expanding their applicability in the aerospace, automotive, civil engineering, and renewable energy sectors [38, 63].

### *Thermo-Chemical Behaviour*

BFs exhibit a complex thermo-chemical response that stems from their multicomponent silicate structure, which incorporates $SiO_2$, $Al_2O_3$, $FeO/Fe_2O_3$, MgO, CaO, and various minor oxides. This chemically diverse network forms a thermally stable amorphous matrix that resists softening and preserves mechanical integrity at temperatures exceeding those tolerated by conventional GFs or organic fibers [64-66]. Typically, BFs retain much of their tensile strength up to 600-700 °C, owing to their high glass-transition and crystallization thresholds, as well as the strong ionic and covalent bonding within the silicate framework. At elevated temperatures, the fibers demonstrate remarkable oxidation resistance and maintain their structural stability without significant morphological distortion [67, 68]. However, under aggressive thermochemical environments, such as prolonged exposure to alkaline solutions, high-temperature moisture, molten salts, or cyclic thermal loading, the fibers may undergo compositional changes, including cation leaching, hydrolysis of unstable oxides, or partial devitrification. These reactions can roughen the fiber surface, reduce defect tolerance, and diminish interfacial bonding in composites [45, 69]. In severe conditions, crystallization of iron and magnesium-rich phases may occur, which can embrittle the fibers and alter their thermo-mechanical performance. To address these challenges, recent research emphasizes surface engineering strategies, including nano-oxide barrier layers, silane-based protective chemistries, and plasma-induced modifications, to enhance resistance to environmentally driven degradation. Overall, the thermochemical robustness of BFs, together with tunable stability through targeted surface treatments, positions them as a promising reinforcement for high-temperature, chemically demanding, and fire-resistant composite applications [70].

### *Durability and Environmental Impact*

BFs offer exceptional long-term durability and significantly lower environmental impact than CFs, GFS, and AFs, firmly establishing them as a resilient and eco-efficient reinforcement for sustainable composite engineering. Derived from naturally occurring volcanic rock, BFs exhibit remarkable resistance to moisture, alkaline and acidic media, ultraviolet radiation, oxidative degradation, and repeated thermal cycling. These properties enable it to maintain structural and mechanical integrity over extended service periods, even in highly aggressive environments such as marine applications, civil and transportation infrastructure, geothermal systems, and high-temperature industrial operations [71, 72]. Chemically, BFs exhibit markedly superior stability compared with E-glass, which is susceptible to alkali-induced degradation in cementitious environments due to the dissolution of silica-rich phases and the subsequent formation of microcracks. The inherently higher proportions of alumina, iron oxides, and magnesium silicates in basalt confer greater chemical inertia, minimizing dissolution reactions and preserving fiber integrity under aggressive conditions.

As a result, BFs maintain their tensile performance in alkaline, acidic, and saline media, making them particularly advantageous for durability-critical reinforcement applications such as geogrids, basalt rebar, and composite elements exposed to corrosive or moisture-rich service environments [73-75]. Compared with AFs, which degrade under UV radiation, moisture, oxidative exposure, and alkaline chemistry, BFs exhibit excellent stability without the need for protective coatings and remain thermally stable up to 800-1000 °C, well beyond the ~500-550 °C degradation onset of aramids. CFs, although thermally stable in inert atmospheres, oxidizes rapidly above 400-600 °C in air and require protective coatings for high-temperature applications; their electrical conductivity also introduces risks of galvanic corrosion in contact with metals in humid environments. BFs, being electrically insulating and naturally corrosion-resistant, do not suffer from this limitation. Environmentally, BFs offer significant benefits: their production via melt-spinning of basalt rock at ~1350-1500 °C requires less energy than the multi-stage, high-temperature (≥2000 °C) PAN-based processes used for CFs, and avoids the hazardous solvents integral to aramid synthesis [76-79]. In contrast, GFs production involves multiple mineral additives, including environmentally challenging borates and fluorides. Life cycle assessments consistently show BFs possessing lower embodied energy, reduced global warming potential, and benign end-of-life behaviour, being non-toxic and inert in landfills. Overall, BF provides superior durability across thermal, chemical, and environmental stressors while simultaneously offering lower environmental burdens, making it an ideal sustainable reinforcement material for modern composite applications where long-term durability and ecological performance are critical [80].

## BFR-POLYMER COMPOSITE MATERIALS (BFRP)

BFRP composites constitute an emerging class of high-performance, durable, and environmentally sustainable materials produced by embedding BFs derived from naturally occurring volcanic rock into polymer matrices [81]. The exceptional physicochemical properties of BFs, including tensile strengths of 2.5-4.8 GPa, Young’s moduli of 85-110 GPa, thermal stability up to 800-1000 °C, and strong resistance to alkaline, acidic, and saline environments, enable BFRPs to outperform conventional fiber reinforced polymers (FRPs) in mechanical reliability and long-term durability [8, 78, 82]. These composites are typically manufactured using thermosetting matrices such as epoxy, vinyl ester, and polyester, or thermoplastics like polypropylene and polyamide, reinforced with continuous, woven, or chopped BFs to achieve improved tensile and flexural strength, enhanced impact toughness, and superior fatigue behavior. BFs possess a naturally rough surface and reactive oxide groups that promote strong interfacial bonding with polymer matrices, ensuring effective load transfer, reduced delamination, and stable performance under static, dynamic, and cyclic loading [83-85]. This strong interface also contributes to their excellent resistance to moisture, UV radiation, corrosive chemicals, and temperature fluctuations, conditions that often accelerate degradation in other FRPs.

Moreover, BFRPs exhibit superior fire resistance and maintain structural integrity at temperatures where AFs begin to thermally degrade, and CFs oxidize [86, 87]. Their processing is compatible with established composite manufacturing methods, including pultrusion, filament winding, resin transfer molding (RTM), vacuum-assisted resin infusion (VARI), and compression molding, supporting both scalability and cost efficiency. Environmentally, BFs offer notable advantages due to their natural origin and straightforward melt-spinning production route, which avoids the energy-intensive and chemically complex precursor synthesis required for carbon and aramid fibers, as well as the mineral additive challenges associated with glass fiber manufacturing [88-91]. These sustainability benefits, combined with strong mechanical and durability properties, make BFRPs attractive for civil infrastructure, automotive and aerospace components, marine applications, and protective structures. Current research focuses on optimizing BF surface treatments and sizing formulations for improved matrix compatibility, developing hybrid composites with CFs, GFs and AFs to leverage synergistic effects, and exploring nanoscale functionalization to enhance toughness, interfacial strength, and multifunctional attributes such as sensing, thermal regulation, and electromagnetic shielding [40, 92, 93].

## HYBRIDIZATION STRATEGIES OF BFRPs

Hybridization of BFRs and polymer matrices has evolved into a sophisticated design paradigm for developing high-performance composites that combine mechanical robustness with environmental durability and cost efficiency [94, 95]. Compared with GFRs, AFRs, and CFRs, BFRs provide a distinctive combination of tensile strength, elastic modulus, thermal stability, and chemical resistance, which contributes to their broad compatibility with diverse polymer matrices. The BFRs are particularly attractive for developing hybrid polymer composites where both performance and durability are critical. In these composite systems, including epoxy, vinyl ester, polyester, and phenolic resins, hybridization strategies commonly focus on improving fiber-matrix interfacial adhesion through targeted surface modification of BFRs [96, 97].

Techniques such as silane coupling, plasma treatment, and nanoparticle-assisted grafting have been shown to enhance surface energy, promote chemical bonding, and minimize stress concentrations at the interphase of the BFRPs. These interfacial engineering approaches yield more efficient load transfer pathways, reduce microcrack initiation, and improve the long-term mechanical stability of the composite materials [56, 98, 99].

In thermoplastic matrices such as polypropylene, polyamide, and bio-based polymers, BFRs significantly enhance load-bearing capability and thermal resistance. Melt-processing techniques and fiber orientation control enable fine-tuning of ductility, stiffness, and energy absorption characteristics of BFRPs [96, 100, 101]. Advanced hybridization approaches, where BFRs are combined with nano-scale fillers such as graphene, CNTs, nano-silica, or layered silicates, which form multi-scale architectures that deliver improvements in flame retardancy, thermal conductivity, gas barrier properties, and dimensional stability [44]. Furthermore, strategies such as stacking-sequence optimization, interlayer toughening, and multi-axial fabric integration enable the creation of graded composites with enhanced interlaminar shear strength and reduced susceptibility to delamination, which are key requirements for aerospace interiors, automotive crash components, and marine structures.

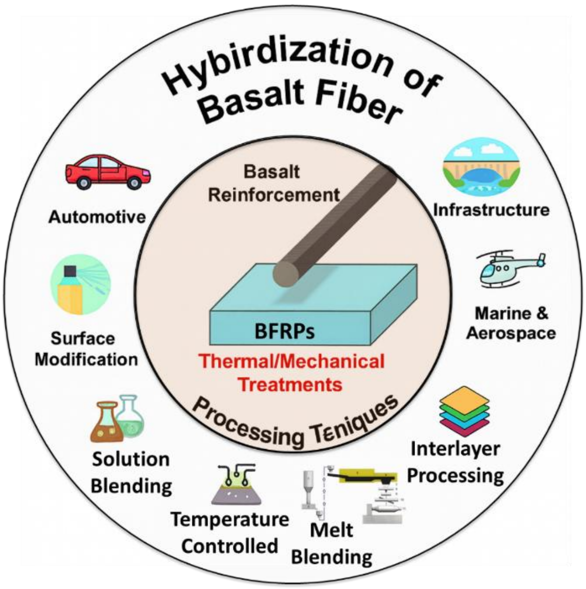


**Figure 3: Schematic of hybridization of BFRPs, processing, and the application of BFRPs in various fields.**

Figure 3 presents the Schematic of hybridization of BFRs, processing, and the application of BFRPs in various fields. Emerging trends in sustainable materials engineering also leverage BFs with biodegradable or recyclable polymers to create environmentally responsible hybrid composites that maintain structural integrity under harsh chemical or thermal exposure [56, 102].

## PROPERTIES OF BFRPs

### *Tensile and Flexural Properties*

BFRPs represent an intermediate-performance composite class that effectively bridges the mechanical and economic gap between GFRP and CFRP systems, combining favourable strength, stiffness, durability, and cost-efficiency. With tensile strengths typically ranging from 300 to 600 MPa and tensile moduli between 15 and 30 GPa, alongside flexural strengths of approximately 400-700 MPa and flexural moduli reaching 20-35 GPa, BFRPs consistently outperform conventional GFRPs composites, largely due to the intrinsically higher tensile capacity of BFRs (2.5-4.8 GPa) and the superior interfacial bonding enabled by their rough, chemically reactive surfaces [44, 103, 104]. Although their tensile and flexural properties remain below those of CFRPs composites, which commonly achieve tensile strengths of 1500-

3500 MPa and moduli exceeding 70-230 GPa, BFRPs offer distinct advantages in terms of reduced brittleness, greater environmental stability, and markedly lower material costs, making them especially suitable for applications where extreme stiffness is not required [105, 106].

Compared with AFRPs, BFRPs exhibit superior compressive strength, enhanced thermal and chemical resistance, and reduced sensitivity to moisture and ultraviolet exposure, even though AFRs retain an edge in toughness and impact energy absorption due to their flexible polymeric structure. The structural performance of BFRPs is highly dependent on parameters such as fiber volume fraction, fiber alignment, matrix selection, and specialized surface treatments designed to optimize fiber-matrix adhesion, with the fibers silanol-rich, textured surfaces promoting efficient load transfer, elevated fracture toughness, and improved flexural behaviour relative to GFRP composites [107]. Fu et al. [108] investigated the mechanical behaviour of BFRs polymer concrete (BPRC) using standardized compressive and flexural testing methods. Compressive strength was evaluated on cubic specimens (100 × 100 × 100 mm) under uniaxial loading at a constant stress rate, with surface lubrication applied to reduce end-friction effects. Flexural performance was assessed through four-point bending tests on prismatic specimens (100 × 100 × 400 mm), allowing reliable evaluation of strength and deformation characteristics, as shown in Figure 4(a). Figure 4(b) illustrates that the incorporation of BFRs into polypropylene fiber (PF) with different matrix strengths (C-30, C-40 and C-50) produces similar trends in compressive strength regardless of matrix strength.

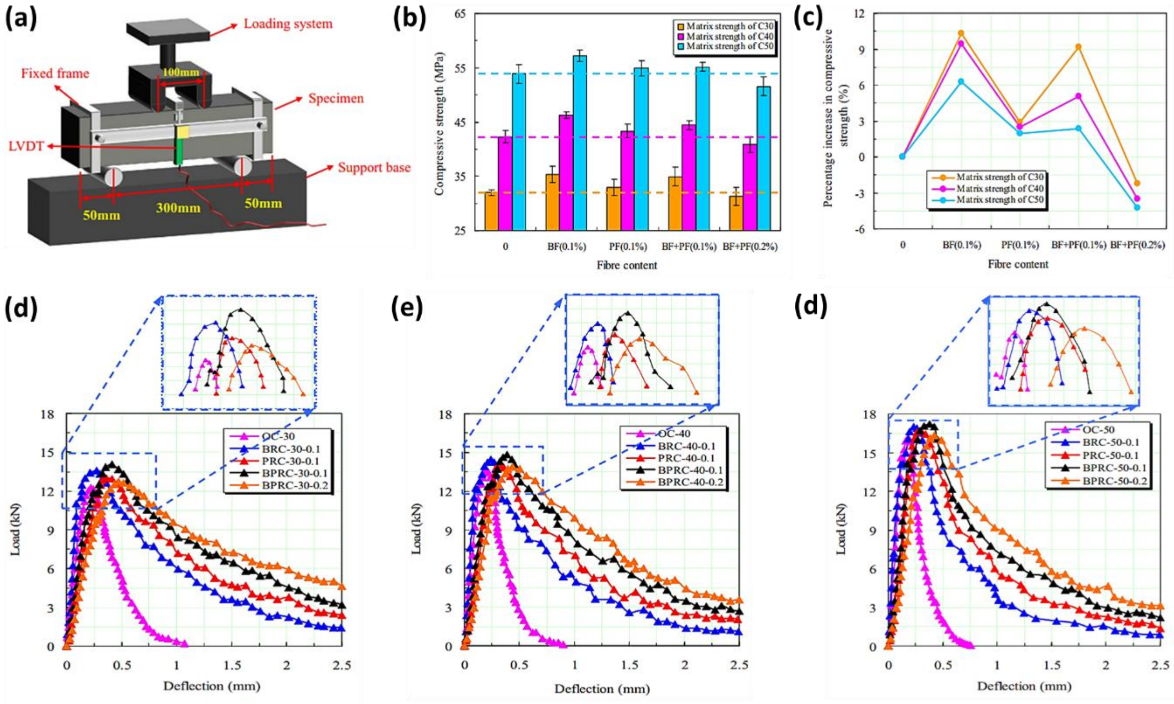


**Figure 4: (a) Schematic of flexural performance test of BFs/Polypropylene fiber-reinforced concrete assessed through four-point bending tests, (b) comprehensive strength, (c) strength efficiency, and (d-f) the flexural load-deflection of BFRs into PF with different matrix strengths (C-30, C-40, and C-50) (Reproduced with permission of [108], Copyright © 2024, Springer Nature).**

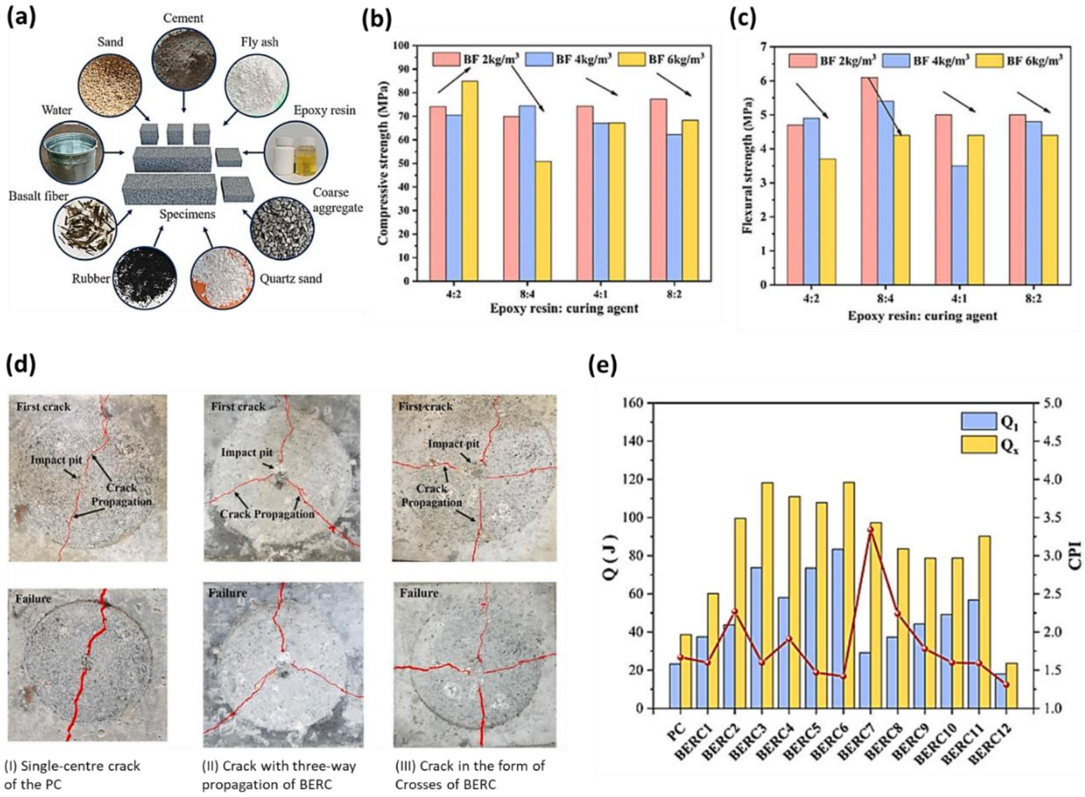
At a low fiber content (0.1%), all fiber configurations enhance compressive strength, showing the most pronounced improvement. This behaviour is mainly attributed to the high stiffness, hydrophilicity, and fine diameter of BFRs, which promote better fiber matrix bonding, effective shrinkage crack control, and crack arrest under compressive loading. In contrast, the lower stiffness and hydrophobic nature of PF result in weaker interfacial bonding and a limited contribution to compressive strength. However, increasing the hybrid fiber content to 0.2% leads to a reduction in strength due to poor dispersion, increased interfacial defects, and entrapped air. As shown in Figure 4(c), the strengthening efficiency of fibers decreases with increasing matrix strength, indicating that fiber reinforcement becomes less effective in high-strength matrices, particularly at excessive fiber contents. Figure 4(d-f) illustrates the flexural load-deflection behaviour of prepared BPRC as influenced by fiber type, fiber content, and matrix strength. Although variations in matrix strength affect the absolute load and deformation levels, the overall response trend remains consistent with fiber incorporation. The presence of fibers enhances flexural resistance and post-cracking deformation capacity, indicating improved crack-bridging and energy dissipation mechanisms that are largely independent of the matrix strength. This suggests that fiber reinforcement governs the flexural response of BPRC by controlling crack initiation and propagation rather than significantly altering the elastic stiffness of the matrix.

### *Impact Resistance and Fracture Toughness*

The impact resistance and fracture toughness of BFRPs highlight their increasing importance as damage-tolerant composite materials, offering a balanced and intermediate performance profile relative to GFRPs, CFRPs, and AFRPs composite each governed by distinct fracture mechanics rooted in their intrinsic fiber chemistry, microstructure, and interfacial behaviour [107, 109]. BFRPs typically demonstrate moderate to high impact toughness, with impact energy absorption values commonly reported in the range of 50 to 100 $kJ/m^2$ significantly higher than those of conventional E-GF composites, which generally fall between 20 to 60 $kJ/m^2$ due to their brittle nature, low strain-to-failure, and limited resistance to crack propagation [110-112]. The enhanced impact performance of BFRPs is largely attributed to the inherently rough and chemically active surface of BFs, which provides superior fiber-matrix adhesion, promotes efficient stress transfer, and enables effective crack-bridging and energy-dissipation mechanisms during impact loading [38]. Dong et al. [113] prepared BFs-epoxy resin reinforced concrete (BERC) using the constituent materials illustrated in Figure 5(a). Their results clearly demonstrate the influence of BFs content on the mechanical performance of BERC. When the epoxy resin content was maintained constant, increasing the BFs content from 2 to 6 $kg/m^3$ resulted in a reduction in both compressive and flexural strengths, as shown in Figure 5(b & c), whereas the splitting tensile strength exhibits a progressive improvement. These findings demonstrate a content-dependent trade-off between compressive and tensile performance, indicating that an optimal BF content of 2 $kg/m^3$ is essential for achieving a balanced mechanical response.

Under impact loading test, concrete fails through rapid crack initiation and unstable propagation from the stress concentration point, exhibiting behaviour distinct from quasi-static compression. BERC displays multi-directional, tortuous crack paths and delayed fragmentation due to fiber bridging, elastic inclusions, and improved matrix bonding (Figure 5d). Compared with plain concrete (PC), BERC generally exhibits a marked improvement in impact resistance, as reflected by higher crack propagation index (CPI) values across most mix designs (Figure 5e). CPI enhancements ranging from modest to substantial are observed depending on fiber and resin content, highlighting the strong sensitivity of impact performance to composite composition. In particular, a combination of 2 $kg/m^3$ BFs and 4 $kg/m^3$ epoxy resin consistently provides superior impact resistance, indicating an optimal synergy between fiber bridging and matrix toughening mechanisms. These mechanisms enhance ductility and increase the energy required for impact failure.

Although aramid-fiber composites remain the benchmark for exceptional toughness derived from their high elongation at break, strong intermolecular hydrogen bonding, and energy-absorbing failure mechanisms, BFRPs provide a more thermally and chemically stable alternative with superior compressive performance, albeit with lower specific impact energy absorption [114]. CFRPs, despite offering unparalleled stiffness and tensile strength, generally exhibit lower impact toughness and fracture energy due to the brittle fracture characteristics of CFs and relatively weaker interfacial bonding, which limits their damage tolerance unless advanced toughening strategies or hybrid laminate configurations are employed. In terms of fracture toughness, BFRPs often exhibit higher critical stress intensity factors and strain energy release rates than GFRP composites, reflecting the role of the BFs surface morphology in enhancing fiber bridging, delaying crack initiation, and suppressing delamination growth attributes, particularly important in structures exposed to cyclic loads, impact events, and aggressive environmental conditions [12, 94, 109]. Overall, BFRPs deliver a well-balanced combination of impact resistance and fracture toughness, outperforming glass composites while providing intermediate behaviour between the highly ductile aramid systems and the brittle yet high-strength carbon composites.



(I) Single-centre crack of the PC

(II) Crack with three-way propagation of BERC

(III) Crack in the form of Crosses of BERC

**Figure 5: (a) Content for the preparation of BFs-epoxy resin reinforced concrete (BERC) specimen, (b) comprehensive strength, (c) flexural strength, (d) the impact failure modes, (e) impact energy, and crack propagation index of BERC specimen (Reproduced with permission of [113], Copyright © 2024, Elsevier Ltd.).**

*Thermal Stability and Fire Performance*

BFs derived from naturally occurring volcanic rock exhibit outstanding thermal robustness, retaining structural integrity and mechanical functionality at sustained temperatures of approximately 800 °C and withstanding short-term thermal exposure approaching 1000 °C with minimal degradation. In comparison, CFR composites, while thermally stable in inert environments, undergo noticeable oxidative degradation and strength loss in air at temperatures above 400-600 °C unless protected by specialized coatings. Relative to GFs, which soften and may undergo devitrification or alkali-induced damage under thermal cycling, BFs maintain superior dimensional and mechanical stability under extended thermal exposure. AFs, despite their high toughness, exhibit limited thermal resistance, decomposing at approximately 500-550 °C and releasing combustible and potentially toxic by-products during fire. Due to their inorganic, non-combustible nature and high melting point (~1450 °C), BFs serve as effective thermal barriers within polymer matrices, thereby reducing heat transfer, flame spread, and smoke generation.

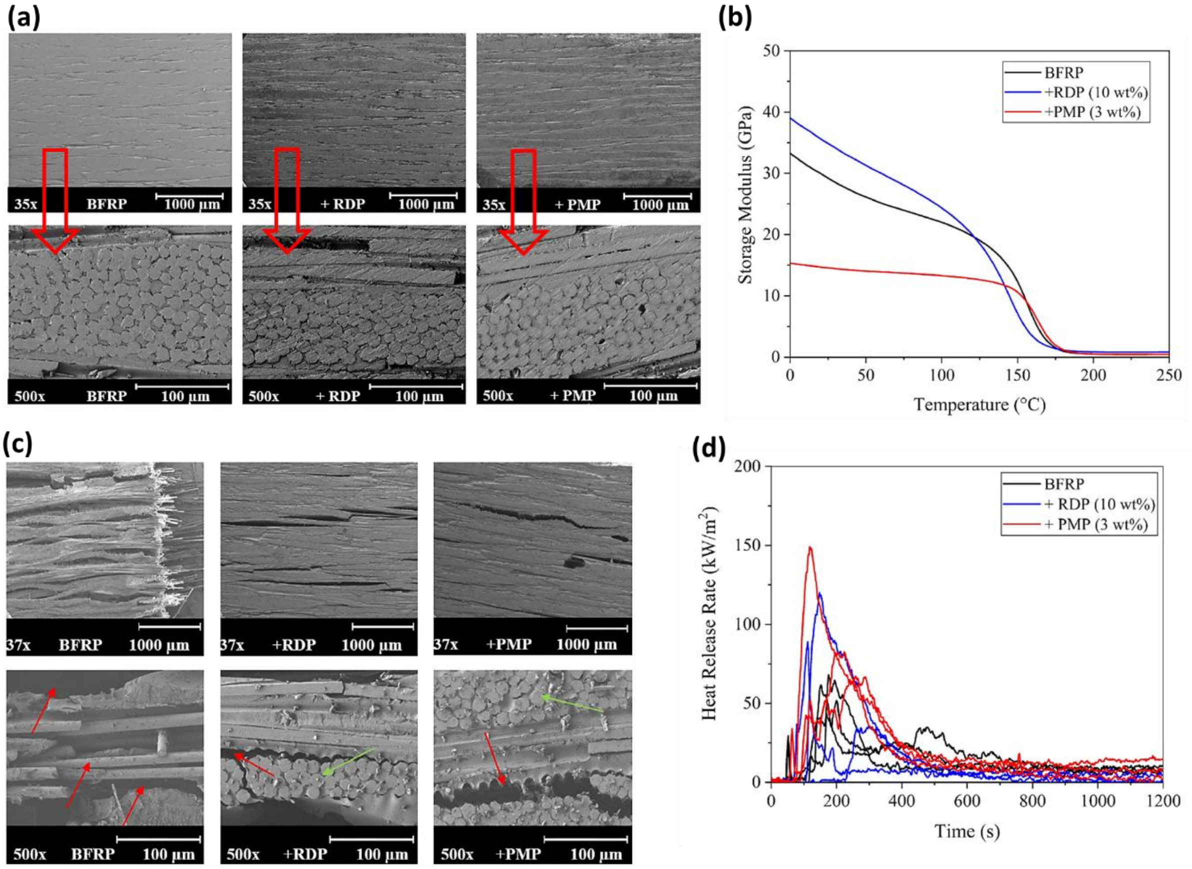


**Figure 6: (a) SEM morphology of BFRP specimens containing 26 layers of fiber reinforcement compared with poly (m-phenylene methylphosphonate) (PMP) and resorcinol bis(diphenyl phosphate) (RDP), (b) dynamic mechanical analysis DMA measurements, (c) SEM images of BFRP after UL94 testing, (d) Heat release rates (HRR) of BFRPs, PMP, and RDP as a function of time (Reproduced with permission of [115], Copyright © 2020, Wiley).**

Consequently, BFRPs demonstrate enhanced flame retardancy, lower heat release rates, and improved fire performance compared with conventional GFRs and AFRs composites, highlighting their suitability for fire-critical and high-temperature applications. Wolter et al. [115] investigated the influence of flame-retardant additives (FRAs) on the fabrication, mechanical performance, and fire behaviour of BFRPs produced via vacuum infusion using resorcinol bis(diphenyl phosphate) and poly-(m-phenylene methylphosphonate) in combination with bisphenol-F and aniline-based benzoxazine monomers, with the comparison of PMP, poly(m-phenylene methylphosphonate) and RDP, resorcinol bis(diphenyl phosphate). Figure 6(a) displays the SEM image of prepared BFRP specimens with 26 layers of FRPs, which confirms that 26-layer BFRP laminates exhibit a dense, homogeneous microstructure with effective fiber impregnation and minimal porosity, demonstrating the reliability of one-step vacuum infusion for producing high-quality and reproducible composites. As static tensile testing at room temperature was insufficient to capture their temperature-dependent performance, they employed dynamic mechanical analysis (DMA) to evaluate the thermomechanical behaviour of BFRPs containing flame-retardant additives (Figure 6b).

The storage modulus (E') indicated that all BFRP systems behave as rigid materials at 25 °C, although PMP-containing composites exhibited reduced stiffness compared with neat and RDP-modified BFRPs. With increasing temperature, E' decreased and showed a pronounced transition associated with the glass-to-rubbery state, while the incorporation of RDP significantly reduced glass transition temperature (Tg), PMP had a negligible effect, and the overall high Tg values confirm the suitability of these BFRPs for applications requiring elevated-temperature performance. Figure 6(c) represents the SEM microstructure of the BFRC specimen, illustrating the composite morphology, while the influence of phosphorus-based flame-retardant additives on the flammability behaviour of BFRPs was systematically evaluated using UL-94 vertical burning and limiting oxygen index (LOI) tests. Post-UL-94 SEM analysis shows that BFRPs without flame retardants experience severe delamination and extensive cracking, whereas phosphorus-based additives significantly reduce microstructural damage and preserve laminate integrity. The heat release rate (HRR) of BFRP, as presented in Figure 6(d), shows a sharp peak shortly after ignition (time to ignition, TTI: 71 ± 36 s), with a maximum HRR of 58 ± 13 kW/m² at around 200 s, followed by a gradual decline to below 15 kW/m². The total heat released over 20 minutes was 17 ± 2 MJ/m², while the FRA without BFRP had a MARHE of 22 ± 1 kW/m². This pattern, typical of charring materials, arises because the BFs are non-combustible. Their study highlights how integrating these flame-retardant agents affects the processing characteristics, thermal stability, and flame resistance of BFRPs, providing insights into optimizing composite formulations to enhance fire performance without compromising mechanical integrity.

BFRPs demonstrate exceptional thermal stability and fire performance, primarily due to the inorganic composition, non-combustibility, and high melting temperature of BFRs. Unlike many conventional FRP composites (GFRPs, AFRPs, and CFRPs) that undergo rapid softening, ignition, or severe loss of mechanical integrity under elevated temperatures, BFRPs exhibit delayed thermal degradation, reduced flame spread, and lower heat release rates. The BFs maintain structural continuity at temperatures where organic fibers typically fail, thereby limiting crack formation, restraining matrix decomposition, and improving residual mechanical properties after thermal exposure. Moreover, the strong interfacial compatibility between BFs and polymer matrices improves load transfer and mitigates heat-induced debonding, thereby enhancing fire resistance. As a result, BFRPs offer improved dimensional stability, enhanced structural reliability, and increased safety margins under fire or high-temperature scenarios, making them particularly attractive for infrastructure, transportation, and industrial applications where stringent fire-safety regulations and long-term thermal durability are critical.

### *Chemical Resistance and Durability*

The chemical resistance and long-term durability of BFRPs distinguish them as robust composite materials capable of sustained performance in harsh, corrosive, and environmentally aggressive conditions, surpassing many traditional PRP systems in durability and reliability [38, 116]. Owing to a silicate-rich mineral structure of BFs, BFRPs display exceptional resistance to chemical attack from acids, alkalis, saline solutions, and a broad range of industrial solvents, enabling BFRPs to maintain mechanical strength, dimensional stability, and fiber-matrix interfacial integrity even after prolonged exposure to corrosive environments. The inherent chemical inertness confers a significant advantage over E-GFs, which are highly susceptible to alkali-induced degradation, surface leaching, and structural deterioration in cementitious or alkaline media, thereby limiting the long-term performance of GFRPs in civil infrastructure applications [117, 118]. Although CFRPs offer strong chemical resistance in neutral or mildly corrosive environments, they may undergo oxidative degradation or matrix hydrolysis under extreme pH conditions, and their durability can be influenced by fiber sizing and resin chemistry, which affect interfacial stability. AFRs, despite their superior toughness, are prone to hydrolytic degradation and are vulnerable to strong acids, oxidizing agents, and long-term moisture exposure, restricting their use in chemically aggressive or humid environments unless supplemented with protective coatings or specially formulated matrices [119, 120]. In contrast, BFRPs exhibit low moisture absorption, minimal swelling, and excellent resistance to hydrothermal effects, reducing the risk of interface debonding and matrix cracking during wet-dry cycles, temperature fluctuations, or marine immersion. Furthermore, BFRPs show strong resistance to UV-induced aging, outperforming AFRPs that suffer severe photodegradation, discoloration, and strength loss under ultraviolet exposure [121].

Overall, the superior chemical stability, environmental resilience, and sustained mechanical performance of BFRPs make them highly suitable for infrastructure, marine, chemical-processing, energy, and outdoor engineering applications where continuous exposure to corrosive media and environmental stressors is unavoidable. These attributes position BF composites as a durable, low-maintenance, and cost-effective alternative to carbon, glass, and aramid fiber systems in modern sustainability-driven design and long-service-life engineering applications.

## APPLICATIONS OF BFRPs

BFRPs have gained increasing prominence as multifunctional engineering materials, with their application spectrum expanding rapidly across diverse industrial sectors, including automations, civil infrastructure, defence and personal protection shown schematically in Figure 7. This growth is primarily attributed to their favourable combination of high mechanical performance, excellent chemical and thermal stability, strong resistance to environmental degradation, and competitive cost. Owing to these attributes, BFRPs are increasingly regarded as viable alternatives to conventional CFRPs, GFRPs and AFRPs, particularly in scenarios demanding durability and long-term reliability under aggressive conditions [49, 122]. In civil infrastructure, BFRPs have been widely adopted as reinforcement materials in concrete structures, including bridge decks, beams, pavements, and components exposed to corrosive environments. Their inherent resistance to alkaline media and dimensional stability within cementitious matrices enable superior durability compared to GFRPs, which are prone to degradation in high-pH conditions. BFs rebars, meshes, and grids have been successfully implemented in large-scale infrastructure, contributing to enhanced life and reduced maintenance demands [76, 123].

The automotive sector has also witnessed increasing use of BFRPs as manufacturers pursue lightweight yet robust materials to comply with stringent fuel-efficiency and emissions standards. BFRPs are increasingly employed in structural and semi-structural automotive components, including bumper systems, interior panels, engine covers, and underbody protection elements. Their high impact resistance, vibration-damping capacity, and thermal stability under cyclic loading conditions make them attractive for automotive applications [124, 125]. In aerospace applications, BFRPs are being actively explored for secondary load-bearing components, interior structures, and fire-sensitive assemblies. Their intrinsic flame resistance, low smoke density, minimal toxic gas emission, and strong fatigue performance render them suitable for cabin panels, flooring systems, and cargo compartment structures. Recent investigations into BF composite structures for unmanned aerial vehicles (UAVs) have reported enhanced damage tolerance and improved manufacturability compared to traditional FRPs, suggesting strong potential for broader aerospace integration [126]. Marine engineering represents another critical application domain for BFRPs, where resistance to moisture ingress, saltwater corrosion, and ultraviolet radiation is essential. BFRPs have been incorporated into hull components, decking systems, boat frames, and offshore structural elements, exhibiting superior durability compared to conventional FRP composites under prolonged marine exposure [127, 128].

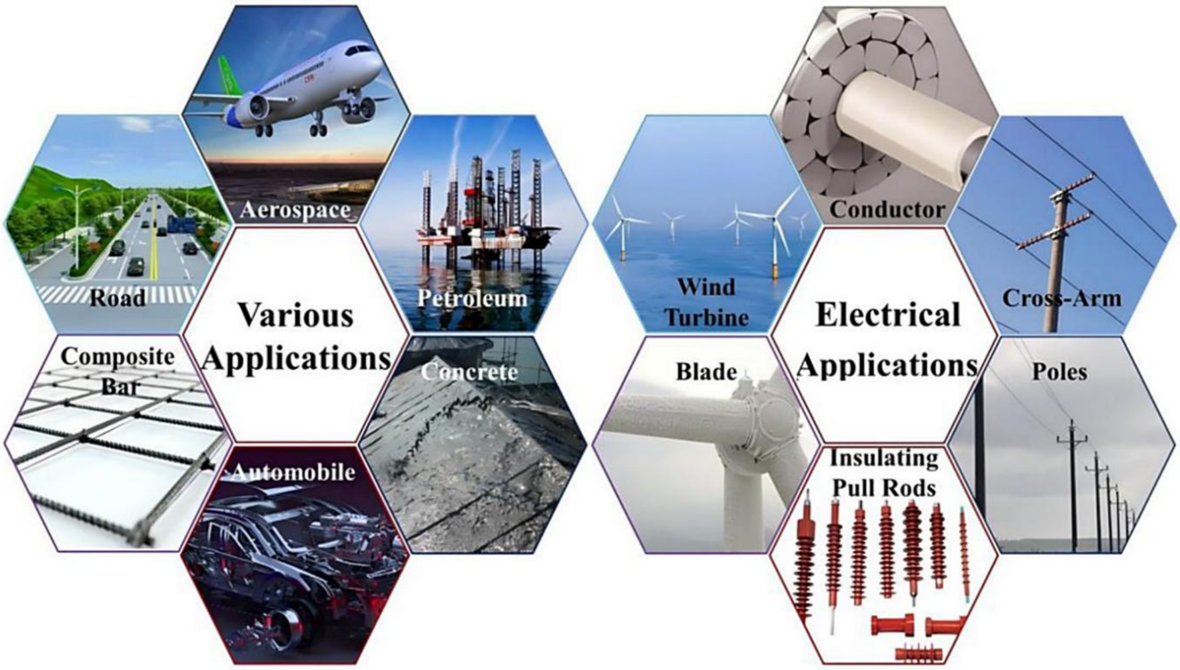


**Figure 7: Applications of BFRPs in various sectors, including automations, civil infrastructure, defence and personal protection (Reproduced with permission of [49], Copyright © 2025, MDPI).**

In the defense and personal protection sectors, BFRPs have attracted attention due to their high energy absorption capability, fracture toughness, and relatively low production cost. These properties enable their application in ballistic protection systems such as helmets, armor panels, and lightweight vehicle protection structures. While AFRPs continue to dominate high-end ballistic applications, BFRPs offer a cost-effective and environmentally sustainable alternative, particularly when employed in hybrid laminate configurations [129, 130]. Today, academic-industrial collaborations are driving innovation in multifunctional BFRPs with enhanced damping, self-sensing functionality, and electromagnetic interference (EMI) shielding capabilities. With recent advancements in fiber surface modification, matrix compatibility, and hybrid composite architectures, BFRPs are poised to play an increasingly significant role in next-generation structural and functional material systems aligned with sustainability and economic performance objectives [131].

## CHALLENGES AND PERSPECTIVES OF BFRPs

BFRPs hold strong promise as environmentally sustainable, cost-effective, and high-performance alternatives to traditional FRPs. Nevertheless, their widespread industrial adoption is tempered by several unresolved scientific, technological, and manufacturing challenges. Addressing these barriers is essential to unlock the potential of BFRPs and establish them as mainstream materials for structural and multifunctional applications [102]. One of the foremost challenges arises from the natural geological variability of basalt, which directly influences fiber quality.

Unlike CFs and GFs produced from controlled and well-characterized precursor chemistry, BFs originate from volcanic rock whose mineral composition can vary based on geographic and geological conditions. Differences in silica, iron oxide, and alkali content can significantly affect melting temperature, viscosity, fiber drawability, and ultimately fiber tensile strength, stiffness, and impact resistance. This intrinsic heterogeneity of BFs and the complicating process can result in inconsistent composite performance. Advancing reliable raw material classification systems, refining melt-processing parameters, and developing standard quality metrics for BFs are therefore vital for ensuring reproducibility and meeting stringent engineering specifications [132, 133].

A major challenge in the widespread adoption of BFRPs is optimizing fiber-matrix interfacial performance, as insufficient interfacial bonding, despite the inherently rough and chemically active surfaces of BFs, can impair fatigue resistance, accelerate hydrothermal degradation, and compromise long-term mechanical reliability under demanding service conditions. This has driven the need for advanced interfacial engineering approaches, including basalt-specific silane coupling agents, plasma surface treatments, nanoscale functional coatings, and organic–inorganic hybrid modifications, to enhance interfacial toughness and durability in both polymer and thermoplastic matrices.

Concurrently, industrial-scale manufacturing of BFs presents challenges related to fiber breakage during drawing, energy-intensive melting operations, limited automation, and production variability, all of which influence cost and quality [133]. Therefore, advancements in furnace design, continuous drawing technologies, surface coating systems, automated winding, and supply-chain integration are essential to achieving economic viability for large-scale applications of BFRPs. In parallel, a comprehensive understanding of the long-term durability and lifecycle performance of BFRPs remains underdeveloped, with limited data on creep behaviour, thermo-oxidative issues, fatigue crack evolution, and interfacial degradation under coupled mechanical and environmental loading, highlighting the need for predictive modeling tools, accelerated ageing protocols, and standardized durability assessment methods to support engineering certification [59, 134].

Hybrid composite architectures combining BFs, with multifunctional capabilities such as self-sensing, electromagnetic interference shielding, thermal insulation, and fire resistance, offer promising pathways for expanding BFRP. Coupled with basalt's natural abundance, comparatively low embodied energy, and potential for recycling, these developments position BFRPs as a sustainable and competitive alternative to conventional fiber reinforcements, with strong prospects for advancing next-generation structural and multifunctional composite technologies.

## CONCLUSION

BFRPs offer a unique synergy of mechanical performance, chemical resistance, environmental durability, and processing versatility, highlighting an alternative to traditional GFRPs, CFRPs and AFRPs. Their low moisture absorption, UV and impact resistance, and thermal stability ensure long-term performance in aggressive environments such as marine, infrastructure, automotive, and aerospace sectors. BFRPs are not only compatible with established composite manufacturing processes, including pultrusion, filament winding, and resin infusion, but also adaptable to both polymer and thermoplastic matrices, supporting scalable, cost-effective production. While challenges remain in fiber handling and sizing optimization, ongoing advancements in surface treatments and hybrid composite designs continue to enhance BFRPs capabilities. BFRPs provide a sustainable, low-maintenance, and high-performance solution for next-generation engineering demands. Driven by the combined requirements of long-term durability, environmental sustainability, and cost competitiveness, BFRPs are anticipated to gain broader adoption and emerge as a key contributor to the evolution of advanced composite materials.

## REFERENCES

[1] D. K. Rajak, D. D. Pagar, P. L. Menezes, and E. Linul, "Fiber-reinforced polymer composites: Manufacturing, properties, and applications," *Polymers*, vol. 11, no. 10, p. 1667, 2019.

[2] H. Abdollahiparsa, A. Shahmirzaloo, P. Teuffel, and R. Blok, "A review of recent developments in structural applications of natural fiber-Reinforced composites (NFRCs)," *Composites and Advanced Materials*, vol. 32, p. 26349833221147540, 2023.

[3] M. Csapó and J. G. Kovács, "Impact of fiber fragmentation on mechanical performance and environmental footprint of recycled glass fiber-reinforced polyamide composites," *Journal of Cleaner Production*, vol. 511, p. 145678, 2025.

[4] A. Andoko et al., "Performance of carbon fiber (CF)/Ceiba petandra fiber (CPF) reinforced hybrid polymer composites for lightweight high-performance applications," *Journal of Materials Research and Technology*, vol. 27, pp. 7636-7644, 2023.

[5] M. Sabet, "Revolutionizing structures: the rise of high-performance composite and nanocomposite polymers," *Polymer Bulletin*, pp. 1-50, 2025.

[6] J. Zhang, V. S. Chevali, H. Wang, and C.-H. Wang, "Current status of carbon fibre and carbon fibre composites recycling," *Composites Part B: Engineering*, vol. 193, p. 108053, 2020.

[7] A. He et al., "Advanced aramid fibrous materials: fundamentals, advances, and beyond," *Advanced Fiber Materials*, vol. 6, pp. 3-35, 2024.

[8] A. A. Musa et al., "Development of high-performance basalt fiber-reinforced polymer composite using a nanocellulose-based surface modification strategy," *Composites Part A: Applied Science and Manufacturing*, vol. 199, p. 109191, 2025.

[9] H. Liu et al., "A Review on Basalt Fiber Composites and Their Applications in Clean Energy Sector and Power Grids," *Polymers*, vol. 14, 2022.

[10] M. F. L. King, V. Srinivasan, and T. Purushothaman, "Basalt Fiber An Ancient Material for Innovative and Modern Application," *Middle-East Journal of Scientific Research*, vol. 22, pp. 308-312, 2014.

[11] S. Bao et al., "Enhancing the Mechanical Properties of Recycled Aggregate Concrete: A Comparative Study of Basalt-and Glass-Fiber Reinforcements," *Buildings*, vol. 15, p. 1718, 2025.

[12] A. Patti, L. Nele, M. Zarrelli, L. Graziosi, and D. Acierno, "A comparative analysis on the processing aspects of basalt and glass fibers reinforced composites," *Fibers and Polymers*, vol. 22, pp. 1449-1459, 2021.

[13] S. Ali et al., "Durability of Basalt and Glass Fiber Composites Under Extreme Environments," *Polymer Composites*, 2025.

[14] Y. G. Thyavihalli Girijappa, S. Mavinkere Rangappa, J. Parameswaranpillai, and S. Siengchin, "Natural Fibers as Sustainable and Renewable Resource for Development of Eco-Friendly Composites: A Comprehensive Review," *Frontiers in Materials*, vol. 6, 2019.

[15] M. K. Gupta, M. Ramesh, and S. Thomas, "Effect of hybridization on properties of natural and synthetic fiber-reinforced polymer composites (2001–2020): A review," *Polymer Composites*, vol. 42, pp. 4981-5010, 2021.

[16] V. Beloshenko, Y. Voznyak, A. Voznyak, and B. Savchenko, "New approach to production of fiber reinforced polymer hybrid composites," *Composites Part B: Engineering*, vol. 112, pp. 22-30, 2017.

[17] M. Agrawal, R. T. Durai Prabhakaran, and P. Mahajan, "Static and fatigue tensile performance of glass/basalt/epoxy hybrid and non-hybrid fiber composites—Role of hybrid sizings and matrix modifications," *Polymer Composites*, vol. 46, pp. 10222-10238, 2025.

[18] M. Jawaid and H. P. S. Abdul Khalil, "Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review," *Carbohydrate Polymers*, vol. 86, pp. 1-18, 2011.

[19] N. M. Nurazzi et al., "A Review on Natural Fiber Reinforced Polymer Composite for Bullet Proof and Ballistic Applications," *Polymers*, vol. 13, 2021.

[20] S.-H. Kim, J.-H. Lee, J.-W. Kim, S.-Y. Lee, and S.-J. Park, "Interfacial Behaviors of Basalt Fiber-Reinforced Polymeric Composites: A Short Review," *Advanced Fiber Materials*, vol. 4, pp. 1414-1433, 2022.

[21] H. A. Ghouti et al., "Structural and mechanical characteristics of silane-modified PIPD/basalt hybrid fiber-reinforced polybenzoxazine composites," *Materials Chemistry and Physics*, vol. 237, p. 121850, 2019.

[22] A. Cevahir, "Glass fibers," in *Fiber Technology for Fiber-Reinforced Composites*, M. Ö. Seydibeyoğlu, A. K. Mohanty, and M. Misra, Eds. Woodhead Publishing, 2017, pp. 99-121.

[23] J. M. Stickel and M. Nagarajan, "Glass fiber-reinforced composites: from formulation to application," *International Journal of Applied Glass Science*, vol. 3, pp. 122-136, 2012.

[24] S. Tungjitpornkull and N. Sombatsompop, "Processing technique and fiber orientation angle affecting the mechanical properties of E-glass fiber reinforced wood/PVC composites," *Journal of Materials Processing Technology*, vol. 209, pp. 3079-3088, 2009.

[25] M. Zhang and J. P. Matinlinna, "E-glass fiber reinforced composites in dental applications," *Silicon*, vol. 4, pp. 73-78, 2012.

[26] Q. Zu, M. Solvang, H. Li, "Commercial glass fibers," in *Fiberglass Science and Technology*, Springer, 2021, pp. 1-87.

[27] Y. Wu et al., "Recent progress in modifications, properties, and practical applications of glass fiber," *Molecules*, vol. 28, p. 2466, 2023.

[28] F. T. Wallenberger, "Commercial and experimental glass fibers," in *Fiberglass and Glass Technology*, 2009, pp. 3-90.

[29] M. Wang, S. Ullah, M. Rizwan, and X. Zhou, "Preparation process of mesophase pitch-based carbon fiber: a review," *RSC Advances*, vol. 15, pp. 39514-39538, 2025.

[30] N. Saito et al., "Application of carbon fibers to biomaterials: a new era of nano-level control of carbon fibers after 30-years of development," *Chemical Society Reviews*, vol. 40, pp. 3824-3834, 2011.

[31] T. M. Prenzel et al., "Bringing light into the dark—overview of environmental impacts of carbon fiber production and potential levers for reduction," *Polymers*, vol. 16, p. 12, 2023.

[32] S. Gellrich et al., "Concept for Predictive Quality in Carbon Fibre Manufacturing," 2024.

[33] L. Yin et al., "Reinforcing effect of aramid fibers on fatigue behavior of SBR/aramid fiber composites," *Polymer Testing*, vol. 80, p. 106092, 2019.

[34] B. A. Patterson et al., "Aramid nanofibers for multiscale fiber reinforcement of polymer composites," *Composites Science and Technology*, vol. 161, pp. 92-99, 2018.

[35] P. M. Gore and B. Kandasubramanian, "Functionalized Aramid Fibers and Composites for Protective Applications: A Review," *Industrial & Engineering Chemistry Research*, vol. 57, pp. 16537-16563, 2018.

[36] H. Wang, Y. Lin, H. Jiang, and Z. Liu, "Inter-layer failure and toughening mechanisms of carbon/aramid hybrid fiber composites interleaved with micro/nano pulps under low-velocity impact load," *Thin-Walled Structures*, vol. 202, p. 112086, 2024.

[37] P. Dharmavarapu and S. R. Mbs, "Aramid fibre as potential reinforcement for polymer matrix composites: a review," *Emergent materials*, vol. 5, pp. 1561-1578, 2022.

[38] Z. Li, J. Ma, H. Ma, and X. Xu, "Properties and applications of basalt fiber and its composites," *IOP Conference Series: Earth and Environmental Science*, vol. 186, p. 012052, 2018.

[39] J. Sim, C. Park, and D. Y. Moon, "Characteristics of basalt fiber as a strengthening material for concrete structures," *Composites Part B: Engineering*, vol. 36, pp. 504-512, 2005.

[40] T. Deák and T. Czigány, "Chemical Composition and Mechanical Properties of Basalt and Glass Fibers: A Comparison," *Textile Research Journal*, vol. 79, pp. 645-651, 2009.

[41] L. Ding, Y. Liu, J. Liu, and X. Wang, "Correlation analysis of tensile strength and chemical composition of basalt fiber roving," *Polymer Composites*, vol. 40, pp. 2959-2966, 2019.

[42] A. G. Novitskii and M. V. Efremov, "Technological aspects of the suitability of rocks from different deposits for the production of continuous basalt fiber," *Glass and Ceramics*, vol. 69, pp. 409-412, 2013.

[43] D. Chen, G. Sun, M. Meng, Q. Li, and X. Jin, "Flexural performance and cost efficiency of carbon/basalt/glass hybrid FRP composite laminates," *Thin-Walled Structures*, vol. 142, pp. 516-531, 2019.

[44] Q. Liu, M. T. Shaw, R. S. Parnas, and A.-M. McDonnell, "Investigation of basalt fiber composite mechanical properties for applications in transportation," *Polymer Composites*, vol. 27, pp. 41-48, 2006.

[45] F. Bauer, M. Kempf, F. Weiland, and P. Middendorf, "Structure-property relationships of basalt fibers for high performance applications," *Composites Part B: Engineering*, vol. 145, pp. 121-128, 2018.

[46] I. R. Chowdhury, R. Pemberton, and J. Summerscales, "Developments and Industrial Applications of Basalt Fibre Reinforced Composite Materials," *Journal of Composites Science*, vol. 6, 2022.

[47] K. Lou et al., "Research on the micro-nano characteristic of basalt fiber and its impact on the performance of relevant asphalt mastic," *Construction and Building Materials*, vol. 318, p. 126048, 2022.

[48] C. Liu et al., "Preparation of continuous silicate fiber: comparison of natural basalt and artificial stimulant with the same chemical composition," *Natural Resources Research*, vol. 32, pp. 1549-1558, 2023.

[49] M. Zhu, M. Zhu, R. Zhai, W. Zhu, and J. He, "Research Progress on the Surface Modification of Basalt Fibers and Composites: A Review," *Materials*, vol. 18, p. 1164, 2025.

[50] M. Valentini et al., "Effect of fiber surface state on the thermomechanical and interfacial properties of in situ polymerized polyamide 6/basalt fiber composites," *Composites Part A: Applied Science and Manufacturing*, vol. 190, p. 108681, 2025.

[51] S. Liu et al., "Surface modification of basalt fibers with improved reactivity, thermal stability, and tensile strength," *Fibers and Polymers*, vol. 25, pp. 3403-3413, 2024.

[52] Y. Wang, X. Huang, J. Wang, and X. Zhang, "Surface microstructure of basalt fiber after surface modification and mechanical properties of concrete reinforced with modified basalt fiber," *Journal of Materials in Civil Engineering*, vol. 35, p. 04023407, 2023.

[53] A. Parkash, A. Kadier, and P.-C. Ma, "Effect of NaOH concentration on the surface and mechanical properties of continuous basalt fibers," *Next Research*, vol. 2, p. 100682, 2025.

[54] S. Ni, W. Luo, and Z. Wang, "Investigating the influence of acid-base/KH550 composite surface modified BF on the properties of fiber-reinforced SBS-modified asphalt mastic," *Construction and Building Materials*, vol. 448, p. 138290, 2024.

[55] L. Yan et al., "Review of research on basalt fibers and basalt fiber-reinforced composites in China (I): Physicochemical and mechanical properties," *Polymers and Polymer Composites*, vol. 29, pp. 1612-1624, 2021.

[56] C. Chen, Y. Ding, X. Wang, and L. Bao, "Recent advances to engineer tough basalt fiber reinforced composites: A review," *Polymer Composites*, vol. 45, pp. 12559-12574, 2024.

[57] A. Asadi et al., "Basalt fibers as a sustainable and cost-effective alternative to glass fibers in sheet molding compound (SMC)," *Composites Part B: Engineering*, vol. 123, pp. 210-218, 2017.

[58] S. Yuan et al., "Effects of brick-concrete aggregates on the mechanical properties of basalt fiber reinforced recycled waste concrete," *Journal of Building Engineering*, vol. 80, p. 108023, 2023.

[59] H. Liu et al., "A Review on Basalt Fiber Composites and Their Applications in Clean Energy Sector and Power Grids," *Polymers*, vol. 14, p. 2376, 2022.

[60] T. M. N. Tran, M. N. Prabhakar, L. D. Woo, and S. Jung-il, "Flame Retardancy and Heat Shielding in Green Polypropylene Composites Using Biohybrid Fibers and Agro-Waste Fillers," *ACS Applied Bio Materials*, vol. 8, pp. 893-902, 2025.

[61] Y. Zheng, Y. Zhang, J. Zhuo, Y. Zhang, and C. Wan, "A review of the mechanical properties and durability of basalt fiber-reinforced concrete," *Construction and Building Materials*, vol. 359, p. 129360, 2022.

[62] F. Li, Z. Guo, and P. Wu, "Mechanical properties of steel fiber RPC, basalt fiber RPC, and hybrid fiber RPC: A review of research progress," *Structural Concrete*, vol. 25, pp. 3953-3965, 2024.

[63] W. Yang et al., "A review of the mechanical properties and durability of basalt fiber recycled concrete," *Construction and Building Materials*, vol. 412, p. 134882, 2024.

[64] M. Lubas et al., "Experimental Study of Amphibolite–Basalt (SiO2-AlO3-CaO-Fe2O3) Glasses for Glass-Ceramic Materials Production," *Materials*, vol. 16, p. 6887, 2023.

[65] N. Jain, V. K. Singh, and S. Chauhan, "Review on effect of chemical, thermal, additive treatment on mechanical properties of basalt fiber and their composites," *Journal of the Mechanical Behavior of Materials*, vol. 26, pp. 205-211, 2017.

[66] F. J. Shi, "A study on structure and properties of basalt fiber," *Applied Mechanics and Materials*, vol. 238, pp. 17-21, 2012.

[67] B. Wang et al., "High-Temperature Mechanical Properties of Basalt Fibers: A Step Towards Fire-Safe Materials for Photovoltaic Applications," *Sustainability*, vol. 16, p. 10853, 2024.

[68] S. M. Niyazova et al., "Physicochemical properties of andesitic basalt mineral fibers," *Glass and Ceramics*, vol. 79, pp. 107-111, 2022.

[69] Y. Zhang et al., "Mechanical and thermal properties of basalt fiber reinforced poly (butylene succinate) composites," *Materials Chemistry and Physics*, vol. 133, pp. 845-849, 2012.

[70] M. A. Shayed, R.-D. Hund, and C. Cherif, "Improvement of thermo-mechanical properties of basalt fiber using heat resistant polymeric coatings," *Fibers and Polymers*, vol. 15, pp. 2086-2094, 2014.

[71] J. Fořt, J. Kočí, and R. Černý, "Environmental efficiency aspects of basalt fibers reinforcement in concrete mixtures," *Energies*, vol. 14, p. 7736, 2021.

[72] S. Ali et al., "Durability of Basalt and Glass Fiber Composites Under Extreme Environments," *Polymer Composites*, 2025.

[73] G. Wu, X. Wang, Z. Wu, Z. Dong, and G. Zhang, "Durability of basalt fibers and composites in corrosive environments," *Journal of Composite Materials*, vol. 49, pp. 873-887, 2015.

[74] Y. H. Zhang, W. L. Zhong, and L. F. Fan, "Long-term durability investigation of basalt fiber-reinforced geopolymer concrete in marine environment," *Journal of Materials Research and Technology*, vol. 31, pp. 593-605, 2024.

[75] E. Quagliarini, F. Monni, F. Bondioli, and S. Lenci, "Basalt fiber ropes and rods: Durability tests for their use in building engineering," *Journal of Building Engineering*, vol. 5, pp. 142-150, 2016.

[76] O. A. Mohamed, W. Al Hawat, and M. Keshawarz, "Durability and mechanical properties of concrete reinforced with basalt fiber-reinforced polymer (BFRP) bars: Towards sustainable infrastructure," *Polymers*, vol. 13, p. 1402, 2021.

[77] M. T. Elshazli, K. Ramirez, A. Ibrahim, and M. Badran, "Mechanical, durability and corrosion properties of basalt fiber concrete," *Fibers*, vol. 10, p. 10, 2022.

[78] G. Alaimo, A. Valenza, D. Enea, and V. Fiore, "The durability of basalt fibres reinforced polymer (BFRP) panels for cladding," *Materials and Structures*, vol. 49, pp. 2053-2064, 2016.

[79] R. Palanivelu and B. Panchanatham, "Strength and durability characteristics of basalt fiber-based engineered geopolymer composites under elevated temperature," *Matéria (Rio de Janeiro)*, vol. 30, p. e20250066, 2025.

[80] C. Dong, G. Howie, R. Costelo, and W. Biswas, "Technical and Eco-Efficiency Implications of the Use of Basalt Fibre in Hybrid Composites," *Intelligent and Sustainable Manufacturing*, vol. 2, p. 10013, 2025.

[81] B. Zuccarello, F. Bongiorno, and C. Militello, "Basalt Fiber Hybridization Effects on High-Performance Sisal-Reinforced Biocomposites," *Polymers*, vol. 14, p. 1457, 2022.

[82] Z. Li et al., "Influence of basalt fiber and polypropylene fiber on the mechanical and durability properties of cement-based composite materials," *Journal of Building Engineering*, vol. 90, p. 109335, 2024.

[83] M. Afroz, I. Patnaikuni, and S. Venkatesan, "Chemical durability and performance of modified basalt fiber in concrete medium," *Construction and Building Materials*, vol. 154, pp. 191-203, 2017.

[84] A. R. Tavadi et al., "Basalt fiber and its composite manufacturing and applications: An overview," *International Journal of Engineering, Science and Technology*, vol. 13, pp. 50-56, 2022.

[85] A. Pavlović, T. Donchev, D. Petkova, and N. Staletović, "Sustainability of alternative reinforcement for concrete structures: Life cycle assessment of basalt FRP bars," *Construction and Building Materials*, vol. 334, p. 127424, 2022.

[86] Z. Li, J. Ma, H. Ma, and X. Xu, "Properties and Applications of Basalt Fiber and Its Composites," *IOP Conference Series: Earth and Environmental Science*, vol. 186, p. 012052, 2018.

[87] U. R. Hashim et al., "Effects of Accelerated Weathering on Degradation Behavior of Basalt Fiber Reinforced Polymer Nanocomposites," *Polymers*, vol. 12, p. 2621, 2020.

[88] R. Shen et al., "An Enhanced Vacuum-Assisted Resin Transfer Molding Process and Its Pressure Effect on Resin Infusion Behavior and Composite Material Performance," *Polymers*, vol. 16, p. 1386, 2024.

[89] L. A. Khan and A. H. Mehmood, "Cost-effective composites manufacturing processes for automotive applications," in *Lightweight Composite Structures in Transport*, J. Njuguna, Ed. Woodhead Publishing, 2016, pp. 93-119.

[90] T. Islam et al., "Advancements and challenges in natural fiber-reinforced hybrid composites: A comprehensive review," *SPE Polymers*, vol. 5, pp. 481-506, 2024.

[91] A. Kulshreshtha, "An overview of composite fabrication, design and cost," *Handbook of polymer blends and composites*, pp. 5-52, 2002.

[92] I. Elfaleh et al., "A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials," *Results in engineering*, vol. 19, p. 101271, 2023.

[93] V. Fiore, T. Scalici, G. Di Bella, and A. Valenza, "A review on basalt fibre and its composites," *Composites Part B: Engineering*, vol. 74, pp. 74-94, 2015.

[94] F. Sarasini et al., "Effect of basalt fiber hybridization on the impact behavior under low impact velocity of glass/basalt woven fabric/epoxy resin composites," *Composites Part A: Applied Science and Manufacturing*, vol. 47, pp. 109-123, 2013.

[95] I. Demirci, A. Avcı, and M. T. Demirci, "Investigation of nano-hybridization effects on low velocity impact behaviors of basalt fiber reinforced composites," *Journal of Composite Materials*, vol. 55, pp. 401-414, 2021.

[96] S. Joshi et al., "Hybridization effect on the mechanical properties of basalt fiber reinforced ZnO modified epoxy composites," *Polymer Composites*, vol. 43, pp. 5704-5714, 2022.

[97] Ö. Y. Bozkurt, "Hybridization effects on tensile and bending behavior of aramid/basalt fiber reinforced epoxy composites," *Polymer Composites*, vol. 38, pp. 1144-1150, 2017.

[98] Y. Wei et al., "Effect of Silane-Modified Nano-Al(2)O(3)-Reinforced Vinyl Ester Resin on the Flexural Properties of Basalt Fiber Composites," *Materials*, vol. 18, 2025.

[99] C. Zhang et al., "Interfacial reinforcement strategy of basalt fiber/polymer composite constructed by interlocking interface composed of ZnO nanowires," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 681, p. 132778, 2024.

[100] S. M. Darshan and B. Suresha, "Effect of basalt fiber hybridization on mechanical properties of silk fiber reinforced epoxy composites," *Materials Today: Proceedings*, vol. 43, pp. 986-994, 2021.

[101] A. Saleem, L. Medina, and M. Skrifvars, "Influence of fiber coating and polymer modification on mechanical and thermal properties of bast/basalt reinforced polypropylene hybrid composites," *Journal of Composites Science*, vol. 4, p. 119, 2020.

[102] P. Murugadoss et al., "Kenaf/Basalt Fiber-Reinforced Epoxy Matrix Hybrid Composites: Current Trends, Challenges, and Future Prospects in Advanced Material Development," *Results in Engineering*, p. 104816, 2025.

[103] S. Khandelwal and K. Y. Rhee, "Recent advances in basalt-fiber-reinforced composites: Tailoring the fiber-matrix interface," *Composites Part B: Engineering*, vol. 192, p. 108011, 2020.

[104] Y. Yao et al., "Comparison of Tensile Properties of Carbon Fiber, Basalt Fiber and Hybrid Fiber Reinforced Composites Under Various Strain Rates," *Applied Composite Materials*, vol. 29, pp. 1147-1165, 2022.

[105] S. Yu et al., "The effect of amino-silane coupling agents having different molecular structures on the mechanical properties of basalt fiber-reinforced polyamide 6,6 composites," *Composites Part B: Engineering*, vol. 163, pp. 511-521, 2019.

[106] V. Dhand, G. Mittal, K. Y. Rhee, S.-J. Park, and D. Hui, "A short review on basalt fiber reinforced polymer composites," *Composites Part B: Engineering*, vol. 73, pp. 166-180, 2015.

[107] O. Çelik, A. Yaşar, and B. Karaçor, "Properties of basalt/aramid fiber reinforced hybrid composites compared to carbon fiber composites," *Polymer Composites*, vol. 44, pp. 3509-3521, 2023.

[108] Q. Fu et al., "Flexural Behavior and Prediction Model of Basalt Fiber/Polypropylene Fiber-Reinforced Concrete," *International Journal of Concrete Structures and Materials*, vol. 16, p. 31, 2022.

[109] D. Chen, Q. Luo, M. Meng, Q. Li, and G. Sun, "Low velocity impact behavior of interlayer hybrid composite laminates with carbon/glass/basalt fibres," *Composites Part B: Engineering*, vol. 176, p. 107191, 2019.

[110] Y. Yao, D. Zhu, H. Zhang, G. Li, and B. Mobasher, "Tensile behaviors of basalt, carbon, glass, and aramid fabrics under various strain rates," *Journal of Materials in Civil Engineering*, vol. 28, p. 04016081, 2016.

[111] B. Karacor and M. Ozcanli, "Thermal and mechanical characteristic investigation of the hybridization of basalt fiber with aramid fiber and carbon fiber," *Polymer Composites*, vol. 43, pp. 8529-8544, 2022.

[112] M. H. Doğru, E. Yeter, İ. Göv, and K. Göv, "Ballistic impact resistance and flexural performance of natural basalt fiber with carbon and glass fibers in inter-ply hybrid composites," *Polymer Composites*, vol. 45, pp. 9785-9801, 2024.

[113] J. Dong et al., "Mechanical behavior and impact resistance of rubberized concrete enhanced by basalt fiber-epoxy resin composite," *Construction and Building Materials*, vol. 435, p. 136836, 2024.

[114] K. Mazur, Z. S. Siwy, A. Adamczyk, and S. Kuciel, "Synergistic effect of aramid and basalt fibers on mechanical, thermal and dynamic properties of polylactide hybrid composites," *Industrial Crops and Products*, vol. 198, p. 116630, 2023.

[115] N. Wolter et al., "Effects of flame-retardant additives on the manufacturing, mechanical, and fire properties of basalt fiber-reinforced polybenzoxazine," *Polymer Engineering & Science*, vol. 61, pp. 551-561, 2021.

[116] W. Mingchao et al., "Chemical durability and mechanical properties of alkali-proof basalt fiber and its reinforced epoxy composites," *Journal of Reinforced Plastics and Composites*, vol. 27, pp. 393-407, 2008.

[117] P. Cousin et al., "Chemical resistance of carbon, basalt, and glass fibers used in FRP reinforcing bars," *Journal of Composite materials*, vol. 53, pp. 3651-3670, 2019.

[118] S. Ying and X. Zhou, "Chemical and thermal resistance of basalt fiber in inclement environments," *Journal of Wuhan University of Technology-Mater. Sci. Ed.*, vol. 28, pp. 560-565, 2013.

[119] A. A. Dalinkevich et al., "Modern basalt fibrous materials and basalt fiber-based polymeric composites," *Journal of Natural Fibers*, vol. 6, pp. 248-271, 2009.

[120] D. Rassokhin et al., "Determining the strength and thermal, chemical resistance of the epoxy polymer composite filled with basalt micro–Nano fiber in the amount of 15–80% by weight," *Eastern-European Journal of Enterprise Technologies*, vol. 2, p. 104, 2020.

[121] B. Ding, L. Zhang, and J. Liu, "The difference in weather resistance and corrosion process for different types of basalt fiber," *Journal of Non-Crystalline Solids*, vol. 590, p. 121678, 2022.

[122] Q. Liu, M. T. Shaw, R. S. Parnas, and A. M. McDonnell, "Investigation of basalt fiber composite mechanical properties for applications in transportation," *Polymer composites*, vol. 27, pp. 41-48, 2006.

[123] A. Patnaik, "Applications of basalt fiber reinforced polymer (BFRP) reinforcement for transportation infrastructure," *Developing a Research Agenda for Transportation Infrastructure*, pp. 1-5, 2009.

[124] C. Paramasivam and R. Venugopal, "Design and development of glass/basalt fiber reinforced composite material for automobile applications," *Journal of Industrial Textiles*, vol. 51, p. 1668S-1681S, 2022.

[125] A. Saleem, L. Medina, and M. Skrifvars, "Hybrid polymer composites of bio-based bast fibers with glass, carbon and basalt fibers for automotive applications—a review," *Molecules*, vol. 25, p. 4933, 2020.

[126] N. Coughlin et al., "Development and mechanical properties of basalt fiber-reinforced acrylonitrile butadiene styrene for in-space manufacturing applications," *Journal of Composites Science*, vol. 3, p. 89, 2019.

[127] V. Fiore, G. Di Bella, and A. Valenza, "Glass–basalt/epoxy hybrid composites for marine applications," *Materials & Design*, vol. 32, pp. 2091-2099, 2011.

[128] P. Davies and W. Verbouwe, "Evaluation of basalt fibre composites for marine applications," *Applied Composite Materials*, vol. 25, pp. 299-308, 2018.

[129] D. Zhu, Y. Tang, and M. Z. Rahman, "Basalt fiber: composites and applications," in *Synthetic and Mineral Fibers, Their Composites and Applications*, Elsevier, 2024, pp. 337-361.

[130] S. Y. Nayak et al., "Potential of natural fibers in composites for ballistic applications–a review," *Journal of Natural Fibers*, vol. 19, pp. 1648-1658, 2022.

[131] H. Liu et al., "A review on basalt fiber composites and their applications in clean energy sector and power grids," *Polymers*, vol. 14, p. 2376, 2022.

[132] Z. M. Zhang et al., "Research Progress on the Impact Resistance of Basalt Fiber-Reinforced Polymer Composites," *IOP Conference Series*, p. 082017.

[133] G. Liu and X. Wang, "Advances in Basalt Fiber Reinforced Cement-based Composites: Mechanical Properties and Durability Insights," *Journal of Engineering Research and Reports*, vol. 27, pp. 225-231, 2025.

[134] J. Li et al., "Advancements in Basalt Fiber-Reinforced Composites: A Critical Review," *Coatings*, vol. 15, p. 1441, 2025.