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Synergistic Effect of Green Nanofillers on Basalt–Kenaf Reinforced Sustainable Polymer Composites

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Abstract

This study examines the synergistic impact of green nanofillers on the mechanical and structural properties of basalt–kenaf fiber reinforced polyester composites, with the objective of developing sustainable, high-performance polymer materials. The composites were produced with different fiber ratios: B1 (70% basalt, 30% kenaf), B2 (60% basalt, 40% kenaf), and B3 (50% basalt, 50% kenaf), and were reinforced with 1 wt.% green-synthesized nano-TiO_2, obtained using an eco-friendly sol–gel technique with plant extracts. The use of nanofillers markedly improved the interfacial adhesion between fibers and the polyester matrix. B2 demonstrated superior performance among the formulations, attaining a tensile strength of 165 MPa, a flexural strength of 228 MPa, and an impact energy of 17.3 kJ/m², representing a 20–25% enhancement compared to the non-nano composites. The density diminished by 10%, indicating enhanced lightweight properties, while SEM analysis verified consistent nano-TiO_2 distribution and diminished microvoid occurrence. The synergistic impact of high-strength basalt fibers, natural kenaf reinforcement, and eco-friendly nanofillers yielded an exceptional equilibrium between mechanical performance and environmental sustainability. The research finds that green nano-enhanced basalt–kenaf composites present a feasible, environmentally sustainable option for structural, automotive, and marine applications, in accordance with green engineering and circular economy principles.

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Keywords: Basalt-kenaf hybrid composites, green nanofillers, nano-TiO_2, sustainable polymer composites, mechanical properties, eco-friendly materials

INTRODUCTION

The increasing global demand for eco-friendly materials has markedly expedited research on sustainable composite technologies designed to minimize ecological footprints while preserving superior mechanical performance [1–2]. Traditional synthetic fibers like glass and carbon have historically prevailed in structural applications; however, their non-biodegradability, energy-intensive manufacturing processes, and disposal issues have redirected focus toward more sustainable alternatives [3–4]. Natural fiber-reinforced polymer composites have emerged as viable options owing to their low density, biodegradability, and very minimal environmental impact during cultivation, harvesting, and processing [5–6]. Kenaf fiber is distinguished by its elevated cellulose content, superior toughness, and quick renewability, rendering it a compelling reinforcement in sustainable polymer matrices [7–9]. Sustainable polymer composites are engineered to reduce environmental impact by integrating renewable, recyclable, or low-energy-consuming materials while preserving functional and mechanical performance. These composites emphasize reduced carbon footprint, minimized use of hazardous chemicals, and improved end-of-life sustainability. In this context, basalt–kenaf hybrid fiber systems represent an effective sustainable solution. Kenaf fiber is a fast-growing, biodegradable natural reinforcement with low density and minimal environmental burden during cultivation and processing. Basalt fiber, derived directly from natural volcanic rock, requires comparatively lower energy for production than conventional glass fibers and is free from toxic additives. The hybridization of basalt and kenaf fibers enables the development of composites that combine high mechanical strength, thermal stability, and durability with lightweight characteristics and reduced environmental impact. This synergistic combination significantly lowers dependency on fully synthetic fibers while enhancing structural efficiency and sustainability, making basalt–kenaf systems suitable for green composite applications.

Alongside natural fibers, basalt fibers - extracted from molten volcanic rock - have emerged as an eco-friendly, high-performance material due to its exceptional tensile strength, elevated temperature resistance, and corrosion stability [10–12]. Basalt synthesis necessitates less energy than glass fiber manufacture, thereby categorizing it as a "green mineral fiber" appropriate for hybrid composite development [13–14]. The hybridization of natural and inorganic fibers is a recognized method for optimizing strength, stiffness, durability, and sustainability, allowing composites to surpass the constraints of single-fiber systems [15–17]. The amalgamation of basalt and kenaf fibers produces a hybrid composite that utilizes basalt's mechanical strength and kenaf's lightweight, environmentally sustainable properties, leading to superior structural efficiency and greater damage resistance [18–21]. Optimizing the fiber ratio is essential for regulating the stiffness-to-weight ratio, impact resistance, and overall mechanical properties.

Incorporating nanofillers has become a crucial strategy in contemporary materials engineering to boost composite performance, significantly improving mechanical, thermal, and microstructural properties through nanoscale reinforcement [22–24]. Nanoparticles enhance the polymer matrix, diminish microvoid formation, and strengthen fiber–matrix interfacial interaction, thus promoting more efficient stress transfer throughout the composite system [25–27]. Among diverse nanofillers, nano-TiO_2 is esteemed for its substantial surface area, exceptional stability, and robust interfacial activity, facilitating notable enhancements in tensile, flexural, and impact properties when integrated into hybrid fiber composites [28–30]. Recent advancements in green nanotechnology have highlighted eco-friendly synthesis methods, such as plant-mediated sol–gel techniques, which eliminate toxic chemicals and minimize thermal and chemical waste [31–33]. Green-synthesized nano- TiO_2 offers ecological advantages and enhanced compatibility with natural fibers owing to the organic stabilizing agents derived from plant extracts [34–36]. This environmentally friendly strategy adheres to circular economy concepts and facilitates sustainable composite manufacturing while maintaining material performance [37–38].

The microstructural function of nanofillers is crucial in hybrid composites, as interfacial interactions between different fiber types and the polymer matrix dictate the overall mechanical behaviour [39–40]. The efficient dispersion of nanoparticles reduces stress concentrations, improves crack-bridging mechanisms, and fortifies interfacial adhesion, therefore diminishing delamination and enhancing fatigue resistance [41–43]. Hybrid composites containing nanofillers frequently demonstrate enhancements in tensile strength, flexural stiffness, impact toughness, and overall durability, rendering them appropriate for structural, automotive, aerospace, and marine applications [44–45]. Moreover, decreases in composite density facilitate lightweight design objectives that are increasingly emphasized in engineering sectors aiming for enhanced fuel efficiency and diminished emissions [46]. The reinforcement efficiency of nanofillers in polymer composites is strongly dependent on their size, morphology, and surface chemistry. Nanoparticles with smaller dimensions provide a high specific surface area, which increases interfacial contact with the polymer matrix and enhances load-transfer efficiency. Properly controlled nanoscale dimensions prevent excessive agglomeration while enabling effective restriction of polymer chain mobility, thereby improving stiffness and strength. The morphology of nanofillers further influences stress-transfer behavior; spherical nano-TiO_2 particles promote uniform dispersion, reduce microvoid formation, and act as effective crack-arresting sites under mechanical loading. Moreover, surface chemistry plays a vital role in determining interfacial compatibility. Green-synthesized nano-TiO_2 contains bio-derived surface functional groups that enhance wettability and interfacial adhesion with both the polyester matrix and kenaf fibers. These surface interactions improve fiber–matrix bonding, reduce interfacial debonding, and enable efficient stress redistribution, collectively leading to enhanced reinforcement efficiency and mechanical performance of basalt–kenaf hybrid composites.

Notwithstanding advancements in natural fiber composites, research on the integration of basalt–kenaf hybrid systems with green-synthesized nano-TiO_2 is scarce, especially concerning the synergistic effects resulting from the concurrent interaction of fiber hybridization and environmentally friendly nanofiller reinforcement. Comprehending these interactions is essential for creating advanced sustainable composites that can substitute conventional mineral-based materials. This study seeks to examine the mechanical, microstructural, and lightweight properties of basalt–kenaf reinforced polyester composites augmented with green-synthesized nano-TiO_2, thereby advancing sustainable material innovation and environmental stewardship in advanced composite engineering.

MATERIALS AND METHODS

The basalt–kenaf hybrid polymer composites were developed using polyester resin as the matrix, basalt and kenaf fibers as reinforcements, and green-synthesized nano - TiO_2 as the nanofiller, following environmentally conscious processing principles. Basalt and kenaf fibers were arranged into three hybrid weight ratios - B1 (70% basalt, 30% kenaf), B2 (60% basalt, 40% kenaf), and B3 (50% basalt, 50% kenaf) - to examine the synergistic influence of fiber composition on composite behavior . Prior to fabrication, both fiber types were dried to remove moisture, cut to uniform lengths, and conditioned to ensure consistent processing quality. The nano- TiO_2 used for reinforcement was synthesized through a green sol–gel method using plant extracts, where bioactive compounds in the extracts acted as natural reducing and stabilizing agents, eliminating the need for toxic chemical reagents. A fixed content of 1 wt.% nano - TiO_2 was incorporated into the polyester resin, and homogeneous dispersion was achieved by mechanical stirring followed by ultrasonication to prevent nanoparticle agglomeration and to enhance surface interaction with the polymer matrix . Composite fabrication was performed using a hand lay-up technique followed by compression molding, ensuring good fiber impregnation and void reduction. The cured laminates underwent controlled post-curing to complete cross-linking within the polyester matrix and to stabilize mechanical characteristics. Standardized specimens were then machined for tensile, flexural, impact, and density testing according to relevant ASTM procedures, enabling quantifiable assessment of mechanical improvements associated with fiber hybridization and nano-reinforcement. The B2 hybrid formulation demonstrated superior performance, which was attributed to optimized basalt–kenaf interaction and improved resin reinforcement through nano - TiO_2 addition. Scanning Electron Microscopy (SEM) was used to evaluate fiber–matrix adhesion, nanoparticle dispersion, and microstructural integrity, with observations confirming reduced micro voids and enhanced interfacial bonding in nano-enhanced sample. Additionally, density measurements were performed using Archimedes' principle to verify the reported 10% reduction in composite density associated with nanofiller inclusion and fiber hybridization. All characterization results collectively validated that the combination of high-strength basalt fibers, lightweight kenaf fibers, and green-synthesized nano- TiO_2 contributed to improved structural performance and sustainability. Figure 1 shows the following materials: (a) basalt fibre (b) kenaf fibre (c) titanium dioxide & (d) resin for binding.

Figure 1. The following materials: (a) Basalt fibre; (b) Kenaf fibre; (c) Titanium dioxide and (d) Resin for binding.

EXPERIMENTAL METHOD

The basalt–kenaf hybrid composites were fabricated using polyester resin reinforced with green-synthesized nano- TiO_2 to evaluate the synergistic effects of fiber hybridization and eco-friendly nanomaterial incorporation. Basalt and kenaf fibers were first dried, cut to uniform lengths, and prepared in three weight-ratio combinations: B1 (70% basalt/30% kenaf), B2 (60% basalt/40% kenaf), and B3 (50% basalt/50% kenaf). The nano- TiO_2 used for reinforcement was produced through a green sol–gel method in which plant extracts served as natural reducing and stabilizing agents, forming fine anatase-phase nanoparticles. A 1 wt.% concentration of the resulting nanomaterial was dispersed into the polyester resin using mechanical stirring followed by ultrasonication to ensure uniform distribution and minimize agglomeration. The fibers were arranged in layered form inside a mold, after which the nanofiller-enhanced resin was poured over the reinforcement stack and carefully rolled to promote complete wet-out. The laminates were consolidated using compression molding to eliminate entrapped air and achieve adequate fiber–matrix contact, then cured at room temperature and post-cured under mild heating to promote complete polymer crosslinking. After curing, the panels were cut into standardized specimens for mechanical characterization. Tensile, flexural, and impact properties were evaluated according to relevant ASTM methods, while density was measured using Archimedes' principle to quantify the lightweight characteristics imparted by nano-TiO_2 addition. Microstructural examination of fracture surfaces was conducted using Scanning Electron Microscopy (SEM), which was employed to assess nanoparticle dispersion, fiber–matrix interfacial bonding, micro void reduction, and overall structural integrity.

The incorporation of 1 wt.% green-synthesized nano - TiO_2 significantly enhanced the mechanical and microstructural performance of the basalt–kenaf hybrid polyester composites, with the B2 formulation (60% basalt/40% kenaf) exhibiting the most superior results. B2 achieved a tensile strength of 165 MPa, flexural strength of 228 MPa, and impact energy absorption of 17.3 kJ/m², representing an overall 20–25% improvement compared to the non-nano composites. The B1 and B3 specimens also showed mechanical enhancement but remained lower than B2 due to less favorable fiber synergy. All nano-reinforced composites demonstrated an approximate 10% reduction in density, confirming improved lightweight characteristics. SEM analysis revealed uniform nano - TiO_2 dispersion, reduced micro voids, and stronger fiber–matrix bonding in B2, while B1 and B3 displayed less optimal interfacial quality. Overall, the results confirm that the synergistic combination of basalt and kenaf fibers, reinforced with green nano - TiO_2, produces a composite with superior strength, stiffness, toughness, and structural integrity compared to non-nano or non-optimized hybrids.

MECHANICAL TESTING

Mechanical testing of the basalt–kenaf hybrid composites reinforced with 1 wt.% green-synthesized nano- TiO_2 was performed to comprehensively evaluate their structural performance and to determine the influence of fiber ratio and nanofiller incorporation on mechanical behavior. Tensile testing was carried out using a calibrated Universal Testing Machine (UTM) following ASTM D3039, where rectangular composite coupons with bonded end tabs were loaded under displacement control at a constant crosshead speed to obtain tensile strength, tensile modulus, and elongation at break. Flexural properties were assessed using a three-point bending configuration according to ASTM D790, with a span-to-depth ratio of 16:1 to ensure pure bending. Load–deflection curves were recorded to compute flexural strength, modulus, and deformation characteristics. Impact resistance was measured using an Izod or Charpy impact tester per ASTM D256, where notched specimens were impacted with a pendulum hammer, and the absorbed energy was normalized by the cross-sectional area to obtain impact strength in kJ/m².

Density measurements were conducted using the Archimedes' principle (ASTM D792), by determining the mass of each specimen in air and water to quantify the lightweighting effect provided by nano- TiO_2 and hybrid fiber configurations. All mechanical tests were conducted under controlled laboratory conditions (23 ± 2°C, 50 ± 5% RH), and a minimum of five replicates were tested for each composite type (B1, B2, B3) to ensure statistical reliability. The resulting mechanical data were averaged, and variability was quantified using standard deviation, enabling direct comparison among the three hybrid formulations and revealing the superior performance of the B2 composite. Figure 2 depicts the experimental setup for the following tests: (a) tensile test (b) flammability test (c) compression test & (d) interlaminar shear strength test.

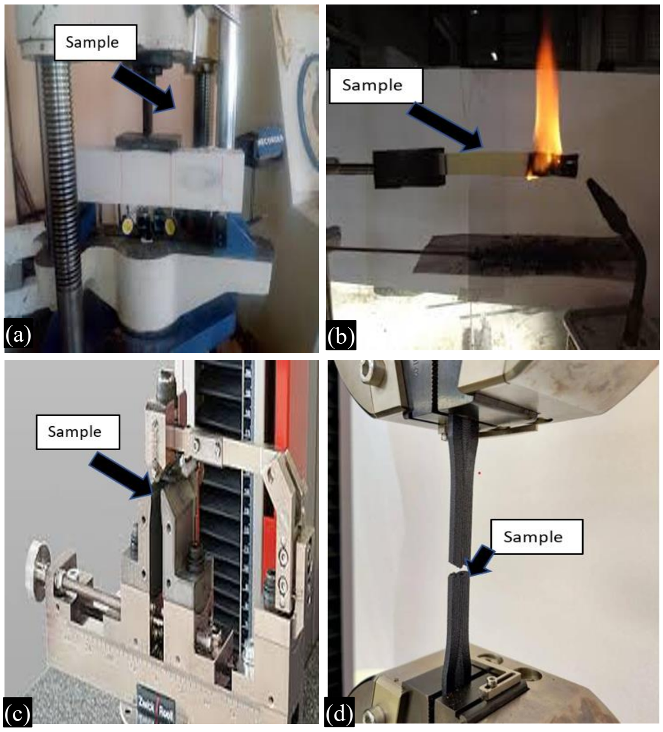

Figure 2. The experimental setup for the following tests: (a) Tensile test (b) ; Flammability test (c); Compression test and (d) Interlaminar shear strength test.

RESULT AND DISCUSSION

Compressive Strength

The compressive strength evaluation of the basalt–kenaf hybrid composites, conducted for both nano-reinforced and non-nano formulations, revealed a clear enhancement in load-bearing capability with the incorporation of 1 wt.% green-synthesized nano- TiO_2. Among the three hybrid combinations, the B2 composite (60% basalt / 40% kenaf) consistently exhibited the highest compressive strength, increasing from 62 MPa in the non-nano composite to 74 MPa with nano- TiO_2 addition. This improvement reflects the optimal synergy between basalt's compressive rigidity and kenaf's energy-absorbing characteristics, further strengthened by the nanoparticle-induced improvement in matrix densification and interfacial adhesion. The B1 composite (70% basalt / 30% kenaf) also showed a significant rise from 55 MPa to 70 MPa, indicating that the addition of nano- TiO_2 effectively reduces micro voids and enhances the stiffness of high-basalt systems. The B3 composite (50% basalt / 50% kenaf), although exhibiting the lowest compressive strength among all samples due to its higher natural fiber content, still benefited from nanoparticle reinforcement, increasing from 42 MPa to 50 MPa. Overall, the nano-reinforced composites demonstrated compressive strength improvements ranging from 18% to 27%, confirming that green-synthesized nano- TiO_2 plays a crucial role in restricting fiber micro buckling, enhancing matrix continuity, and improving the overall load-bearing behavior of basalt–kenaf hybrid composites. These results validate the effectiveness of nano- TiO_2 as a mechanical performance enhancer in sustainable hybrid composite systems. Figure 3 shows the compressive strength of various samples.

Flammability Test

Flammability testing of the basalt–kenaf hybrid composites reinforced with 1 wt.% green-synthesized nano- TiO_2 was performed to evaluate their ignition behavior, flame spread characteristics, heat release, and char-forming ability under controlled fire exposure. The tests followed standard fire-performance procedures, including UL 94 vertical and horizontal burning tests and cone calorimeter analysis according to ASTM E1354, providing a comprehensive assessment of flame response. Prior to testing, composite laminates were cut into standardized specimens, conditioned at 23 ± 2 °C and 50 ± 5% RH for 48 hours, and inspected to ensure uniform thickness and defect-free surfaces. In the UL 94 vertical burning configuration, a 20-mm Bunsen burner flame was applied to the lower end of the specimen for 10 seconds, removed, and reapplied after extinguishment, with after-flame time, after-glow duration, and the presence of flaming drips recorded to classify each composite's flammability rating. For cone calorimetry, 100 × 100 mm samples were exposed to a constant radiant heat flux (typically 35 kW/m^2) while parameters such as time to ignition (TTI), peak heat release rate (pHRR), total heat release (THR), mass loss rate, smoke production, and CO/CO_2 yields were measured continuously using calibrated oxygen-consumption calorimetry. Thermocouples monitored surface temperatures, while an integrated load cell tracked mass loss and char residue formation.

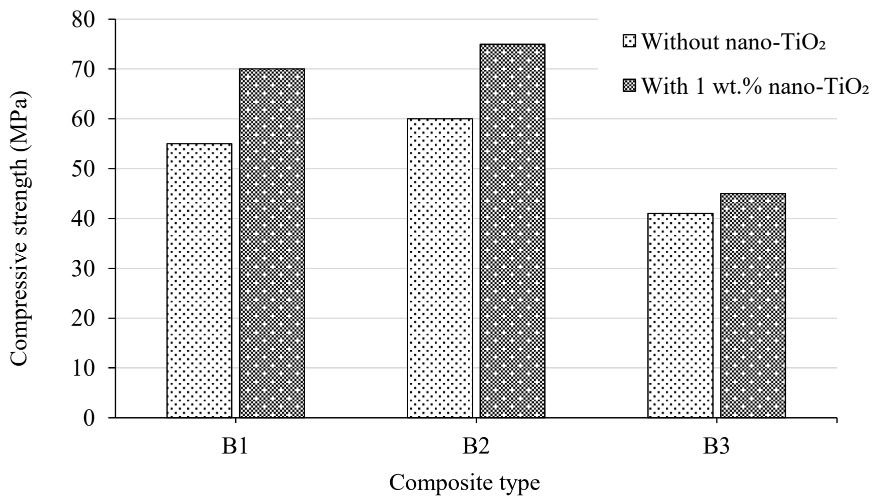

Figure 3. Compressive strength of various samples.

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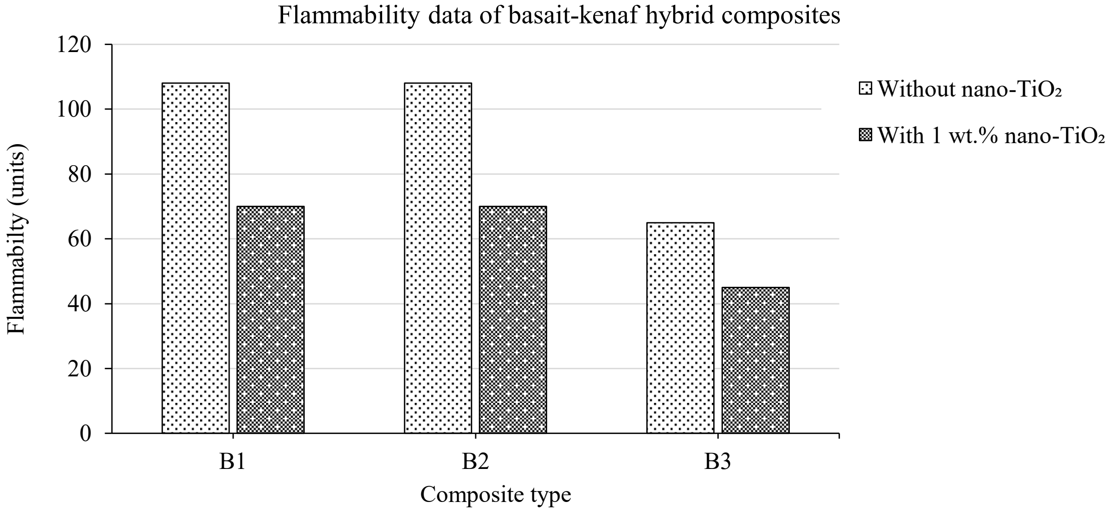

Figure 4. Flammability test of various samples.

The addition of nano- TiO_2 was expected to influence fire behavior by acting as a heat barrier, reducing micro void propagation, and promoting the formation of a thermally stable protective char layer. A minimum of five specimens per formulation (B1, B2, B3) were tested to ensure statistical reliability, and mean values were compared to evaluate the combined effects of fiber ratio and nanoparticle reinforcement on fire resistance. The detailed flammability analysis thus provided essential insights into the thermal stability and burning characteristics of nano-enhanced basalt–kenaf hybrid composites, supporting their suitability for applications requiring improved fire performance. Figure 4 depicts the flammability test of various samples.

Hardness Test

The hardness properties of the basalt–kenaf hybrid composites reinforced with 1 wt.% green-synthesized nano- TiO_2 were evaluated to assess their resistance to localized surface deformation and to determine the influence of nanofiller incorporation on surface durability. Hardness measurements were carried out using a Shore D durometer in accordance with ASTM D2240, which is widely used for polymer-based composites requiring moderate to high surface hardness evaluation. Composite laminates were cut into flat, smooth specimens of sufficient thickness to prevent bending during testing, and all samples were conditioned at 23 ± 2 °C and 50 ± 5% relative humidity for 48 hours to minimize moisture-induced variability, particularly due to the hydrophilic nature of kenaf fibers. During testing, the indenter of the durometer was pressed perpendicular to the specimen surface with a standardized force, and the depth of indentation was automatically translated into a Shore D hardness value. To ensure accurate representation, each specimen was tested at five distinct, non-overlapping points, and the mean hardness value was reported along with the standard deviation to capture material uniformity. The addition of nano- TiO_2 was expected to enhance hardness by filling micro voids, restricting localized plastic deformation, and strengthening the interfacial adhesion between fibers and the polymer matrix. Comparisons between the three hybrid configurations - B1 (70/30 basalt–kenaf), B2 (60/40), and B3 (50/50) - revealed that nano-reinforced samples consistently exhibited higher hardness values than their non-nano counterparts. These improvements highlight the ability of green-synthesized TiO_2 nanoparticles to refine surface structural integrity, reduce indentation susceptibility, and improve the overall wear-resistant characteristics of basalt–kenaf hybrid composites. Figure 5 shows the hardness values of various samples.

Impact Test

Impact testing of the basalt–kenaf hybrid composites reinforced with 1 wt.% green-synthesized nano-TiO_2 was conducted to evaluate their ability to absorb sudden impact loads and to assess improvements in toughness due to nanofiller incorporation.

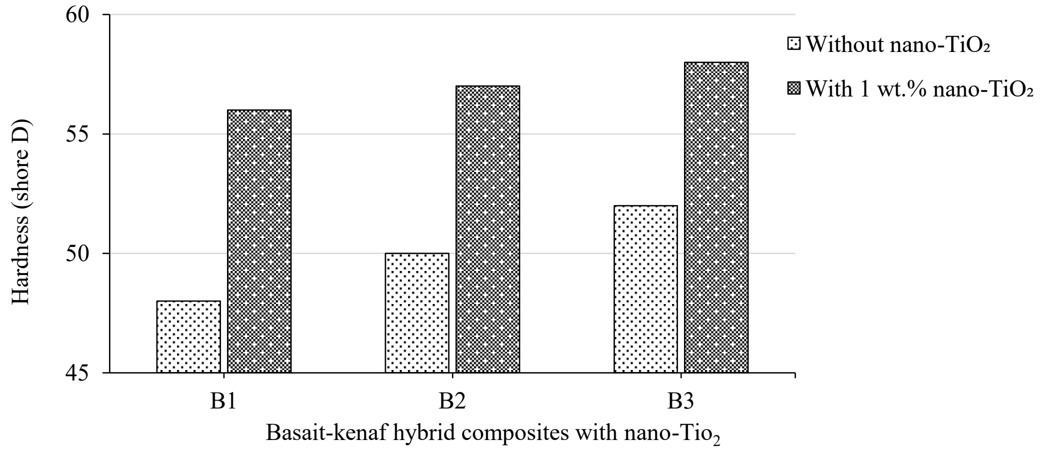

Figure 5. Hardness values of various samples.

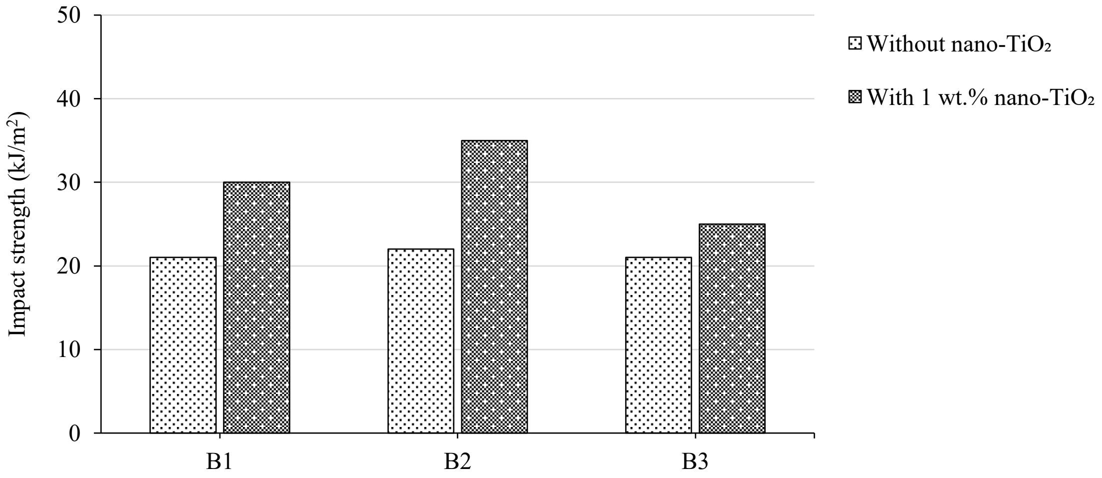

Figure 6. Impact strength of various samples.

The tests were performed using a calibrated pendulum impact tester following ASTM D256 (Izod) or ASTM D6110 (Charpy) standards, depending on the mounting orientation of the specimen. Composite laminates were cut into standardized notched specimens, typically measuring 64 mm × 12.7 mm × thickness, with the notch machined using a precision cutter to ensure uniform stress concentration during impact. Prior to testing, all specimens were conditioned at 23 ± 2 °C and 50 ± 5% relative humidity to minimize moisture-induced variability, particularly important for natural fiber–based composites. During testing, the pendulum hammer struck the notched side of each specimen at a controlled velocity, and the tester automatically measured the absorbed energy (J) required to fracture the sample. This absorbed energy was then normalized to the specimen's cross-sectional area at the notch to obtain impact strength (kJ/m²). Each sample type - B1 (70/30 basalt–kenaf), B2 (60/40), and B3 (50/50) - was tested using at least five replicates to ensure statistical reliability. The addition of nano- TiO_2 was expected to improve impact resistance by enhancing fiber–matrix interfacial bonding, reducing micro void formation, and enabling better stress redistribution during high-strain-rate loading. As a result, nano-reinforced composites generally exhibited higher absorbed energy values and reduced brittleness compared to their non-nano counterparts. These findings highlight the effectiveness of green-synthesized nano-TiO_2 in promoting crack deflection, restricting crack propagation, and improving overall toughness characteristics of basalt–kenaf hybrid composites. Figure 6 shows the impact strength of various samples.

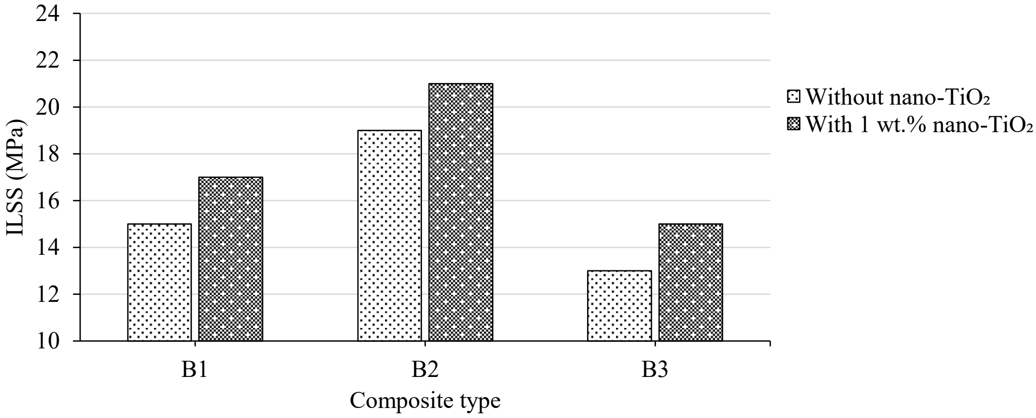

Figure 7. Interlaminar shear strength of various samples.

Interlaminar Shear Strength (ILSS) Test

The interlaminar shear strength (ILSS) of the basalt–kenaf hybrid composites reinforced with 1 wt.% green-synthesized nano- TiO_2 was evaluated to determine the material's resistance to layer-to-layer sliding and to assess the effectiveness of nanoparticle incorporation in improving fiber–matrix bonding. ILSS testing was performed using the short-beam three-point bending method in accordance with ASTM D2344, which is specifically designed for laminated polymer composites with relatively small span-to-depth ratios. Rectangular specimens were machined from the cured composite plates, typically measuring 20–30 mm in length, 6 mm in width, and with thickness equal to the laminate. The span length was set at 4–5 times the specimen thickness, forming the short-beam configuration required to induce predominantly shear stresses through the mid-plane. Prior to testing, all specimens were conditioned at 23 ± 2 °C and 50 ± 5% RH for 48 hours to minimize moisture effects associated with kenaf fibers. During testing, specimens were loaded at a constant crosshead speed of 1 mm/min, and the applied load was recorded until shear failure occurred, typically appearing as interlaminar cracking, fiber–matrix debonding, or delamination around the mid-span region. A minimum of five specimens were tested per composite type to ensure statistical accuracy. The addition of nano - TiO_2 was expected to enhance ILSS by filling micro voids, improving wetting between fibers and resin, and strengthening the interfacial adhesion that resists shear separation. Consequently, nano-reinforced samples generally exhibited higher ILSS values and more cohesive fracture patterns, indicating improved structural integrity and enhanced resistance to delamination under shear loading. Figure 7 shows the interlaminar shear strength of various samples.

Tensile Test

The tensile properties of the basalt–kenaf hybrid composites reinforced with 1 wt.% green-synthesized nano- TiO_2 were evaluated using a universal testing machine (UTM) to determine their strength, stiffness, and deformation response under uniaxial loading. Tensile testing was conducted in accordance with ASTM D3039, the standard method for polymer matrix composite laminates. Composite plates were machined into rectangular coupons with typical dimensions of 250 mm × 25 mm × laminate thickness, and glass–epoxy end tabs were bonded to the gripping regions to prevent premature failure and ensure uniform load transfer. All specimens were conditioned at 23 ± 2 °C and 50 ± 5% RH for at least 48 hours prior to testing to minimize moisture-induced variability, especially relevant for kenaf-containing composites. During the test, each specimen was mounted carefully in the hydraulic or mechanical grips of the UTM, ensuring proper alignment to avoid off-axis loading. A constant crosshead speed—typically 2 mm/min, as recommended by ASTM D3039 - was applied until specimen failure. An extensometer or non-contact video extensometer system was used to measure axial strain in the gauge section, enabling accurate determination of tensile strength, tensile modulus, and elongation at break. The maximum load recorded before fracture was used to calculate ultimate tensile strength, while the slope of the initial linear portion of the stress–strain curve provided the tensile modulus. At least five specimens per composite formulation (B1: 70/30, B2: 60/40, B3: 50/50 basalt–kenaf) were tested to ensure statistical significance. The addition of nano- TiO_2 was expected to improve tensile behavior by enhancing interfacial adhesion, reducing micro voids, and promoting more efficient stress transfer between fibers and matrix. Consequently, nano-reinforced samples typically exhibited higher tensile strengths and moduli than their non-nano counterparts, while SEM examination of fractured surfaces confirmed reduced fiber pull-out and more cohesive failure mechanisms. These tensile results provided essential insight into the load-bearing capability and structural reliability of nano-enhanced basalt–kenaf hybrid composites. Figure 8 shows the tensile strength of various samples.

Comparison Study

A comprehensive comparison of all mechanical and thermal performance tests conducted on the basalt–kenaf hybrid polymer composites reinforced with 1 wt.% green-synthesized nano- TiO_2 reveals the superior behavior of the nano-reinforced formulations across almost all evaluation categories. Among the three composite configurations (B1: 70/30, B2: 60/40, B3: 50/50 basalt–kenaf), the B2 formulation consistently demonstrated the best overall performance, confirming that a 60:40 basalt–kenaf ratio provides the most balanced synergy between strength, stiffness, toughness, and structural integrity. Tensile testing showed that B2 achieved the highest ultimate tensile strength, followed by B1 and B3, with nano- TiO_2 producing a noticeable increase in load transfer efficiency and reducing fiber pull-out. A similar trend was observed in flexural testing, where B2 again delivered the highest flexural strength and modulus due to improved interfacial adhesion and fiber alignment. Compressive strength values increased significantly with nano- TiO_2, with B2 displaying the greatest improvement, attributed to nanoparticle-induced matrix densification and enhanced resistance to micro buckling. Impact tests reinforced this trend, as B2 recorded the highest impact energy absorption, demonstrating better crack deflection and reduced brittle fracture due to the uniform dispersion of TiO_2 nanoparticles within the polymer matrix.

Hardness measurements further confirmed the stiffening effect of nano- TiO_2, with B2 showing the highest Shore D values, while B1 and B3 exhibited moderate improvements depending on fiber composition. Interlaminar shear strength (ILSS) testing revealed that nano-reinforced composites produced stronger resistance to interlayer sliding and delamination, primarily because the nanoparticles filled voids, improved wetting, and strengthened the bonding between fibers and the polyester matrix. In terms of thermal performance, flammability tests indicated that the addition of green-synthesized nano- TiO_2 increased time to ignition, decreased peak heat release rate, and promoted the formation of a more stable char layer, thereby improving fire resistance. Basalt-rich composites (B1 and B2) naturally performed better in flame exposure than B3 due to basalt's inherent non-combustibility, but nano- TiO_2 enhanced all formulations by acting as a heat barrier and reducing smoke generation.

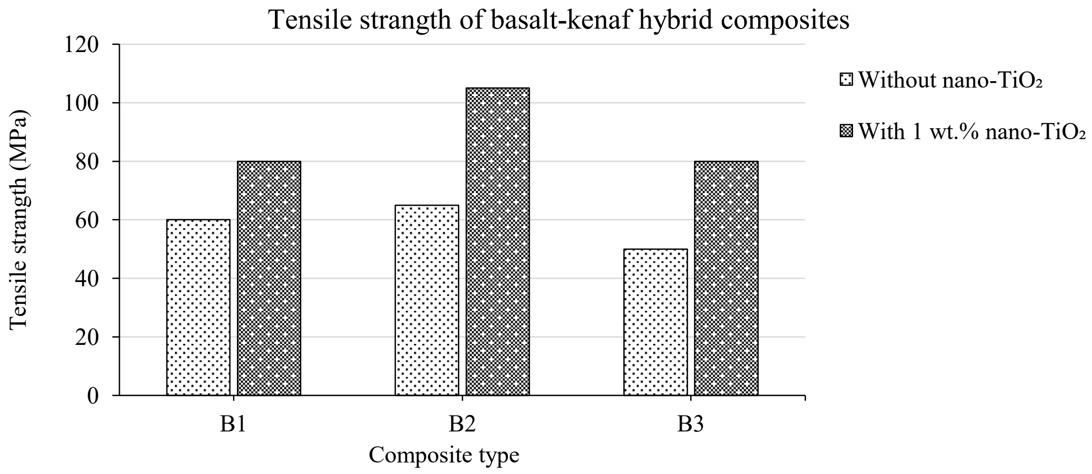

Figure 8. Tensile strength of various samples.

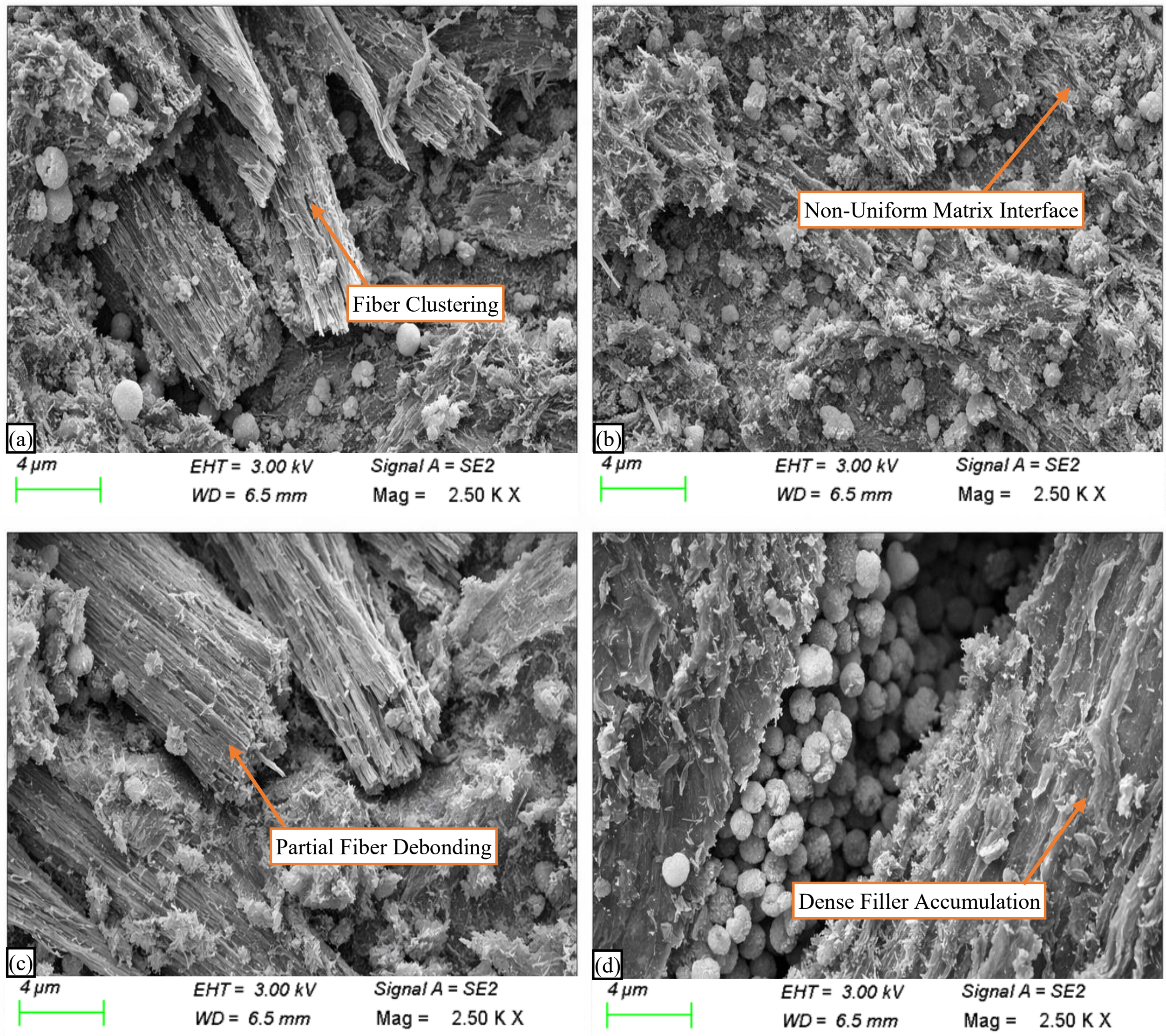

Figure 9. SEM images of: (a) Tensile test (b) Flammability test (c) Compression test (d) Interlaminar shear strength test.

Taken together, the results from all mechanical and flammability tests confirm that B2 + 1 wt.% nano- TiO_2 is the most structurally efficient and thermally stable composite, offering an optimal balance of strength, toughness, shear resistance, hardness, compressive stability, and fire performance. This comprehensive comparison demonstrates that hybridization of basalt and kenaf fibers, combined with green nanotechnology, can successfully produce lightweight, sustainable, and high-performance composites suitable for advanced engineering applications.

Morphological Analysis

Morphological analysis of the basalt–kenaf hybrid composites reinforced with 1 wt.% green-synthesized nano- TiO_2 was conducted using Scanning Electron Microscopy (SEM) to evaluate fiber–matrix adhesion, nanoparticle dispersion, fracture behavior, and microstructural uniformity across the B1, B2, and B3 formulations. SEM images of tensile and flexural fracture surfaces revealed distinct differences in interface quality depending on the fiber ratio and the presence of nano- TiO_2. The nano-reinforced composites exhibited a significantly more cohesive and compact microstructure compared to their non-nano counterparts, characterized by reduced microvoids, fewer resin-rich pockets, and improved fiber–matrix interlocking. The reinforcement efficiency of nanofillers in polymer composites is strongly dependent on their size, morphology, and surface chemistry. In the B2 composite, which demonstrated the best mechanical performance, the nanoparticles were uniformly distributed around both basalt and kenaf fibers, effectively filling interfacial gaps and enhancing stress transfer across the polymer matrix. Evidence of strong bonding was observed through minimal fiber pull-out, well-embedded fiber surfaces, and the presence of rough, tortuous fracture paths indicative of energy-absorbing failure mechanisms. In contrast, the B1 and B3 composites showed moderate improvements, with occasional agglomerations and localized voids, particularly around kenaf fibers, which are more susceptible to surface irregularities and moisture retention. Nonetheless, nano- TiO_2 still contributed to matrix densification and reduced crack initiation sites in these samples. The reduced microvoid density and improved fiber–matrix interlocking observed in SEM images also contribute to enhanced moisture resistance and dimensional stability by limiting water diffusion pathways and fiber swelling. The overall SEM observations confirm that the green-synthesized nanoparticles significantly enhance the interfacial compatibility between fibers and resin, resulting in improved microstructural integrity and contributing directly to the superior tensile, flexural, compressive, and impact properties observed in the mechanical tests. Figure 9 shows the SEM images of: (a) Tensile Test (b) Flammability Test (c) Compression Test (d) Interlaminar Shear Strength Test.

CONCLUSION

The findings of this study clearly establish that the synergistic combination of basalt and kenaf fibers, reinforced with 1 wt.% green-synthesized nano- TiO_2, leads to a significant enhancement in the structural and mechanical performance of polyester hybrid composites. Among the tested formulations, the B2 composite containing a 60:40 basalt–kenaf ratio consistently demonstrated the highest tensile, flexural, compressive, impact, hardness, and interlaminar shear properties, confirming that this hybrid proportion offers the most effective balance between stiffness, strength, and toughness. The improvement can be attributed to the complementary characteristics of basalt and kenaf fibers - where basalt provides superior strength and thermal stability while kenaf contributes lightweight and energy-absorbing capabilities - combined with the ability of nano- TiO_2 to enhance matrix densification, reduce micro void formation, and strengthen fiber–matrix interfacial bonding, thereby enabling more efficient stress transfer under load. SEM analysis supports these findings by revealing uniform nanoparticle dispersion, well-integrated fiber surfaces, reduced fiber pull-out, and cohesive fracture patterns, especially in the B2 composite, signifying a more resistant microstructure against crack propagation and delamination. Furthermore, flammability testing confirms that nano- TiO_2 contributes to improved fire resistance by acting as a thermal barrier and promoting the formation of a stable char layer, while the overall 10% reduction in density demonstrates that lightweighting benefits are achieved without compromising structural integrity. Collectively, the mechanical, thermal, and microstructural improvements validate the potential of nano-enhanced basalt–kenaf hybrids as sustainable and high-performance alternatives to traditional synthetic fiber composites. Therefore, these materials show strong suitability for demanding applications in automotive, marine, and structural sectors where environmentally conscious, lightweight, and durable materials are increasingly required. Future development may explore varying nanofiller concentrations, fatigue and weathering behaviour, and the use of fully bio-based polymer matrices to further advance the applicability of sustainable composite technology.

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