Recycling and Enrichment of Functional Behaviour of High Density Polyethylene Composites With Boron Carbide–Natural Neem Fiber: Performance Study

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**Abstract:** By reinforcing recycled high-density polyethylene (rHDPE) with chopped neem fiber (length < 5 mm) and boron carbide (B₄C, 30 nm) this work offers a sustainable method for creating high-performance composites. Extrusion was used to create four composite variants: a control, HDPE with 5 weight percent B₄C, and HDPE with B₄C and neem fiber, both untreated and treated with NaOH. Environmental (water absorption), thermal and mechanical - flexural strength tests were conducted. The inclusion of NaOH-treated neem fiber greatly increases flexural strength and decreases water uptake, whereas B₄C significantly improves stiffness and thermal stability according to the results. In vehicle panels, where economical, environmentally friendly, and long-lasting materials are crucial the optimized composite (HDPE + 5 weight percent B₄C + 10 weight percent NaOH-treated neem fiber) is a promising option.

# Introduction

The quest for circular economy techniques in polymer sciences has made recycled high density polyethylene more important. The mechanical properties of rHDPE are often deteriorated by impurities and polymer chain scission even though it is still largely processable [1-3]. To repair and enhance its functional characteristics researchers have turned to natural fibers and nanoscale reinforcements [4-5].

The ceramic nanoparticle boron carbide is characterized by its low density (~2.5 g/cm³), great hardness, and resistance to heat. Its dispersion in thermoplastics can raise the thresholds for thermal breakdown and increase stiffness. A cheap lignocellulosic waste product, neem fiber provides biodegradable and renewable reinforcement. However unless chemically treated its low interfacial adhesion with hydrophobic polymers may hinder performance. By eliminating hemicellulose and wax alkali treatment improves surface roughness and reactivity and strengthens fiber-matrix bonding.

Sustainable recycling methods are desperately needed due to the growing amount of plastic trash, especially for high-density polyethylene which is extensively utilized in consumer goods and packaging. Due to contamination and thermal deterioration, Chen and Selvinsimpson emphasized the mechanical limitations of recycled HDPE (rHDPE) which calls for reinforcement techniques to recover its structural qualities [1]. Boron carbide (B₄C) has become a viable nanofiller among advanced fillers due to its low density, great thermal stability and exceptional toughness. [6-9] emphasized the significance of bio-based fibers such as jute, flax and kenaf, in terms of their mechanical contribution to polymer matrices, availability and biodegradability. [10-12] demonstrated substantial mechanical improvements in biodegradable packaging composites by removing cellulose nanofibers from coconut trash. The synergistic advantages of integrating natural fibers with synthetic and nano-reinforcements in polymer composites to achieve balanced strength, toughness and eco compatibility are highlighted by recent hybridization efforts as summarized [13-15]. However, poor interfacial adhesion with hydrophobic polymer matrices is a prevalent problem with natural fibers. Alkali treatment of pineapple leaf fiber greatly boosted fiber matrix interaction, resulting in improved compressive and thermal performance according to [16-17]. Another issue with bio fiber composites is water absorption in discovered that extended exposure to moisture decreased mechanical performance, highlighting the necessity of efficient surface treatment [18-22].

Sdding inorganic fillers such as ammonium polyphosphate to polyethylene composites enhanced their fire retardancy and thermomechanical performance in terms of thermal stability and flame resistance [23-26]. Natural fiber-reinforced composites have been effectively used in automotive applications to lessen the environmental impact and vehicle weight. After reviewing a number of hybrid natural fiber composites, verified their applicability in interior components, bumpers and automobile panels [27-29]. The cost-effectiveness, durability and recyclability of HDPE based hybrid composites were highlighted as key elements for industry adoption [30-32].

Nano hybrid composites, such as those that combine jute, kenaf and glass fibers, and found that they significantly improved flexural and impact performance attributes crucial for vehicle design [33-37]. Fiber chemical treatment is still a crucial area for improvement. In their investigation of the effects of bicarbonate and sodium carbonate treatments on sisal fibers found that the fibers were more compatible with the polymer matrix and had better roughness [38-40]. examined how chemical recycling and bio based reinforcement techniques can reduce the life-cycle impact of plastic composites in the larger framework of polymer sustainability [41-43]. Research on neem and banana hybrid fiber composites is especially pertinent found that fibers treated with NaOH had better tensile performance and less moisture sensitivity indicating that neem might be used as a functional reinforcement [44-48].

The aim of this study is to examine the influence of B₄C and neem fiber, both separately and in combination on the performance of rHDPE composites made via extrusion. The applicability of these biohybrid composites for automobile paneling applications was assessed based on their mechanical, thermal and water resistance characteristics.

# Materials and Methods

## Materials

The major matrix material employed in this experiment was polylactic acid pellets specifically the Ingeo 4032D grade provided by Nature Works LLC and because of its high mechanical strength with good processability of this grade of PLA is ideal for injection molding composite manufacture. As the reinforcing nanomaterial 99.9% pure silver nanoparticles with an average diameter of 50 nm were utilized. These nanoparticles were recognized to have antibacterial properties and enhance the functional performance of polymer matrices. Chopped natural hemp fibers ranging in length from 2 to 4 mm were added as an additional reinforcing measure while ethanol a solvent used during the mixing process was used to break up nanoparticle agglomerates and ensure equal dispersion of the AgNPs inside the PLA matrix.Prior to inclusion the hemp fibers were alkalized for four hours with a 5% sodium hydroxide solution and then dried in an oven. This chemical treatment was required to improve the interfacial adhesion between the hydrophilic fibers and the hydrophobic PLA matrix by eliminating surface contaminants and non cellulosic components [49-50].

## Composite Formulations

The matrix material used in composite development was recycled high-density polyethylene derived from post-consumer plastic waste. Waste plastic was cleaned to eliminate impurities and pollutants before being pelletized for consistency and simplicity of processing. High-quality Boron Carbide (B₄C) nanoparticles (average particle size of 30 nanometers, purity of 99.5%) were used as a nanofiller. The nanoparticles were chosen because of their high hardness and thermal stability. To add natural reinforcement and improve the composite's eco-friendliness, neem (Azadirachta indica) bast fibers were used. These fibers were cut into lengths of less than 5 mm to ensure consistent distribution in the matrix. In addition to employing raw neem fibers an alkali treatment method was used on a part of the fibers to promote fiber-matrix adhesion. The fibers were soaked in a 5% sodium hydroxide solution for four hours to remove hemicellulose and surface contaminants and then the preserved fibers were carefully cleaned with distilled water and oven-dried at 80°C to completely remove moisture.

**TABLE 1**Composite Formulations

|  |  |
| --- | --- |
| **Sample** | **Description** |
| 1 | HDPE (control) |
| 2 | HDPE + 5 wt% B₄C |
| 3 | HDPE + 5 wt% B₄C + 10 wt% neem fiber (untreated) |
| 4 | HDPE + 5 wt% B₄C + 10 wt% neem fiber (NaOH treated) |

To examine the effects of neem fibers and B₄C nanoparticles on the performance of recycled HDPE four composite compositions were developed. The initial formulation was a control sample made completely of HDPE that had been reprocessed. To assess the impact of adding nanofiller the second formulation included 5 weight % B₄C nanoparticles in the HDPE matrix. The third sample examined the synergistic effect of hybrid reinforcement by combining 5 weight percent B₄C with 10 weight % untreated neem fibers. In order to examine the impact of fiber surface modification on composite properties the fourth formulation substituted 10 weight % NaOH treated neem fibers for the untreated fibers.

## Fabrication Process

All raw materials including HDPE pellets B₄C nanoparticles and neem fibers were pre dried in an oven at 80°C prior to processing in order to guarantee uniformity and reduce the impact of moisture. To guarantee initial uniform dispersion the dried components were weighed in accordance with the recipe and then manually dry-mixed. A twin screw extruder running between 180°C and 200°C was then fed this mixture which allowed HDPE to melt and the micro and nano scale reinforcements to disperse uniformly. Granules were then formed by pelletizing the extrudate strands.These pellets were put into preheated moulds and compressed for five minutes at 190°C maintaining at a constant pressure of 5 MPa and then cooling and demolding of the resultant specimens produced standard samples fit for thermal and mechanical assessment.

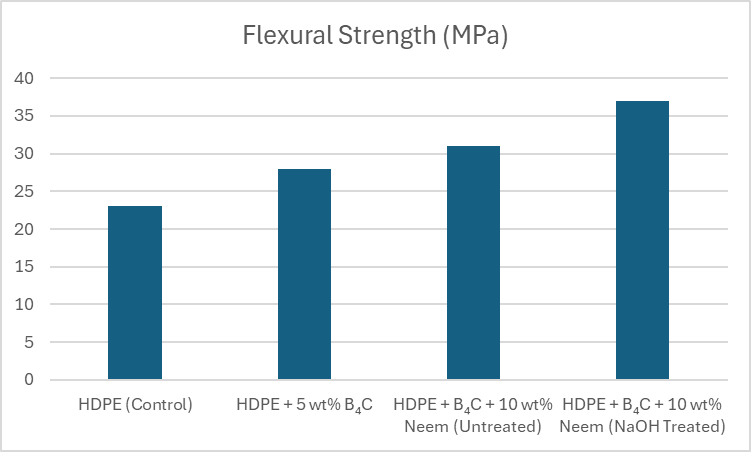
# Results and Discussion

## Flexural Strength

**TABLE 2.** Flexural Strength

| **Sample** | **Flexural Strength (MPa)** | **% Increase from Control** |
| --- | --- | --- |
| HDPE (Control) | 23 | — |
| HDPE + 5 wt% B₄C | 28 | +21.7% |
| HDPE + B₄C + 10 wt% Neem (Untreated) | 31 | +34.8% |
| HDPE + B₄C + 10 wt% Neem (NaOH Treated) | 37 | +60.9% |

ASTM D790 was followed when testing flexural strength. Because of the higher stiffness from the ceramic reinforcement the flexural strength of rHDPE increased from 23 MPa to 28 MPa when B₄C was added. Untreated composites with 10 weight percent neem fiber reached 31 MPa while the fiber composite treated with NaOH reached 37 MPa which was 60% higher than the control. The absence of fiber pull out and increased wettability are signs that the alkali treatment enhanced fiber matrix adhesion and stress transmission.



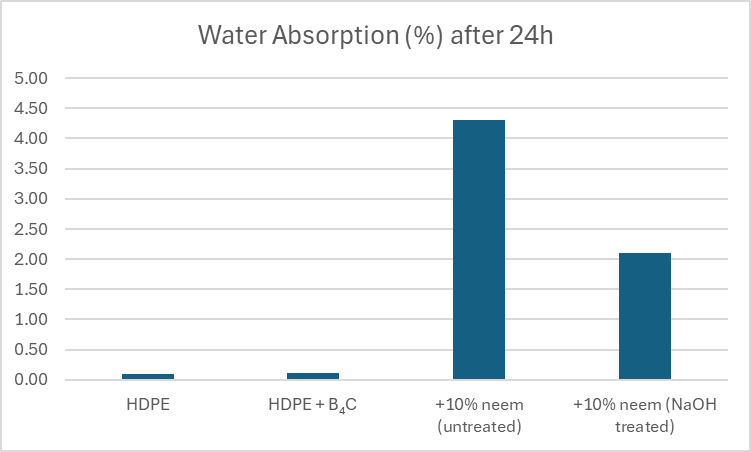
**FIGURE 1.** Flexural Strength

## Water Absorption

Despite HDPE with its hydrophobic nature the polar groups added by natural fibers enhance water absorption. Alkali treatment decreased the water absorption from the untreated neem fiber composite to 2.1% indicating better interfacial sealing and fewer capillary gaps.

**TABLE 3.** Water Absorption

|  |  |
| --- | --- |
| **Sample** | **Water Absorption (%) after 24h** |
| HDPE | 0.1 |
| HDPE + B₄C | 0.12 |
| +10% neem (untreated) | 4.3 |
| +10% neem (NaOH treated) | 2.1 |



**FIGURE 2.** Water Absorption

## Thermal Stability

Thermogravimetric analysis was employed to analyze the thermal degradation comportment of the created composites. The baseline thermal resilience of the unreinforced recycled HDPE matrix was demonstrated by a degradation initiation temperature of roughly 355°C. When 5 weight % boron carbide (B₄C) nanoparticles were added to HDPE the degradation beginning was moved to about 372°C suggesting that the ceramic nanofiller exceptional heat tolerance had improved thermal resistance. Composites made of neem fiber had a wider deterioration range starting between 330°C and 350°C. The lignocellulosic character of the natural fibers which breaks down at comparatively lower temperatures is the cause of this decrease in thermal stability.Mixing B₄C and NaOH treated neem fibers resulted in a composite with delayed degradation at around 366°C and combination of thermally stable B₄C nanoparticles with fiber treatment increased interfacial bonding, stabilizing and reducing lignocellulose breakdown. This hybrid composition thus provided an ideal blend of reinforcing and thermal endurance.

**TABLE 4.** Thermal Stability

| **Sample** | **Degradation Onset Temp (°C)** |
| --- | --- |
| HDPE (Control) | 355 |
| HDPE + 5 wt% B₄C | 372 |
| HDPE + B₄C + 10 wt% Neem (Untreated) | 330–350 |
| HDPE + B₄C + 10 wt% Neem (NaOH Treated) | 366 |

# Application in Automotive Panels

Materials with a combination of good heat resistance, low moisture sensitivity, dimensional stability and moderate mechanical strength are needed for both exterior and interior automotive components. The hybrid composites based on HDPE that have been developed show promise for these kinds of uses. B₄C nanoparticles improve the flexural rigidity of components allowing them to maintain their shape throughout use. The greater resistance to thermal deterioration ensures that they can withstand high temperatures caused by direct sunlight or close proximity to engine components. In addition, adding NaOH treated neem fibers helps to reduce water absorption, increase dimensional stability and resistance to warping or swelling in humid situations.The composite with HDPE + 5 wt% B₄C + 10 wt% NaOH treated neem fibre exhibited superior performance among the formulations rendering it extremely appropriate for automotive parts such as interior door panels, underbody covers, dashboard trims and protective cladding. The utilization of natural fibers and recycled HDPE is consistent with sustainability objectives, as it encourages the repurposing of agricultural residues and plastic waste within the context of a circular economy.

# Conclusion

The potential of biohybrid composites derived from recycled HDPE reinforced with 5 wt% boron carbide nanoparticles and 10 wt% NaOH treated neem fibers is successfully demonstrated in this study. The flexural strength of the optimized formulation increased by 60%, suggesting that it possessed improved rigidity and load-bearing capacity. Thermogravimetric analysis demonstrated that the matrix's thermal stability was enhanced, with degradation commencing at approximately 366°C. This underscores the significance of B₄C in enhancing the matrix heat resistance. The water absorption was diminished by 50% in contrast to composites with untreated fibers which supports the efficacy of alkali treatment in improving moisture resistance and fiber matrix compatibility. The performance improvements were substantial as a consequence of the synergistic interaction between the thermally stable ceramic nanofiller and the surface-modified natural fibers.

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