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Benzoylation-Induced Interfacial Enhancement in Cassava Peel–Ldpe Composites with Insights into Morphological, Mechanical and Water Absorption Properties

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Abstract

This study examines the effect of benzoylation surface treatment on the morphological, mechanical, and water absorption properties of cassava peel–reinforced low-density polyethylene (LDPE) composites. Neat LDPE, unbenzoylated composites (UCPLC), and benzoylated composites (BCPLC) were compared. Scanning electron microscopy confirmed the influence of surface treatment, revealing cracks, voids, and filler pull-out in UCPLC, while BCPLC displayed smoother, denser morphologies with minimal interfacial separation. Neat LDPE showed the lowest tensile (21.08 MPa), flexural (13.43 MPa), and compressive strength (9.84 MPa), reflecting its ductility and limited load-bearing capacity. Incorporating cassava peel filler improved strength, with UCPLC reaching 41.87 MPa (tensile) and 26.63 MPa (flexural), though performance declined at higher loadings due to filler agglomeration. BCPLC exhibited consistently superior performance. Tensile strength ranged from 42.67 MPa at 5 wt% to 60.33 MPa at 25 wt%, nearly three times that of neat LDPE, while flexural strength peaked at 41.52 MPa (20 wt%). Compressive strength also improved, reaching 25.56 MPa at 20 wt% and 28.77 MPa at 25 wt%, compared with 19.87 MPa and 16.57 MPa for UCPLC at equivalent loadings. Moisture uptake was substantially reduced by benzoylation. After 10 days, UCPLC absorbed 2.66–5.20% water (5–25 wt%), whereas BCPLC recorded only 1.46–3.04%, compared to 0.44% for neat LDPE. This reduction reflects enhanced filler–matrix adhesion and lower void density. Overall, benzoylation significantly improved compatibility between cassava peel filler and LDPE, yielding composites with superior tensile (60.33 MPa), flexural (41.52 MPa), compressive (28.77 MPa), and water resistance (3.04%) compared to UCPLC and neat LDPE. These results highlight benzoylated cassava peel as a cost-effective reinforcement for high-performance biocomposites.

Keywords: Benzoylation, Biocomposites, Cassava peel, Interfacial Adhesion, LDPE, Mechanical properties.

1.0 Introduction

The growing awareness of environmental sustainability, combined with regulatory pressure and the urgent need to reduce reliance on petroleum-derived materials, has intensified interest in renewable resources for material development [1]. Natural fibers obtained from plants and agro-waste residues have emerged as

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viable alternatives to synthetic fibers due to their low density, biodegradability, cost-effectiveness, and favorable mechanical properties [2]. Among these, cassava peels, a largely underutilized agro-industrial by-product, present significant potential as reinforcement in polymer composites [3]. Their utilization not only provides a sustainable solution to agricultural waste management but also reduces the environmental footprint associated with synthetic fillers [4].

Despite these advantages, cassava peel fibers share the inherent drawbacks of lignocellulosic materials. The hydroxyl-rich structure of cellulose, hemicellulose, and lignin renders them highly hydrophilic, leading to excessive moisture uptake, dimensional instability, and poor interfacial adhesion with hydrophobic polymer matrices [5]. This incompatibility results in weak stress transfer across the fiber–matrix interface and compromises the overall mechanical performance of the composites [6]. Addressing this limitation requires surface modifications that alter fiber chemistry to improve compatibility with polymer matrices.

Benzoylation has gained prominence as an effective chemical treatment for enhancing fiber–matrix adhesion in natural fiber composites [7]. In this process, hydroxyl groups on the fiber surface react with benzoyl chloride, introducing hydrophobic benzoyl functional groups that reduce polarity and moisture affinity while improving interfacial compatibility [8]. Beyond improving adhesion, benzoylation facilitates better mechanical interlocking, enhances load transfer, and significantly reduces water absorption, thereby improving the mechanical durability of the resulting composites [9]. For cassava peel fibers, benzoylation offers a pathway to overcome their hydrophilic limitations and transform them into efficient reinforcements for polymer matrices.

The chemical modification of cassava peels through benzoylation not only strengthens composite performance but also contributes to sustainable materials innovation [10]. By converting an abundant agro-waste into a high-value engineering material, this approach aligns with circular economy principles and supports the development of eco-efficient polymer composites with potential applications in automotive, construction, aerospace, and consumer products [11].

2.0 Material and Methods

2.1 Sample Collection and Preparation

Cassava peels were collected from farmers and households in Anyigba, Dekina Local Government Area, Kogi State, Nigeria. The peels were washed thoroughly with distilled water to remove contaminants and soluble impurities, air-dried for 12 h, and oven-dried at 65 °C for 36 h until constant weight was achieved. The dried peels were cut, ground, and sieved using a mechanical sieve shaker to obtain particles with a uniform size of 300 µm. low density polyethylene

(LDPE) sachet wastes were shredded into smaller fragments to serve as the recycled polymer matrix.

2.2 Sample Pre-treatment

To eliminate extractable compounds that could interfere with benzoylation, the cassava peel powder was subjected to Soxhlet extraction using an acetone/n-hexane mixture (4:1 v/v) for 5 h. The extracted fibers were dried in a laboratory oven at 60 °C for 16 h prior to chemical modification [12]

2.3 Benzoylation Treatment of Fibers

The dried cassava peel fibers were first alkalized by immersion in 10% NaOH solution for 4 h to activate the hydroxyl groups of cellulose and lignin. The fibers were then filtered, washed thoroughly with distilled water to neutrality, and partially dried [13]. Subsequently, the fibers were treated with a 10% benzoyl chloride solution in ethanol at a fiber-to-liquor ratio of 1:20. The reaction was carried out for 15 min at room temperature with continuous stirring to facilitate benzoyl group substitution onto the fiber surface. After treatment, the fibers were washed with ethanol followed by distilled water until neutral pH was attained, oven-dried at 70 °C for 24 h, and stored in airtight containers for composite fabrication [14].

2.4 Preparation of Benzoylated and Unbenzoylated Fiber Composites

Low density polyethylene (LDPE) composites were fabricated through melt mixing followed by compression molding. The shredded PP was plasticized on a two-roll mill at 170 °C for 10 min with counter-rotating rolls. Once homogenized, the cassava peel filler (untreated or benzoylated) was introduced gradually at loadings of 0–25 wt% (0, 5, 10, 15, 20, and 25%), while maintaining a roll speed of 500 rpm [15] The compounded blends were subsequently compression-molded using a hydraulic press (Model 12000) equipped with electrically heated platens set at 150 °C. The mixture was subjected to a pressure of 4 MPa for 10 min, cooled under pressure, and then molded to obtain the composite specimens [16].

Table 1: Compound Design / Formulation for the Benzoylated and Unbenzoylated Cassava Peel LDPE Composites

S/N	Mass of ingredients	FORMULATION (LDPE(g) / FILLER(g))					
1	**LDPE (g)**	100	95	90	85	80	75
2	**Cassava Peel Powder (g)**	0	5	10	15	20	25

2.5 Polymer Composite Test

The mechanical and physical characterization of the composites was performed in accordance with established ASTM standards to ensure accuracy, reproducibility, and comparability of results. The tensile strength evaluation was conducted following ASTM D638-14 [17], which specifies the procedure for determining the tensile properties of plastics and composites under uniaxial loading conditions. Flexural strength measurements were carried out according to ASTM D790-17 [18], a standard designed to assess the flexural modulus and strength through a three-point bending configuration.

To evaluate the resistance of the material to compressive loads, compressive strength testing was performed in line with ASTM D695-14 [19]. Impact strength, a critical parameter reflecting the material's ability to absorb energy under sudden loading, was determined in accordance with ASTM D256-18 [20]. Furthermore, the water absorption behavior of the composites, which provides insight into their dimensional stability and durability in humid environments, was assessed using ASTM D570-18 [21]. Finally, the morphological characteristics and interfacial bonding between the fiber and polymer matrix were examined through scanning electron microscopy, conducted following the guidelines of ASTM D984-14 [22].

3.0 Results and Discussions

3.1 Morphological Property

Results from the SEM plots (Figure 1- 8) in the UCPLC samples revealed the presence of surface cracks, microvoids, and gaps between the cassava peel filler and the LDPE matrix, particularly at lower filler contents. These features indicate poor interfacial bonding and weak stress transfer, consistent with the reduced tensile, flexural, and impact properties relative to the treated composites. For instance, at 5 wt% loading, the fracture surfaces showed prominent voids and

regions of filler pull-out, confirming that the polar hydroxyl groups of untreated cassava peel interacted poorly with the hydrophobic LDPE matrix. This weak interaction not only facilitated crack initiation and propagation but also increased susceptibility to water penetration, as reported in the water absorption results.

With increasing filler loading in UCPLC (10–20 wt%), the density of cracks and voids gradually decreased, and the fracture surfaces appeared more compact. At 20 wt%, fewer visible interfacial gaps were observed compared to the 5 wt% sample. This trend can be attributed to the greater number of filler particles occupying the polymer matrix, which reduced the extent of unfilled regions and improved load distribution [23]. Nevertheless, even at higher filler contents, the untreated composites still exhibited notable microvoids and incomplete bonding, which are characteristic of insufficient compatibility between hydrophilic fillers and hydrophobic matrices.

The BCPLC samples, on the other hand, displayed markedly different fracture morphologies at all filler loadings. At 5 wt% loading, although some voids were still visible, their number and size were significantly reduced compared to UCPLC at the same loading. The surfaces appeared smoother and more integrated, indicating improved adhesion between the filler and the LDPE matrix. As filler loading increased to 10–15 wt%, the micrographs showed progressively fewer cracks and voids, and the matrix–filler interface became increasingly uniform. At 20 wt%, the fracture surface exhibited dense packing of filler within the LDPE matrix, with minimal signs of pull-out or interfacial separation, suggesting effective stress transfer and reduced crack propagation [24].

The observed improvement in BCPLCs morphology can be directly linked to the effect of benzoylation treatment. By grafting bulky benzoyl groups onto the filler surface, the hydrophilic hydroxyl groups of cassava peel were partially masked, reducing the polarity mismatch with the hydrophobic LDPE matrix. This modification enhanced interfacial compatibility and allowed for better wetting of the filler by the polymer melt during processing [25]. Consequently, benzoylated composites exhibited fewer interfacial voids, reduced crack propagation, and more uniform dispersion of filler particles compared to their unbenzoylated counterparts.

In addition to interfacial adhesion, the reduction in cracks and voids with increasing filler loading in both UCPLCs and BCPLCs indicates that higher filler contents improve the structural integrity of the composites by reducing empty regions in the polymer matrix [26]. However, the distinction lies in the degree of improvement: while the UCPLCs showed partial reduction in cracks with filler loading, BCPLCs consistently exhibited a more cohesive and compact

morphology with minimal defects, reinforcing the superior mechanical and water resistance properties observed in the treated composites.

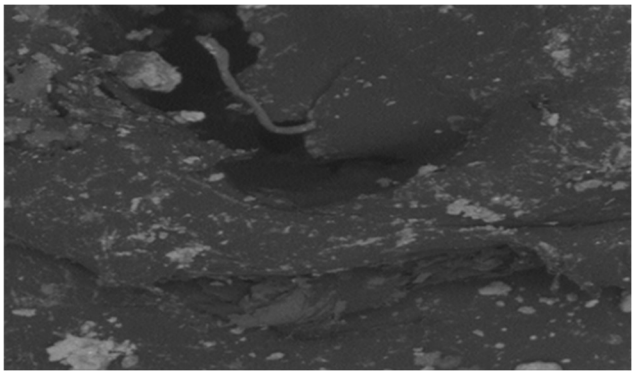


Figure 1: SEM Micrograph of 5 wt% Unbenzoylated Cassava Peel LDPE Composite

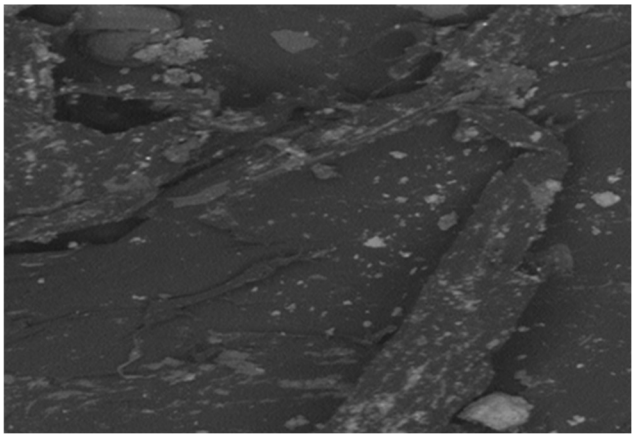


Figure 2: SEM Micrograph of 10 wt% Unbenzoylated Cassava Peel LDPE Composite

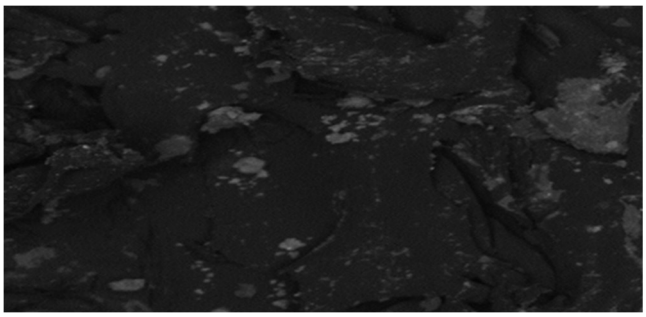


Figure 3: SEM Micrograph of 15 wt% Unbenzoylated Cassava Peel LDPE Composite

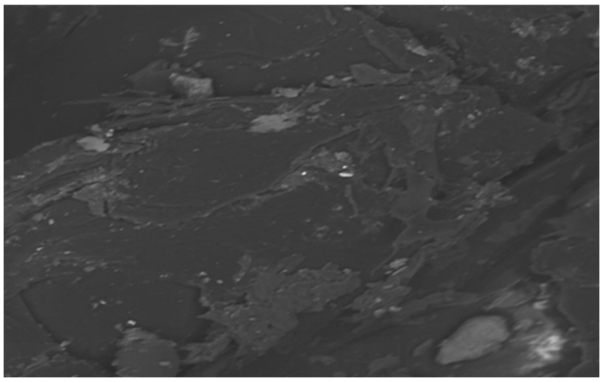


Figure 4: SEM Micrograph of 20 wt% Unbenzoylated Cassava Peel LDPE Composite

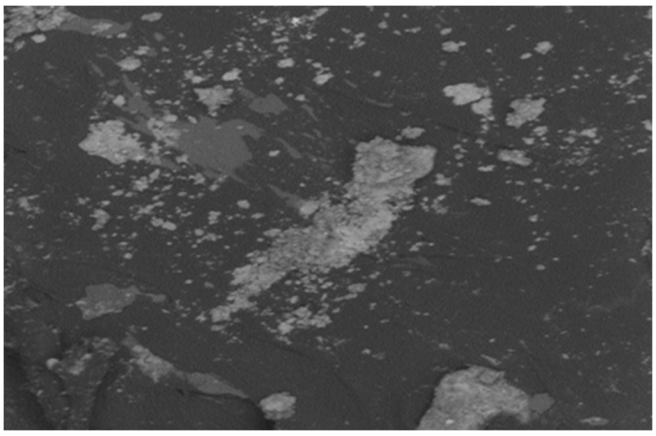


Figure 5: SEM Micrograph of 5 wt% Benzoylated Cassava Peel LDPE Composite

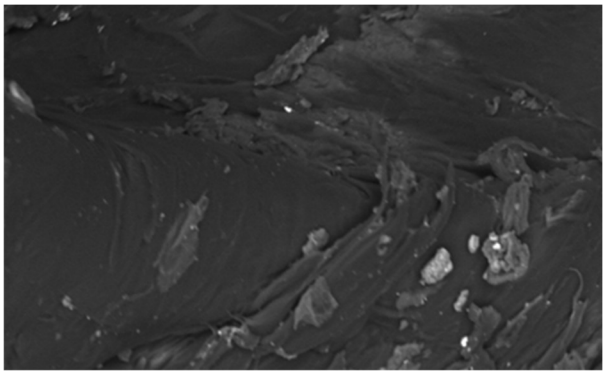


Figure 6: SEM Micrograph of 10 wt% Benzoylated Cassava Peel LDPE Composite

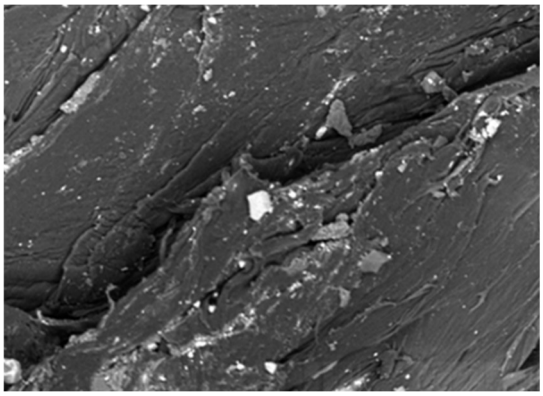


Figure 7: SEM Micrograph of 15 wt% Benzoylated Cassava Peel LDPE Composite

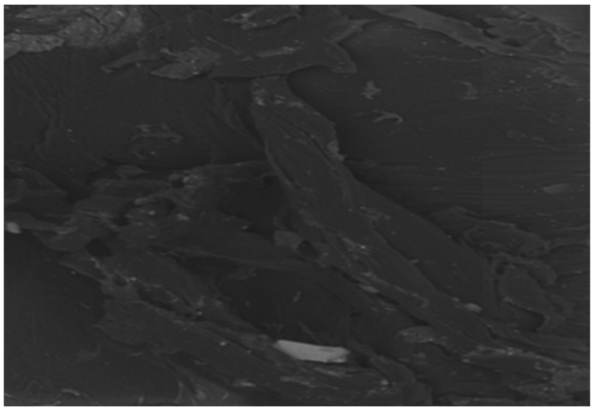


Figure 8: SEM Micrograph of 20 wt% Benzoylated Cassava Peel LDPE Composite

3.2 Mechanical Property

3.2.1 Tensile Strength

The tensile strength of the benzoylated cassava peel–LDPE composites (BCPLC) was evaluated in comparison with the unbenzoylated cassava peel–LDPE composites (UCPLC) and the neat low-density polyethylene (LDPE) control in Figure 9. The results demonstrated significant improvements in mechanical performance due to both the incorporation of cassava peel filler and the benzoylation surface treatment.

The control LDPE sample exhibited the lowest tensile strength of 21.08 MPa, reflecting the inherent weakness of LDPE as a soft and ductile thermoplastic with limited resistance to applied stress. This baseline performance highlights the need for reinforcement to improve the load-bearing ability of LDPE in structural applications [12].

The incorporation of cassava peel filler into LDPE led to progressive increases in tensile strength for the unbenzoylated composites (UCPLC). At 5 wt% filler loading, the tensile strength improved to 26.56 MPa, increasing further to 28.84 MPa at 10 wt%, 32.93 MPa at 15 wt%, 35.57 MPa at 20 wt%, and reaching a maximum of 41.87 MPa at 25 wt% filler loading. The increase is attributed to the reinforcing role of the cassava peel filler, which restricts polymer chain mobility and assists in stress transfer. However, since the filler surface is hydrophilic and chemically incompatible with the

hydrophobic LDPE matrix, interfacial adhesion remains weak. This poor filler–matrix interaction limits stress transfer efficiency, resulting in only moderate improvement in tensile strength for the UCPLC composites [27].

In contrast, the benzoylated cassava peel–LDPE composites (BCPLC) exhibited a remarkable enhancement in tensile strength across all filler loadings compared with both the neat LDPE and UCPLC. At 5 wt% filler loading, the tensile strength increased sharply to 42.67 MPa, compared to 26.56 MPa for UCPLC. At 10 wt%, the BCPLC attained 48.56 MPa, while the corresponding UCPLC only reached 28.84 MPa. Further increases were observed with higher filler contents, with tensile strengths of 53.55 MPa at 15 wt%, 56.56 MPa at 20 wt%, and a maximum of 60.33 MPa at 25 wt% filler loading. This consistent superiority of the benzoylated composites highlights the effectiveness of surface modification in reinforcing the filler–matrix interface.

The improved performance of BCPLC is attributed to the benzoylation treatment, which replaces hydrophilic hydroxyl groups on the cassava peel surface with non-polar benzoyl groups [28]. This chemical modification enhances filler compatibility with the LDPE matrix by reducing hydrophilicity, increasing surface roughness, and strengthening interfacial adhesion. As a result, stress transfer between filler and matrix is more efficient, minimizing fiber pull-out and reducing interfacial voids during tensile loading [29].

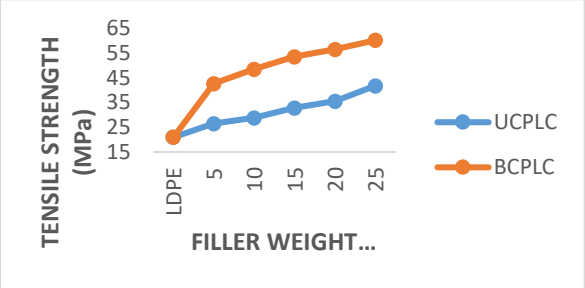


Figure 9: Plot of Tensile Strength against Filler Compositions for Cassava Peel LDPE Composites

3.2.2 Flexural Strength

Results of the plot of the flexural strength (Figure 10) revealed that the control (LDPE sample) exhibited the lowest flexural strength of 13.43 MPa, reflecting the limited rigidity of LDPE, which is a soft and ductile polymer. This value establishes the baseline against which the reinforcing effect of cassava peel filler and benzoylation treatment is measured.

For the UCPLC composites, flexural strength improved progressively up to 15 wt% filler loading. At 5 wt%, the value increased to 17.28 MPa, followed by 21.43 MPa at 10 wt%, and a maximum of 26.63 MPa at 15 wt%. Beyond this point, however, a slight reduction was observed, with flexural strength decreasing to 24.34 MPa at 20 wt% and 22.62 MPa at 25 wt%. This trend suggests that while moderate filler loading improves stiffness and bending resistance by restricting polymer chain movement, excessive filler content leads to particle agglomeration and

weak interfacial bonding [30]. These defects promote stress concentration and microcrack initiation under bending stress, resulting in reduced flexural strength at higher loadings [31]. By comparison, the BCPLC composites consistently exhibited much higher flexural strength than both LDPE and UCPLC across all filler loadings. At 5 wt%, the value reached 28.77 MPa, which is nearly double that of the UCPLC (17.28 MPa). Further improvements were recorded at higher filler loading; 33.31 MPa at 10 wt%, 37.16 MPa at 15 wt%, and a maximum of 41.52 MPa at 20 wt%. At 25 wt% filler, a slight decline to 39.23 MPa was observed, though the value remained far superior to that of the unbenzoylated composites (22.62 MPa).

The remarkable improvement in the BCPLC is attributed to the benzoylation treatment, which enhances filler–matrix adhesion by reducing the hydrophilicity of cassava peel particles and introducing non-polar benzoyl groups compatible with the LDPE matrix. This chemical modification reduces interfacial voids and improves stress transfer efficiency, thereby increasing resistance to bending deformation [32]. The higher values for BCPLC across all compositions confirm that chemical treatment not only increases flexural strength but also delays the onset of performance decline at higher filler loadings.

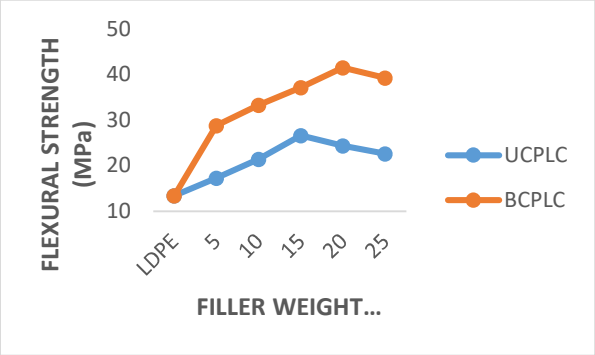


Figure 10: Plot of Flexural Strength against Filler Compositions for Cassava Peel LDPE Composites

3.2.3 Compressive strength

The compressive strength values (Figure 11) indicated that the control LDPE recorded the lowest compressive strength of 9.84 MPa, reflecting the inherent softness and ductility of LDPE, which limits its load-bearing capacity under compression [33]. This value provides the benchmark for evaluating the reinforcing role of cassava peel fillers.

For the UCPLC composites, a gradual increase in compressive strength was observed with filler loading up to 20 wt%. At 5 wt%, the compressive strength rose to 12.12 MPa, then to 14.56 MPa at 10 wt%, and further to 17.72 MPa at 15 wt%. The peak value of 19.87 MPa was achieved at 20 wt%, representing nearly double that of neat LDPE. However, at 25 wt% loading, a decline to 16.57 MPa was recorded, suggesting that beyond optimal filler content, the formation of microvoids, poor particle dispersion, and weak bonding between filler and matrix lead to stress

localization and premature failure under compressive loads [34].

In contrast, the BCPLC composites exhibited consistently higher compressive strength across all filler loadings compared to both UCPLC and neat LDPE. At 5 wt%, compressive strength increased sharply to 16.86 MPa, compared to 12.12 MPa for UCPLC. The values continued to rise with increasing filler content: 20.44 MPa at 10 wt%, 22.32 MPa at 15 wt%, and a maximum of 25.56 MPa at 20 wt%. Even at 25 wt% loading, the BCPLC maintained a relatively high compressive strength of 28.77 MPa, showing a continued reinforcing effect rather than the decline observed in UCPLC.

The superior compressive strength of BCPLC can be explained by the structural densification effect induced by benzoylation treatment. Unlike untreated cassava peel, benzoylated filler surfaces become less polar and more compatible with LDPE. This not only improves interfacial bonding but also reduces the likelihood of microvoid formation and filler–matrix debonding under compressive stress [35]. As a result, the composites become more compact and rigid, distributing applied loads more uniformly throughout the matrix. Additionally, benzoylation reduces the tendency of cassava fibers to swell or deform under pressure, thereby enhancing dimensional stability during compression [36].

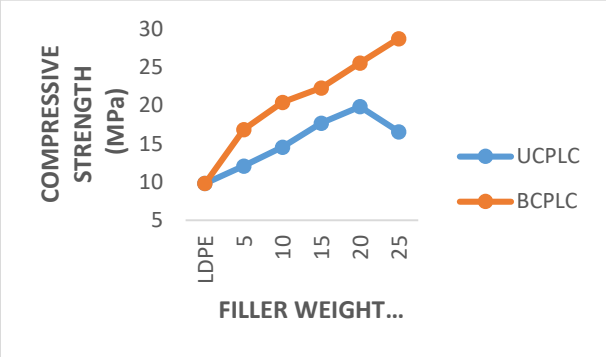


Figure 11: Plot of Compressive Strength against Filler Compositions for Cassava Peel LDPE Composites

3.2.4 Impact Strength

The plot of the impact strength shown in Figure 12 revealed that the control LDPE exhibited the highest impact strength of 65.33 J/m, which is consistent with its well-known ductility and toughness. LDPE's long polymer chains, combined with its relatively high molecular mobility, allow it to absorb and redistribute impact energy effectively without fracturing [37].

For the UCPLC composites, a progressive reduction in impact strength was observed with increasing filler loading. At 5 wt%, the impact strength decreased to 58.38 J/m, followed by further reductions to 55.25 J/m at 10 wt%, 52.23 J/m at 15 wt%, 48.32 J/m at 20 wt%, and 45.17 J/m at 25 wt%. This downward trend reflects the introduction of rigid, lignocellulosic filler particles into the flexible LDPE matrix, which reduces chain mobility and makes the material more prone to brittle fracture [38]. Additionally, weak interfacial adhesion in UCPLC creates microvoids and crack initiation sites, allowing

cracks to propagate easily under impact stress, thereby reducing energy absorption capacity [39]. The BCPLC composites also showed a reduction in impact strength with increasing filler loading compared to neat LDPE, but the decline was less severe than in the UCPLC. At 5 wt%, the impact strength of BCPLC was 61.47 J/m, higher than the 58.38 J/m of UCPLC. Similarly, values of 59.58 J/m at 10 wt%, 56.63 J/m at 15 wt%, 52.44 J/m at 20 wt%, and 50.16 J/m at 25 wt% were consistently superior to the corresponding UCPLC values.

The improved performance of BCPLC over UCPLC can be attributed to the energy dissipation mechanisms enhanced by benzoylation. Benzoylated fillers establish stronger interfacial adhesion with the LDPE matrix, which hinders crack initiation and delays crack propagation during sudden loading. Instead of catastrophic brittle failure, the stronger interface promotes mechanisms such as crack deflection, crack pinning, and micro-fibrillation, which consume more impact energy [40]. Thus, while the incorporation of fillers reduces the overall toughness compared to neat LDPE, benzoylation treatment ensures that the composites retain better impact resistance than untreated counterparts.

Notably, at 25 wt% filler loading, the UCPLC recorded only 45.17 J/m, while the BCPLC maintained 50.16 J/m, showing that benzoylation reduced the loss in toughness by creating a more unified and cohesive composite structure. However, both values remain significantly lower than neat LDPE (65.33 J/m), highlighting that while filler reinforcement enhances stiffness and strength, it compromises toughness due to the restriction of polymer chain mobility.

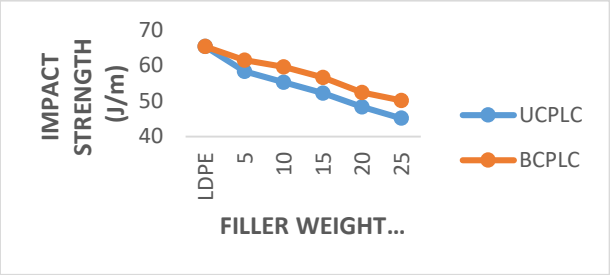


Figure 12: Plot of Impact Strength against Filler Compositions for Cassava Peel LDPE Composites

3.3 Water Absorption Property

Water absorption result presented in Figure 13 and 14 showed that the control LDPE exhibited very low water uptake throughout the immersion period, with values of 0.38% at 24 h, increasing only slightly to 0.44% after 120 h, and stabilizing at 0.43% after 240 h (10 days). This behavior reflects the hydrophobic, non-polar nature of LDPE, which prevents the penetration of water molecules into its polymeric matrix [41].

In contrast, the UCPLC samples absorbed significantly more water, and the uptake increased with filler loading. At 5 wt%, water absorption rose to 2.31% after 24 h, stabilizing at 2.66% after 10 days. Similarly, values increased to 2.97–3.58% for 10 wt%, 3.79–4.41% for 15 wt%, 4.02–4.82% for 20 wt%, and peaked at

4.71–5.20% for 25 wt% filler loading. This pronounced water absorption is attributable to the lignocellulosic nature of cassava peel, which contains hydroxyl groups in cellulose, hemicellulose, and lignin. These polar groups strongly interact with water molecules through hydrogen bonding, leading to swelling and moisture ingress [42]. Moreover, the untreated composites possess weak filler–matrix adhesion, which creates microvoids and interfacial gaps that act as pathways for water diffusion, thereby compounding the moisture uptake [43].

The BCPLC samples, on the other hand, showed significantly reduced water absorption across all filler loadings compared with UCPLC. At 5 wt%, water absorption was limited to 1.10% after 24 h and stabilized at 1.46% after 10 days, which is almost half of the corresponding UCPLC value (2.66%). Similarly, at 10 wt%, absorption reached only 1.73% after 10 days compared to 3.58% for UCPLC. This trend continued with higher loadings, where water uptake was 2.41% at 15 wt%, 2.63% at 20 wt%, and 3.04% at 25 wt%, still far below the UCPLC values of 4.41%, 4.82%, and 5.20%, respectively.

The lower water absorption of the benzoylated composites can be explained by pore-size refinement and reduced capillarity rather than simply hydrophobicity. During benzoylation, the bulky benzoyl groups grafted onto the filler surface partially block hydroxyl groups while simultaneously enhancing interfacial adhesion with the LDPE matrix. This improved adhesion reduces the formation of microcracks and interfacial voids that would otherwise act as channels for water penetration [44]. Furthermore, the denser and more compact interface reduces capillary suction, thereby slowing the diffusion and transport of water into the composite structure [45]. As a result, the benzoylated composites not only absorb less water but also exhibit greater dimensional stability over time compared to the untreated composites.

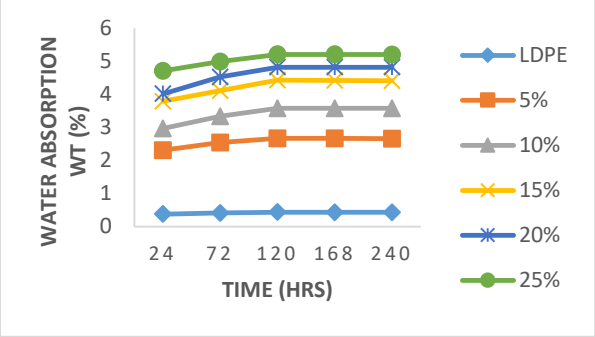


Figure 13: Plot of Water Absorption against Filler Compositions for Unbenzoylated Cassava Peel LDPE Composites

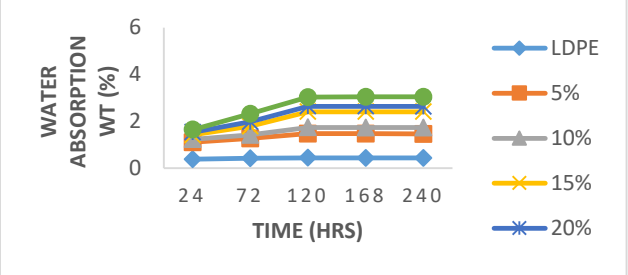


Figure 14: Plot of Water Absorption against Filler Compositions for Benzoylated Cassava Peel LDPE Composites

4.0 Conclusion

Morphological analysis by SEM confirmed the improved matrix–filler adhesion in the benzoylated composites, evidenced by fewer cracks, reduced filler pull-out, and more cohesive fracture surfaces. This work has shown that benzoylation of cassava peel fillers markedly improves the interfacial bonding and overall performance of cassava peel–LDPE composites.

Compared to neat LDPE and untreated composites, the benzoylated composites exhibited significant enhancements in tensile, flexural, and compressive strengths, while also retaining better impact resistance. Benzoylation reduced the polarity mismatch between the hydrophilic filler and hydrophobic LDPE matrix, resulting in efficient stress transfer, fewer interfacial voids, and improved dimensional stability through reduced water uptake. These results establish benzoylation as an effective strategy for upgrading agro-waste fillers into sustainable reinforcements for thermoplastics, offering a pathway to high-performance and eco-friendly composite materials.

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