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EFFECT OF NANOCLAY (HALLOYSITE) ON THE MECHANICAL PROPERTIES OF RECYCLED POLYPROPYLENE FILLED NAOH TREATED MAIZE COB POWDER COMPOSITES

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ABSTRACT
This study investigates the influence of halloysite nanoclay (NC) on the mechanical properties of recycled polypropylene (rPP) composites reinforced with untreated maize cob powder (UMCP) and NaOH-treated maize cob powder (NaOH TMCP). Composites were fabricated with filler loadings of 10–40 wt% at particle sizes of 100–500 µm, and NC additions of 2–8 wt%, using two-roll mill and compression molding machines. Mechanical characterizations included tensile strength, elongation at break, tensile modulus, flexural strength, flexural modulus, hardness, and impact strength were carried out on the fabricated samples. Results demonstrate that NaOH treatment significantly enhances interfacial adhesion, leading to improved tensile strength (up to 25.32 MPa at 20 wt% TMCP, 100 µm), flexural strength (up to 47.0 MPa at 20 wt% TMCP, 4 wt% NC), hardness (up to 86.9% at 500 µm, 8 wt% NC), and moduli, while reducing elongation at break and impact strength due to increased brittleness. Optimal performance was achieved at 20 wt% filler loading, 100 µm particle size, and 2–4 wt% NC, with larger particles favoring hardness but compromising toughness. The hybrid reinforcement system offers a sustainable approach for valorizing agricultural waste in eco-friendly composites for automotive, packaging, and structural applications, balancing stiffness and processability.

Keywords: *Recycled polypropylene, Maize cob powder, Halloysite nanoclay, NaOH treatment, Mechanical properties, Biocomposites*

1.0 Introduction

Recycled polypropylene (rPP) composites incorporate fillers such as natural fibers, glass fibers, nanoclay, or waste particles into an rPP matrix to enhance mechanical properties and sustainability through waste valorization (Zhiltsova et al., 2024; Onuoha et al., 2017). Hardness, measured by Shore D or Vickers tests, indicates resistance to indentation and is crucial for applications in automotive, packaging, and construction (ASTM International, 2023). Rigid fillers like nanoclay improve hardness by 3-18% via better stress distribution, while maize cob powder (MCP) may reduce it at high loadings due to poor dispersion (Prashantha et al., 2011; Onuoha et al., 2017). Multiple recycling cycles have minimal impact on hardness in compatibilized systems (Barbosa et al., 2017).

Recycled polypropylene (rPP) composites use fillers like MCP or nanoclay to improve performance and repurpose wastes (Onuoha et al., 2017; Zhiltsova et al., 2024). Flexural modulus, assessed by three-point bending, measures bending stiffness vital for load-bearing uses (ASTM International, 2023). MCP enhances modulus at optimal levels, but agglomeration limits gains at higher loadings; nanoclay increases it by 15-36% through exfoliation, especially in hybrids (Prashantha et al., 2011; Nagaraja et al., 2020).

Tensile modulus, determined via uniaxial tension, quantifies elastic stiffness for structural applications (ASTM International, 2023). MCP reinforces via rigid particles, with agglomeration restricting benefits at high levels; nanoclay boosts modulus by 15-36% via efficient stress transfer in hybrid systems (Prashantha et al., 2011; Nagaraja et al., 2020; Onuoha et al., 2017).

Using agricultural residues like MCP in rPP promotes circular economy principles and addresses plastic waste concerns (Zhiltsova et al., 2024). Poor interfacial compatibility requires NaOH treatment for better adhesion (Zaaba & Ismail, 2019). Halloysite nanoclay can offer synergistic effects in hybrids (Nagaraja et al., 2020; Prashantha et al., 2011). This study evaluates halloysite nanoclay's impact on mechanical properties (tensile, flexural, hardness, impact) of rPP composites with NaOH-treated MCP, varying loading, particle size, and nanoclay content for sustainable optimization.

2.0 Materials and Methods

2.1 Materials

Recycled polypropylene (rPP) sourced from Sabon gari Market served as the polymer matrix, reinforced with maize cob powder (sourced from Kaduna) or NaOH (sourced from Sigma Aldrich)-treated maize cob powder (NaOH TMCP) at loadings of 10–40 wt% and particle sizes of 100–500 µm, supplemented with halloysite nanoclay (NC sourced from Sigma Aldrich) at 0–8 wt%. Sodium hydroxide (NaOH, 5 %) was used for filler treatment.

2.2 Equipment

i) Two Roll Mill (CP 5183, North Bergen, U. S. A.)
ii) Compression Moulding Machine (DT879-7585, Wenzhou Zhingang, China)
iii) Tensile Strength Testing Machine (Model TM2101-T7, China)
iv) Flexural Strength Tester (Universal Material Testing Machine, Cat Nr Model:26)
v) Impact Resistance Tester (Charpy Impact Testing Machine, Cat. Mr. Model:42)
vi) Hardness Testing Machine (Vickers Hardness Tester MV1-PC, Mh-v CM.07/2012-1329)

2.3 Composite Fabrication and Testing

Composites were prepared via two-roll milling and compression molding, standard methods for thermoplastic agro-waste composites (Onuoha et al., 2017; Zhiltsova et al., 2024). In two-roll milling, maize cob powder, rPP, and nanoclay were mixed for uniform dispersion (Onuoha et al., 2017). Compression molding then consolidated the material under heat and pressure to form dense parts (Zhiltsova et al., 2024). Mechanical properties were evaluated using standardized tests: tensile strength per ASTM D638, flexural strength per ASTM D790, Charpy impact per ASTM D6110, and Vickers hardness per principles of ASTM E384 (ASTM International, 2022, 2017, 2018, 2021).

Tensile testing followed ASTM D638 on a tester with 10 kN capacity to assess strength, ductility, and stiffness under uniaxial load (ASTM International, 2022; Onuoha et al., 2017). Specimens were rectangular bars (100 mm × 15 mm × 5 mm), conditioned at 23 ± 2°C and 50 ± 5% humidity for ≥40 hours (ASTM International, 2022). Testing used 2 mm/min crosshead speed, with secure gripping to avoid slippage. Load and elongation were recorded until failure, yielding stress-strain curves for tensile strength, elongation at break, and modulus. At least five replicates per formulation ensured statistical reliability (Onuoha et al., 2017). This approach provides insights into filler-matrix interactions for optimizing rPP composite performance.

3.0 Results and Discussion

Figure 3.1 shows that all maize cob powder (MCP)–filled recycled polypropylene (rPP) composites exhibited lower tensile strength than neat rPP due to matrix discontinuity and stress concentration at the filler–matrix interface (Dinh et al., 2018). Tensile strength increased with MCP loading up to 20 wt% as a result of improved reinforcement and stress transfer, but declined at higher loadings because of filler agglomeration and weak interfacial adhesion (Jamila, 2022; Nuhu, 2020; Jack et al., 2020). Smaller MCP particles (100 µm) produced higher tensile strength owing to better dispersion and interfacial bonding, while larger particles promoted premature failure (Obasi et al., 2021; Onuoha et al., 2017). The addition of 2 wt% halloysite nanoclay enhanced tensile strength through improved stress distribution, but higher nanoclay contents reduced performance due to agglomeration, confirming an optimum nanoclay loading (Jack et al., 2020; Jamila, 2022).

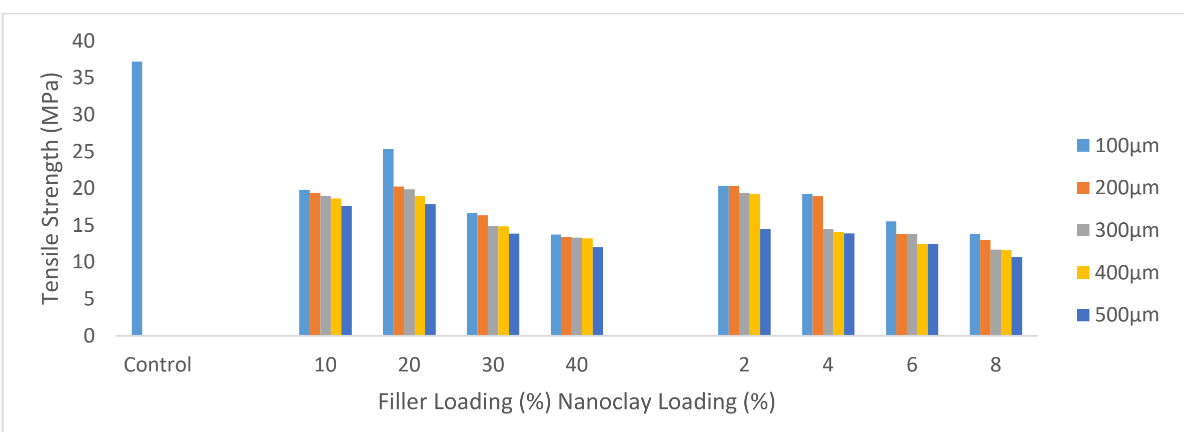

Figure 1: Effect of Maize Cob Powder and Nanoclay Loadings (%) on the Tensile Strength (MPa) of UMCP/rPP Composites at Different Maize Cob Particle Size (µm)

Figures 3.1 and 3.2 show that NaOH-treated maize cob powder (NaOH TMCP)/rPP composites consistently exhibited higher tensile strength than untreated MCP (UMCP)/rPP composites due to improved surface roughness, reduced hydrophilicity, and enhanced filler–matrix interfacial adhesion resulting from alkali treatment (Dinh et al., 2018; Koay et al., 2014; Jack et al., 2020; Nuhu, 2020). Smaller filler particles (100 µm) produced superior tensile strength compared to larger sizes because of better dispersion and more effective load transfer (Asim et al., 2015; Obasi et al., 2021; Onuoha et al., 2017). Tensile strength increased with filler loading up to an optimum of 20% before declining at higher contents due to agglomeration and matrix insufficiency (Mourad et al., 2012). The addition of 2 wt% halloysite nanoclay further enhanced tensile strength, while higher nanoclay loadings reduced performance due to agglomeration and structural inhomogeneity (Jack et al., 2020; Jamila, 2022).

Figure 3.3 shows that neat rPP exhibited the highest elongation at break, confirming its ductile nature, while UMCP incorporation caused a sharp reduction due to restricted polymer chain mobility and increased composite rigidity (Bledzki & Gassan, 1999; Faruk et al., 2012). Elongation at break decreased with increasing filler loading and filler particle size as a result of reduced matrix continuity and increased stress concentration sites (Nabi Saheb & Jog, 1999; Thwe & Liao, 2002). Composites with smaller particles (100 µm) showed higher elongation due to better dispersion and delayed crack propagation (Li et al., 2007; Ku et al., 2011). Low nanoclay contents (2–4%) maintained or slightly improved elongation through enhanced dispersion and stress redistribution, whereas higher nanoclay loadings (6–8%) significantly reduced elongation because of increased rigidity and nanoclay agglomeration (Ray & Okamoto, 2003; Pavlidou & Papaspyrides, 2008; Alexandre & Dubois, 2000; Utracki et al., 2007).

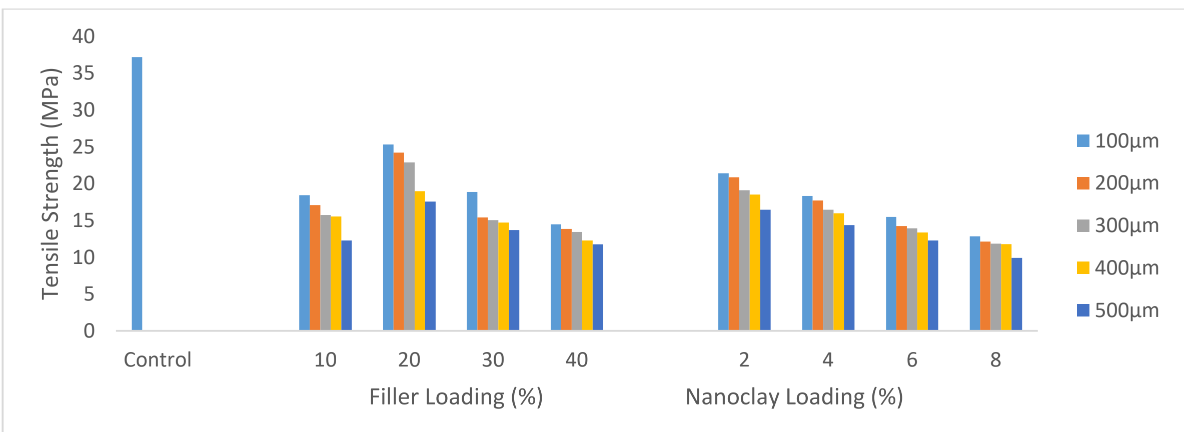

Figure 2: Effect of Maize Cob Powder and Nanoclay Loadings (%) on the Tensile Strength (MPa) of NaOH TMCP/rPP Composites at Different Maize Cob Particle Size (µm)

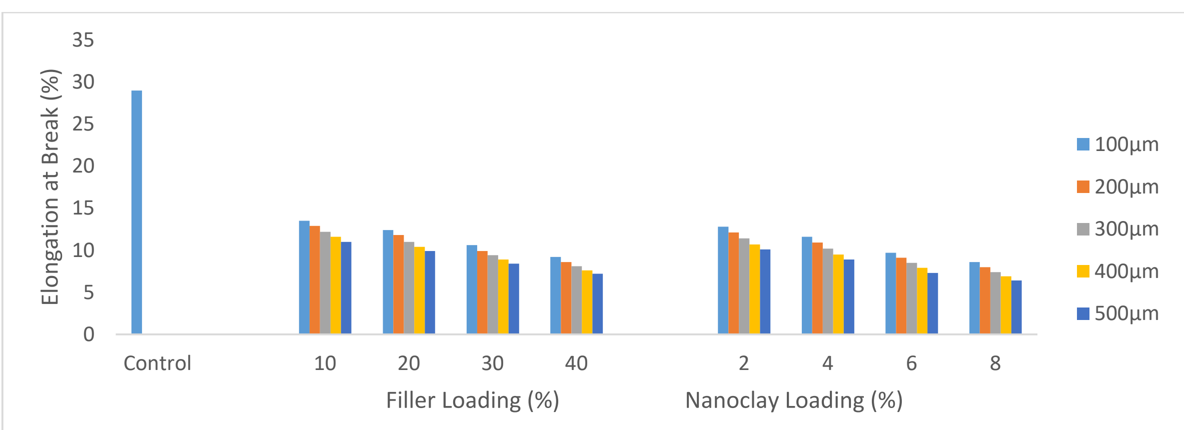

Figure 3: Effect of Maize Cob Powder and Nanoclay Loadings (%) on the Elongation at Break (%) of UMCP/rPP Composites at Different Maize Cob Powder r Size (µm)

The elongation at break of NaOH-treated maize cob powder (NaOH TMCP)/rPP composites decreased compared to neat rPP (Figure 3.4) due to increased stiffness and restricted polymer chain mobility introduced by rigid lignocellulosic fillers (Joseph et al., 2002; Mohanty et al., 2005; Faruk et al., 2012). Elongation declined with increasing filler loading and particle size because of filler agglomeration, reduced matrix continuity, and increased stress concentration sites (Nabi Saheb & Jog, 1999; Thwe & Liao, 2002). Smaller particles (100 µm) exhibited higher ductility owing to better dispersion and enhanced interfacial adhesion from NaOH treatment (Bledzki & Gassan, 1999; Li et al., 2007). Low nanoclay contents (2–4%) maintained or improved elongation through improved dispersion and stress redistribution, while higher nanoclay loadings (6–8%) reduced elongation due to increased rigidity and agglomeration (Ray & Okamoto, 2003; Pavlidou & Papaspyrides, 2008; Alexandre & Dubois, 2000; Utracki et al., 2007).

Figure 3.5 shows that the tensile modulus of UMCP/rPP composites is consistently higher than that of neat rPP, reflecting the stiffening contribution of rigid maize cob biofillers and the reinforcing effect of halloysite nanoclay within the polymer matrix (Obasi et al., 2021; Žiganova et al., 2022). As the UMCP content increases, the tensile modulus rises and reaches an optimum at approximately 30 wt%, where effective stress transfer and filler–matrix interaction dominate the mechanical response. Beyond this optimum loading, excessive filler content leads to particle agglomeration, poor dispersion, and weak interfacial regions, which reduce the efficiency of stress transfer and consequently lower the stiffness of the composites (Daramola et al., 2023; Babji et al., 2020). Particle size also plays a significant role, as composites reinforced with finer UMCP particles in the range of 100–200 µm consistently exhibit higher tensile modulus due to improved interfacial contact, larger specific surface area, and more efficient load transfer between filler and matrix (Karuppuchamy, 2015; Khakifirouz et al., 2019). The addition of nanoclay further enhances the tensile modulus, with optimum improvement observed at about 4 wt%. At higher nanoclay contents, nanoparticle aggregation and reduced dispersion limit reinforcement efficiency and result in diminished modulus gains (Galgali et al., 2004; Zawawi et al., 2021).

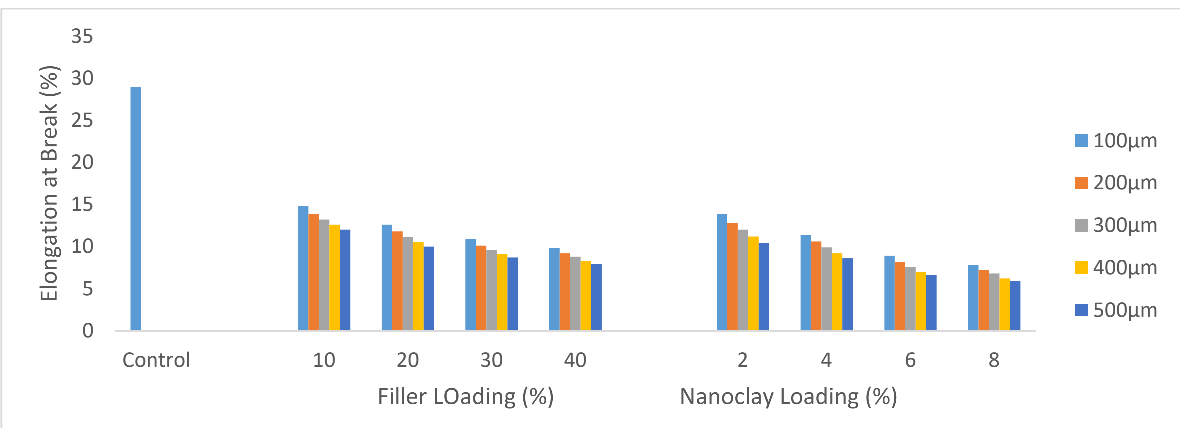

Figure 4: Effect of Maize Cob Powder and Nanoclay Loadings (%) on the Elongation at Break (%) of NaOH TMCP/rPP Composites at Different Filler Size (µm)

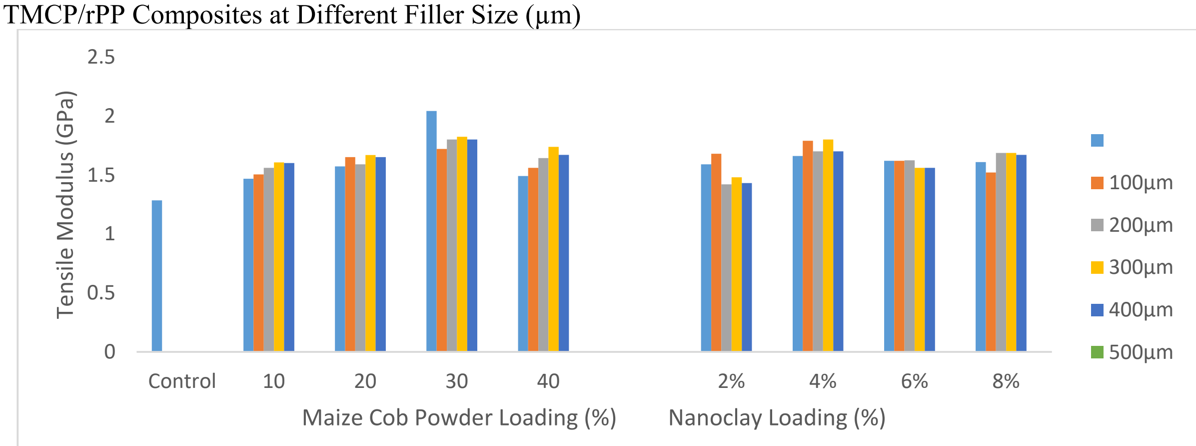

Figure 5: Effect of Maize Cob Powder and Nanoclay Loadings (%) on the Tensile Modulus (GPa) of UMCP/rPP Composites at Different Maize Cob Powder Size (µm)

Figure 3.6 presents the tensile modulus of NaOH-treated maize cob powder (TMCP)/recycled polypropylene (rPP) composites relative to neat rPP (1.284 GPa). All TMCP/rPP composites exhibit higher modulus than the control, confirming that alkali treatment improves filler–matrix adhesion and load transfer, leading to enhanced stiffness (Daramola et al., 2023; Obasi et al., 2021). The tensile modulus increases with filler loading and reaches an optimum at about 30 wt%, after which a slight decline occurs due to residual agglomeration and microstructural defects at higher filler contents (Obasi et al., 2021; Bichang'a et al., 2024). Finer TMCP particles (100–200 µm) consistently produce higher modulus than coarser particles because of their larger surface area and more effective stress transfer (Daramola et al., 2023). Relative to neat rPP, peak modulus values are approximately 24–35% higher, in agreement with trends reported for treated biofiller–PP systems (Obasi et al., 2021; Bichang'a et al., 2024). The addition of halloysite nanoclay further enhances stiffness, with optimum performance at 4 wt%, while higher nanoclay contents reduce modulus due to nanoparticle aggregation and stress concentration effects (Normasmira et al., 2013; Žiganova et al., 2022).

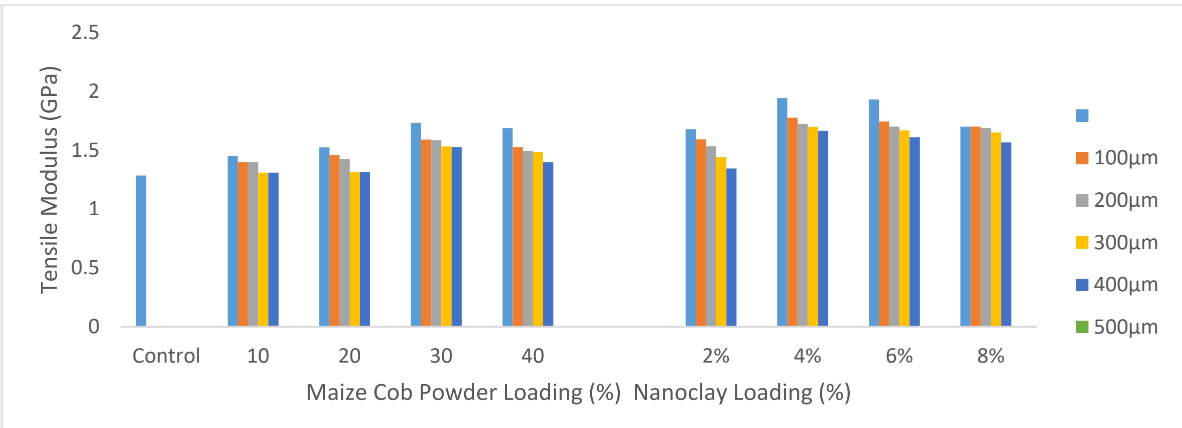

Figure 6: Effect of Filler and Nanoclay Loadings (%) on the Tensile Modulus (GPa) of NaOH TMCP/rPP Composites at Different Filler Size (µm)

Figure 3.7 illustrate the flexural strength (MPa) of untreated maize cob powder (UMCP)/recycled polypropylene (rPP) composites, with a consistent control value of 33.6 MPa representing the baseline strength of the unfilled rPP matrix across all filler particle sizes from 100 to 500 µm. Analysis of the filler loading trends reveals that flexural strength consistently improves over the control with UMCP addition, reaching a peak at 20% loading before declining at higher concentrations across all particle sizes. At 100 µm, the strength increases from 33.6 MPa in the control to 37.34 MPa at 20% filler, then decreases to 35.62 MPa at 40%. This pattern persists for larger sizes, albeit with lower peak values, such as 37 MPa at 200 µm and 35.09 MPa at 500 µm, suggesting an optimal filler incorporation around 20%, beyond which agglomeration or inadequate dispersion likely impairs the matrix-filler interface and reduces load transfer efficiency (Fu et al., 2008; Rajeshkumar et al., 2021). Furthermore, smaller filler particles demonstrate superior flexural strengths at equivalent loadings; at 20% filler, the value is 37.34 MPa for 100 µm compared to 35.09 MPa for 500 µm, indicating that finer particles offer greater surface area for enhanced interfacial bonding with the rPP matrix, while larger ones may create stress concentrations or voids that compromise performance (Fu et al., 2008; Wambua et al., 2003). These findings are consistent with existing literature on natural filler-reinforced polypropylene composites, where studies on materials like corn cob powder or snail shell in PP report flexural strength enhancements up to 15–20 wt% due to effective stress distribution, followed by declines from filler aggregation (Rajeshkumar et al., 2021). Smaller particle sizes are also noted to improve mechanical properties through better dispersion and adhesion, as evidenced in comparisons of 150 µm versus 300 µm fillers, although exceptions exist in systems like carbon fiber/PP, where tensile strength may decrease with rising filler content, emphasizing the role of filler type in determining optimal ranges (Fu et al., 2008).

The result shows similar enhancements over the control, with maximum flexural strength occurring at 4% nanoclay across all filler sizes; at 100 µm, the value peaks at 39.07 MPa at 4% nanoclay, exceeding filler-only maxima, before dropping to 35.72 MPa at 8%. This suggests nanoclay serves as a synergistic reinforcer, potentially aiding UMCP filler dispersion or boosting matrix stiffness through exfoliation (Guo et al., 2018; Rajeshkumar et al., 2021). As with fillers, smaller UMCP particle sizes yield higher strengths under nanoclay additions, with 39.07 MPa at 100 µm versus 36.69 MPa at 500 µm for 4% loading, possibly due to improved compatibility and intercalation in finer-particle matrices (Fu et al., 2008). These results align with research on nanoclay in PP composites, which highlights mechanical improvements, such as elevated flexural modulus, at 3–5 wt% due to nanoscale dispersion enhancing rigidity and thermal stability (Guo et al., 2018). However, higher loadings frequently result in performance reductions from agglomeration, impacting properties like impact strength and water absorption, while in hybrid setups with wood flour or fibers, nanoclay provides additional benefits but may compromise ductility, reflecting the observed declines at 6–8% (Rajeshkumar et al., 2021; Spoerk et al., 2018).

Figure 3.8 demonstrates that the flexural strength of NaOH-treated TMCP/rPP composites increases with filler loading up to an optimum of approximately 20 wt%, after which a decline is observed. At low to moderate filler contents, alkali treatment improves fibre surface roughness and interfacial adhesion, promoting effective stress transfer between the TMCP particles and the rPP matrix. However, at higher filler loadings, particle agglomeration, insufficient matrix wetting, and reduced matrix continuity lead to stress concentration sites that adversely affect flexural performance (Faruk et al., 2012; Mohanty et al., 2018). Composites reinforced with smaller TMCP particle sizes (100 µm) consistently exhibit higher flexural strength than those with larger particles, owing to improved dispersion, higher specific surface area, and stronger interfacial bonding within the polymer matrix (Nabi Saheb & Jog, 1999; Yang et al., 2020). Additionally, the incorporation of halloysite nanoclay further enhances flexural strength, with optimum performance observed at 4–6 wt% due to improved stiffness and load transfer efficiency. Beyond this range, excessive nanoclay causes aggregation and increased brittleness, resulting in reduced flexural strength (Ray & Okamoto, 2003; Pavlidou & Papaspyrides, 2008; Liu et al., 2019).

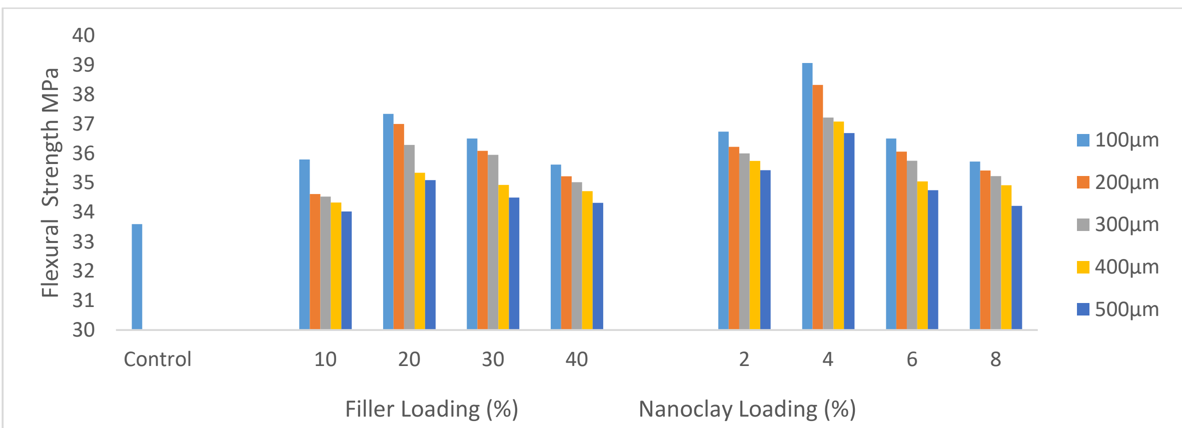

Figure3.7: Effect of Filler and Nanoclay Loadings (%) on the Flexural Strength (MPa) (%) of rPP /UMCP Composites at Different Filler Size (µm)

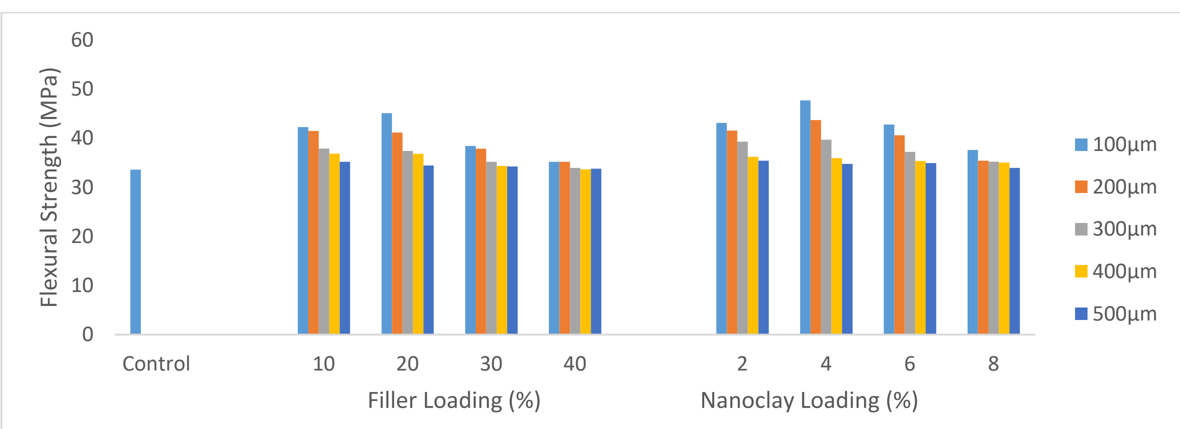

Figure 8: Effect of Filler and Nanoclay Loadings (%) on the Flexural Strength (MPa) (%) of NaOH TMCP/rPP Composites at Different Filler Size (µm)

Modulus increases (Figure 3.9) with UMCP (10–40 wt%) and nanoclay contents but decreases with particle size, reflecting filler rigidity and interfacial effects (Faruk et al., 2012; Pickering et al., 2016). For 100 µm fillers, modulus rises from 0.61 GPa (10 wt%) to 0.68 GPa (40 wt%), limited by poor adhesion in untreated systems (Callister & Rethwisch, 2020; George et al., 2001; Mohanty et al., 2018). Smaller particles enhance stress transfer via higher surface area (Nabi Saheb & Jog, 1999; Yang et al., 2020). Nanoclay boosts modulus (0.72–0.80 GPa at 2–8 wt% for 100 µm), via stiffness and chain restriction, though agglomeration diminishes gains (Ray & Okamoto, 2003; Liu et al., 2019; Pavlidou & Papaspyrides, 2008). Combined, near-additive reinforcement yields max ~0.80 GPa at high loading/small particles/8 wt% nanoclay (Thakur et al., 2014; Liu et al., 2019)

Figure 3.10 reflects hybrid-filled polymer composites' behavior, where NaOH-treated maize cob powder (MCP) and halloysite nanoclay stiffen recycled polypropylene (rPP) matrix (Faruk et al., 2012; Thakur et al., 2014; Yang et al., 2020). Flexural modulus increases with MCP loading (10–40 wt%), from ~0.82 GPa (10 wt%, 100 µm) to ~0.96 GPa (40 wt%), due to load sharing, though limited by interfacial issues (Callister & Rethwisch, 2020; Pickering et al., 2016; Mohanty et al., 2018). Modulus decreases with particle size (0.93 GPa at 100 µm to 0.82 GPa at 500 µm, 30 wt%), as smaller particles enhance stress transfer (Nabi Saheb & Jog, 1999; George et al., 2001). Nanoclay boosts modulus (0.98–1.10 GPa at 2–8 wt%, 100 µm), with diminishing returns >6 wt% from agglomeration (Pavlidou & Papaspyrides, 2008; Liu et al., 2019; Ray & Okamoto, 2003). Max ~1.1 GPa combines small particles, high loading, moderate nanoclay, indicating near-additive synergy (Thakur et al., 2014; Liu et al., 2019). NaOH improves adhesion via roughness (George et al., 2001; Kabir et al., 2012).

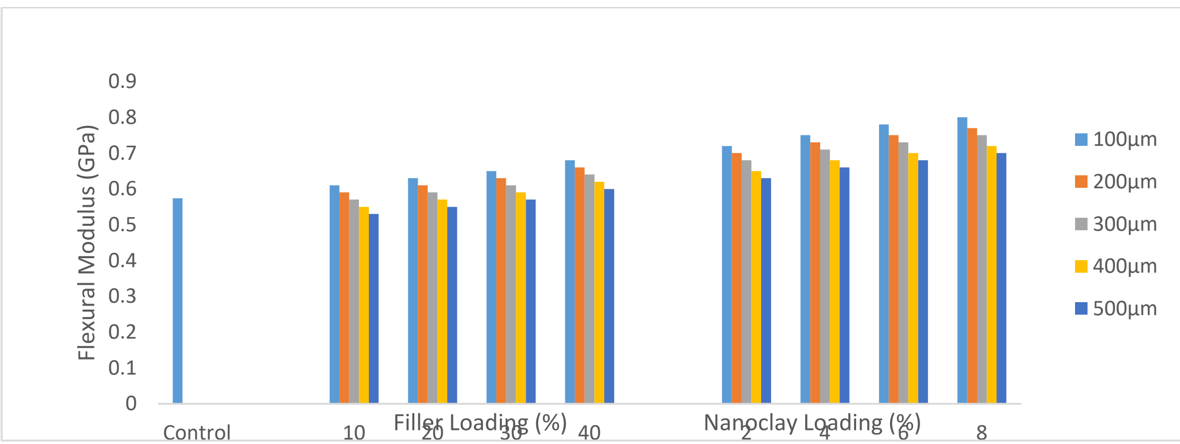

Figure 9: Effect of Filler and Nanoclay Loadings (%) on the Flexural Modulus (GPa) (%) of rPP /UMCP Composites at Different Filler Particle Size (µm)

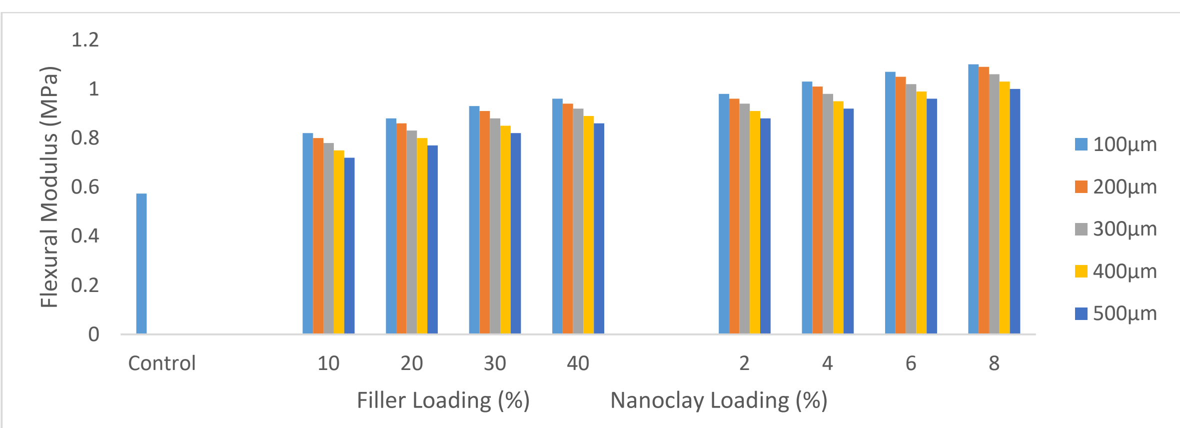

Figure 10: Effect of Filler and Nanoclay Loadings (%) on the Flexural Modulus (GPa) (%) of NaOH TMCP/rPP Composites at Different Filler Particle Size (µm)

Figure 3.11 indicates that untreated maize cob powder (UMCP) and halloysite nanoclay (NC) significantly enhance hardness of recycled polypropylene (rPP) composites, dependent on particle size. Control (neat rPP) hardness is 20.7%, showing low deformation resistance. UMCP progressively increases hardness with loading (10–40%), consistent with stiffening in natural fiber composites (Bledzki & Gassan, 1999; Faruk et al., 2012). For 100 µm, from 28.2% (10%) to 55.4% (40%); for 500 µm, from 40.3% to 70.3%, due to rigid particles restricting mobility (Nabi Saheb & Jog, 1999). Larger particles yield higher values, e.g., 40% loading: 55.4% (100 µm) to 70.3% (500 µm), aiding load transfer (Ayrilmis et al., 2013; Yang et al., 2006). NC amplifies: 100 µm from 33.6% (2%) to 65.3% (8%); 500 µm from 46.2% to 80.8%, via stiffness and efficiency (Pavlidou & Papaspyrides, 2008; Du et al., 2006). NC promotes interfacial interaction, restricting movement for synergy (Ray & Okamoto, 2003; Alexandre & Dubois, 2000). Max 80.8% confirms hybrid efficacy.

Figure 3.12 demonstrate that NaOH treatment, filler loading, particle size, and nanoclay enhance hardness of recycled polypropylene (rPP) composites. Control (neat rPP) hardness is 20.7%, reflecting low deformation resistance. NaOH-treated maize cob powder (TMCP) progressively increases hardness, confirming alkali-treated lignocellulosic efficiency (Bledzki & Gassan, 1999; Faruk et al., 2012). For 100 µm TMCP, hardness rises from 44.5% (10% loading) to 66.5% (40%); for 500 µm, from 61.5% to 86.3%, due to rigid particles restricting mobility and NaOH improving adhesion by removing impurities (Kabir et al., 2012; Nabi Saheb & Jog, 1999). Larger particles yield higher values, resisting deformation (Ayrilmis et al., 2013; Yang et al., 2006). Nanoclay further boosts: 100 µm from 52.4% (2%) to 71.2% (8%); 500 µm from 59.3% to 86.9%, via stiffness and restriction (Ray & Okamoto, 2003; Pavlidou & Papaspyrides, 2008). Synergy fills voids, but agglomeration limits gains at high loadings (Alexandre & Dubois, 2000; Pavlidou & Papaspyrides, 2008).

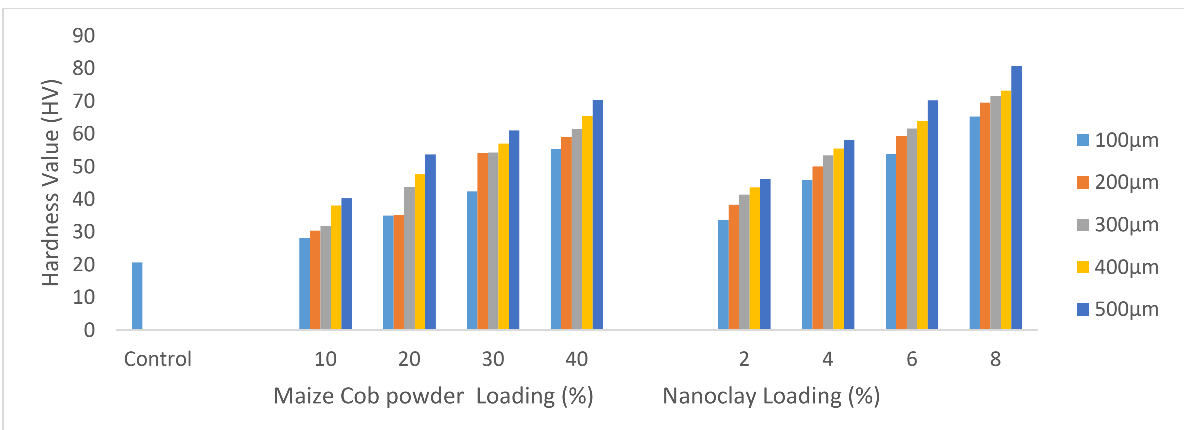

Figure 11: Effect of Filler and Nanoclay Loadings (%) on the Hardness Value (HV) (%) of rPP /UMCP Composites at Different Filler Particle Size (µm)

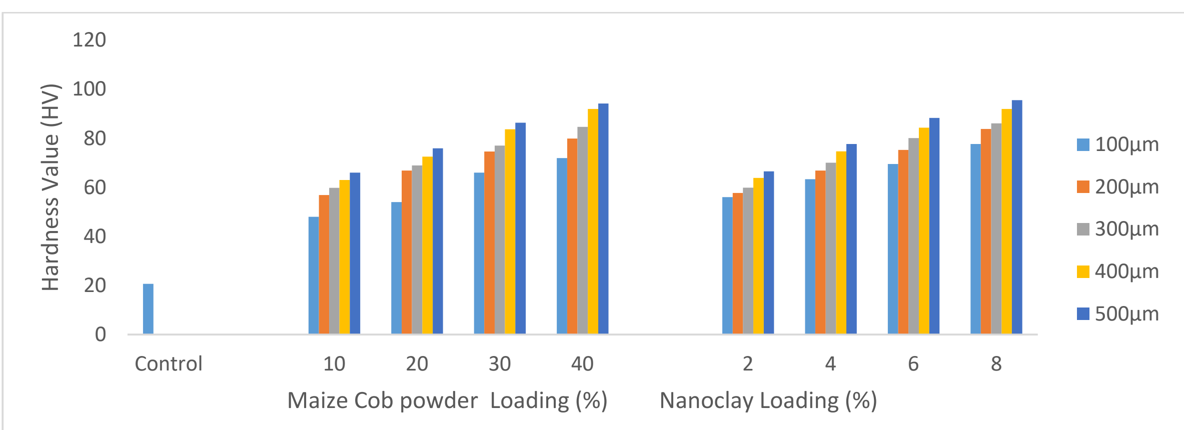

Figure 12: Effect of Filler and Nanoclay Loadings (%) on the Hardness Value (HV) (%) of NaOH TMCP/rPP Composites at Different Filler Particle Size (µm)

In Figure 3.13 control (neat rPP) shows 0.65 J/m², reflecting high ductility; UMCP incorporation reduces it, indicating brittleness in natural filler thermoplastics (Bledzki & Gassan, 1999; Faruk et al., 2012). Impact decreases with UMCP loading (10–40%): 100 µm from 0.45 J/m² (10%) to 0.40 J/m² (40%); 500 µm from 0.36 J/m² to 0.25 J/m², due to stress concentrators limiting deformation (Nabi Saheb & Jog, 1999). Larger particles worsen values (e.g., 30% loading: 0.42 J/m² at 100 µm to 0.30 J/m² at 500 µm), creating defects (Yang et al., 2006; Ayrilmis et al., 2013). Nanoclay (2–8%) slightly improves at low levels but decreases overall: 100 µm from 0.48 J/m² (2%) to 0.40 J/m² (8%); 500 µm from 0.36 J/m² to 0.30 J/m², via stress redistribution at low loads but agglomeration/stiffness at high (Ray & Okamoto, 2003; Pavlidou & Papaspyrides, 2008).

In Figure 3.14 control (neat rPP) shows 0.65 J/m², due to high ductility; TMCP reduces it, indicating brittleness in alkali-treated systems (Bledzki & Gassan, 1999; Faruk et al., 2012). Impact decreases with TMCP loading (10–40%): 100 µm from 0.60 J/m² (10–20%) to 0.50 J/m² (40%); 500 µm from 0.50 J/m² to 0.42 J/m², as rigid particles restrict mobility and create stress sites (Nabi Saheb & Jog, 1999). Larger particles lower values (30% loading: 0.52 J/m² at 100 µm to 0.45 J/m² at 500 µm), causing defects (Yang et al., 2006; Ayrilmis et al., 2013). Nanoclay (2–8%) further decreases: 100 µm from 0.53 J/m² (2%) to 0.46 J/m² (8%); 500 µm from 0.42 J/m² to 0.35 J/m², via stiffening and agglomeration limiting energy absorption (Ray & Okamoto, 2003; Pavlidou & Papaspyrides, 2008).

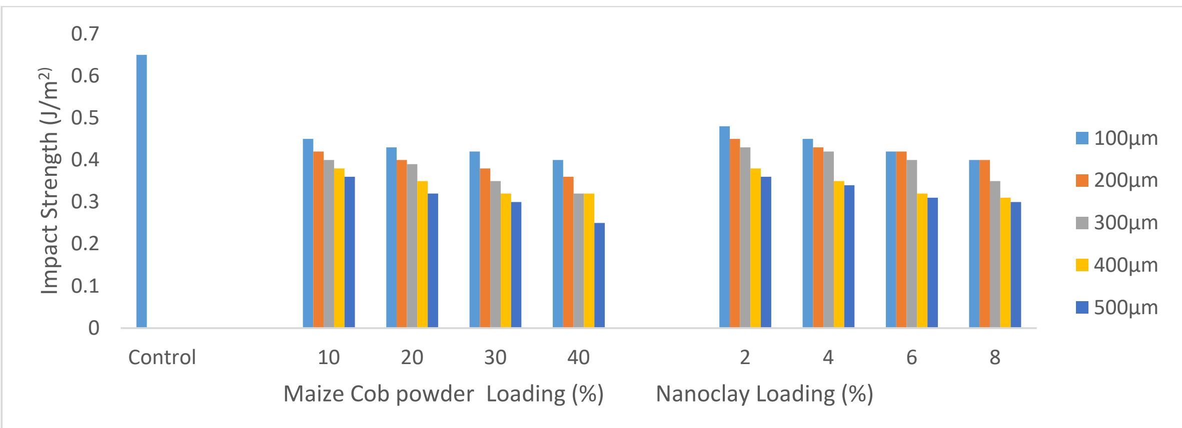

Figure 13: Effect of Filler and Nanoclay Loadings (%) on the Impact Strength (**J/m²**) (%) of UMCP/rPP Composites at Different Filler Particle Size (µm)

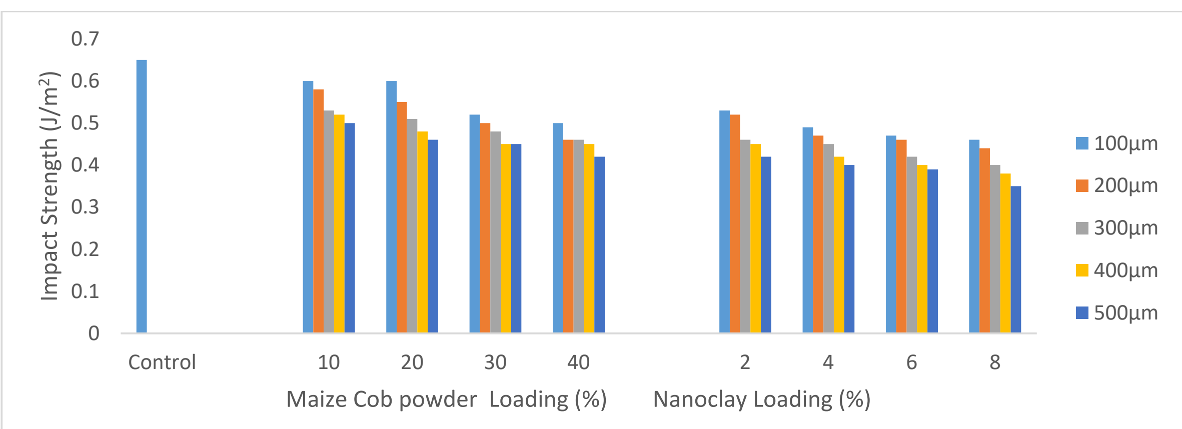

Figure 14: Effect of Filler and Nanoclay Loadings (%) on the Impact Strength (**J/m²**) (%) of NaOH TMCP/rPP Composites at Different Filler Particle Size (µm)

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