

Influence of Palm Kernel Shell Particle Size on the Performance of Waste Polystyrene Matrix Composites

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ABSTRACT

The valorisation of agricultural and plastic wastes provides a sustainable path for developing eco-friendly composite materials. This study investigates the influence of palm kernel shell (PKS) particle size on the physical, mechanical, and morphological properties of waste polystyrene matrix (WPS) composites. PKS particles of 100 μm , 200 μm , and 300 μm were incorporated at a constant filler loading of 10 wt.% and fabricated using a compression moulding machine. In addition, scanning electron microscopy (SEM) analysis was selectively carried out on composites containing 100 μm and 300 μm PKS particles at filler loadings of 10 wt.% in order to use morphological properties to elucidate the observed mechanical properties using the best-performing and worst-performing composite samples based on the physical and mechanical properties. The composites were characterised by physical, mechanical, and morphological properties as per ASTM standards to determine density, water absorption, tensile, flexural, impact, and hardness properties, and morphology using scanning electron microscopy (SEM). The result shows that density does not consistently increase or decrease with particle size due to the effects of agglomeration and porosity. However, 200 μm showed a better density of 1.13 g/cm^3 compared to 100 μm and 300 μm , with density values of 1.11 g/cm^3 and 1.12 g/cm^3 . Water absorption increased significantly in composites containing 200–300 μm particles, indicating increased void formation and weaker filler–matrix interactions, while 100 μm had the lowest water absorption (1.81%). The results also showed a decrease in tensile strength, tensile modulus, and elongation at break, flexural strength, flexural modulus, and impact as the filler particle size increased. The smallest particle size of 100 μm showed the best values for tensile strength, tensile modulus, elongation at break, flexural strength, flexural modulus, and impact, with the corresponding values of 17.27 MPa, 2.75 GPa, 8.46 %, 50.12 MPa, 2832.23 GPa, 0.35 J, while hardness has the best value of 53.8 HV at 300 μm , respectively. These improvements with 100 μm were attributed to their larger surface area, better filler dispersion and improved interfacial adhesion between PKS particles and the WPS matrix, as confirmed by SEM observations. On the other hand, coarse particles introduced stress concentration sites, voids, and microdefects, which promoted brittle failure. Therefore, the study concludes that 100 μm PKS particles are optimal for producing lightweight WPS composites with balanced physical and mechanical properties, suitable for non-structural applications, while contributing to sustainable waste management and waste upcycling.

Keywords: Palm kernel shell, waste polystyrene (WPS) composites, particle size effect, compression moulding, physical properties, mechanical properties, waste valorization, sustainable composites, biofiller.

INTRODUCTION

Plastic pollution has emerged as one of the most critical environmental challenges of the 20th century, driven by the rising global production and disposal of polymeric materials (Laura 2025). The increasing use of plastics has overwhelmed existing waste-management systems, particularly in developing regions of Asia and Africa, where collection infrastructure or framework is often inadequate. Even industrialised nations continue to struggle with low recycling efficiency, resulting in

a mounting volume of plastic waste disposal across land and waterways (Masud *et al.*, 2022; Mourshed *et al.*, 2017). With global plastic production rising from 2.3 million tonnes in 1950 to 448 million tonnes in 2015, an output projected to double by 2050, the urgency for sustainable material alternatives has never been more pronounced (Laura, 2025).

In response to the ecological and economic implications of synthetic polymers, researchers and

industries are increasingly exploring natural, renewable, and waste-derived reinforcements for polymer composites (Wei and Meyer, 2015; Saba *et al.*, 2015). These sustainable fillers provide pathways for reducing the environmental footprint of engineering materials while improving performance in structural, automotive, and consumer applications (Yan *et al.*, 2016; Yan and Chouw, 2013; Satyanarayana *et al.*, 2008). Natural fibres, in particular, have gained significant attention as substitutes for conventional reinforcements owing to their low density, biodegradability, and favourable mechanical characteristics (Ho *et al.*, 2012; Sathishkumar *et al.*, 2012). Their adoption has been notable in the automotive and aerospace sectors, where they increasingly supplement or replace glass and carbon fibres in interior and semi-structural components (Huda *et al.*, 2014).

Beyond natural fibres, agricultural and lignocellulosic wastes represent a rapidly expanding class of bio-fillers capable of enhancing the sustainability of polymer products (Thakur *et al.*, 2014). Materials such as rice husks, coconut shells, groundnut shells, wood flour, pineapple leaf fibres, and palm kernel shells (PKS) have been successfully incorporated into polymer matrices to improve strength, modify physical properties, and reduce production costs (Gupta *et al.*, 2015). These fillers provide dual benefits: they convert environmentally burdensome wastes into value-added reinforcements and simultaneously reduce reliance on petrochemical-based composites.

Palm kernel shells are a by-product of the palm oil industry and are often discarded as waste or burned, leading to environmental issues. The improper disposal of palm kernel shells contributes to land and air pollution, and the burning process releases greenhouse gases, exacerbating climate change and impacting human health and the environment. In Nigeria, Palm kernel shell waste is abundant, where over 2.5 million tonnes are generated annually (Shahbandeh, 2022). Despite its potential for applications ranging from activated carbon production to composite reinforcement, a significant proportion of PKS is still disposed of indiscriminately or burned in the open, contributing to both land and air pollution (Ifeanyi *et al.*, 2022). Its high lignocellulosic content, light weight, and favourable mechanical properties make PKS attractive for polymer reinforcement, offering improvements in strength, thermal stability, and cost efficiency when properly integrated into a composite (Ikumapayi and Akinlabi, 2018; Daud *et al.*, 2016; Afolalu *et al.*, 2018).

Polystyrene plastics, commonly known as Styrofoam, have been a popular material for packaging and food containers for decades due to their lightweight and insulating properties. However, the widespread use of polystyrene plastic has raised concerns about its negative impact on the environment (GON Plastics, 2025). At the same time, polystyrene remains one of the most problematic polymer wastes globally. Although not conventionally recyclable, waste polystyrene can be repurposed as a matrix material in composite fabrication, enabling partial recovery of its embodied energy while reducing environmental pollution (Zafar and Siddiqui 2020). Its extensive use in packaging and insulation—combined with its non-biodegradable nature—shows the compelling need to develop alternative strategies for reuse. Incorporating agricultural waste fillers such as PKS into waste polystyrene matrices offers a promising pathway toward sustainable composite development, particularly in low-cost construction, interior components, and lightweight structural applications (Wang *et al.*, 2020).

Despite the growing interest in natural-fibre and bio-filler composites, research specifically determining the effect of particle size of palm kernel shell fillers on the properties of waste-polystyrene composites remains limited. Particle size fundamentally governs interfacial adhesion, filler dispersion, surface area, and load transfer within composites.

The physical, mechanical and morphological properties have been studied in order to determine the major application areas for the fabricated composites. This will not only remove wastes from the environment but also create wealth from waste and give rise to new developed polymeric materials.

MATERIALS AND METHODS

Materials

The raw materials used for the fabrication of the composites were waste polystyrene (e.g., expanded polystyrene (EPS) food containers) and palm kernel shell (PKS).

Composite Fabrication

Preparation of Waste Polymer Matrix

The waste polystyrene (e.g., expanded polystyrene (EPS) food containers) was handpicked at the back of the female hostel, Division of Agricultural Colleges (DAC), ABU Zaria, Kaduna State, Nigeria. Subsequently, the waste polystyrenes were washed and cleaned to further eliminate dirt, as the case may be. Afterwards, they were air-dried and flaked into approximately 20 mm x 20 mm in length

and width, respectively. Finally, the waste polymer containers were stored in the laboratory for the study.

Preparation of Filler (Palm Kernel Shell Particles)

The palm kernel shell was collected, cleaned, washed, dried and ground using a Jaw crusher at the Technology Hall, Department of Chemical Engineering, ABU Zaria. Subsequently, the ground particles were sieved using a standard sieve to separate them into three different sizes of 100 µm, 200 µm, and 300 µm, respectively.

Formulation of Palm Kernel Shell Waste Polystyrene-Filled Composites: The formulation of palm kernel shell-filled waste polystyrene composites was prepared using PKS particle sizes of 100 µm, 200 µm, and 300 µm at 10 wt.% filler loadings, with neat (0 wt.%) waste polystyrene serving as the control.

Fabrication of PKS/PS Waste Composite: The palm kernel shell particles and waste polystyrene (e.g., expanded polystyrene (EPS) food containers) matrix were compounded and mixed in a two-roll mill machine following the ASTM D 15 – 627 standard.

The polystyrene matrix was introduced into the rollers heated at 180 °C, where it was melted and flowed. Subsequently, the palm kernel shell particles were added and mixed for five minutes to obtain a homogeneous mixture. This procedure was repeated for three different particle sizes (100 µm, 200 µm, and 300 µm) using 10 wt.% filler loadings. The mixtures were collected and placed in a metal mould of 150 mm x 150 mm x 5 mm dimensions. They were pressed on a compression moulding machine at 160 °C and 2.5 Pa pressure for five minutes. The resulting composites were removed from the machine and stored for future experiments.

The compounding and pressing were performed in the Polymer Processing Laboratory of the Polymer Technology Department at the Nigerian Institute of Leather Science and Technology, Zaria. Finally, the composite sheet was cut into various dimensions for physical, mechanical and morphological characterizations.

Characterization of Composites: The characterizations were carried out according to ASTM standards for testing materials. The composite samples were conditioned for 24 hours at room temperature, after which they were subjected to the various tests.

Physical Properties

Density: The mass of each sample was determined using an A&D Weighing HR-200 analytical balance, and the volume was determined using the length, width and height of the sample. The density of the samples was determined according to ASTM D792 by displacement and computed as the ratio of mass to volume.

$$\rho = \frac{m}{v} \quad \dots 1$$

where: ρ is the density, m is the mass in kg or g, and v is the volume in cm^3 or m^3

Water Absorption: Water absorption is used to determine the amount of water absorbed under specified conditions and will be carried out according to ASTM D570. The samples were conditioned in an oven at 45 °C for 72 hours. Then, placed inside desiccators for 24 hours and finally weighed (W1) using a Mettler Balance. The weighed samples were then placed inside a plastic container containing water for 24 hours. The samples were then removed from the water, dried with tissue paper and then weighed (W2). This procedure will be repeated for 30 days. The percentage water absorption will be calculated and recorded using the formula:

$$\text{Water Absorption (\%)} = \frac{\text{Final weight} - \text{Initial weight}}{\text{Initial weight}} \times 100 \quad \dots 2$$

Mechanical Properties

The composite samples were conditioned for 24 hours at room temperature, after which they were subjected to the following mechanical test:

Tensile Properties: The tensile test was carried out using a tensile properties tester (Tensile Tester TM2101-T7) according to ASTM D638 with a maximum force of 10 KN. The sample dimensions were 100 mm x 15 mm x 5 mm in length, width and thickness, respectively. A cross-head speed of 2 mm/min was used.

The test specimens were held in the grips of the testing machine by the lower and upper jaws, tightened evenly and firmly to prevent any slippage as the test commenced. The resistance and elongation of the specimens were detected and recorded by the load cell until a failure or rupture occurred. From the tensile test, tensile parameters (tensile strength (breaking point), elongation at break and tensile modulus) were determined and recorded.

$$\text{Tensile Strength} = \frac{F}{A} \quad \dots 3$$

where, F= force, A= cross-sectional area

Flexural Properties: The flexural or 3-point bending test was carried out on Enerpac Universal Material Testing Machine (Universal Material Testing Machine Cat No. Model: 26) with a maximum load of 100 kN and a crosshead speed of 5 mm/min. The test was carried out according to ASTM D790. The sample dimensions will be 100 mm x 15 mm x 5 mm in length, width and thickness, respectively. The specimens were positioned horizontally on the sample compartment of the machine, and then the test would start. The flexural strength and modulus were determined and recorded.

$$\text{Flexural strength} = \frac{3PL}{2bd^2} \quad \dots 4$$

$$\text{Flexural modulus} = \frac{PL^3}{4Wbd^3} \quad \dots 5$$

where:

P = maximum load in kN,
L = gauge span of the sample in mm,
b = sample width in mm,
d = sample thickness in mm,
w = deflection

Impact Strength: The impact strength of the composite samples was measured using the Charpy Impact Tester (Model no. 6957, capacity of 15 joules) according to ASTM E23 (unnotched) standard. Samples were tested at room temperature

by a single swing of the pendulum hammer using Norwood. The specimen size was 100 mm x 15 mm x 5 mm. Each sample was placed on the vice and clamped firmly. The pendulum hammer was raised to the required height and then released, and struck the sample at once. Then, the impact energy absorbed by the specimen was recorded. The impact strength of the samples in joules per square metre was recorded.

Hardness: The hardness of the sample was measured using a Vickers Hardness Tester MV1-PC, Mh-v CM. 07/2012-1329, with a maximum capacity of 0.1 Kgf (150 HV), following the ASTM D2240 standard. The test will be performed at a temperature of 23 ± 2 °C. The specimen will have a dimension of 30 mm x 10 mm x 5 mm and will be mounted in a specimen compartment. The indentation point was focused, and then five different points were indented on each specimen. The hardness values were recorded, and the average of the five readings was calculated and reported.

Morphological Property

The morphology of the palm kernel shell particles (PKSP) waste polystyrene composites (100 µm) was studied using a Scanning Electron Microscope (SEM) ZEISS Sigma 300 VP (Graz, Austria) at an accelerating voltage of 0.02 kV – 30 kV and magnification of 10x - 1 000 000x and 300 µm was analysed using a Thermo Scientific Phenom ProX desktop scanning electron microscope. The samples were pulverized to about 0.15 mm (≈100 mesh) before imaging at magnifications ranging from ×500 to ×150,000.

RESULTS AND DISCUSSIONS

Table 1. Influence of Palm Kernel Shell Particle Size on Composite Physical and Mechanical Properties at 10 wt.% filler loading

PKS Particle Size (µm)	Density (g/cm ³)	Water Absorption (%)	Tensile strength (MPa)	Tensile Modulus (GPa)	Elongation at Break (%)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Impact (J)	Hardness (HV)
100	11.1		17.27	2.75	8.46	50.12	2832.23	0.35	40.2
200	1.13		13.76	2.61	8.31	42.82	2643.2	0.25	36.5
300	1.12		10.21	2.5	7.94	32.76	2589.87	0.23	53.8

Density

The density of the composite material is an important factor to consider when choosing a material with a specific high strength instead of low density. The influence of particle size on the density of the PKS/WPS composites at 10 wt.% was presented in Figure 1. It was observed from the graph that the density of PKS/WPS composites does not consistently increase or decrease with

particle size due to the effects of agglomeration and porosity. The 100 µm particle size shows a density of 1.11 g/cm³, which shows a reduction in the lower intrinsic density of PKS compared to the polymer matrix, as well as the introduction of micro-voids due to incomplete wetting and imperfect packing of the filler within the matrix. A slight increase in density was observed at 200 µm with a density of 1.13 g/cm³, which may be attributed to improved

particle packing and reduced agglomeration at the intermediate particle size, leading to lower porosity and better space-filling within the polymer matrix. Studies by Siraj *et al.* (2022) also report that intermediate particle sizes can result in higher composite density, due to improved filler dispersion and reduced void content. Their studies revealed that the 25 μm has a better density than the composite sheet prepared from 5 μm particles, attributed to the fact that 25 μm particles are bigger in size and nature than the 5 μm particles, thereby contributing to a greater density value. However, a further increase in particle size to 300 μm resulted in a decrease in density to 1.12 g/cm^3 . This can be

attributed to the reduced surface area and poorer contact between the larger PKS particles and the polymer matrix, which promotes weak interfacial interaction and increased porosity. Larger particles tend to reduce the contact area, leading to poor adhesion, higher void content, increased composite volume, and consequently lower volume. Similar findings reported by Umaru *et al.* (2022), density variation with particle size is not strictly increasing or decreasing; rather, it depends on packing efficiency and porosity, where larger particles led to decreased density due to void formation.

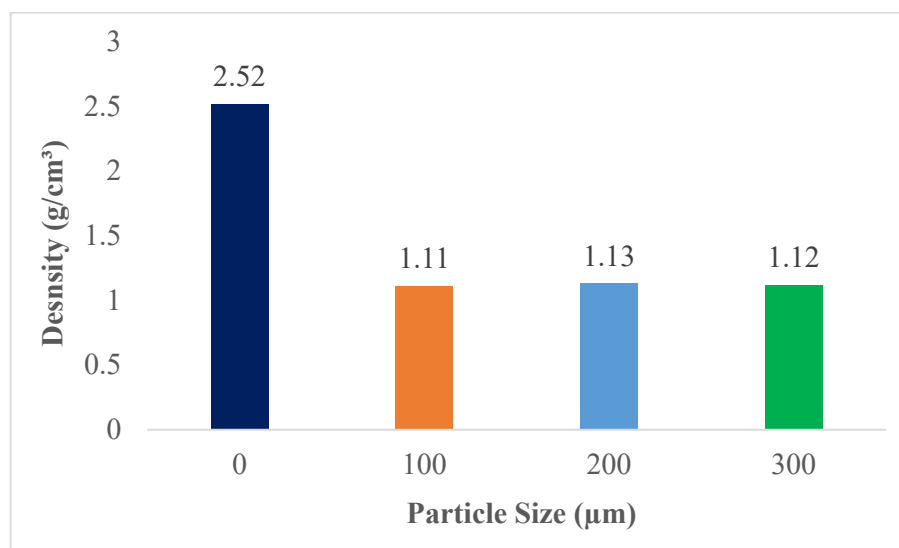


Figure 1: Influence of Particle Size on the Density of PKS/WPS Composites

Water Absorption

Figure 2 shows the percentage water absorption of PKS/WPS composite at different particle sizes for 30 days, but the composite saturated at 25 days. The general trend was that, as the particle size increased from 100 μm to 300 μm , water absorption for the samples increased as well. This is because Palm kernel shell (PKS) is a lignocellulosic natural filler which contains cellulose, hemicellulose, and lignin, which carry the hydroxyl (-OH) groups on their surfaces. These hydroxyl groups are hydrophilic, which naturally attract and bond with water molecules (Sahu and Gupta, 2020). Composites reinforced with 300 μm PKS exhibited the highest moisture uptake with a water absorption rate from 2.4-2.51 %, followed by those with 200 μm particles with a water absorption rate from 2-2.1 %, while the 100 μm composites showed the lowest absorption throughout immersion with a water absorption rate of 1.81-1.83 %. However, the control sample, which is the waste polystyrene (e.g., expanded polystyrene (EPS) food containers), has the lowest value of 0.83 % and maintained this value throughout, which could be attributed to its

hydrophobic (repels water) nature. This study agrees with the findings of Achukwu *et al.* (2020), who also observed little water absorption by the control sample in flamboyant (*Delonix regia*) pod polyester composites.

This behaviour is also attributed to the increased porosity associated with coarse particles, which creates wider capillary pathways for water ingress. Smaller particles fill the matrix more efficiently and reduce void connectivity, limiting water diffusion. The larger particles also possess less contact with the polymer matrix, increasing the number of hydrophilic sites exposed to water (Umaru *et al.*, 2022). SEM analysis aligned with these findings by revealing more pronounced voids and interfacial gaps in composites containing larger PKS particles.

The composite reached its saturation point at Day 25. This showed that by Day 25, all the available hydrophilic sites on the PKS filler, particularly the hydroxyl groups, had been fully saturated by water molecules. Once these sites were fully saturated, there were no longer any concentration points to

allow further water diffusion into the material composite. Since no significant weight gain was observed beyond Day 25, it was scientifically correct to stop the water absorption test at that point. This behaviour is consistent with Fickian diffusion kinetics, where moisture uptake rises initially and

then plateaus at equilibrium. The fact that saturation occurred at 25 days rather than 30 days means this particular PS/PKS composite system reached equilibrium faster than initially thought, which is a valid and acceptable experimental outcome.

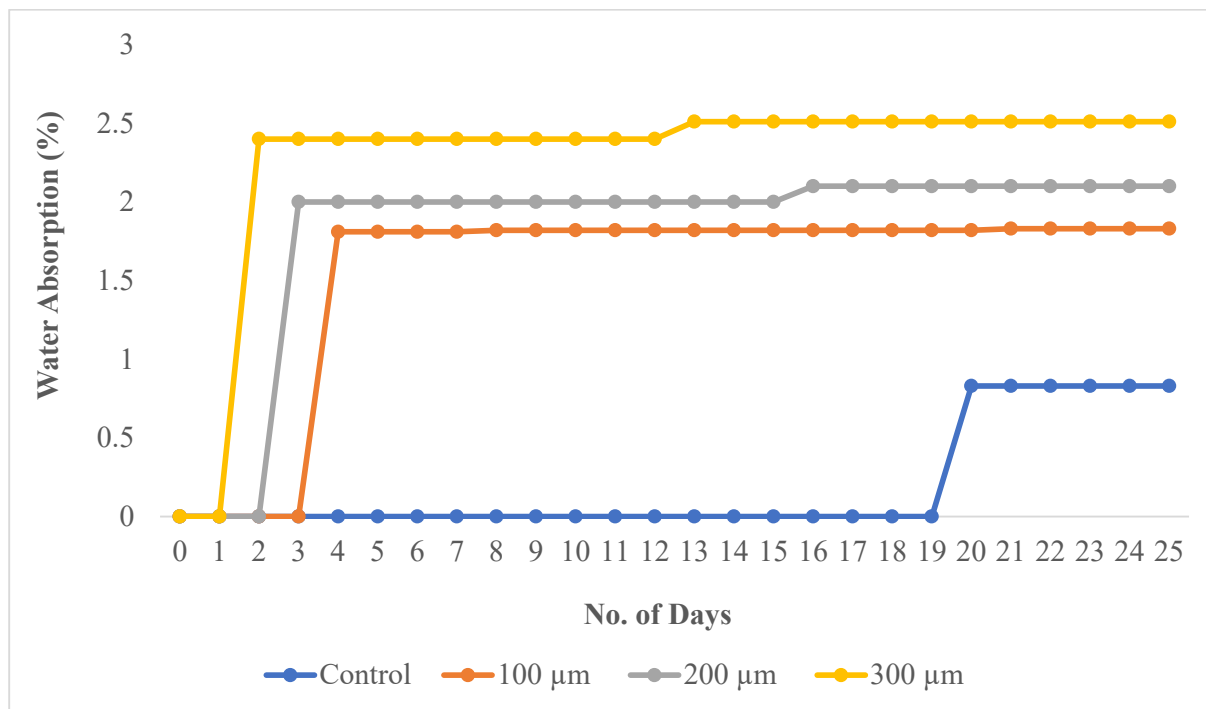


Figure 2: Influence of Particle Size on the Water Absorption of PKS/WPS Composites

Tensile strength/Modulus

Tensile strength is a term used to describe how much load a material can withstand when loaded in tension. It may refer to the yield, ultimate, or fracture (breaking) strength. The tensile strength of the PKS/WPS composites was observed to decrease with increasing particle size, as shown in Figure 3. Composites with 100 µm particles recorded the highest tensile strength value of 17.27 MPa. However, 300 µm particles have the lowest strength value of 10.22 MPa. The decrease seen in Figure 3 could be attributed to the lower surface area provided by the larger particle size, which led to irregular dispersion of the filler particles, which in turn reduced the efficient transfer from the polymer matrix to the filler particles. Similar reports were observed by Umaru *et al.* (2022), Ameh *et al.* (2015), and Okey-Onochie *et al.* (2020).

The tensile modulus of a composite material indicates its stiffness and ability to resist deformation under stress. The tensile modulus of

the PKS/WPS composites was found to decrease with increasing particle size, as observed in Figure 3. Smaller PKS particles (100 µm) produced higher tensile modulus values of 2.75 GPa, while 200 µm and 300 µm particles had the lowest modulus at 2.61 GPa and 2.50 GPa, respectively. The increased modulus at 100 µm particle sizes could be attributed to improved stress transfer and more effective restriction of polymer chain mobility (Onuoha *et al.*, 2017), whilst larger or coarser particles of 300 µm showed weaker reinforcement efficiency, likely due to poor wetting and inadequate interfacial bonding, which limits their ability to contribute to rigidity. The improved modulus at a smaller particle size can also be attributed to their larger surface area, which promotes better dispersion and stronger interfacial adhesion with the polymer matrix. A decrease in modulus with an increase in particle size was also reported by Bolcu and Stanescu (2020) in their work “A study of the mechanical properties of composite materials with a dammar-based hybrid matrix and two types of flax fabric reinforcement”.

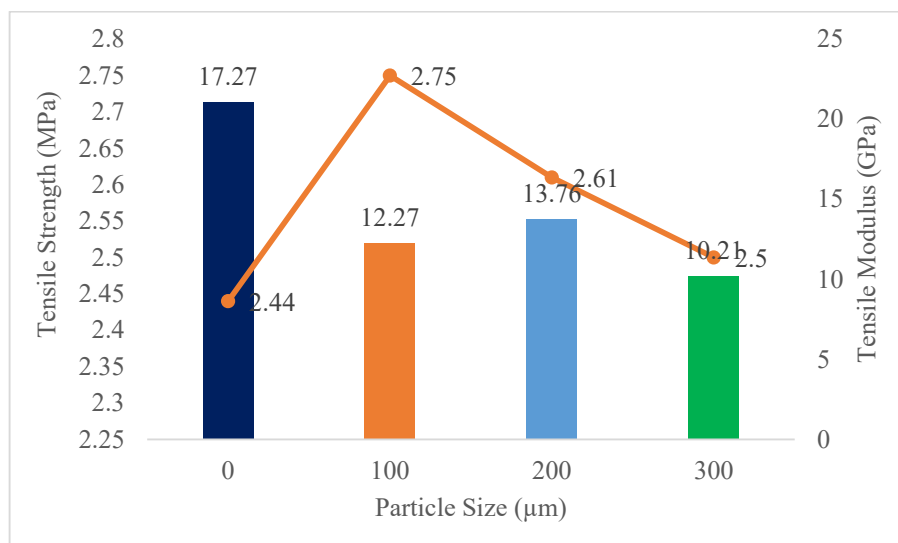


Figure 3: Influence of Particle Size on the Tensile Strength and Modulus of PKS/WPS Composites

Elongation at Break

Elongation at break represents the material's ability to undergo deformation before fracture, including the composite's ductility. Figure 4 shows the elongation at break of the PKS/WPS composites, which was found to decrease with increasing particle size. The 100 μm composites showed the highest elongation of 8.46 % because of their uniform dispersion. On the other hand, composites containing 200 μm and 300 μm particles have the

lowest elongation at break values of 8.31 % and 7.94 %, which fractured earlier due to the presence of stress concentration points and hindered molecular mobility around coarse fillers. The decline in elongation indicates that the composites became more brittle with larger particles. This is due to the reduced polymer chain mobility. Similar trends were reported by Achukwu *et al.* (2023) and Mehdi *et al.* (2009).

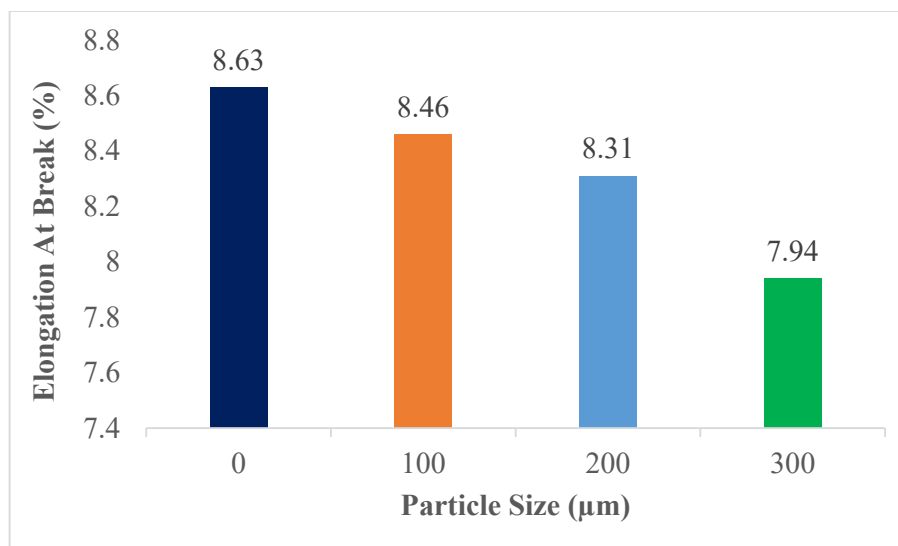


Figure 4: Influence of Particle Size on the Elongation at Break of PKS/WPS Composites

Flexural Properties

Flexural strength is also known as the cross-bending strength of the samples or the fracture strength. It's also defined as the ability of a material to resist deformation under load. From Figure 5, the maximum flexural strength of PKS/WPS composite was found to be 50.12 MPa at 100 μm. However, the lowest flexural strength was at 300 μm with a

value of 32.76 MPa. The observed decrease in flexural strength could be due to an air trap, which leads to microcrack formation in the interface under loading and non-uniform stress transfer due to the PKS filler agglomeration in the WPS matrix. The smaller particle sizes (100 μm) provided better flexural strength, likely due to their better

dispersion and stronger matrix-filler interaction (Kolawale *et al.*, 2015; Daniel *et al.*, 2017).

Figure 5 also shows that the flexural modulus of the PKS/WPS composites decreased with an increase in particle size from 100 μm , 200 μm , and 300 μm , respectively. The 100 μm particle size shows the

highest modulus of 2832.23 GPa, whilst the 200 μm and 300 μm particle size showed the lowest modulus of 2643.2 GPa and 2589.87 GPa, respectively. The decrease could be attributed to weak mechanical interlocking and stress localization provided by larger particles (Onuoha *et al.*, 2017; Lawal *et al.*, 2023).

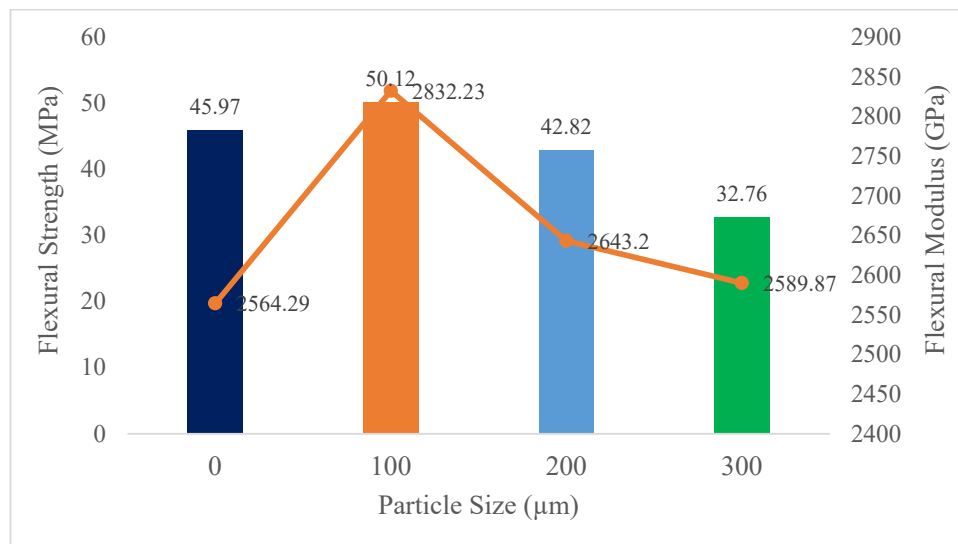


Figure 5: Influence of Particle Size on the Flexural Strength and Modulus of PKS/WPS Composites

Impact Strength

The impact strength of a composite material is a measure of the ability of a material to resist cracking, fracturing, or plastic deformation under sudden and intense impact or shock loads. Figure 6 shows that the impact decreased with an increase in particle size. The results observed show that the impact decreased with an increase in particle size, with the smaller particle size of 100 μm giving a higher impact strength, with a value of 0.35 J and 0.23 J being the lowest impact obtained at 300 μm ,

respectively. This indicates that smaller particle sizes improved impact strength due to better dispersion, greater surface area, and stronger particle-matrix bonding, which made energy absorbed more uniformly under impact (Anslem *et al.*, 2020). However, the decrease observed with larger particles provided lower impact strength due to poor interfacial adhesion and stress concentration points, voids, and weak zones increasing, causing premature failure under impact (Lawal *et al.*, 2023; Achukwu *et al.*, 2023).

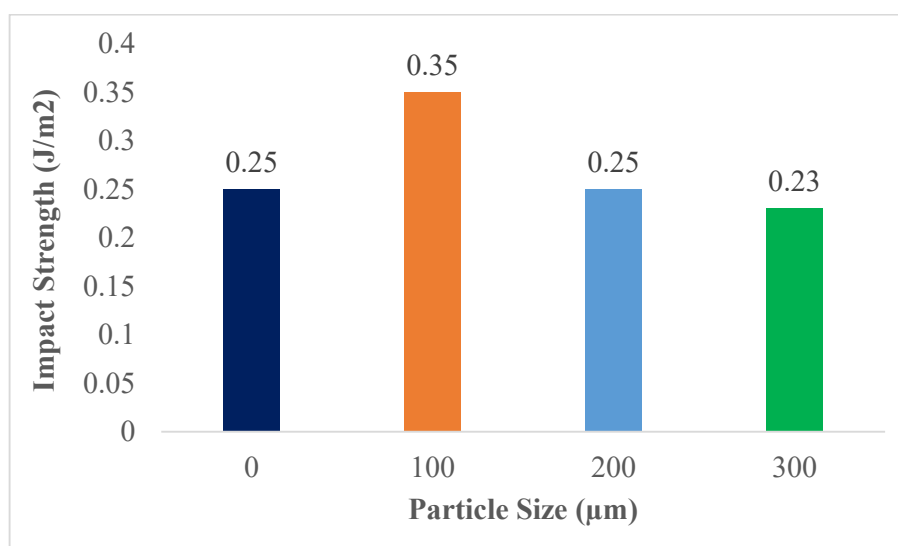


Figure 6: Influence of Particle Size on the Impact Strength of PKS/WPS Composites

Hardness

Figure 7 shows the Vickers hardness values of the PKS/WPS composites across the three particle sizes. The hardness results did not follow a simple normal trend with increasing particle size. The neat WPS control recorded a hardness of 32.8 HV. The addition of 100 μm PKS particles increased hardness to 40.2 HV, which is attributed to the reinforcing effect of well-dispersed filler particles that offered greater resistance to surface indentation. At 200 μm , hardness declined slightly to 36.5 HV, consistent with the onset of particle agglomeration and a reduction in surface filler density at this intermediate particle size (Rahman *et al.*, 2010). The 300 μm composite recorded the highest hardness value of 53.8 HV, which appears opposite to the same composite exhibiting the lowest tensile strength (10.21 MPa), flexural strength (32.76 MPa), and impact strength (0.23 J) among all tested formulations. This behaviour

could be explained by the fundamental difference between hardness and bulk mechanical measurements. Hardness measures resistance to localized surface indentation and is therefore sensitive to the material present at and near the composite surface, rather than the bulk microstructure. Coarser PKS particles, owing to their larger dimensions and the flow behaviour of the polymer melt during compression moulding, tend to migrate toward and concentrate at the composite surface. As a result, the Vickers indenter could make a direct contact with the hard lignocellulosic PKS material rather than the softer WPS matrix, registering a higher hardness value. This surface-hardening effect is therefore independent of bulk load-bearing performance and does not contradict the inferior tensile, flexural, and impact results recorded at 300 μm . Similar findings were reported by Bosan *et al.* (2020)

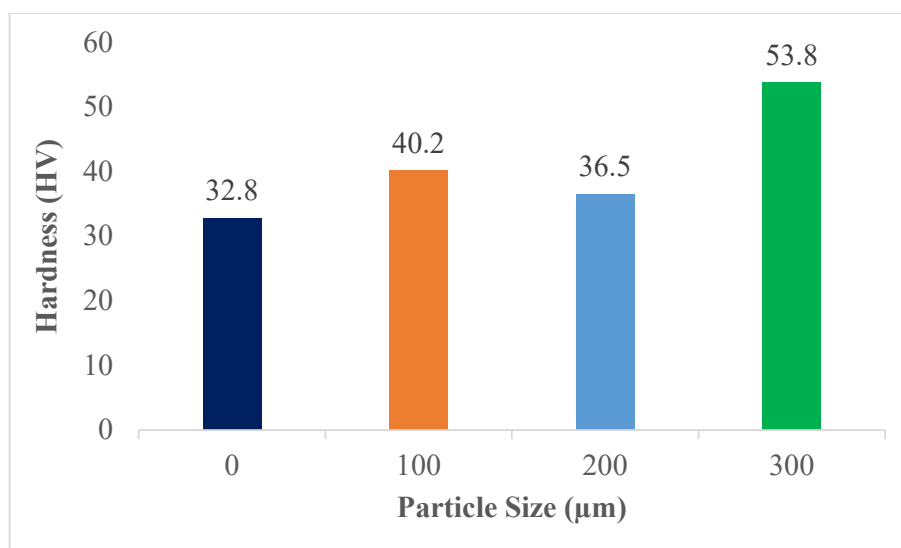


Figure 7: Influence of Particle Size on the Hardness of PKS/WPS Composites

4. Morphological Analysis

Table 2. Relationship between particle size, microstructural features, and composite performance.

PKS Particle Size (μm)	Filler Loading (wt.%)	SEM Morphology	Mechanical Performance	Water Absorption Behaviour
100	10	Uniform dispersion, good interfacial bonding, minimal voids	Highest tensile, flexural, and impact strength	Lowest water uptake
300	10	Agglomeration, interfacial debonding, large voids	Lowest mechanical performance	Highest water uptake

Plates 1 and 2 show the SEM micrographs of the fracture surfaces of PKS/WPS composites containing 100 μm and 300 μm PKS particles at a constant filler loading of 10 wt.%. The two samples were selected in order to use morphological properties to elucidate the observed mechanical

properties, using the best-performing and worst-performing composite samples based on the physical and mechanical properties.

The SEM micrograph of the composite containing 100 μm PKS reveals a compact and homogeneous

microstructure, with finer particles more uniformly dispersed within the WPS matrix and minimal evidence of filler pull-out. The reduced particle size increases the effective surface area available for matrix–filler interaction, promoting better mechanical interlocking and enhanced resistance to particle debonding during fracture. This superior interfacial condition directly supports the stronger bulk mechanical response recorded for this composite, specifically, the highest tensile strength (17.27 MPa), flexural strength (50.12 MPa), and impact strength (0.35 J) among all particle sizes tested. The well-distributed filler also restricts void formation, reducing potential sites for crack initiation and thereby contributing to greater resistance to both static and dynamic loading.

In contrast, the composite containing 300 μm PKS exhibits a rough and heterogeneous fracture surface, characterized by interfacial gaps, microcracks, and conspicuous filler pull-out (Wilson García *et al.*, 2021). The presence of partially detached PKS particles and voids at the matrix–filler interface indicates incomplete wetting of the larger particles by the waste polystyrene matrix during the fabrication of the composites (Raghavendra *et al.*, 2012). The coarser particle dimensions reduce the available surface area per unit volume, reducing the extent of contact between matrix–filler and resulting in weak interfacial adhesion and inefficient stress transfer during mechanical loading. These observations are reflected directly in the inferior mechanical properties recorded at this particle size, tensile strength (10.21 MPa), flexural strength (32.76 MPa), and impact strength (0.23 J), where the enlarged interfacial gaps and pull-out cavities act as stress concentration sites, promoting premature crack propagation and earlier composite failure.

Furthermore, the higher void content and interfacial debonding observed in the 300 μm composite provide a morphological explanation for its increased water absorption. The interconnected voids and gaps at the filler–matrix interface serve as diffusion pathways for moisture ingress, consistent with Fickian diffusion behaviour. In comparison, the more compact microstructure of the 100 μm composite restricts moisture penetration, explaining its lower water absorption of 1.81%. These findings confirm that particle size exerts a significant influence on the interfacial morphology of PKS/WPS composites, with finer particles producing a more favourable microstructure that supports superior mechanical and physical performance."

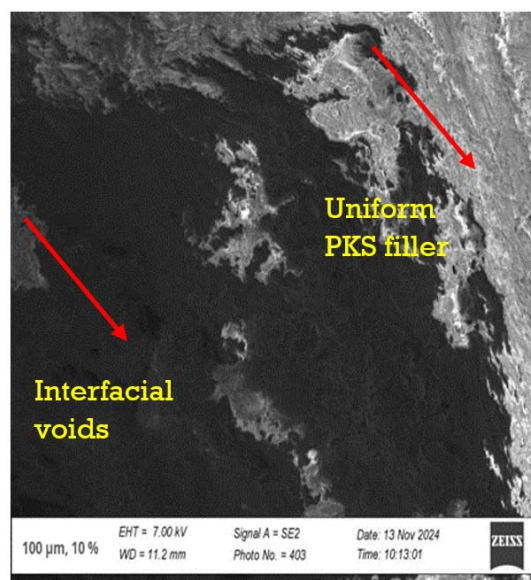


Plate 1: 100 μm at 10 wt.% PKS

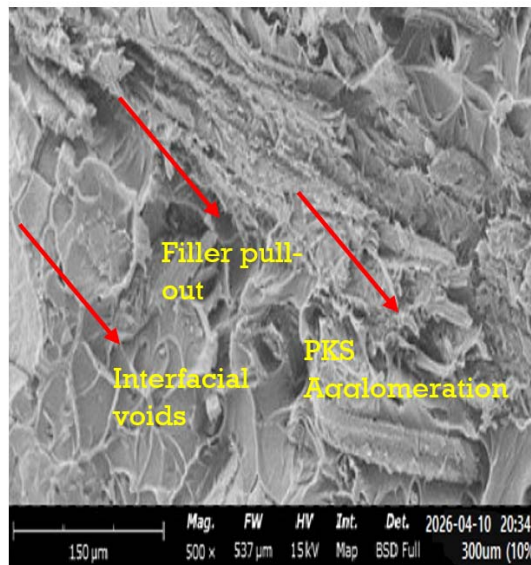


Plate 2: 300 μm at 10 wt.% PKS

CONCLUSION

The study has successfully fabricated and investigated the influence of palm kernel shell particle size on the performance of waste polystyrene matrix composite at a constant filler loading of 10 wt.%. Among the particle sizes investigated, the composite fabricated with 100 μm PKS particles gave the most balanced and superior properties, including the highest tensile strength (17.27 MPa), flexural strength (50.12 MPa), and impact strength (0.35 J), as well as the lowest water absorption (1.81%), while 300 μm obtained the highest hardness properties. Compared to a larger particle size, the 100 μm sample showed approximately a 69% improvement in tensile strength and a 27% reduction in water absorption,

showing the effectiveness of finer particles in increasing interfacial interaction.

The improved performance of the 100 µm PKS-filled composite could be attributed to improved filler dispersion, increased surface area for matrix–filler bonding, and reduced void formation, as confirmed by SEM analysis. In contrast, composites containing larger PKS particles (300 µm) exhibited increased agglomeration and interfacial defects, which adversely affected the mechanical performance of the composites.

Based on the result obtained from the fabricated composite, the 100 µm PKS-filled WPS composite is suitable for lightweight, non-load-bearing, and indoor applications. In addition, the study demonstrates a viable pathway for the sustainable upcycling of agricultural and plastic wastes into value-added composite materials, thereby contributing to environmental pollution reduction. Thus, offering practical guidelines for designing composite materials that require little water absorption.

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