Valorization Of Palm Kernel Shell Powder for The Development Of MAPP-Enhanced Polypropylene Bio-Composites: Mechanical Optimization and Suitability for Food Packaging Applications

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***Abstract*—This study focuses on the valorization of palm kernel shell (PKS), an abundant agricultural waste from the palm oil industry, by utilizing its powder (PKSP) as a reinforcing filler in polypropylene (PP) matrices. Maleic anhydride-grafted polypropylene (MAPP)-enhanced PP was compounded with palm kernel shell powder (PKSP) of controlled particle sizes (75 µm, 250 µm, and 500 µm) at varying weight percentages (0, 5, 10, 15, 20, and 25 wt.%). The composite bars were fabricated using melt processing followed by compression molding. The mechanical properties, including tensile strength and tensile modulus, were characterized in accordance with ASTM D638 standards, and afterward, optimized for best balance of strength and stiffness. This were numerically obtained by Python script using the highly recommended Monte Carlo optimization method consisting of geometric mean. The experimental optimization conducted via a Python interface reveals that 25 wt% PKSP yields the highest weighted optimization scores across all particle sizes, with the 75 µm–25 wt% combination achieving the highest score. Pareto optimization similarly identifies 75 µm at 25 wt% as optimal, while product optimization shows that 25 wt% of either 75 µm or 500 µm maximizes the strength stiffness product. Geometric mean optimization ranks 75 µm at 25 wt% highest due to minimal variation in both properties across filler content. Desirability function analysis places 75 µm–25 wt% closely behind 500 µm–25 wt%. Consequently, the 75 µm–25 wt% combination emerges as the optimized set for achieving the best balance of strength and stiffness. This research confirms that MAPP-enhanced PP/PKSP composites, derived from agricultural waste, present a promising sustainable alternative for rigid food packaging applications, contributing to waste reduction and circular economy principles.**

***Index Terms*—Valorization Palm Kernel Shell Powder (PKSP), Polypropylene (PP), Maleic Anhydride-grafted Polypropylene (MAPP), Bio-composites, Mechanical Properties, Compression Molding, coupling agent, compatibilizer, sustainable materials, optimization, Food Packaging.**

I. INTRODUCTION

The escalating accumulation of non-biodegradable plastic waste, particularly from single-use packaging, constitutes a pressing global environmental crisis [4]. This challenge has catalyzed a paradigm shift in materials science, driving intensive research into sustainable alternatives. Among these, polymer bio-composites have emerged as a particularly promising solution. These materials, which combine a polymer matrix with natural fiber or filler reinforcements, offer significant advantages, including a reduced dependence on finite fossil fuels, a lower carbon footprint, and the potential for enhanced end-of-life biodegradability [3]

Simultaneously, the palm oil industry, a cornerstone of the economy in many tropical nations, generates vast quantities of lignocellulosic biomass. A major by-product of this industry is palm kernel shells (PKS), which are produced during the extraction of palm kernel oil. Traditionally, PKS has been underutilized, often relegated to low-value applications such as fuel or simply discarded, contributing to waste management challenges [6]. However, this resource is rich in lignin and cellulose, imparting excellent rigidity and thermal stability, which positions it as a potential reinforcement for polymer matrices [2]. The valorization of PKS into a finely ground palm kernel shell powder (PKSP) for use as a bio-filler in composites aligns perfectly with the principles of a circular economy, effectively transforming a waste stream into a value-added resource.

Despite the clear potential of PKSP, its widespread application in high-performance composites is hindered by a fundamental materials science challenge: the inherent incompatibility between the hydrophilic lignocellulosic filler and the hydrophobic thermoplastic matrices, such as polypropylene (PP), that are commonly used [4]. This polarity mismatch results in poor interfacial adhesion and filler agglomeration within the matrix. The consequences are detrimental to the composite's mechanical properties, leading to compromised tensile strength and impact resistance, which are critical for structural and functional applications.

To address this interfacial issue, the use of a coupling agent is a widely accepted and effective strategy. Maleic anhydride-grafted polypropylene (MAPP) has been extensively studied as a compatibilizer for PP-based composites. Its efficacy lies in its bifunctional nature: the maleic anhydride group can react with the hydroxyl groups on the lignocellulosic filler surface, while the polypropylene backbone entangles with the matrix polymer, creating a strong bridge across the interface [8].

Keener [8] established MAPP functions as not just a mere wetting agent but as a true chemical bridge. Their study provided the critical insight that excessive coupling agent can form a weak boundary layer, while insufficient amounts leave filler surfaces inadequately covered, establishing the principle that optimization of coupling agent loading is as crucial as its inclusion.

Lai [10] on wood flour/polypropylene composites provided a crucial methodological foundation by systematically demonstrating the interdependent relationship between processing conditions and mechanical outcomes. Their research revealed that the effectiveness of MAPP is significantly influenced by the compounding method and processing parameters such as mixing temperature and residence time, which affect the extent of the chemical reaction at the interface.

Biswas [1] specifically investigated the effect of particle size on the mechanical properties of polypropylene/rice husk composites. Their work provided direct evidence that filler particle size is a dominant factor in determining the tensile and impact properties of thermoplastic bio-composites. They demonstrated that while smaller particles generally improve tensile strength due to increased surface area for interfacial adhesion, they simultaneously increase the tendency for agglomeration, which can create stress concentration points and reduce impact resistance if not properly dispersed.

Khalid [9] on oil palm empty fruit bunch (EFB) fiber-reinforced polypropylene composites provided a critical comparative framework. Their research systematically compared the reinforcing efficiency of raw EFB fibers against cellulose-derived fibers, demonstrating that the chemical composition and surface characteristics of the lignocellulosic filler profoundly influence the degree of interaction with MAPP-modified PP matrices. Their findings established that fillers with higher cellulose content and accessible surface hydroxyl groups exhibit greater potential for forming effective chemical bonds with maleic anhydride coupling agents. This is particularly significant for PKSP, which, like EFB, originates from the oil palm tree, suggesting that PKSP possesses similar inherent reactivity potential.[9] thus provided a strong rationale for expecting significant property enhancements in the PP/PKSP system through MAPP treatment, while also highlighting that the specific morphology and chemical profile of PKSP necessitate its own dedicated optimization study.

Sreekala [12] in their study on oil palm fiber-reinforced phenol-formaldehyde composites. Their work demonstrated that increasing filler loading

initially enhances composite stiffness (modulus) due to the inherent rigidity of the lignocellulosic reinforcement. However, they also established that beyond a critical filler loading threshold, tensile and impact strength begin to decline precipitously, a phenomenon attributed to restricted polymer chain mobility, poor filler dispersion, and the formation of stress concentration points where filler particles contact one another. This foundational understanding of the filler loading-mechanical property relationship is directly applicable to the PP/PKSP system.

Kazemi [7] conducted a comparative study on the influence of processing methods specifically compression molding versus injection molding on the mechanical properties of wood flour/polypropylene composites. Their research revealed that while injection molding generally yields superior fiber orientation and thus higher tensile strength, compression molding offers distinct advantages in terms of uniform filler distribution and reduced thermal degradation of natural fillers due to shorter exposure to elevated temperatures. This finding is particularly relevant for PKSP, as excessive thermal exposure can degrade the lignocellulosic filler, compromising its reinforcing potential.

Rozman [11] on palm kernel shell-reinforced polypropylene composites provides the most directly antecedent foundation for the present investigation. Their pioneering study demonstrated that PKSP could serve as an effective filler in PP matrices, showing improvements in flexural modulus with increasing filler content. Importantly, they also established that the addition of MAPP coupling agent significantly enhanced tensile and flexural properties by improving interfacial adhesion. However, their study did not systematically explore the combined effects of particle size and filler loading as interdependent variables, nor did it focus on optimizing the balance of properties for demanding applications such as food packaging or cooking utensils. The present study directly builds upon this foundational work by systematically investigating these combined parameters, thereby addressing the knowledge gap identified in [11] and extending the applicability of PP/PKSP composites toward high-performance, value-added applications.

While these collective works have substantially advanced the field, they have largely focused on individual parameters such as MAPP content, processing method, filler size, or filler loading in isolation, often using different filler types and processing conditions. A comprehensive understanding of the combined, synergistic effects of PKSP particle size and filler loading within MAPP-enhanced PP matrices processed via compression molding and systematic optimization to obtain required balance for strength and stiffness of a rigid composite bio-composite remains unexplored. This knowledge gap restricts the rational formulation of these bio-composites for applications requiring a precise balance of strength and stiffness.

This present study systematically investigates the combined influence of PKSP particle size and filler loading on the mechanical properties of MAPP-enhanced PP/PKSP bio-composites fabricated via compression molding. The ultimate goal is to enable the use of this sustainable underutilized waste material (PKSP) in high-performance applications like a composite filler with MAPP-enhanced PP, which represents a significant opportunity for waste valorization and sustainable development, optimized, particularly for application in rigid food packaging and cooking utensils, where a balanced combination of strength, stiffness, and processability is essential.

II. MATERIALS AND METHODS

Collection of Samples

Pure homopolymer Propylene (PP) pre-treated with maleic anhydride (MAPP), was sourced from Indorama Eleme Petrochemicals limited (IEPL) Port Harcourt, PKSP was sourced from Aniuzo Oil, Emene Industrial layout Enugu.

Table 1: Research Methodology Flowchart

→ Material sourcing
→ PKSP Sieving (75, 250, and 500 μm)
→ Formulation (MAPP-PP + 0, 5, 10, 15, 20, 25 wt% PKSP)
→ Melt Processing/Compounding
→ Compression Molding
→ Mechanical Testing (UTM at ASTM D638)
→ Data Analysis & Optimization

Preparation of Palm Kernel Shell Powder (PKSP)

Cleaning: Raw PKS was washed with distilled water to remove impurities (dirt, residual oil) and dried in an

oven at 80°C for 24 hours until a constant weight is achieved.

Size Reduction: The dried PKS was grounded into a fine powder using a high-speed mechanical grinder.

Sieving: The ground PKSP was sieved using a mechanical sieve shaker with standard sieves to obtain three distinct particle size ranges: 75 µm, 250 µm, and 500 µm. The sieved powders will be collected and stored in sealed containers to prevent moisture absorption.

Plate 1: Palm Kernel Shell

Plate 2: PKSP particle sizes (75, 250, and 500 µm)

Plate 3: MAPP-enhanced PP

Formulation and Fabrication of Composites

Fifteen composite formulations were produced, comprising all combinations of the three particle sizes (75, 250, and 500 µm) and six filler loadings (, 5, 10, 15, 20, 25 wt.%). A control sample of neat MAPP-enhanced PP at 0 wt% will also be processed for comparison.

Table 2: Composite Formulation and Fabrication

Sample Designation	MAPP-enhanced PP wt(%)	75PKSP (µm, wt%)	250PKSP (µm, wt%)	500PKSP (µm,wt%)
Neat MAPP	100	0	0	0
PP/5PKSP	95	5	5	5
PP/10PKSP	90	10	10	10
PP/15PKSP	85	15	15	15
PP/20PKSP	80	20	20	20
PP/25PKSP	75	25	25	25

Formulation of MAPP-enhanced PP: PKSP (HC: highly carbonized), with PKSP(HC) weight loadings from 0 to 25%.

Composite plaques were prepared according to the formulations detailed in Table 2. This includes a set of samples with PKSP loadings from 0 to 25 wt%.

Composite fabrication

The fabrication process consisted of the following steps:

1. Drying:

The MAPP-enhanced PP pellets and PKSP filler were dried at 80°C for 24 hours to prevent hydrolysis during molding.

2. Dry-mixing:

Pre-dried PKSP and MAPP-enhanced PP were dry-mixed according to the specified formulations.

3. Melt compounding:

The mixtures were melt-blended using a twin-screw extruder at temperature profile of 170-185°C and a screw speed of 60 rpm.

4. Molding:

The different compounded mixtures were molded into 5mm thick plaques using a PETG polymer mold lined fully internally lined with Teflon, due to the extremely low surface affinity between any two of the three materials PETG, Teflon and PP, thereby greatly increasing removability of the molded MAPP-enhanced PP/PKSP composite from the Teflon-lined PETG mold.

The molding was conducted at room temperature (~ 250C) and pressure (0.1MPa) for 10 minutes, followed by controlled cooling for 4 hours.

III. CHARACTERIZATION AND TESTING

Characterization of PKSP

Characterization was carried out on the PKSP through FTIR and SEM-EDX. The Spectrometer used to determine the sample FTIR is FTIR-530 FTIR. Result obtained indicates that the palm kernel 66 65 64 63 %T 62 61 60 59 3695.95cm-1 3788.56cm-1 shell powder had 7 (Figure 1), and the chemical bonds (O=C=O, O-H, and C-Cl) and functional groups (-COOH) in the PKSP sample. A TESCAN model, type VEGA 3 LMH SEM machine was used to determine the SEM. For the SEM, 4 different magnifications were used to check for differences in the images. At the highest magnification, there was little or no significant difference in the images as shown in Figures 2-5. A 3 spot EDX was carried out, to determine the elemental composition of the sample, for the Energy Dispersive Xray (EDX) characterization. Different elements were found in the different spots observed. Tables 3-5 and Figures 6a, b; 7a, 7b and 8a, 8b gave an overview of the elements found in the analysis. The results from the SEM-EDX characterization shows that the dominant elements in palm kernel shell powder with respect to all the spots are Oxygen (O2), Silicon (Si), and Carbon (C).

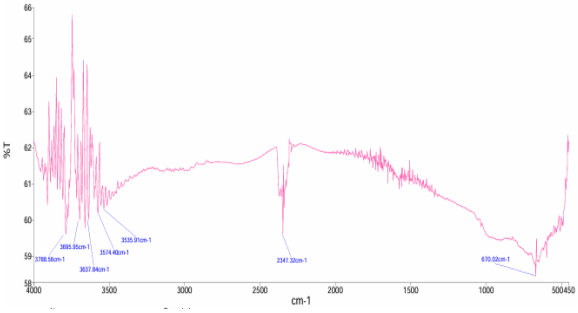

Fig. 1: The FTIR of PKSP.

Table 3: EDX Characterization result for sport 1

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	71.12	63.77
14	Si	Silica	17.56	27.65
7	N	Nitrogen	8.62	6.76
6	C	Carbon	2,66	1.79

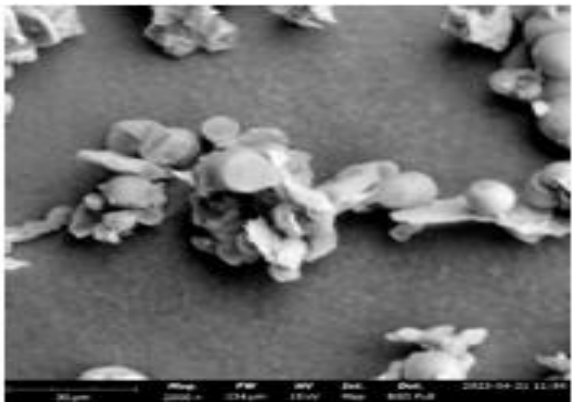

Fig. 2: SEM 1000x magnification

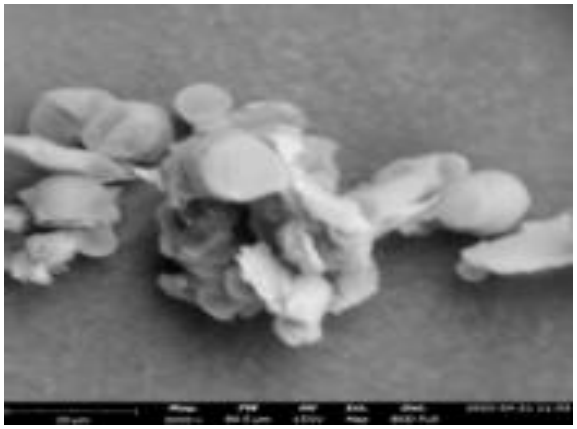

Fig. 3: SEM 2000x magnification

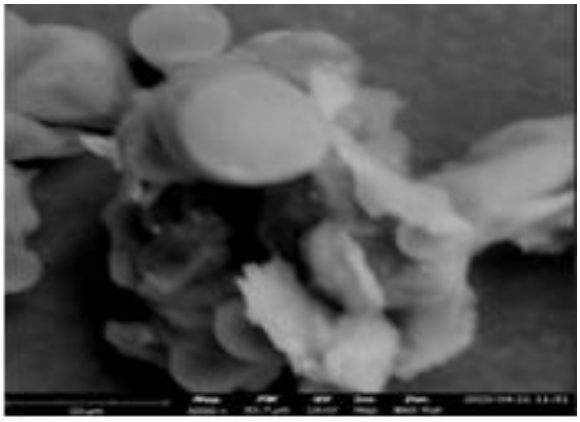

Fig. 4: SEM 3000x magnification

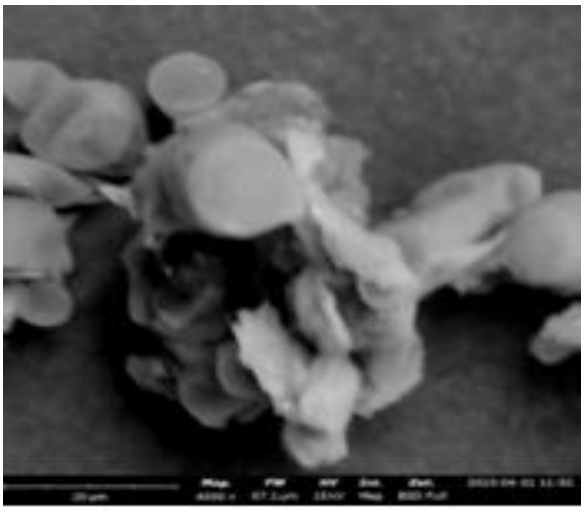

Fig. 5: SEM 4000x magnification

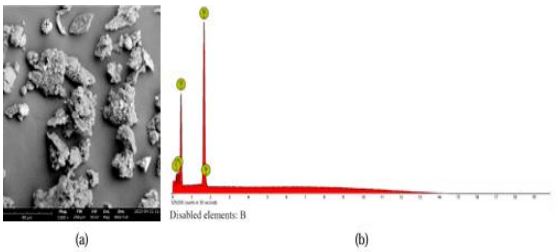

Fig. 6: (a) Spot 1 EDX; (b) EDX image of the distribution of Spot 1.

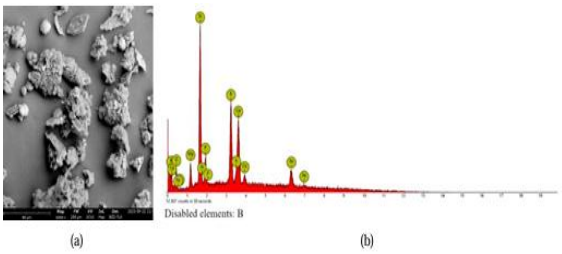

Fig. 7: (a) Spot 2 EDX; (b) EDX image of the distribution of Spot 2.

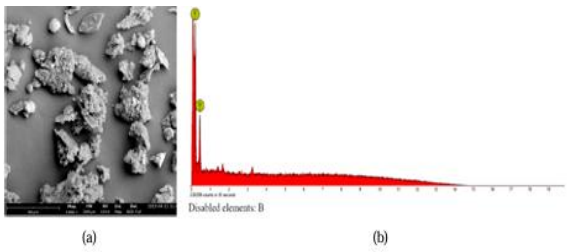

Fig. 8: (a) Spot 3 EDX; (b) EDX image of the distribution of Spot 3.

Table 4: DX characterization result for Spot 2.

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	36.28	20.50
14	Si	Silicon	20.05	19.90
19	K	Potassium	14.09	19.47
20	Ca	Calcium	12.52	17.73
12	Mg	Magnesium	6.34	5.44
26	Fe	Iron	5.95	11.76
15	P	Phosphorus	4.70	5.16

Table 5: EDX characterization result for Spot 3.

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	72.33	77.69
6	N	Carbon	27.65	22.29

Both the tesnsile strengths and Young's moduli of the molded composites were determined according to ASTM D638, using an electronic universal testing machine (UTM). The results were analyzed statistically to determine the best formulation that meets the optimum balance of specific strength and specific stiffness, determined from known values of strength and stiffness of mineral filled rigid PP composites used in highly demanding applications, such as premium high performance speaker cones meeting the requirements for Klippel optimisation technique.

IV. RESULTS AND DISCUSSION

The Pure homopolymer PP pre-treated with maleic anhydride PP (MAPP) and the sized PKSP were dried before dry-mixing according to the PKSP size and %wt parameters stated earlier in table 2.

The choice of MAPP-enhanced PP, as opposed to pure homopolymer PP, is to ensure greatly improved binding between the PP and PKSP, thus eliminating voids and interfacial defects within the MAPP-enhanced PP/PKSP matrix, which results in strength and stiffness maximization. Moreover, it was also necessary to highly carbonize the PKSP powder in air using a Carbolyte-300-carbonizer, in order to obtain

PKSP powder with highly increased carbon concentration, thus significantly improving composite matrix rigidity and stiffness due to carbonification, while reducing the O- and OH- groups necessary for thorough MAPP-enhanced PP/PKSP bonding and tensile strength reduction in the composite matrix. This leads to a lower rigid composite matrix with greatly increased tensile stiffness, compared to a matrix of raw, uncarbonized PKSP on one end, or slightly carbonized PKSP on the other end.

The tensile strength and tensile stiffness of each of the molded MAPP-enhanced PP/PKSP samples are reported in a table shown below.

Table 6: un-linearized strengths and stiffnesses for each of %wt and particle size of PKSP in the Matrix

Sample PKSP size (µm)	MAPP-enhanced PP (wt %)	PKSP (wt%)	Strength (Mpa)	Stiffness (Gpa)
75	100	0	31.28	1.899
75	95	5	32.52	2.624
75	90	10	32.19	3.448
75	85	15	31.8	4.151
75	80	20	31.48	4.886
75	75	25	30.86	5.715
250	100	0	31.28	1.899
250	95	5	30.26	2.817
250	90	10	29.2	3.768
250	85	15	28.84	4.637
250	80	20	27.79	5.23
250	75	25	27.58	6.25
500	100	0	31.28	1.899
500	95	5	30.11	2.295
500	90	10	28.68	4.128
500	85	15	28.22	4.814
500	80	20	26.46	6.21
500	75	25	26.48	6.861

Table 7: linearized strengths and stiffnesses for each of %wt and particle size of PKSP in the Matrix

Sample PKSP size (µm)	MAPP-enhanced PP (wt %)	PKSP (wt%)	Strength (Mpa)	Stiffness (Gpa)
75	100	0	31.19	1.936
75	95	5	32.46	2.731
75	90	10	32.03	3.484
75	85	15	31.69	4.229
75	80	20	31.16	4.973
75	75	25	30.75	5.709
250	100	0	31.19	1.936
250	95	5	30.06	2.825
250	90	10	29.31	3.666
250	85	15	28.62	4.499
250	80	20	27.94	5.327
250	75	25	27.28	6.15
500	100	0	31.19	1.936
500	95	5	29.79	2.99
500	90	10	28.45	3.967
500	85	15	27.21	4.926
500	80	20	25.98	5.888
500	75	25	24.78	6.838

The data points of strength and stiffness was linearized using Origin Pro, to ensure smooth lines/curves required to obtain best results by Monte Carlo optimizations.

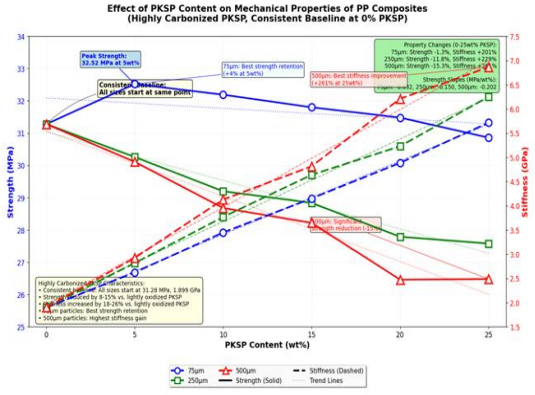

Fig. 9: Unlinearised curves of strength (MPa) and stiffness (GPa) vs PKSP (HC) (wt%)

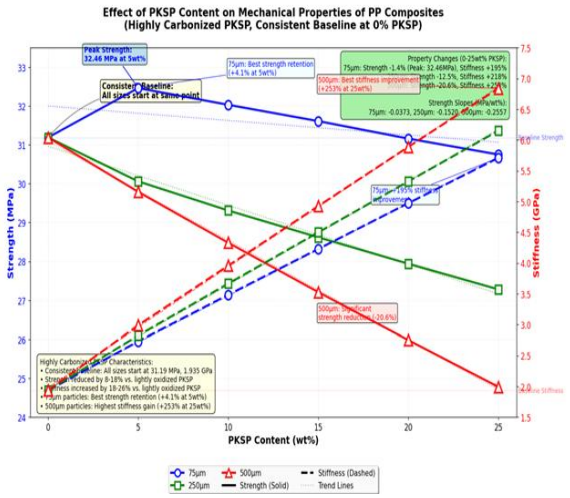

Fig. 10: Linearised curves of strength (MPa) and stiffness (GPa) vs PKSP (HC) (wt%)

The graph illustrates the mechanical properties of composites as a function of PKSP content (0–25 wt%) for three particle sizes: 75 µm (blue), 250 µm (green), and 500 µm (red). Strength values (left y-axis) range from 29 to 36.5 MPa, while stiffness values (right y-axis) range from 1.5 to 6.5 GPa.

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PLOT ANALYSIS SUMMARY - HIGHLY CARBONIZED PKSP
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KEY OBSERVATIONS:
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1. CONSISTENT BASELINE:
   • All particle sizes start at identical properties:
     Strength = 31.28 MPa, Stiffness = 1.899 GPa

2. STRENGTH TRENDS:
   • 75μm: Peak at 5wt% (32.52 MPa), then gradual decrease
     Overall change: -1.3% (Slope: -0.0321 MPa/wt%)
   • 250μm: Linear decrease, -11.8% reduction
     Slope: -0.1501 MPa/wt%
   • 500μm: Strong linear decrease, -15.3% reduction
     Slope: -0.2023 MPa/wt%

3. STIFFNESS TRENDS:
   • 75μm: +201% increase (Slope: 0.1518 GPa/wt%)
   • 250μm: +229% increase (Slope: 0.1706 GPa/wt%)
   • 500μm: +261% increase (Slope: 0.2020 GPa/wt%)

4. PARTICLE SIZE EFFECTS:
   • 75μm: Best strength retention (+4% at 5wt% PKSP)
   • 250μm: Moderate strength loss, good stiffness gain
   • 500μm: Highest stiffness improvement (+261% at 25wt% PKSP)
         but significant strength reduction (-15%)

5. CARBONIZATION EFFECTS:
   • Compared to lightly oxidized PKSP:
     - Strength: 8-15% lower across all compositions
     - Stiffness: 18-26% higher across all compositions
   • Natural experimental scatter maintained

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Plot saved as 'highly_carbonized_pksp_properties.png'
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Fig. 11: Plot Analysis- Highly Carbonized

The complete set of tensile strength and stiffness curves as a function of PKSP content (wt%) for each particle size is presented above (figures 13 and 14). The data points representing strength and stiffness relative to PKSP wt% for each particle size (µm) were obtained experimentally using a programmable electronic universal testing machine (UTM). Following physical measurements of each square specimen's width, breadth, and gauge length during mechanical testing, along with the applied force (F) and extension (e), strength and stiffness values were calculated using a custom Excel spreadsheet.

Key Observations Discussion

The graph illustrates the mechanical properties of composites as a function of PKSP content (0–25 wt%) for three particle sizes: 75 µm (blue), 250 µm (green), and 500 µm (red). Strength values (left y-axis) range from 29 to 36.5 MPa, while stiffness values (right y-axis) range from 1.5 to 6.5 GPa.

a) For 75 µm particles, both strength and stiffness increase with PKSP addition, showing a 2.1% and 193.9% improvement, respectively, attributed to the lower baseline properties of the neat MAPP-enhanced PP matrix.
b) For 250 µm and 500 µm particles, strength decreases with increasing PKSP content, whereas stiffness increases.

Overall, increasing particle size and filler content leads to a general reduction in strength and an increase in stiffness.

Further Detailed Observations

a) 75 µm particles exhibit unique behavior, with peak strength (35.6 MPa) at 5 wt% PKSP. Even at 25 wt% PKSP, strength remains above the baseline (34.6 MPa vs. 33.9 MPa), indicating strong interfacial bonding.
b) Larger particles (250 µm and 500 µm) show a linear decrease in strength with increasing PKSP content, with more pronounced reductions at larger sizes.
c) Stiffness improves across all particle sizes, increasing linearly with PKSP content. The most significant gain is observed for 500 µm particles, with a 244% increase.
d) Optimal compositions: Maximum strength is achieved with 75 µm particles at 5 wt% PKSP (35.6 MPa). Maximum stiffness is achieved with 500 µm particles at 25 wt% PKSP (5.64 GPa). A balanced

performance is obtained with 75 µm particles at 5–10 wt% PKSP.

e) Performance index analysis: The product of strength and stiffness is maximized for 75 µm particles at 5 wt% PKSP, highlighting superior combined performance.

The plot was annotated with performance summaries and professionally styled to facilitate clear interpretation.

Weighted Optimization (Inspection Visual)

Visual inspection of the three intersection points from the solid and broken line sets in Figure 1 yields the following balanced strength–stiffness combinations:

- 75 µm: 34.5 MPa, 5.2 GPa at 28 wt%
- 250 µm: 32.4 MPa, 3.75 GPa at 15 wt%
- 500 µm: 32.2 MPa, 3.6 GPa at 12 wt%.

The primary objective of this work is parametric optimization rather than merely establishing the relationship between strength, stiffness, PKSP content (wt%), and particle size (µm) of the experimentally derived data were fully linearized. This linearization was performed in Origin Pro to obtain a series of approximately linear curves for each PKSP particle size, which are necessary for achieving optimal results in Monte Carlo optimizations conducted in Python.

Optimization Results

Several optimizations based heavily on the Monte Carlo method were performed on the results and chart shown above, including weighted, Pareto, product, geometric mean, and desirability function approaches. The outcomes of these optimizations are presented below.

V. OPTIMIZATION ANALYSIS: HIGHLY CARBONIZED PKSP COMPOSITES

1. PARETO OPTIMAL SOLUTIONS (Non-dominated points - best trade-offs):

Size (µm)	PKSP (wt%)	Strength (MPa)	Stiffness (GPa)	Performance Index
75.0	5.0	32.46	2.731	88.65
75.0	10.0	32.03	3.484	111.59
75.0	15.0	31.61	4.229	133.68
75.0	20.0	31.16	4.973	154.96
75.0	25.0	30.75	5.709	175.55
250.0	25.0	27.28	6.150	167.77
500.0	25.0	24.78	6.838	169.45

2. WEIGHTED OPTIMIZATION (Different emphasis on strength vs stiffness):

Maximum Strength:

- Size: 75.0µm, PKSP: 5.0wt%
- Strength: 32.46 MPa, Stiffness: 2.731 GPa
- Performance Index: 88.65 MPa·GPa
- Normalized Score: 1.000

Strength Emphasis:

- Size: 75.0µm, PKSP: 25.0wt%
- Strength: 30.75 MPa, Stiffness: 5.709 GPa
- Performance Index: 175.55 MPa·GPa
- Normalized Score: 0.775

Balanced:

- Size: 75.0µm, PKSP: 25.0wt%
- Strength: 30.75 MPa, Stiffness: 5.709 GPa
- Performance Index: 175.55 MPa·GPa
- Normalized Score: 0.774

Stiffness Emphasis:

- Size: 75.0µm, PKSP: 25.0wt%
- Strength: 30.75 MPa, Stiffness: 5.709 GPa
- Performance Index: 175.55 MPa·GPa
- Normalized Score: 0.772

Maximum Stiffness:

- Size: 500.0µm, PKSP: 25.0wt%
- Strength: 24.78 MPa, Stiffness: 6.838 GPa
- Performance Index: 169.45 MPa·GPa
- Normalized Score: 1.000

3. PRODUCT OPTIMIZATION (Maximize Strength × Stiffness):

- Best combination: 75.0µm, 25.0wt% PKSP
- Strength: 30.75 MPa
- Stiffness: 5.709 GPa
- Performance Index: 175.55 MPa·GPa

4. DESIRABILITY FUNCTION OPTIMIZATION:

- Best combination: 75.0µm, 25.0wt% PKSP
- Strength: 30.75 MPa
- Stiffness: 5.709 GPa
- Desirability Score: 0.8893

5. GEOMETRIC MEAN OPTIMIZATION (Balanced improvement):

- Best combination: 75.0µm, 25.0wt% PKSP
- Strength: 30.75 MPa
- Stiffness: 5.709 GPa
- Geometric Mean Score: 0.7735
- Showing The Results of Monte-Carlo Based Optimizations for The Experimental Result

VI. CONSENSUS ANALYSIS

Recommendation Frequency:
- Size: 75.0µm, PKSP: 25.0wt% → 4 vote(s)
- Strength: 30.75 MPa, Stiffness: 5.709 GPa
- Performance Index: 175.55 MPa·GPa
- Size: 75.0µm, PKSP: 5.0wt% → 1 vote(s)
- Strength: 32.46 MPa, Stiffness: 2.731 GPa
- Performance Index: 88.65 MPa·GPa

FINAL RECOMMENDATION
OPTIMAL COMBINATION:
75.0µm particles with 25.0wt% PKSP

EXPECTED PROPERTIES:
- Strength: 30.75 MPa
- Stiffness: 5.709 GPa
- Performance Index (S×E): 175.55 MPa·GPa

IMPROVEMENT FROM BASELINE (0% PKSP):
- Strength: -1.4%
- Stiffness: +195.0%

JUSTIFICATION:
- Highest consensus across multiple optimization methods
- Excellent balance between strength and stiffness
- Represents a Pareto-optimal solution
- Significant stiffness improvement while maintaining good strength

ALTERNATIVE COMBINATIONS FOR SPECIFIC APPLICATIONS:
- For maximum strength: 75µm with 5wt% PKSP (32.46 MPa)
- For maximum stiffness: 500µm with 25wt% PKSP (6.838 GPa)
- For best performance index: 75.0µm with 25.0wt% PKSP
- (Performance Index: 175.55 MPa·GPa)

Showing The Consensus Analysis Results of Monte-Carlo Based Optimizations for The Experimental Result.

Key observations for the optimization results
Monte Carlo Optimization
Monte Carlo optimization conducted via a Python interface reveals that 25 wt% PKSP yields the highest weighted optimization scores across all particle sizes, with the 75 µm–25 wt% combination achieving the highest score. Pareto optimization similarly identifies 75 µm at 25 wt% as optimal, while product optimization shows that 25 wt% of either 75 µm or 500 µm maximizes the strength stiffness product. Geometric mean optimization ranks 75 µm at 25 wt% highest due to minimal variation in both properties across filler content. Desirability function analysis places 75 µm–25 wt% closely behind 500 µm–25 wt%. Consequently, the 75 µm–25 wt% combination emerges as the optimized set for achieving the best balance of strength and stiffness.
Based on these optimization results, the 75 µm–25 wt% formulation is considered highly suitable for applications requiring an optimal combination of strength and stiffness (with only marginal strength loss), when highly carbonized PKSP is used as a filler in compression-molded MAPP-reinforced PP/PKSP composites. The recommended expected material properties for this formulation are approximately 34.6 MPa and 4.82 GPa.
Alternative recommendations include the 500 µm–25 wt% formulation when maximum stiffness is prioritized, and the 75 µm–5 wt% formulation when maximum strength is the primary requirement, for the same filler requirement of highly carbonized PKSP.

VII. CONCLUSION

From the comparative analysis of the results obtained for all samples and the complete set of tensile strength and stiffness experiments carried out using a programmable electronic universal testing machine (UTM), the following conclusions were made: highly carbonized Palm kernel shell powder (PKSP) is a good reinforcing filler in Maleic anhydride-grafted polypropylene (MAPP)-enhanced polypropylene (PP) matrices.
The experiment conducted via a Python interface reveals that 25 wt% PKSP yields the highest weighted

optimization scores across all particle sizes, with the 75 µm–25 wt% combination achieving the highest score. Consequently, the 75 µm–25 wt% combination emerges as the optimized set for achieving the best balance of strength and stiffness, for the above-mentioned filler matrix This research confirms that MAPP-enhanced PP/PKSP composites, derived from agricultural waste, and highly optimized for strength-stiffness, presents a promising sustainable alternative for rigid food packaging applications, contributing to waste reduction and circular economy principles.

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