

Determination and Optimization of Mechanical Properties of Polypropylene / Palm Kernel Shell Powder Composites for Rigid Food Packaging Applications

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Abstract—The primary objective of this project work is to develop and optimize a very rigid, bio-composite material formulation with enhanced mechanical properties optimized for rigid food serving/packaging and applications. The palm kernel shell powder (PKSP) was properly characterized, maleic anhydride-grafted polypropylene (MAPP)-enhanced polypropylene (PP)/PKSP composite square rods of 15 mm x 15mm x 100mm were fabricated via melt blending and compression molding, with PKSP loadings varying from 5% wt to 25% wt, for each of PKSP particle sizes 75µm, 250µm and 500µm. The tensile strength and tensile stiffness, were systematically evaluated using an electronic Universal Testing Machine (UTM-YYL016) american society for testing and materials (ASTM) standard, and afterwards, highly optimized PKSP particle size and PKSP (wt.%) combinations for best balance of strength and stiffness, were numerically obtained using Python scripts via the highly adopted Monte Carlo optimization methods. The recommended optimized PKSP particle size and PKSP (wt.%) combinations for best balance of strength and stiffness, best overall strength, and best overall stiffness are (75µm, 25wt% at 166.77 MPa·GPa), (75µm, 5wt% at 35.60 MPa) and (500µm, 25wt% at 5.64 GPa) respectively. The results indicate that the incorporation of PKSP generally enhances stiffness, but with a slight cost in tensile strength, thus confirming that PKSP is a viable and sustainable reinforcing filler for PP, thereby validating its utilization for food packaging application, value-added waste valorization, contributing to the circular economy and the development of greener materials.

Index Terms—Polypropylene (PP), palm kernel shell powder (PKSP), Maleic Anhydride-grafted Polypropylene (MAPP), bio-composite, natural filler, mechanical properties, compatibilizer, compression molding, optimization, sustainable materials, food packaging, waste valorization, greener materials.

I. INTRODUCTION

The global polymer industry faces mounting pressure to balance high-performance requirements (strength, stiffness, thermal stability, cost-effectiveness) with environmental sustainability [2]. This imperative stems from three converging crises: petroleum feedstock depletion, persistent plastic waste accumulation in ecosystems, and stringent regulations targeting single-use plastics across 120+ nations [18]; [16].

The scale is alarming. Packaging constitutes about 40% of plastic consumption, predominantly single-use [16]. Of the 8.3 billion metric tons of virgin plastics produced through 2015, 6.3 billion tons became waste only 9% recycled, 12% incinerated, and 79% landfilled or environmental [6]. Unchecked, plastics could consume 12% of the global carbon budget by 2050.

Within this context, polymer biocomposites natural renewable fillers with synthetic or biobased matrices offer a pathway to circular materials economy, reducing virgin plastic use, lowering carbon

footprints, and valorizing agricultural waste. Natural fiber-reinforced polymer composites (NFRPCs) have attracted substantial interest across automotive, construction, and consumer goods sectors [3], owing to their low density, competitive specific properties, biodegradability, low cost, abundance, and renewability [15].

Korol [12] in his research work indicated that Life cycle assessments confirm environmental advantages: replacing talc or CaCO_3 with agricultural residues in PP composites reduced cumulative energy demand by 12–18% and global warming potential by 15–22%.

Recent advances have expanded NFRPC performance.

Madu [13] explored that alkali-treated palm kernel shell particles (PKSP) in PP achieved 28% tensile strength improvement with enhanced electrical insulation.

Kaavessina [8] in his research work on packaging signified that activated carbon from PKSP showed antistatic packaging promise at 4 wt% loading.

Abdul Khalil [1] expounded that the global palm oil industry (Malaysia, Indonesia, Thailand) produced about 78 million metric tons of crude palm oil in 2024/2025 [20], generating 0.5–0.7 tons of palm kernel shells (PKS) per ton of oil. PKS characterized by high density (1.2–1.4 g/cm³), high lignin (40–50%), and exceptional hardness is typically combusted as low-grade fuel or landfilled, causing emissions and environmental externalities. Valorizing PKS as composite filler aligns with industrial symbiosis and SDGs 9, 12, and 13, with rigid food-serving utensils and packaging identified as promising applications [10].

George [4] however spotted the fundamental challenge that impedes the optimal mechanical properties. The incompatibility between hydrophilic lignocellulosic fillers and hydrophobic PP matrices. Polar hydroxyl groups on cellulose/hemicellulose/lignin surfaces form hydrogen bonds with water but weak interactions with non-polar PP chains.

Yang [21] and Premalal [17] in their research works reportedly indicated that this incompatibility between

hydrophilic lignocellulosic fillers and hydrophobic PP matrices causes poor wetting, interfacial voids, filler agglomeration, and ineffective stress transfer manifesting as reduced tensile strength and impact resistance with increasing filler content, despite stiffness gains.

Keener [9] in their research work on compatibilizer specified that Maleic anhydride-grafted polypropylene (MAPP) is the preferred compatibilizer; its anhydride moiety forms covalent ester bonds with filler hydroxyls, while its PP backbone entangles with matrix chains.

Mohaiyiddin [14] and Kim [11] indicated that MAPP (3–5 wt%) increased wood flour/PP tensile strength by 30–50% and PKSP/PP composites by up to 40%. Alternative strategies (silanes, alkali treatment) exist, but MAPP remains industrially preferred for melt processability, low cost, and food-contact regulatory status.

Optimizing MAPP-enhanced PP/PKSP composites requires systematic investigation of two critical, interacting parameters: PKSP particle size and filler loading.

Fu [4] and George [5] in their profound work on optimization identified that Smaller particles offer greater specific surface area for bonding but greater agglomeration tendency; larger particles disperse better but introduce larger stress concentrations. An optimal intermediate size (250–425 µm) was reported for oil palm frond/PP [7] and 300 µm for doum palm shell/PP [19]. Similarly, filler loading exhibits a trade-off: moderate levels (20–30 wt%) improve properties, but excessive loading causes agglomeration and defects [21];[8]. Critically, the particle size loading interaction remains understudied; optimal size may vary with loading due to coupled mechanisms of stress transfer, agglomeration, and defect formation.

Madu [13] emphasised that compression molding offers low capital cost, high-viscosity processability, and minimal waste is industrially relevant for producing PKSP/PP biocomposites for rigid food-contact applications requiring dimensional accuracy and mechanical reliability.

The existing literature on PKSP/PP composites exhibits three gaps: Firstly, parameters are varied one at a time without exploring interaction. Secondly, particle size ranges are often narrow and thirdly MAPP effectiveness has rarely been evaluated across full factorial combinations of size and loading. Consequently, a comprehensive understanding of the combined effects on mechanical properties is lacking, preventing reliable optimization for demanding applications like reusable utensils and rigid packaging trays.

This study systematically investigates the independent and interactive effects of PKSP particle size (fine, intermediate, coarse fractions) and filler loading on tensile properties of MAPP-compatible PP/PKSP composites processed via compression molding. By maintaining consistent, industrially relevant conditions and characterizing properties per ASTM standards, this research aims to develop an optimized formulation balancing strength and stiffness for targeted food-contact applications while valorizing an underutilized agricultural waste stream.

II. MATERIALS AND METHODS

Collection of Materials

Propylene (PP) pre-treated with maleic anhydride (MAPP), was sourced from Indorama Eleme Petrochemicals limited (IEPL) Port Harcourt and was further dried at 90° C for 10 hours to remove residual moisture before processing. Palm kernel shell (PKS) was sourced from Aniuo Oil, Emene Industrial layout Enugu. The shells were cleaned, dried, milled, and sieved to a particle sizes of 75µm, 250µm and 500µm. Prior to processing, the PKSP was further partially carbonized at 300°C to remove the moisture and light volatiles without fully destroying the biomass structure and to yield a carbon-rich solid.

Design of Experiments (DOE)

Python script of a Monte Carlo-based Design of Experiments (DOE) was used for tensile strength and tensile stiffness of MAPP-enhanced polypropylene with partially oxidized PKSP filler, considering 3 particle sizes and 5 filler loadings (full factorial would be 15 experiments, but Monte Carlo optimization can prioritize or augment them).

Mathematical Formulation

A Monte Carlo mathematical formula for polymer composite optimization was used for the design calculation.

Let the design vector be

$$\mathbf{X} = [x_1, x_2, x_3, \dots, x_n]$$

where

- X_1 = Particle size (µm)
- X_2 = Filler loading (wt%)
- X_3 = MAPP content (wt%)
- X_4 = Processing temperature (optional)
- X_5 = Screw speed (optional)

Each variable is sampled from a uniform distribution within its experimental limits:

$$x_i \sim U(x_{i,\min}, x_{i,\max})$$

The response is predicted using the quadratic response surface model:

$$\hat{Y} = \beta_0 + \sum_{i=1}^n \beta_i X_i + \sum_{i=1}^n \beta_{ii} X_i^2 + \sum_{i < j} \beta_{ij} X_i X_j$$

The Monte Carlo optimization searches for the design vector that maximizes (or minimizes) the objective:

$$\mathbf{X}^* = \arg \max_{\mathbf{X} \in \Omega} \hat{Y}(\mathbf{X})$$

where Ω is the feasible design space defined by the variable bounds.

For multi-response optimization (e.g., maximizing tensile strength, tensile modulus, flexural strength, and impact strength simultaneously), a composite objective such as the geometric mean or desirability function can be used:

$$D = \left(\prod_{i=1}^m d_i \right)^{1/m}$$

where d_i is the individual desirability of the i -th response and m is the number of responses. The optimal formulation is obtained by maximizing the overall desirability:

$$\mathbf{X}^* = \arg \max_{\mathbf{X} \in \Omega} D(\mathbf{X})$$

Experimental Design Framework

Table 1 : Experimental Design Framework

Factor	Levels	Rationale
PKSP Particle Size	75, 250, 500 μm	Three distinct sizes to evaluate the effect of filler fineness on mechanical properties
Filler Loading	0, 5, 10, 15, 20, 25 wt%	Five loading levels and neat MAPP - enhanced PP (0 wt.%) as a control baseline

Composite formulation

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 PP/PKSP

matrix, which results in strength and stiffness maximization. Moreover, it was also necessary to lightly carbonize the PKSP using a Carbolyte-300 carbonizer, in order to obtain PKSP powder with just slightly increased carbon concentration, thus significantly improving composite matrix rigidity and stiffness due to carbonification, while still preserving

the O- and OH- groups necessary for thorough MAPP-enhanced PP/PKSP bonding and tensile strength preservation in the composite matrix. This leads to a highly rigid composite matrix with greatly increased tensile stiffness, compared to a matrix of raw, uncarbonized PKSP on one end, or thoroughly carbonized PKSP on the other end. Another significant advantage of using slightly carbonized PKSP with preserved O- and OH- groups, is preservation of tensile strength, with increasing stiffness. 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%.

Table 2: Composite Matrix Formulation

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

Composite fabrication

The fabrication process consisted of the following steps:

1. Drying: The MAPP-enhanced PP pellets and slightly carbonized PKSP filler were dried at 90°C for 10 hours to removed absorbed moisture, which could otherwise cause voids during measurement and melt processing.

2. Weighing: The required amount of MAPP-enhanced PP and slightly carbonized PKSP were accurately weighed using a digital balance with a precision of ± 0.01 g, according to the formulation in Table 3.1. the total batch weight for each formulation was kept constant at 500g to maintain consistent processing conditions.

3. Pre-mixing (Dry Blending): The weighed MAPP-enhanced PP and the partially carbonized PKSP fillers were initially dry-mixed manually in a high-speed laboratory blender at room temperature for 5 minutes at 1000 rpm. This set ensures a preliminary homogenous distribution of the PKSP particulates within the PP matrix before melt processing according to the specified formulations.

4. Melt compounding: The mixtures were melt-blended using a twin-screw extruder at a temperature profile of 170-185°C from the speed zone to the die with a screw speed of 60 rpm. The mixture was compounded for 10 minutes to achieve uniform dispersion of the PKSP particles within the molten PP matrix for each composite formulation.

5. Molding: The different compounded mixtures was placed into a square shaped mold cavity (dimension of 15 mm x 15 mm x 100 mm) that was preheated to 180° C. The compounded mixture was properly pressed inside the mold and was held for 5 minutes to allow the materials to fully fill the mold cavity and eliminate internal voids.

6. Cooling: the mold was then cooled to room temperature under pressure using a water circulating cooling system for 4 hours at a rate of approximately 10°C/mm to prevent thermal shrinkage and warpage.

7. Demolding: After cooling, the solidified square composites rods were carefully removed from the mold.

Characterization and Testing

Both the tensile strengths and stiffness of the molded composites were determined according to American Society for Testing and Materials (ASTM) standard, using an electronic universal testing machine (UTM). The results was 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 techniques.



Plate 1: MAPP enhanced Polypropylene



Plate 2: Dried Palm kernel shell



Plate 3: PKSP (75 µm, 250 µm and 50µm).



Plate 4: The molded test pieces

III. RESULTS AND DISCUSSION

Characterization of PKSP

The PKSP characterization was carried out through Fourier- transform infrared (FTIR) spectroscopy,

Scanning Electron Microscopy (SEM) and Energy – Dispersive X-ray spectroscopy (EDX). The Spectrometer used to determine the sample FTIR is FTIR-530 FTIR. A TESCAN model, type VEGA 3 LMH SEM machine was used to determine the SEM

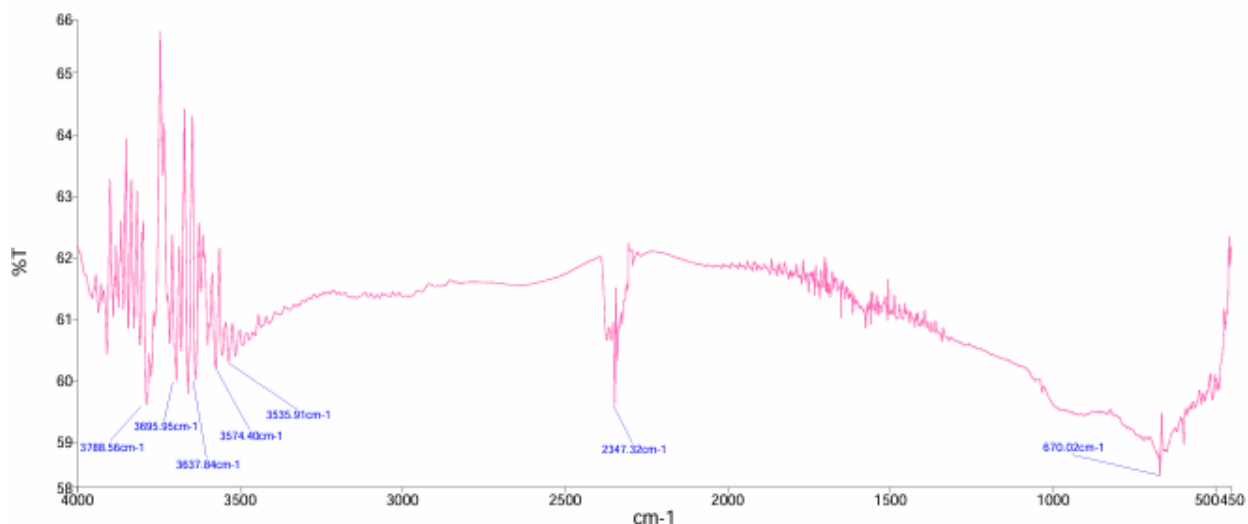


Figure 1: The FTIR of PKSP

Table 3: PKSP FTIR Major Peaks

Wavenumber (cm ⁻¹)	Functional Group	Interpretation
3728 cm ⁻¹	O–H stretching	Free hydroxyl groups from cellulose, absorbed water, and phenolic compounds
3638 cm ⁻¹	O–H stretching	Alcoholic and phenolic hydroxyl groups
3574 cm ⁻¹	O–H stretching	Hydrogen-bonded hydroxyl groups in lignin/cellulose
3346 cm ⁻¹	Broad O–H stretch	Strong indication of cellulose and moisture content
2347 cm ⁻¹	CO ₂ absorption	Atmospheric carbon dioxide or instrumental artifact
1600–1500 cm ⁻¹	Aromatic C=C stretching	Presence of lignin aromatic structures
1450–1370 cm ⁻¹	C–H bending	Cellulose and hemicellulose vibrations
1200–1000 cm ⁻¹	C–O stretching	Alcohols, ethers, and polysaccharides
670 cm ⁻¹	C–H out-of-plane bending	Aromatic compounds and lignin-related structures

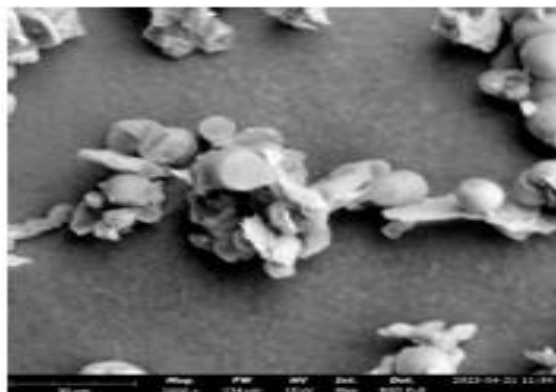


Figure 2: SEM 1000x magnification

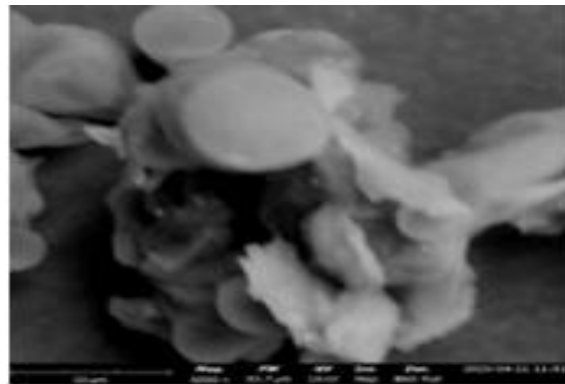


Figure 5: SEM 4000x magnification

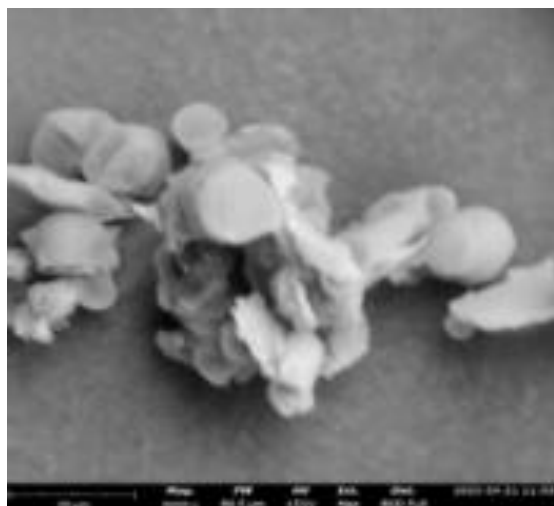


Figure 3: SEM 2000x magnification

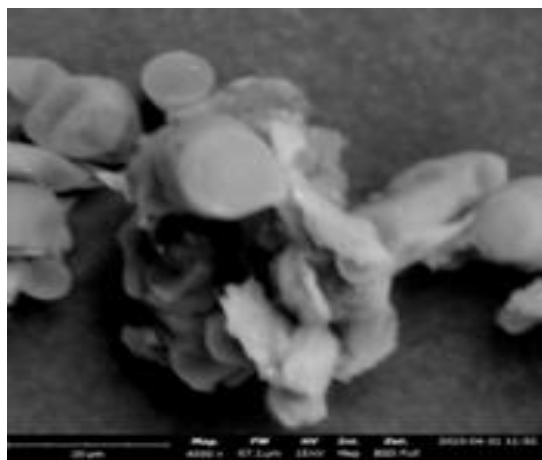


Figure 4: SEM 3000x magnification

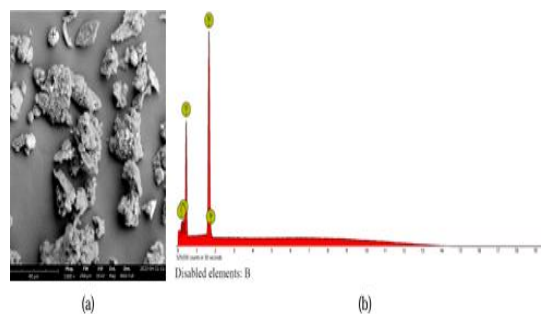


Fig. 6: (a) Spot 1 EDX; (b) EDX image of the distribution of Spot 1.

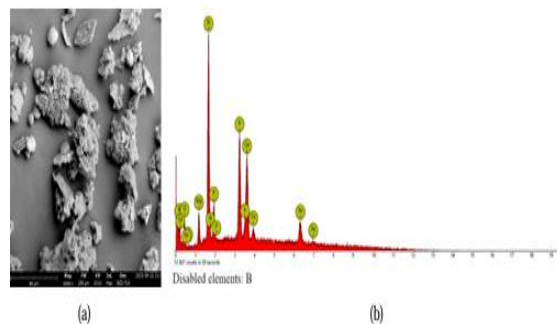


Fig. 7: (a) Spot 2 EDX; (b) EDX image of the distribution of Spot 2.

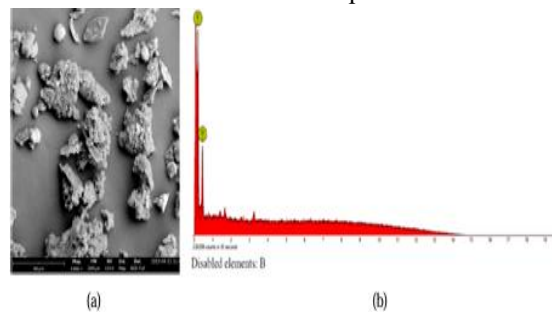


Fig. 8: (a) Spot 3 EDX; (b) EDX image of the distribution of Spot 3.

Table 4: 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

Table 5: EDX Characterization result for sport 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 6: EDX Characterization result for sport 3

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

The FTIR spectrum of PKSP (Figure 1) shows seven distinct peaks (Table 3), corresponding to the presence of O–H, C–O, and C–H chemical bonds, as well as C=O functional groups in the sample. For SEM analysis, images were captured at four different magnifications to assess any morphological variations. At the highest magnification, no significant differences were observed among the images, as presented in Figures 2–5. EDX characterization was

performed at three different spots to determine the elemental composition of the sample. The elemental distributions varied across the analyzed spots, with detailed results summarized in Tables 4–6 and illustrated in Figures 6a–b, 7a–b, and 8a–b. Overall, the SEM-EDX analysis indicates that oxygen (O), silicon (Si), and carbon (C) are the dominant elements detected in all examined spots of the palm kernel shell powder.

Table 7: Strengths and stiffnesses for each of wt.% and particle size of PKSP in the matrix.

Sample PKSP size (um)	MAPP-enhanced PP (wt%)	PKSP (wt%)	Strength (MPa)	Stiffness (GPa)
75	100	0	33.9	1.64
75	95	5	34.04	2.276
75	90	10	34.18	2.912
75	85	15	34.32	3.548
75	80	20	34.46	4.184
75	75	25	34.6	4.82
250	100	0	33.9	1.64
250	95	5	33.4	2.34
250	90	10	32.9	3.04
250	85	15	32.4	3.74
250	80	20	31.9	4.44
250	75	25	31.4	5.14
500	100	0	33.9	1.64
500	95	5	33.15	2.44
500	90	10	32.4	3.24
500	85	15	31.65	4.04
500	80	20	30.9	4.84
500	75	25	30.15	5.64

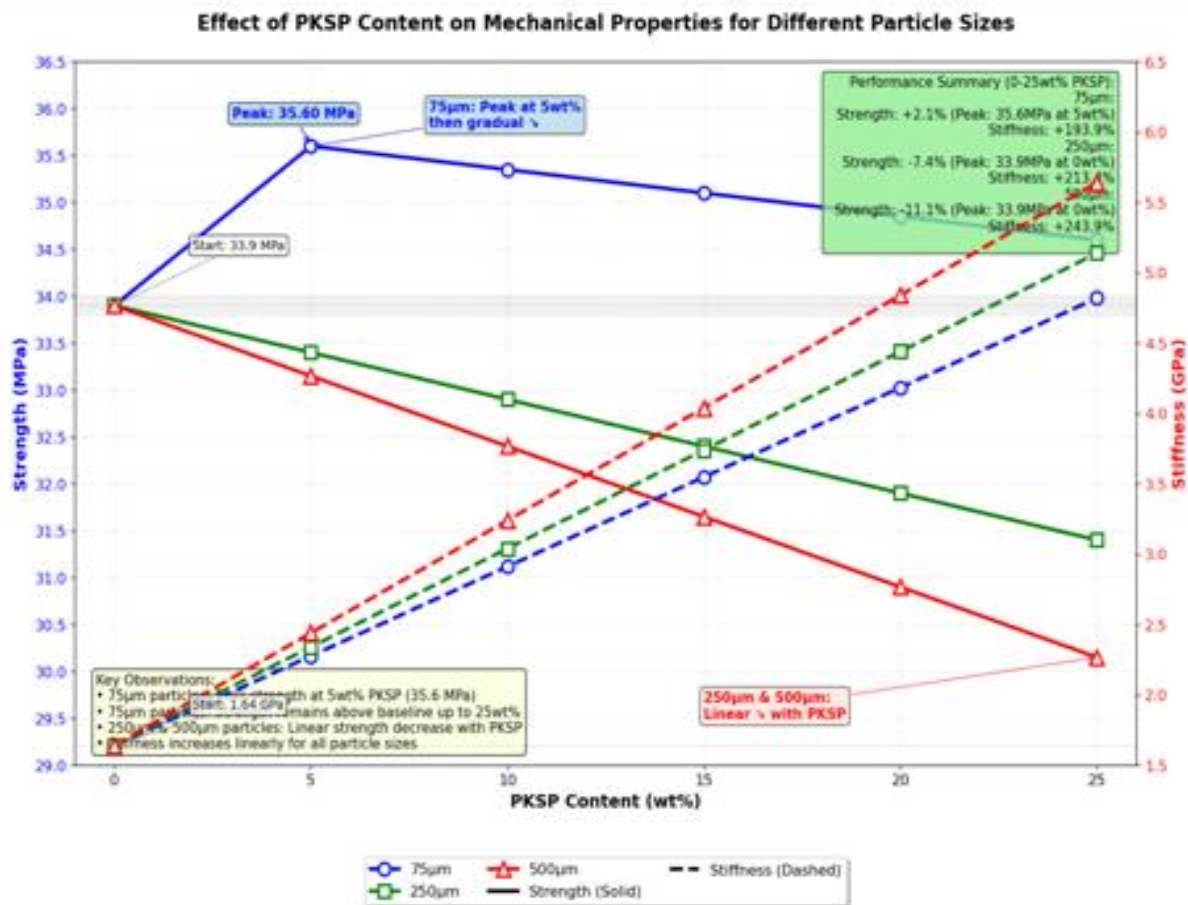


Figure 9: showing the plots of strength (MPa) and stiffness (GPa) versus PKSP content (wt.%)

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 34.0 to 35.60 MPa, while stiffness values (right y-axis) range from 1.5 to 6.5 GPa.

Optimization results

Several different optimizations relying heavily on the Monte-Carlo basis were performed on the results and chart shown above. These include weighted, Pareto, product, geometric mean and desirability function optimizations.

The results of the optimizations are displayed below:

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COMPREHENSIVE OPTIMIZATION ANALYSIS FOR PKSP COMPOSITES
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1. WEIGHTED OPTIMIZATION (Equal weights for Strength & Stiffness):
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Size: 75 $\mu\text{m}$ , PKSP: 25wt% | Strength: 34.60 MPa, Stiffness: 4.820 GPa | Score: 0.806
Size: 250 $\mu\text{m}$ , PKSP: 25wt% | Strength: 31.40 MPa, Stiffness: 5.140 GPa | Score: 0.552
Size: 500 $\mu\text{m}$ , PKSP: 25wt% | Strength: 30.15 MPa, Stiffness: 5.640 GPa | Score: 0.500

2. PARETO OPTIMAL SOLUTIONS (Non-dominated points):
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1. Size: 75 $\mu\text{m}$ , PKSP: 5wt% | Strength: 35.60 MPa, Stiffness: 2.276 GPa
2. Size: 75 $\mu\text{m}$ , PKSP: 10wt% | Strength: 35.35 MPa, Stiffness: 2.912 GPa
3. Size: 75 $\mu\text{m}$ , PKSP: 15wt% | Strength: 35.10 MPa, Stiffness: 3.548 GPa
4. Size: 75 $\mu\text{m}$ , PKSP: 20wt% | Strength: 34.85 MPa, Stiffness: 4.184 GPa
5. Size: 75 $\mu\text{m}$ , PKSP: 25wt% | Strength: 34.60 MPa, Stiffness: 4.820 GPa
6. Size: 250 $\mu\text{m}$ , PKSP: 25wt% | Strength: 31.40 MPa, Stiffness: 5.140 GPa
7. Size: 500 $\mu\text{m}$ , PKSP: 25wt% | Strength: 30.15 MPa, Stiffness: 5.640 GPa

3. PRODUCT OPTIMIZATION (Maximize Strength  $\times$  Stiffness):
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Size: 75 $\mu\text{m}$ , PKSP: 25wt% | Strength: 34.60 MPa, Stiffness: 4.820 GPa | Product: 166.77 MPa·GPa
Size: 250 $\mu\text{m}$ , PKSP: 25wt% | Strength: 31.40 MPa, Stiffness: 5.140 GPa | Product: 161.40 MPa·GPa
Size: 500 $\mu\text{m}$ , PKSP: 25wt% | Strength: 30.15 MPa, Stiffness: 5.640 GPa | Product: 170.05 MPa·GPa

4. GEOMETRIC MEAN OPTIMIZATION:
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Size: 75 $\mu\text{m}$ , PKSP: 25wt% | Strength: 34.60 MPa, Stiffness: 4.820 GPa | Geometric Mean: 0.806
Size: 250 $\mu\text{m}$ , PKSP: 20wt% | Strength: 31.90 MPa, Stiffness: 4.440 GPa | Geometric Mean: 0.474
Size: 500 $\mu\text{m}$ , PKSP: 10wt% | Strength: 32.40 MPa, Stiffness: 3.240 GPa | Geometric Mean: 0.406

5. DESIRABILITY FUNCTION OPTIMIZATION:
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Size: 75 $\mu\text{m}$ , PKSP: 25wt% | Strength: 34.60 MPa, Stiffness: 4.820 GPa | Desirability: 0.911
Size: 250 $\mu\text{m}$ , PKSP: 25wt% | Strength: 31.40 MPa, Stiffness: 5.140 GPa | Desirability: 0.897
Size: 500 $\mu\text{m}$ , PKSP: 25wt% | Strength: 30.15 MPa, Stiffness: 5.640 GPa | Desirability: 0.920
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Figure 10: showing the results of Monte-Carlo based optimizations for the experimental results

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3D DESIRABILITY INTERACTION PLOT FOR PKSP COMPOSITE
OPTIMIZATION
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Total data points: 18
Size range: 75.0 - 500.0 µm
PKSP range: 0.0 - 25.0 wt%
Strength range: 30.42 - 35.65 MPa
Stiffness range: 1.589 - 5.504 GPa

Response Surface Models:
Strength Model R²: 0.9309
Stiffness Model R²: 0.9963

Strength Model Coefficients:
Size: -0.0177
PKSP: 0.0628

Stiffness Model Coefficients:
PKSP: 0.1310

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Figure 11a: 3D Desirable interaction plot for PKSP Composite Optimization

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GENERATING 3D DESIRABILITY INTERACTION PLOTS
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Processing: Equal Importance (50/50)
Optimal Point - Size: 50.0 µm, PKSP: 25.0%, Desirability:
0.8759
Predicted - Strength: 35.46 MPa, Stiffness: 4.704 GPa

Processing: Strength-Focused (75/25)
Optimal Point - Size: 50.0 µm, PKSP: 25.0%, Desirability:
0.9190
Predicted - Strength: 35.46 MPa, Stiffness: 4.704 GPa

Processing: Stiffness-Focused (25/75)
Optimal Point - Size: 50.0 µm, PKSP: 25.0%, Desirability:
0.8349
Predicted - Strength: 35.46 MPa, Stiffness: 4.704 GPa

Processing: Strength-Dominant (90/10)
Optimal Point - Size: 50.0 µm, PKSP: 21.5%, Desirability:
0.9506
Predicted - Strength: 35.58 MPa, Stiffness: 4.276 GPa

Processing: Stiffness-Dominant (10/90)
Optimal Point - Size: 132.5 µm, PKSP: 25.0%, Desirability:
0.8196
Predicted - Strength: 33.64 MPa, Stiffness: 4.901 GPa

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Figure 11b: 3D Desirable interaction Plot continues

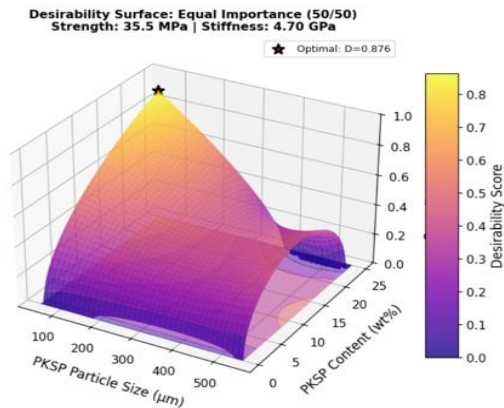


Figure 12.1: 3D Desirability surface Plot for [Strength and Stiffness (50/50)]

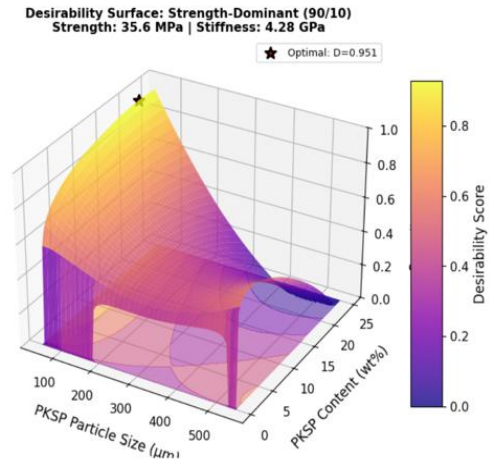


Figure 12.4: 3D Desirability surface Plot [Strength-Dominant (90/10)]

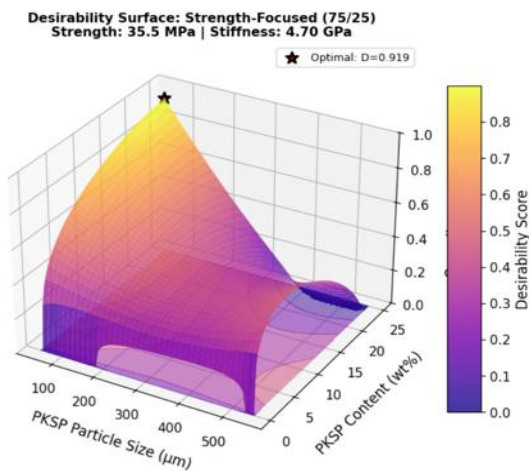


Figure 12.2: 3D Desirability Surface Plot [Strength Focus (75/25)]

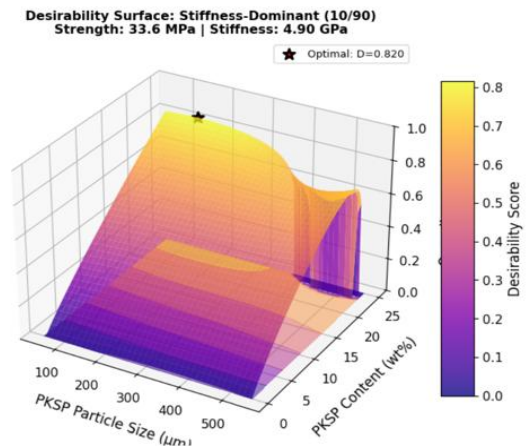


Figure 12.5: 3D Desirability surface Plot [Stiffness-Dominant (10/90)]

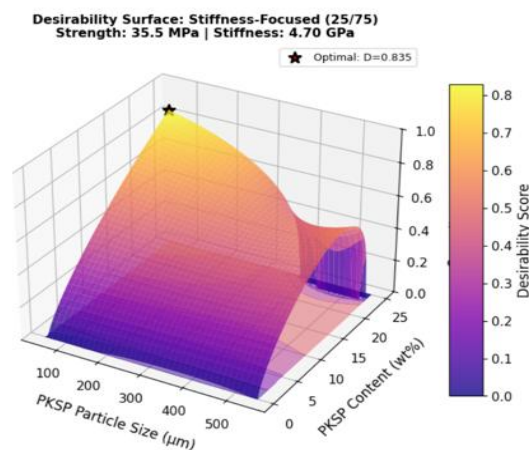


Figure 12.3: 3D Desirability Surface Plot [Stiffness-focused (25/75)]

IV. DISCUSSION

The graph above shows the plots of strength (Mpa) and stiffness (GPa) versus PKSP content (wt.%) for PKSP sizes 75, 250 and 500μm. The color encoding is Blue (75μm), Green (250μm) and Red (500μm). Strength values on the y-axis ranges from 29 to 36.5MPa, stiffness values on the opposite side of the y-axis ranges from 1.5 to 6.5GPa, while the PKSP content (wt.%) values on the x-axis ranges from 0 to 25%. The graph also shows key performance observations, including that:

a.) increases for both strength (2.1%) and stiffness (193.9%), for size 75μm. This is largely due to a lower

strength and stiffness value for pure MAPP-enhanced PP, than for PKSP (75µm)-filled MAPP-enhanced PP. b.) for both 250 and 500µm, strength reduces as PKSP (wt.%) increases, while stiffness increases.

c.) for both increasing particle size (µm) and increasing filler content (wt.%), strength generally reduces, while stiffness generally increases.

Other observations include:

a.) 75µm particles show unique behavior: strength peaks at 5wt% PKSP (35.6 Mpa). Even at 25wt% PKSP, strength remains above baseline (34.6 MPa vs 33.9 Mpa). This suggests excellent interfacial bonding for small particles

b.) larger particles show linear degradation: 250µm and 500µm particles show linear decrease in strength with PKSP. The decrease is more pronounced for larger particles

c.) stiffness improves for all: all particle sizes show significant stiffness improvement. Stiffness increases linearly with PKSP content, with the largest improvement for 500µm particles (+244% increase)

d.) Optimal recommendations: Maximum strength: 75µm particles with 5wt% PKSP (35.6 Mpa). Maximum stiffness: 500µm particles with 25wt% PKSP (5.64 Gpa). Best balance: 75µm particles with 5-10wt% PKSP

e.) Performance Index Analysis: The maximum product of strength × stiffness helps identify balanced performance. 75µm particles at 5wt% PKSP give excellent combined performance. The plot clearly visualizes these trends with annotations, performance summaries, and professional styling for clear interpretation.

Weighted optimisation, visual observation

Visual inspection of the 3 intersection points of the 3 sets of blue, green and red solid and broken lines in Figure 1 leads to the following observation/conclusion:

a.) The 3 intersection points corresponding to the blue (75µm), green (250µm) and red (500µm) sets of lines are (34.5MPa, 5.2GPa, 28wt%), (32.4MPa, 3.75GPa, 15wt%) and (32.2MPa, 3.6GPa, 12wt%) respectively. These are the 3 intersection points where the values of strength and stiffness are weightedly balanced for each of the 3 PKSP sizes 75, 250 and 500µm respectively.

Monte-Carlo optimisation

Results of the Monte-Carlo optimisation on Python interface reveal interesting results. Weighted optimisation reveals that 25wt% show the highest optimisation for all three PKSP sizes, with (75µm, 25wt%) having the highest score. Pareto optimisation reveals that 75µm at 25 or 25wt% gives best results. Likewise, product optimisation shows that 25wt% of 75 or 500µm maximises the product of strength and stiffness. Geometric mean optimisation gives the highest score to PKSP at 75µm and 25wt%, due to 75µm having the lowest variation of both strength and stiffness for PKSP content (wt%). Desirability function analysis also shows PKSP at (75µm, 25wt%) coming closely behind (500µm, 25wt%) in score. It is therefore not so surprising that (75µm, 25wt%) has been returned as the optimised set for best combination of strength and stiffness.

Going by the results of this optimisation work, (75µm, 25wt%) may be one of the most suitable for obtaining best strength and stiffness combinations, especially maximising stiffness with only a barely marginal loss in strength, when optimally treated PKSP (lightly oxidised carbonised) is used as a filler in compression molded MAPP-reinforced PP/PKSP composite applications. From the report's final recommendation, expected material properties from the use of optimally treated PKSP (lightly oxidised carbonised) as a filler in compression molded MAPP-reinforced PP/PKSP, may be up to and around (34.6MPa. 4.82GPa).

Another candidate PKSP set to consider would be (500µm, 25wt%), especially when fully maximised stiffness is highly desirable in certain applications. On the other hand, when maximum strength is desirable, the PKSP set (75µm, 5wt%) may be highly advantageous.

V. CONCLUSION

Based on the comparative analysis of tensile strength and stiffness data for all samples collected via a programmable electronic universal testing machine (UTM), the following conclusions are drawn: The slightly carbonized palm kernel shell powder (PKSP) acts as an effective reinforcing filler in maleic anhydride-grafted polypropylene (MAPP)-enhanced polypropylene (PP) matrices.

Testing conducted through a Python-controlled interface shows that a 25 wt.% PKSP loading yields

the highest weighted optimization scores across all particle sizes, with the 75 μm and 25 wt.% combination achieving the top score. This formulation is therefore identified as the optimal balance between strength and stiffness for the given filler matrix system.

Overall, this study confirms that MAPP-enhanced PP/PKSP composites derived from agricultural waste and optimally tuned for strength and stiffness performance offer a promising sustainable alternative for rigid food packaging, supporting waste reduction and circular economy objectives.

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