

# OPTIMIZATION OF PROCESS PARAMETERS FOR ENHANCING THE PROPERTIES OF BREADFRUIT SEED COAT-REINFORCED LOW-DENSITY POLYETHYLENE COMPOSITE

Paul Chukwulozie Okolie, Ezenwa Obiora Nnaemeka, Calistus Princewill Odeh, Chibuzo Ndubuisi Okoye, Madumere Augustine Uzodinma and Chima Bright Nwachinemere

Department of Mechanical Engineering, Nnamdi Azikiwe University, Awka, Nigeria

\*Corresponding author, email: pc.okolie@unizik.edu.ng

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## Abstract

This study investigates the optimization of process parameters to enhance the properties of breadfruit seed coat-reinforced low-density polyethylene composite ceiling boards. The research focused on assessing the effects of mixing ratio, press temperature, pressure, and press time on key material properties, including water absorption (WA), thermal conductivity (K), flexural strength (FS), and fire performance (FP). Breadfruit seed coats (BSCs) were treated with sodium hydroxide (NaOH) and acetic acid (CH<sub>3</sub>COOH) to modify their surface properties before being mixed with kaolin (as a fire retardant) and low-density polyethylene (LDPE) to form composite boards through hydraulic pressing. The study also statistically analyzed and optimized the fabrication parameters using Response Surface Optimal Design (RSOD). The results demonstrated that kaolin content and mixing ratio significantly influenced WA, K, FS, and FP, while press temperature, pressure, and time had varying degrees of impact. The optimized parameters (20% mixing ratio, 180°C press temperature, 15 MPa press pressure, and 10 min press time) gave the optimal moisture resistance, thermal insulation, superior mechanical strength, and fire resistance. The findings highlight the potential of breadfruit seed coat composites as sustainable, cost-effective, and eco-friendly alternatives to conventional ceiling materials. This study contributes to agricultural waste recycling in composite manufacturing, promoting environmental sustainability while meeting modern construction demands.

## 1. Introduction

Waste generation and improper disposal pose significant environmental challenges, particularly in developing countries like Nigeria. Agricultural waste constitutes a substantial portion of the total waste produced annually. Nigeria generates over 10 million tons of agricultural waste, including wheat straws, fruit bunches, hazelnut shells, peanut shells, coffee husks, rice husks, maize husks, and breadfruit seed coats [1-5]. In Southeastern Nigeria, breadfruit seed coats are commonly burned or discarded, contributing to air pollution, greenhouse gas emissions, and environmental degradation. The underutilization of these agro-wastes presents an opportunity for their conversion into high-value composite materials, offering both environmental and economic benefits.

One promising approach to waste valorization is the development of composite materials, such as ceiling boards, by reinforcing polymers with agricultural residues. Various agro-wastes, including sugarcane bagasse, rice husks, cornstalks, sawdust, and palm kernel shells, have been explored for composite production, reducing dependence on wood-based materials [6,7]. In Nigeria, the growing demand for ceiling boards has led to deforestation, timber shortages, and increased raw material costs, highlighting the need for sustainable alternatives [8-11].

This research focuses on optimizing process parameters to enhance the mechanical, thermal, and fire-resistant properties of breadfruit seed coat-reinforced low-density polyethylene (LDPE) composites. By employing a systematic approach to parameter optimization, including mixing ratio,

press temperature, press pressure, and press time, the study aims to determine the ideal conditions for improving water resistance, thermal insulation, mechanical strength, and fire performance. Studies have shown that composite materials from agricultural residues exhibit high durability, reduced water absorption, and improved thermal insulation [12-15]. This work contributes to the sustainable utilization of agricultural waste while addressing challenges related to ceiling board production, waste management, and environmental conservation.

## 2. Experimental Procedure

### 2.1. Processing of Breadfruit Seed Coats and Ceiling Board Fabrication

The key materials used in this study included breadfruit seed coats (BSCs), kaolin, low-density polyethylene (LDPE), acetic acid (CH<sub>3</sub>COOH), and sodium hydroxide (NaOH). The breadfruit seed coats were thoroughly washed with clean water to eliminate dirt, residual particles, and sand. To modify the surface properties of the BSCs, they were treated with a 1 mol/dm<sup>3</sup> sodium hydroxide (NaOH) solution to remove lignin, cellulose, and hemicellulose components. Following this treatment, the BSCs were neutralized in 0.5 mol/dm<sup>3</sup> acetic acid, rinsed with distilled water and dried completely to remove residual moisture. The dried seed coats were then ground and sieved to a particle size of 60 μm for uniformity in the composite mixture.

Kaolin was introduced as a fire retardant, maintaining a balanced filler-to-binder ratio based on previous research [6,7]. The proportions of kaolin were varied using the Central Composite Design (CCD) tool within the Design Expert software, as outlined in Table 1. The low-density polyethylene (LDPE) was sieved to 60 μm to match the filler size. The measured quantities of BSCs, LDPE, and kaolin were thoroughly mixed in a container using a stirring rod to achieve a homogeneous mixture. The mixture was poured into a rectangular mold lined with metal sheets and placed within a hydraulic press set to the specified temperature, pressure, and time (Table 1) to consolidate the composite. Once compressed, the composite ceiling boards were allowed to cool and cut into appropriate sample sizes for further testing.

### 2.2. Water Absorption Test (WA)

The study investigated the water absorption capacity of the ceiling boards following the ASTM D1037-99 standard (ASTM, 1999). Test samples were oven-dried at 80°C for 24 hours and weighed with 0.001 g precision (initial dry weight, M<sub>0</sub>). The samples were then partially submerged in distilled water for 24 hours and surface-dried using tissue paper. The percentage of water absorption (WA) was calculated using Equation (1).

$$WA = \frac{M_1 - M_0}{M_0} \times 100(1)$$

Where M<sub>0</sub> is the initial dry weight (g), and M<sub>1</sub> is the wet weight (g) after immersion.

**Table 1. Design layout of low-density polyethylene-reinforced breadfruit seed coats formulation**

Std	Factor 1 A: Mixture Ratio (wt%)	Factor 2 B: Press Temp. (°C)	Factor 3 C: Press Pressure (MPa)	Factor 4 D: Press Time (min)
1	20	180	7	10
2	60	180	7	10
3	20	200	7	10
4	60	200	7	10
5	20	180	15	10
6	60	180	15	10
7	20	200	15	10
8	60	200	15	10
9	20	180	7	20
10	60	180	7	20
11	20	200	7	20
12	60	200	7	20
13	20	180	15	20
14	60	180	15	20

Std	Factor 1 A: Mixture Ratio (wt%)	Factor 2 B: Press Temp. (°C)	Factor 3 C: Press Pressure (MPa)	Factor 4 D: Press Time (min)
15	20	200	15	20
16	60	200	15	20
17	0	190	11	15
18	80	190	11	15
19	40	170	11	15
20	40	210	11	15
21	40	190	3	15
22	40	190	19	15
23	40	190	11	5
24	40	190	11	25
25	40	190	11	15
26	40	190	11	15
27	40	190	11	15
28	40	190	11	15
29	40	190	11	15
30	40	190	11	15

### 2.3. Fire Performance Test (FP)

The fire resistance of the composite ceiling boards was determined using a cone calorimeter (Fire Testing Technology LTD., UK) based on the ISO 5660-1 standard. Test specimens were placed horizontally, and a heat flux of 35 kW/m<sup>2</sup> was applied using an edge frame. The key parameters measured included Heat release rate (HRR), recorded in kW/m<sup>2</sup>, which indicates the intensity of combustion. Time to ignition (TTI), represents the time required for the specimen surface to sustain a luminous flame.

### 2.4. Flexural Strength Test (FS)

The flexural strength of the composite ceiling board was determined using a Universal Testing Machine (UTM) following the ASTM D1037 (1999) standard. The three-point bending method applied a concentrated load at the center of a beam specimen measuring 200 × 20 × 10 mm, supported at both ends. The flexural strength (FS) was calculated using Equation (2).

$$FS = \frac{3PL}{2BD^2} \quad (2)$$

Where:

FS = Flexural strength (N/mm<sup>2</sup>)

P = Applied load (N)

L = Distance between supports (mm)

B = Width of the specimen (mm)

D = Thickness of the specimen (mm)

### 2.5. Thermal Conductivity Test (K)

The study evaluated the thermal conductivity (K) using an automated Lee's Disc apparatus based on the ASTM 1553 method. A heat source maintained at 50°C was applied at the top surface, while the bottom plate temperature was recorded at 5-minute intervals for 60 minutes to track heat transfer. Afterwards, the metal disc was reheated to 10°C above the original heating temperature and allowed to cool below the final heating temperature to determine the heat loss rate. The thermal conductivity (K) was calculated using Equation (3).

$$\frac{de}{dt} = \frac{kA\theta B - \theta A}{d} \quad (3)$$

Where K is the thermal conductivity, A is the cross-sectional area of the sample, given as A = (πD<sup>2</sup>)/4, de/dt is the rate of heat loss, and (θB - θA) is the temperature difference.

## 2.6. Statistical analysis and optimization of experimental data

We employ a Response Surface Optimal Design (RSOD) to analyze the significant effects of mixing ratio, press temperature, pressure, and press time on the water absorption (WA), thermal conductivity (K), flexural strength (FS), and fire performance (FP) of low-density polyethylene-reinforced breadfruit seed coat-based ceiling boards. The statistical significance of these factors was determined using p-values, allowing for an in-depth understanding of their influence on material properties. We varied the independent variables within specific ranges: mixing ratio (0–80 wt%), press temperature (170°C–210°C), press pressure (3–19 MPa), and press time (5–25 min). Each combination of these parameters was analyzed to assess its impact on WA, K, FS, and FP, ensuring the optimization of material performance.

The optimal combination of processing parameters for the optimal performance of the ceiling board was established by statistically optimizing the experimental data. The RSOD model helped identify an ideal balance between these properties, ensuring that the developed composite ceiling boards exhibited superior durability, insulation efficiency, and fire resistance. This systematic approach provides a quantitative basis for selecting the best fabrication conditions, supporting the potential use of breadfruit seed coat composites as a sustainable alternative to conventional ceiling materials.

## 3. Results and discussion

### 3.1. Experiment results

Table 2 shows the experimental results of the effects of mixture ratio, press temperature, pressure, and time on the water absorption, thermal conductivity, flexural strength, and fire performance of low-density polyethylene-reinforced breadfruit seed coat-based ceiling boards. The results show low water absorption of 2.941% with a 60 wt% mixture ratio, 200°C press temperature, 15 MPa pressure, and 10 min press time. In contrast, the highest absorption (23.809%) occurred at 0 wt% kaolin, 190°C, 11 MPa, and 15 min, indicating poor humidity resistance. The lowest thermal conductivity (0.106 Wm<sup>-1</sup>K<sup>-1</sup>) was recorded at 80 wt% kaolin, 190°C, 11 MPa, and 15 min, demonstrating excellent heat insulation. Flexural strength was highest (0.833 MPa) at 0 wt% kaolin, suggesting that lower kaolin content improved mechanical strength. Increased kaolin content significantly enhanced fire performance, with the maximum Time to Ignition (224 sec) observed at 80 wt% kaolin, 190°C, 11 MPa, and 15 min.

**Table 2. Water absorption, thermal conductivity, flexural strength, and fire performance of low-density polyethylene-reinforced breadfruit seed coats**

Samples	Water Absorption (W <sub>A</sub> ), %	Thermal conductivity (Wm <sup>-1</sup> K <sup>-1</sup> )	Flexural strength (MPa)	Fire performance (Sec)
1	4.762	0.313	0.613	113.80
2	11.538	0.204	0.411	200.90
3	4.762	0.317	0.659	115.60
4	5.556	0.315	0.410	198.80
5	8.333	0.210	0.628	109.60
6	9.091	0.209	0.412	198.50
7	3.571	0.360	0.661	115.90
8	2.941	0.205	0.418	200.00
9	5.001	0.360	0.615	111.30
10	15.385	0.218	0.415	200.50
11	4.167	0.360	0.653	113.00
12	3.448	0.219	0.416	198.60
13	9.091	0.336	0.662	111.50
14	19.048	0.205	0.413	200.70
15	9.524	0.365	0.671	109.60
16	11.765	0.207	0.397	200.00
17	23.809	0.317	0.833	105.00
18	4.001	0.106	0.308	224.00
19	4.762	0.180	0.511	175.80
20	5.556	0.194	0.517	177.00
21	3.846	0.190	0.508	175.30

Samples	Water Absorption (W <sub>A</sub> ), %	Thermal conductivity (Wm <sup>-1</sup> K <sup>-1</sup> )	Flexural strength (MPa)	Fire performance (Sec)
22	10.714	0.190	0.510	175.60
23	8.696	0.188	0.513	176.00
24	4.348	0.190	0.511	175.30
25	8.001	0.190	0.509	175.90
26	3.846	0.193	0.511	175.60
27	3.845	0.190	0.510	176.00
28	4.001	0.189	0.508	175.80
29	3.846	0.190	0.511	175.80
30	4.001	0.191	0.512	175.90

### 3.2. Statistical analysis of experimental results

The statistical analysis of the experimental data using Response Surface Optimal Design (RSOD) (Table 3) provides significant insights into the influence of mixing ratio (A), press temperature (B), press pressure (C), and press time (D) on the water absorption (WA), thermal conductivity (K), flexural strength (FS), and fire performance (FP) of low-density polyethylene-reinforced breadfruit seed coat-based ceiling boards. Figure 1 depicts the 3D surface plots for WA, K, FS, and FP of low-density polyethylene-reinforced breadfruit seed coats. The model's p-values for WA (0.0492), K (0.0013), FS (< 0.0001), and FP (< 0.0001) are all lower than the threshold value of 0.05, indicating that the statistical models for these properties are significant and provide reliable predictions for the optimization of the properties of ceiling board.

The statistical analysis of WA reveals that the individual factors (A, B, C, and D) recorded p-values above 0.05, suggesting that variations in mixing ratio, press temperature, pressure, and time do not independently influence the water absorption characteristics. However, combined factors AD, BC, BD, and CD recorded p-values of 0.0482 and 0.0238, demonstrating a significant interactive effect on WA. Statistical analysis of thermal conductivity shows that only factor A (mixing ratio) recorded a p-value lower than 0.05, meaning that the proportion of breadfruit seed coats, kaolin, and polyethylene in the composite significantly influenced the thermal conductivity. The insignificant effects of B (press temperature), C (press pressure), and D (press time) suggest that variations in these processing parameters do not significantly alter the heat insulation properties of the ceiling board. The dominance of the mixing ratio in affecting thermal conductivity aligns with the understanding that higher kaolin content improves thermal insulation due to its low thermal conductivity. The presence of kaolin as a filler reduces the heat transfer between the ceiling and indoor space, making the material more energy-efficient for insulation applications.

The analysis of flexural strength shows that factors A (mixing ratio), B (press temperature), and the interaction factor AB (mixing ratio and press temperature) have a significant influence, as their p-values are below 0.05. This result indicates the composition of materials, and the applied processing temperature largely controlled the flexural strength of the board. The interaction effect of AB further supports the idea that an optimum combination of material composition and heat application is required to achieve the best flexural strength. The statistical analysis of the fire performance shows that only factor A (mixing ratio) recorded a significant effect, as its p-value was below 0.05. This finding confirms that higher kaolin levels significantly delay the time to ignition and reduce heat release rates. Other factors such as B, C, and D have no significant effect on the fire performance of the ceiling board. The study demonstrated that material composition governs the thermal stability and flame resistance of ceiling boards rather than processing conditions.

**Table 3: Analysis of Variance (ANOVA) for water absorption (WA), thermal conductivity (K), flexural strength (FS), and fire performance (FP) of low-density polyethylene-reinforced breadfruit seed coats**

Source	WA		K		FS		FP		
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	
Model	0.105	0.0492	6.22	0.0013	197.78	< 0.0001	61.20	< 0.0001	significant
A	0.1746	0.6820	22.52	< 0.0001	2694.14	< 0.0001	244.75	< 0.0001	
B	2.11	0.1672	1.46	0.2383	5.18	0.0380	0.0141	0.9065	

Source	WA		K		FS		FP	
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
C	1.82	0.1971	0.6187	0.4389	1.73	0.2081	0.0104	0.9196
D	0.5707	0.4617	0.2816	0.6003	0.2136	0.6506	0.0242	0.8777
AB	1.78	0.0202			8.77	0.0097		
AC	0.0624	0.0806			4.19	0.0587		
AD	0.5198	0.0482			1.18	0.2935		
BC	0.0025	0.0961			1.28	0.2754		
BD	0.0193	0.0891			1.28	0.2754		
CD	1.51	0.0238			0.1536	0.7007		
A <sup>2</sup>	5.97	0.0273			49.44	<		
						0.0001		
B <sup>2</sup>	0.0128	0.0911			0.3470	0.5646		
C <sup>2</sup>	0.4602	0.0507			0.0004	0.9851		
D <sup>2</sup>	0.2269	0.0640			0.1304	0.7231		
Residual								
Lack of Fit	1.243	0.0062	1935	<	90.79	<	9980.8	<
				0.0001		0.0001		0.0001
Pure Error								
Cor Total								

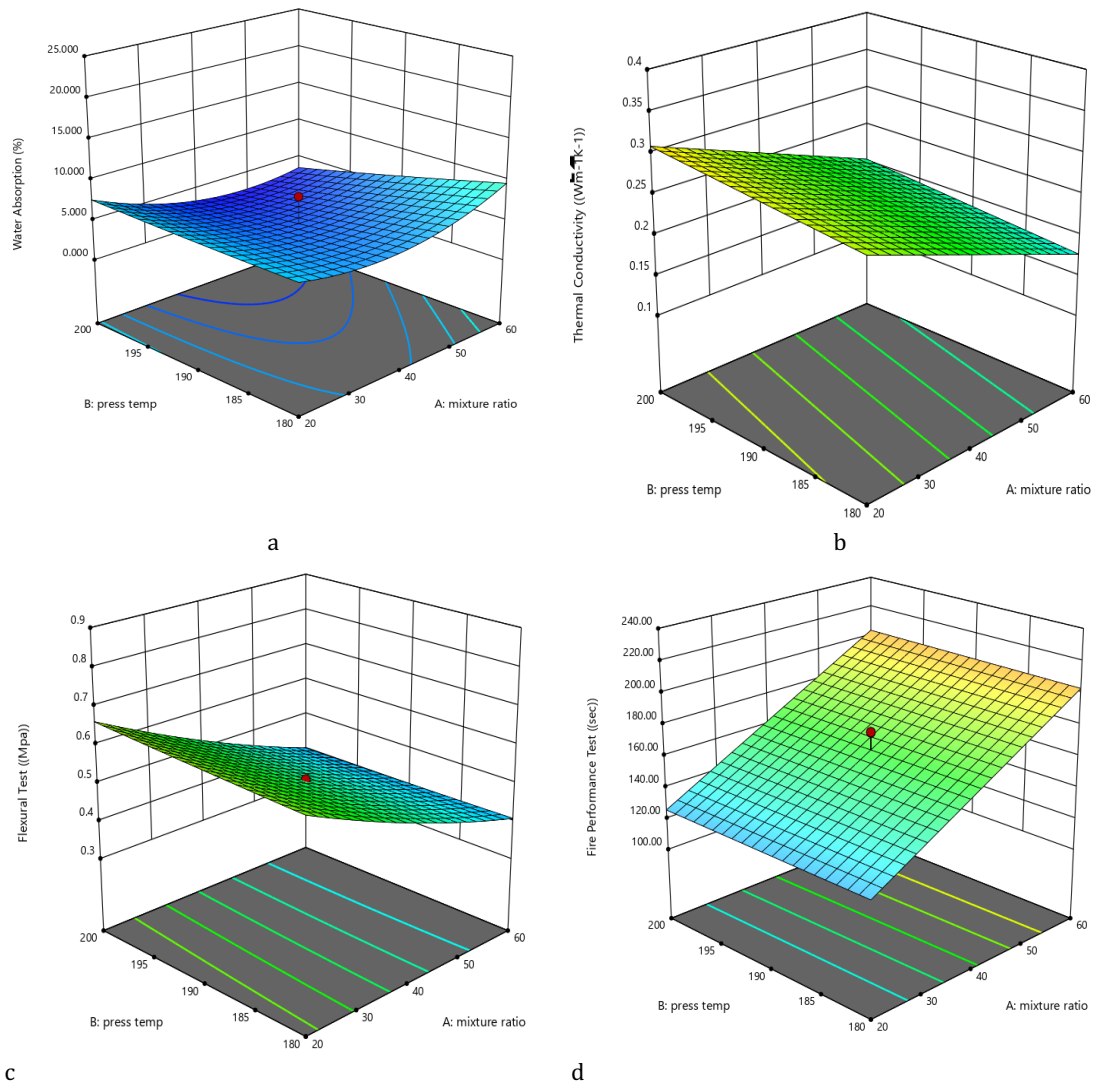


Figure 1. 3D surface plot for (a) WA, (b) K, (c) FS, and (d) FP of low-density polyethylene-reinforced breadfruit seed coats.

### 3.3. Optimization of statistical data

The optimization results presented in Table 4 reveal that the optimal combination of factors for achieving the best performance of the low-density polyethylene-reinforced breadfruit seed coat-based ceiling board is 20% mixing ratio, 10 minutes press time, 15 MPa press pressure, and 180°C press temperature. These parameters showed the most effective in balancing water absorption, thermal conductivity, flexural strength, and fire performance, ensuring durability and functionality.

**Table 4. Results of optimized statistical data**

S/N	Mix. Ratio	Press Time	Press Temp.	Press Pressure	Thermal Cond.	Water Absorption	Flexural Test	Fire Performance	Desirability
1	20	10	180	15	0.261	8.358	0.639	135.43	0.827
2	20.00	10	180	14.963	0.261	8.344	0.639	135.44	0.827
3	20.27	10	180.0	15	0.261	8.297	0.637	135.95	0.827
4	20.00	10.00	180.0	14.889	0.262	8.320	0.639	135.43	0.827
5	20.43	10	180.0	15	0.260	8.261	0.636	136.27	0.827
6	20.00	10	180.0	14.835	0.262	8.302	0.639	135.45	0.827
7	20.62	10.00	180	14.998	0.260	8.216	0.635	136.65	0.827
8	20	10	180	14.799	0.262	8.291	0.639	135.44	0.827
9	20.08	10.13	180	14.999	0.261	8.357	0.639	135.58	0.827
10	20.91	10	180	14.998	0.259	8.154	0.633	137.2	0.827

### 4. Conclusion

The optimization of process parameters for enhancing the properties of breadfruit seed coat-reinforced low-density polyethylene composite ceiling boards have demonstrated the significant influence of material composition and processing conditions on key performance metrics. The study revealed that mixing ratio and kaolin content significantly enhanced water absorption, thermal conductivity, flexural strength, and fire resistance. At the same time, press temperature, pressure, and time exhibited varying degrees of influence. The optimized combination of a 20% mixing ratio, 10 minutes press time, 15 MPa press pressure, and 180°C press temperature resulted in an optimal balance of low water absorption (improved moisture resistance), enhanced thermal insulation, high flexural strength, and superior fire performance. Statistical analysis using Response Surface Optimal Design (RSOD) confirmed the significance of these parameters, validating their impact on ceiling board properties. The findings underscore the potential of breadfruit seed coats and kaolin as sustainable, eco-friendly reinforcements in composite materials, offering a viable alternative to traditional wood-based ceiling boards. This study contributes to the advancement of agricultural waste recycling in composite manufacturing, promoting environmental sustainability while meeting the increasing demand for cost-effective and fire-resistant building materials.

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