

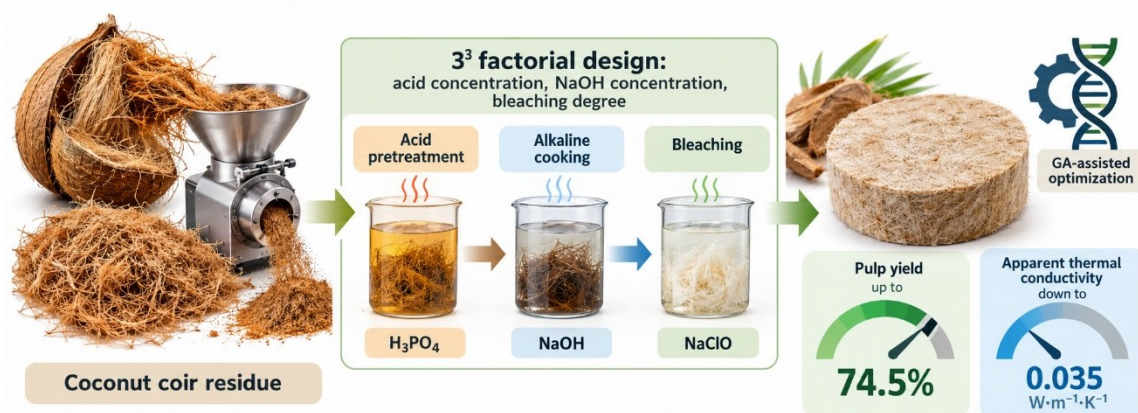
From Coconut Coir to Bio-Based Insulation Panels: Factorial Design and Genetic-Algorithm Exploration of Pulp Yield and Thermal Conductivity

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GRAPHICAL ABSTRACT



From Coconut Coir to Bio-Based Insulation Panels: Factorial Design and Genetic-Algorithm Exploration of Pulp Yield and Thermal Conductivity

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Coconut coir is an abundant lignocellulosic agro-industrial residue that can be processed into fibrous pulp for exploratory bio-based insulation panels. This study used a complete three-level, three-factor (3^3) factorial design to examine the effects of phosphoric-acid pretreatment concentration, sodium-hydroxide cooking concentration, and bleaching chlorometric degree on gravimetric pulp yield and apparent thermal conductivity. Second-order regression equations and coefficient-magnitude (Pareto) rankings were used as exploratory tools to describe treatment effects, and a genetic algorithm was used to identify a candidate compromise within the tested factor bounds. Observed pulp yields ranged from 20.1% to 74.5%, and apparent thermal conductivity ranged from 0.035 to 0.170 $\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$. The candidate conditions gave model-predicted values of 92.4% pulp yield and 0.041 $\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$ apparent thermal conductivity; these values were not independently confirmed experimentally. Because compositional analysis of the recovered solid was not performed, the material is described as treated fibrous pulp rather than purified cellulose. The results provide an exploratory basis for further optimization, which should include composition, moisture, and independent confirmation measurements before practical insulation performance is claimed.

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Keywords: Coconut coir; Treated fibrous pulp; Apparent thermal conductivity; Factorial design; Exploratory optimization

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INTRODUCTION

The demand for bio-based insulation has stimulated interest in lignocellulosic residues, including coconut coir, as locally available raw materials (Raza *et al.* 2024). Raw coconut coir itself has been investigated as an insulation-board feedstock (Panyakaew and Fotios 2011); its direct use can reduce processing requirements, but the suitability of a panel depends on density, fibre architecture, moisture uptake, biological durability, fire behaviour, and the intended application. The present work does not experimentally compare raw-coir panels with treated-pulp panels and therefore does not claim superiority over raw coir.

The present study evaluates how an acid pretreatment-soda cooking-bleaching sequence affects gravimetric pulp yield and apparent thermal conductivity. The gravimetric yield is the mass fraction of dried treated pulp relative to the starting dry coir; it is not a measurement of cellulose content or cellulose recovery. The work is intended as an exploratory material-processing study for non-structural building-envelope applications,

such as roof/ceiling cavities or internal wall systems. Further assessments of moisture sensitivity, biological durability, fire behaviour, mechanical integrity, and regulatory compliance are required before construction use can be proposed.

Sodium-hydroxide pulping, commonly termed soda pulping when sodium hydroxide is the principal cooking chemical, can remove part of the lignin and hemicellulose while preserving a fibrous pulp fraction. Its outcome depends jointly on alkali concentration, temperature, residence time, liquor-to-solid ratio, and the severity of any preceding treatment. Increased alkaline severity can improve delignification but lower pulp yield through carbohydrate degradation (Brännvall 2017). Bleaching can further modify residual lignin and chromophoric structures, but its chemical demand and potential effect on fibre properties must be considered. These trade-offs motivate the simultaneous exploratory assessment of the three treatment variables in this study.

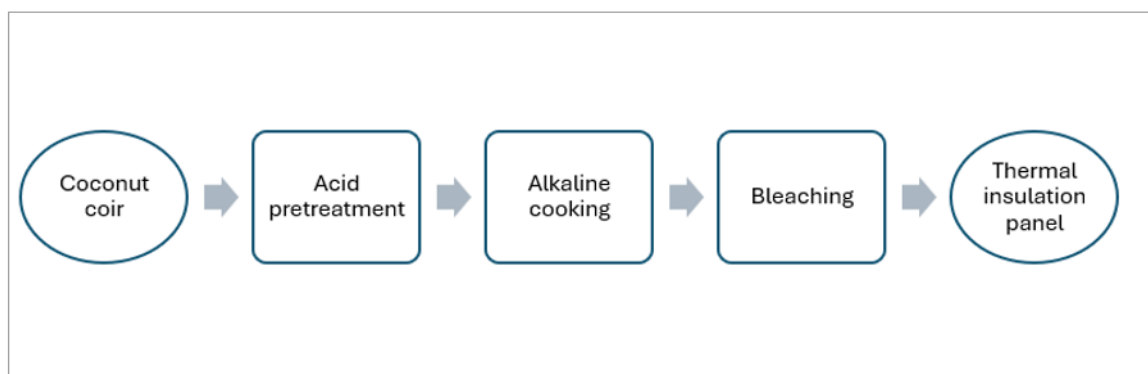


Fig. 1. Conceptual diagram of the process of transforming coconut fiber into thermal insulation panels

This study used a complete 3^3 factorial design to explore the effects of acid pretreatment concentration, alkaline cooking concentration, and bleaching chlorometric degree on gravimetric pulp yield and apparent thermal conductivity of coconut-coir-derived panels (Fig. 1). Regression equations and coefficient-magnitude rankings were used to describe the experimental trends, and a genetic algorithm was used to identify a candidate compromise within the tested factor bounds. The study does not establish cellulose purity, demonstrate superiority over raw coir, or validate an industrial insulation product.

EXPERIMENTAL

Materials

Plant material and reagents

Coconut husk fibers (Bourre de coco) were used as a raw lignocellulosic material. Prior to chemical treatment, the husks were mechanically ground using a rotary screw mill to produce a homogeneous fibrous mass with individualized fibers. The following reagents were used: orthophosphoric acid (H_3PO_4 , 85%) for acid pretreatment, caustic soda (NaOH , 99%) for alkaline cooking, and sodium hypochlorite solution (NaClO) at variable chlorometric degree for bleaching. Distilled water was used as the solvent throughout (Chandra *et al.* 2016).

Equipment

Mass measurements were performed on an electronic balance (Sartorius, 0.01 g precision, 3.1 kg capacity). Thermal treatments were conducted in a ventilated oven (Memmert), and reactions were maintained under stirring using a magnetic stirrer (RSLAB-1C). The pH was monitored with a Hanna HI 8424 pH meter, and temperature was measured with mercury and laser thermometers. Solid–liquid separation was performed on a Büchner filtration apparatus, and the fibrous material was sieved through a 500 µm mesh prior to treatment. Standard laboratory glassware (500 mL round-bottom flasks, 250 mL Erlenmeyer flasks) was used throughout. Insulation panels were formed using a 500 mL beaker, a mold, and a hydraulic press (1000 daN capacity).

Methods

Cellulose extraction procedure

A treated fibrous pulp was produced from coconut husk fibres through an acid pretreatment, soda cooking, and bleaching sequence (Cardoso and Gonçalves 2016).

Acid pretreatment

An acid pretreatment step, rather than an alkaline one, was selected upstream of alkaline cooking, since the hemicelluloses solubilized during acid hydrolysis retain potential value for downstream bioethanol production, whereas alkaline pretreatment degrades hemicelluloses into non-fermentable compounds (Zhang *et al.* 2024). A 15 g sample of ground fibrous material was combined with orthophosphoric acid (H₃PO₄) solution at concentrations ranging from 0.05 to 0.15 M, using a fibrous-material-to-solution ratio of 3% to 6% (w/v). The mixture was heated at 100 to 150 °C for 30 to 40 min under mild agitation (250 rpm). The pre-hydrolyzed mixture was then vacuum filtered on a Büchner funnel, and the recovered solid residue was carried forward to alkaline extraction.

Alkaline extraction

The acid-pretreated residue was dispersed in a 500 mL round-bottom flask containing an excess of NaOH solution, at a solid-to-liquid ratio of 10% to 5% (w/v) and NaOH concentrations ranging from 10 to 100 g/L. The mixture was heated under reflux at 110 to 170 °C for 1 to 3 h under agitation (500 rpm). Following cooking, the mixture was vacuum-filtered, and the residue was washed three times with hot water (60 to 100 °C) to remove water-soluble impurities. The washed residue was then subjected to bleaching.

Bleaching

The alkaline-cooked residue was immersed in a NaClO (sodium hypochlorite) solution at chlorometric degrees ranging from 1 to 5 degrees Chl, using a solid-to-liquid ratio of 10% to 15% (w/v), and left to react for 12 to 22 h at pH 9 to 11 (Martin-Sampedro *et al.* 2015). The bleached residue was vacuum-filtered, washed three times with cold water, pressed, and oven-dried at 60 degrees C for 3 h. No compositional analysis of cellulose, lignin, hemicellulose, ash, or moisture content was performed. Accordingly, the dried solid is designated treated fibrous pulp, not purified cellulose (Dollie 2019).

Pulp yield was calculated as 100 x (dry mass of treated fibrous pulp / initial dry mass of ground coconut coir),

$$Rdt = \frac{m_{ext}}{m_{raw}} \times 100 \quad (1)$$

where the numerator is the dry mass of treated fibrous pulp and the denominator is the initial dry mass of ground coconut coir. This gravimetric response does not quantify cellulose content or cellulose recovery.

Experimental design

A complete three-level, three-factor factorial design (3^3) was used to evaluate the effects of process parameters on extraction yield and thermal conductivity (Yates 1937; Vaillé and Goupy 2008; Mishra and Jalan 2021; Dhairiyasamy *et al.* 2025). The three independent factors and their coded levels are given below (Table 1).

Table 1. Factors and Level (Low, Medium, High)

Factor	Low	Medium	High
Acid concentration (M) : X_1	0.05	0.10	0.15
Alkaline (NaOH) concentration (g/L) : X_2	10	50	100
Bleaching chlorometric degree ($^{\circ}\text{Chl}$): X_3	1	3	5

- Acid concentration (X_1 , M): 0.05 (low) - 0.10 (medium) - 0.15 (high)
- Alkaline (NaOH) concentration (X_2 , g/L): 10 (low) - 50 (medium) - 100 (high)
- Bleaching chlorometric degree (X_3 , $^{\circ}\text{Chl}$): 1 (low) - 3 (medium) - 5 (high)

The two response variables were pulp yield (Y_1 , %) and apparent thermal conductivity (Y_2 , $\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$). The full factorial matrix comprised 27 treatment combinations. No yield measurements were available for replicated centre-point experiments; therefore, no pure-error estimate or hypothesis test based on centre-point replication was used for pulp yield (Table 2).

Table 2. Table of Experiments

Run	X_1 (M)	X_2 (g/L)	X_3 ($^{\circ}$)
1	0.05	10	1
2	0.10	10	1
3	0.15	10	1
4	0.05	50	1
5	0.10	50	1
6	0.15	50	1
7	0.05	100	1
8	0.10	100	1
9	0.15	100	1
10	0.05	10	3
11	0.10	10	3
12	0.15	10	3
13	0.05	50	3
14	0.10	50	3
15	0.15	50	3
16	0.05	100	3
17	0.10	100	3
18	0.15	100	3
19	0.05	10	5
20	0.10	10	5
21	0.15	10	5
22	0.05	50	5

Run	X_1 (M)	X_2 (g/L)	X_3 (°)
23	0.10	50	5
24	0.15	50	5
25	0.05	100	5
26	0.10	100	5
27	0.15	100	5

Statistical Modeling

For each response variable, a second-order polynomial model of the following general form was fitted:

$$Y = A_0 + A_1X_1 + A_2X_2 + A_3X_3 + A_{12}X_1X_2 + A_{13}X_1X_3 + A_{23}X_2X_3 + A_{123}X_1X_2X_3 + A_{11}X_1^2 + A_{22}X_2^2 + A_{33}X_3^2 \quad (2)$$

In Eq. 2, Y is the response (yield or thermal conductivity), X_1 , X_2 , and X_3 are the coded factors, and A_i are the regression coefficients. Coefficients were estimated by multiple linear regression using the Data Analysis add-in in Microsoft Excel.

Significance testing

Because the factorial treatment combinations were not replicated for pulp yield, coefficient ranking was not interpreted as formal statistical significance testing. Absolute coefficient magnitudes and the Pareto ranking were used only as exploratory indicators of relative influence within the fitted equations (Sampath 2013; Rheem *et al.* 2017; Fadjare Frempong *et al.* 2021; Onwuakor and Ngene 2026).

Model reduction

The reduced equations retained terms selected by the exploratory coefficient-magnitude ranking. They should be interpreted as descriptive approximations to the data, not as inferentially validated predictive models.

Model validation

Model fit was assessed by comparing fitted and observed responses at the same factorial design points. This is an in-sample descriptive comparison, not an independent validation. The reported coefficients of determination were 43.97% for pulp yield and 54.59% for apparent thermal conductivity; thus, substantial response variation remained unexplained (Mayer and Butler 1993; Saunders *et al.* 2012; Camirand Lemyre *et al.* 2022).

Multi-objective optimization

A genetic algorithm implemented in Scilab was used to search the fitted response equations within the coded factor bounds for a candidate compromise between higher pulp yield and lower apparent thermal conductivity. The procedure was exploratory because no independent confirmation experiment was performed at the candidate conditions. It therefore does not establish an experimentally verified optimum (Sivanandam and Deepa 2008; Correa *et al.* 2024).

Fabrication of thermal insulation material

The treated fibrous pulp was combined with water at a mass ratio of 3 g pulp to 2 g water and compacted with a hydraulic press to form circular panels. For the 29 fabricated panels, thickness and pressing force were recorded. Pressing conditions were not experimental design factors and their effects were not separately modelled. Apparent

thermal conductivity was estimated by a custom heated-plate procedure under room conditions maintained at 20 degrees C and 50% relative humidity. One face of a circular specimen was heated and the opposite-face temperature was measured with a laser thermometer after a 900 s test period. The heated circular contact diameter was 0.03775 m. Using a transferred energy Q of 200 J, specimen thickness e (m), temperature difference ΔT (K), test time $t = 900$ s, and contact area $A = \pi d^2/4$, the apparent thermal conductivity was calculated as $\lambda_{app} = Qe/(A \Delta T t)$. This non-standard procedure did not include a correction for heat losses or an equilibrium-moisture measurement; the resulting values are therefore reported as apparent thermal conductivity rather than standardized material thermal conductivity.

To contextualize this non-standard procedure, no recognized standard test method for building-insulation thermal conductivity (e.g., ASTM C518 or ISO 8301 guarded hot-plate/heat-flow-meter methods) was applied in this exploratory study; such methods require calibrated reference specimens and controlled steady-state heat flow that were outside the scope of the present low-cost screening approach. One specimen was tested per experimental run, with the exception of the centre-point condition, for which three panels (the design replicate and two additional panels) were tested under identical conditions (20 °C, 50% relative humidity) to provide a preliminary indication of measurement repeatability, yielding apparent thermal-conductivity values of 0.0730, 0.0439, and 0.0500 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ (Table 3). No reference material of known thermal conductivity was tested alongside the panels to independently verify instrument accuracy. Standardized thermal-conductivity testing following ASTM C518 or ISO 8301, with appropriate specimen conditioning and heat-loss correction, is identified as a priority for confirmation of the present exploratory results.

RESULTS AND DISCUSSION

Extraction Yield and Thermal Conductivity Across the Experimental Design

Across the 27 factorial treatment combinations, gravimetric pulp yield ranged from 20.1% to 74.5%, with the highest yield in run 12 and the lowest in run 13. Apparent thermal conductivity of the corresponding samples ranged from 0.0354 to 0.1708 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$; the lowest observed value was obtained in run 4. Two additional centre-point panels were available for apparent thermal-conductivity repeatability only. Together with run 14, they gave 0.0730, 0.0439, and 0.0500 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ (mean 0.0556; standard deviation 0.0153 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) (Fig. 2).

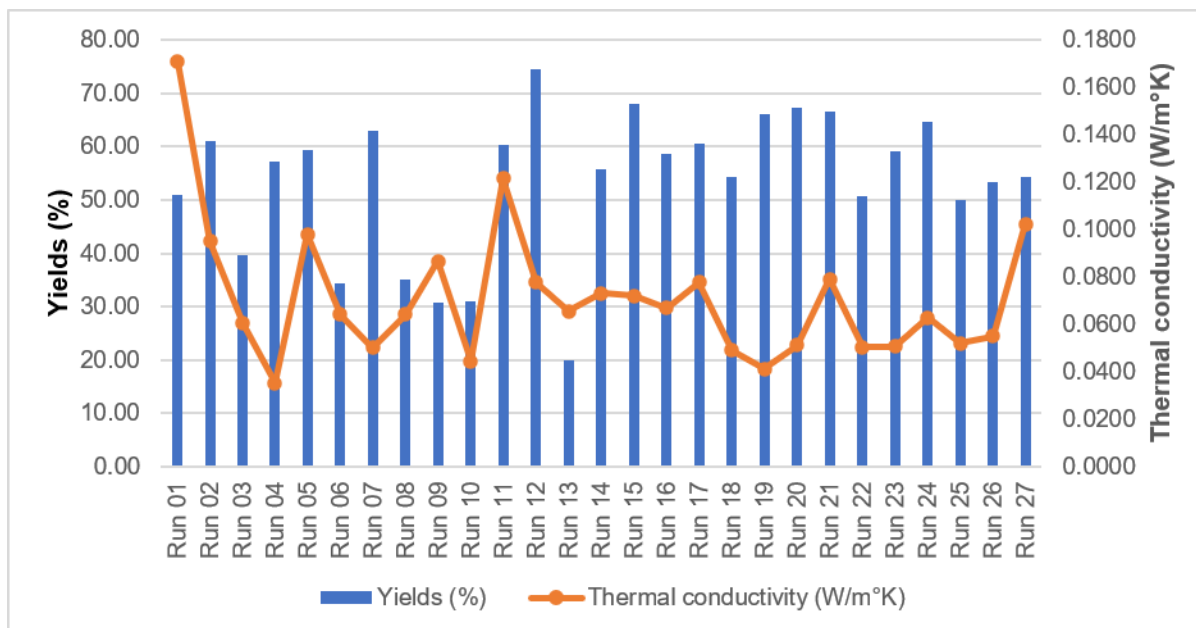


Fig. 2. Graphic representation of yields and thermal conductivity by run

Table 3. Gravimetric Pulp Yields and Apparent Thermal Conductivity Measurements

Run (i)	Pulp Yield (%)	Apparent Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$)
Run 1	50.93%	0.1708
Run 2	61.07%	0.0951
Run 3	39.53%	0.0605
Run 4	57.07%	0.0354
Run 5	59.40%	0.0981
Run 6	34.33%	0.0641
Run 7	63.00%	0.0502
Run 8	35.07%	0.0642
Run 9	30.67%	0.0866
Run 10	30.93%	0.0444
Run 11	60.27%	0.1214
Run 12	74.47%	0.0778
Run 13	20.07%	0.0656
Run 14	55.80%	0.0730
Run 15	67.87%	0.0721
Run 16	58.73%	0.0668
Run 17	60.53%	0.0777
Run 18	54.20%	0.0491
Run 19	66.13%	0.0413
Run 20	67.33%	0.0511
Run 21	66.60%	0.0791
Run 22	50.67%	0.0505
Run 23	59.00%	0.0507

Run (i)	Pulp Yield (%)	Apparent Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$)
Run 24	64.67%	0.0628
Run 25	50.00%	0.0520
Run 26	53.27%	0.0550
Run 27	54.20%	0.1022

Regression Coefficients and Factor Significance

Extraction yield

Multiple linear regression produced the following coefficients for the full second-order model: constant - 0.555; acid concentration (X_1) - 0.0217; alkaline concentration (X_2), -0.0320; chlorometric degree (X_3) - 0.0560; X_1X_2 , -0.0544; X_2X_3 , -0.0165; X_1X_3 - 0.0709; $X_1X_2X_3$ - 0.0308; X_1^2 , -0.0497; X_2^2 - 0.0218; X_3^2 , -0.00156.

The coefficient-magnitude ranking identified chlorometric degree and the acid concentration $\times$ chlorometric degree interaction among the largest terms in the fitted pulp-yield equation (Table 4). In the absence of replicated pulp-yield observations, these rankings are descriptive and are not reported as formal statistical significance tests.

The Pareto ranking of absolute coefficients is retained as an exploratory visualization of the fitted pulp-yield equation. It does not provide p-values or independent evidence of factor significance (Fig. 3).

Table 4. Factors and their Regression Coefficients

Factors	Coefficients
Constant	0.555
X_1	0.0217
X_2	-0.0320
X_3	0.0560
X_1X_2	-0.0544
X_2X_3	-0.0165
X_1X_3	0.0709
$X_1X_2X_3$	0.0308
X_1^2	-0.0497
X_2^2	0.0218
X_3^2	-0.00156

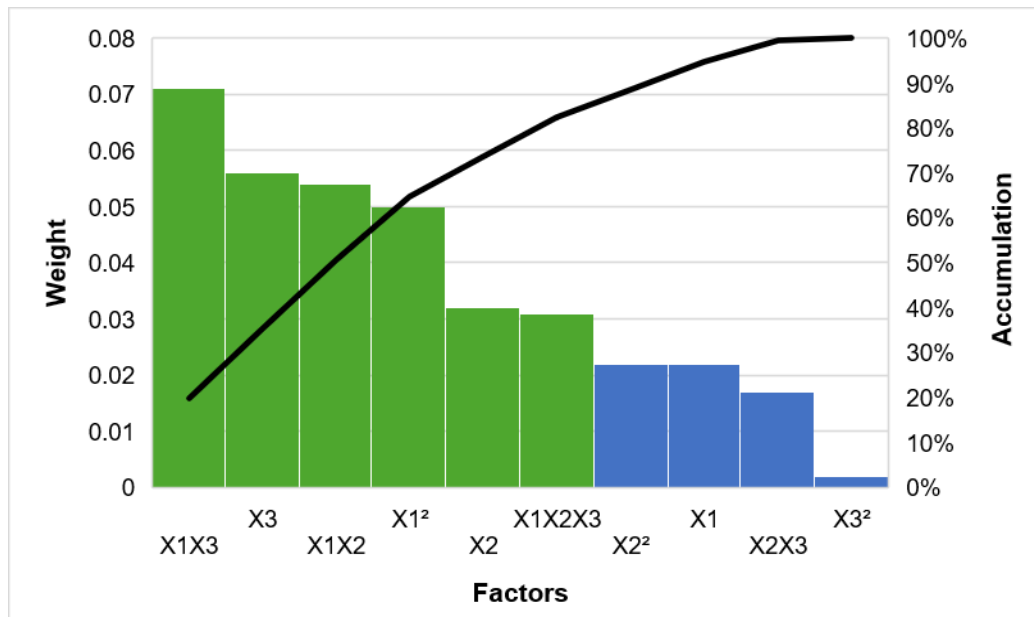


Fig. 3. Pareto chart of factors

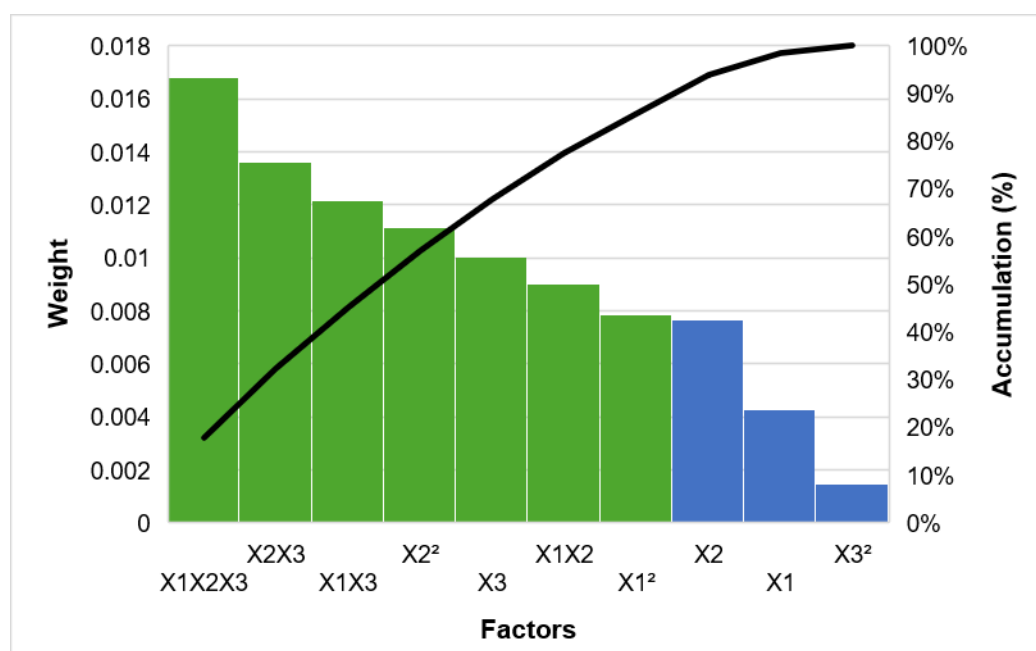
Thermal Conductivity

Regression on the thermal conductivity response produced the following coefficients: constant, 0.0698; X_1 , 0.00429; X_2 , -0.00765; X_3 , -0.0100; X_1X_2 , 0.00900; X_2X_3 , 0.0136; X_1X_3 , 0.0121; $X_1X_2X_3$, -0.0168; X_1^2 , -0.00785; X_2^2 , 0.0111; X_3^2 , -0.00146.

For apparent thermal conductivity, the coefficient-magnitude ranking identified higher-order and interaction terms among the largest fitted coefficients. Given the limited model fit and the observed centre-point variability, these findings are interpreted as exploratory patterns rather than definitive factor effects (Table 5; Fig. 4).

Table 5. Table of Factors and their Coefficients for Thermal Conductivity

Factors	Coefficients
Constant	0.0698
X_1	0.00429
X_2	-0.00765
X_3	-0.0100
X_1X_2	0.00900
X_2X_3	0.0136
X_1X_3	0.0121
$X_1X_2X_3$	-0.0168
X_1^2	-0.00785
X_2^2	0.0111
X_3^2	-0.00146

**Fig. 4.** Pareto chart of coefficients for thermal conductivity

Effect of Individual Process Steps on Extraction Yield

Pivot-table analysis of mean yield as a function of each processing step showed the following: (Figs. 5-8).

- Acid pretreatment (X_1): Mean yield increased from 49.7% (0.05 M) to 56.9% (0.10 M), followed by a decrease to 54.1% (0.15 M). The overall influence of this factor on yield was 12.6%.
- Alkaline cooking (X_2): Mean yield was 57.5% at 10 g/L, 52.1% at 50 g/L, and 51.1% at 100 g/L (overall mean, 53.6%). The overall influence of this factor on yield was 11.4%.
- Bleaching (X_3): Mean yield increased from 47.9% (1 °Chl) to 53.6% (3 °Chl) to 59.1% (5 °Chl) (overall mean, 53.6%). The overall influence of this factor on yield was 19.0%, the highest among the three process steps.

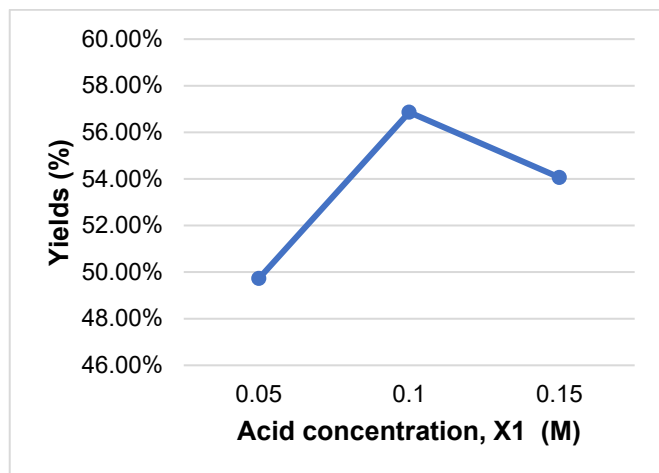


Fig. 5. Evolution of yield as a function of acid concentration

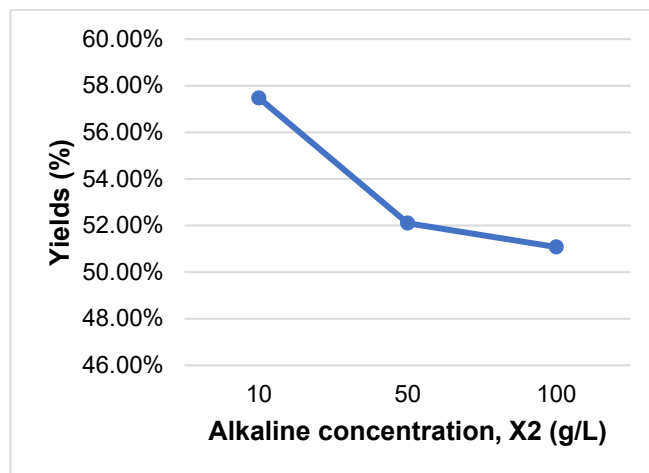


Fig. 6. Evolution of yield as a function of alkaline concentration

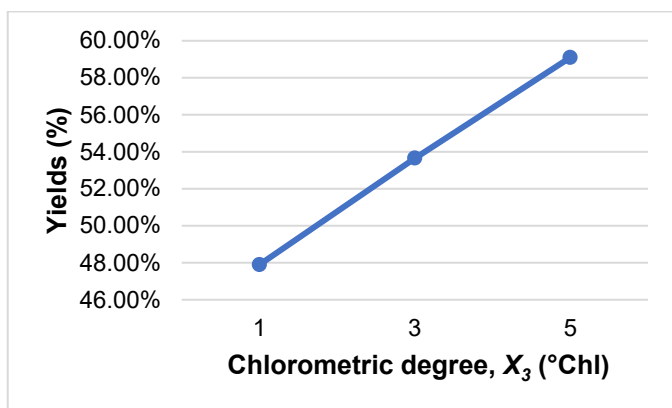


Fig. 7. Evolution of yield as a function of chlorometric degree

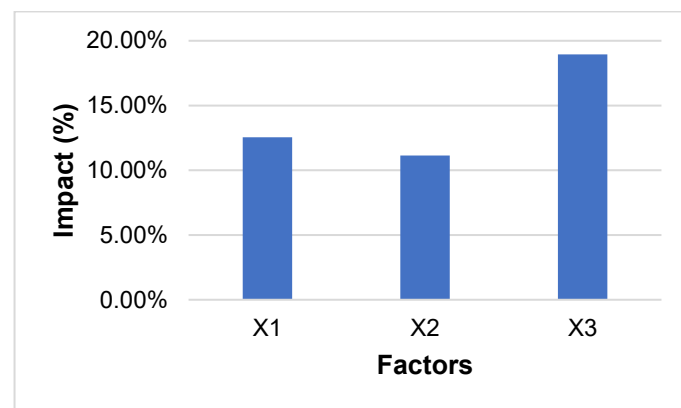


Fig. 8. Diagram comparing the impact of each factor on extraction yield

Reduced Model Equations

Based on the exploratory coefficient ranking, reduced polynomial equations were fitted for pulp yield and apparent thermal conductivity. The equations summarize the present data but are not independently validated predictive models (Tables 6 and 7).

$$Rdt = 0.555111 - 0.032000X_2 + 0.056000X_3 - 0.054389X_1X_2 + 0.070944X_1X_3 - 0.049667X_1 + 0.030533X_1X_2X_3 \quad (3)$$

$$Cd_{Therm} = 0.06919858 - 0.01679547X_1X_2X_3 + 0.01359255X_2X_3 + 0.01213538X_1X_3 + 0.01114733X_2^2 - 0.01000952X_3 + 0.00899806X_1X_2 \quad (4)$$

In these expressions, Rdt is the pulp extraction yield, Cd_{Therm} is the thermal conductivity of the insulation material ($W/m \cdot K$), X_1 is acid concentration, X_2 is alkaline concentration, and X_3 is bleaching chlorometric degree (coded values).

The following tables report descriptive regression summaries. The quantities previously labelled as formal validation or lack-of-fit statistics should not be interpreted as such because replicated response data were not available for pulp yield.

Table 6. Descriptive Regression Summary for Pulp Yield

Regression Statistics	
Multiple regression correlation coefficient	66.31%
Coefficient of determination, R^2	43.97%
Lack-of-fit test	Not estimated
Standard error	12.86%
Runs	27

Table 7. Descriptive Regression Summary for Apparent Thermal Conductivity

Regression Statistics	
Multiple regression correlation coefficient	73.89%
Coefficient of determination, R^2	54.59%
Lack-of-fit test	Not estimated
Standard error	2.45%
Runs	27



Fig. 9. Photographs of the samples of thermal insulation materials obtained

Genetic Algorithm Optimization

The genetic-algorithm search identified a candidate point at coded levels $X_1 = -0.966319$, $X_2 = -0.827685$, and $X_3 = 0.985896$. The fitted equations predicted a pulp yield of 92.4% and apparent thermal conductivity of $0.041 \text{ W} \cdot \text{m}^{-1} \text{K}^{-1}$ at this point. These are model-based exploratory predictions, not experimentally confirmed optimum values (Pavlović *et al.* 2023; Sevindik *et al.* 2024; Wang *et al.* 2025). Notably, the lowest observed apparent thermal conductivity in the factorial runs was $0.0354 \text{ W} \cdot \text{m}^{-1} \text{K}^{-1}$.

Thermal Insulation Panel Fabrication

Treated fibrous pulp obtained under the experimental conditions was processed into pressed circular panels. The present work demonstrates fabrication feasibility only; it does not establish product durability, moisture resistance, fire performance, mechanical performance, or suitability for a specific construction use (Fig. 9).

Overall process performance

The candidate point identified by the genetic algorithm was located near the lower acid and alkali bounds and the upper bleaching bound. The predicted 92.4% pulp yield was higher than the observed range and was not confirmed experimentally. It should therefore not be compared as a demonstrated improvement over conventional pulping yields or industrial benchmarks.

Mechanistic interpretation of factor effects

The observed mean pulp-yield trend with acid concentration increased from 49.7% at 0.05 M to 56.9% at 0.10 M and then decreased to 54.1% at 0.15 M. This pattern is consistent with the possibility that moderate acid pretreatment changes hemicellulose accessibility; however, because composition was not measured, the data cannot quantify hemicellulose removal or cellulose preservation (Zhang *et al.* 2024).

The observed mean pulp yield decreased as NaOH concentration increased across the tested levels. This pattern is compatible with more severe alkaline treatment causing greater mass loss, including possible carbohydrate degradation, but compositional measurements would be needed to determine which constituents were removed (Testova *et al.* 2014; Li *et al.* 2017).

The mean gravimetric pulp yield increased with chlorometric degree in the tested dataset. Since no lignin, brightness, colour, or cellulose-composition measurements were performed, this observation cannot establish bleaching efficiency, pulp purity, or an appearance-related benefit. Here, chlorometric degree is treated only as a bleaching-intensity variable.

Interaction effects and model structure

The fitted equations contain interaction terms, suggesting that the experimental responses may depend on combinations of pretreatment, cooking, and bleaching conditions. Because the models explain only part of the response variability and were not independently validated, these interaction patterns should be regarded as hypotheses for confirmation experiments rather than definitive mechanisms.

Comparison with the optimization objectives

The candidate point lies near the boundaries of the tested factor domain. This position, together with the lack of an independent confirmation run, limits confidence in the predicted response values. Future work should experimentally test the candidate point and, if warranted, extend the design space using replicated observations.

Limitations

Several limitations constrain the interpretation of these findings. First, gravimetric pulp yield does not establish cellulose content, purity, or cellulose recovery because no compositional analysis was performed. Second, no independent confirmation experiment was conducted at the genetic-algorithm candidate point. Third, the fitted equations had

modest in-sample R^2 values and cannot be regarded as validated predictive models. Fourth, apparent thermal conductivity was estimated by a custom heated-plate method at 20 degrees C and 50% relative humidity without heat-loss correction, specimen equilibrium-moisture measurement, or standardized conditioning. Fifth, no direct raw-coir-panel comparison, mechanical testing, dimensional-stability testing, biological-durability testing, or fire testing was performed. Finally, pressing conditions were recorded but not controlled as experimental factors.

These limitations mean that the reported candidate conditions and thermal results should guide future confirmation experiments rather than be interpreted as a verified process optimum or a construction-ready product claim.

CONCLUSIONS

1. Coconut coir was processed through an acid pretreatment-soda cooking-bleaching sequence and formed into exploratory bio-based insulation panels. A complete 3^3 factorial design related gravimetric pulp yield and apparent thermal conductivity to acid concentration, NaOH concentration, and bleaching chlorometric degree.
2. Second-order regression equations and coefficient-magnitude rankings were used to describe the observed factorial data. Their modest in-sample fit and the absence of independent confirmation mean that they should not be interpreted as validated predictive models.
3. The genetic algorithm identified a boundary-adjacent candidate with model-predicted values of 92.38% pulp yield and $0.041 \text{ W} \cdot \text{m}^{-1} \text{K}^{-1}$ apparent thermal conductivity. These values were not experimentally confirmed and do not demonstrate cellulose recovery, a validated optimum, or superiority to raw coconut coir or conventional industrial pulping.
4. The work demonstrates the feasibility of preparing treated-pulp panels from coconut coir and identifies conditions for future confirmation studies. Compositional analysis, replicated yield measurements, standardized thermal testing under defined moisture conditions, raw-coir comparison, and durability, fire, and mechanical evaluations are required before practical insulation claims can be made.

REFERENCES CITED

- Brännvall, E. (2017). "The limits of delignification in kraft cooking," *BioResources* 12(1), 2081-2107. <https://doi.org/10.15376/biores.12.1.Brannvall>
- Camirand Lemyre, F., Chalifoux, K., Desharnais, B., and Mireault, P. (2022). "Squaring things up with R^2 : What it is and what it can (and cannot) tell you," *Journal of Analytical Toxicology* 46(4), 443-448. <https://doi.org/10.1093/jat/bkab036>
- Cardoso, M. S., and Gonzalez, J. C. (2016). "Aproveitamento da casca do coco-verde (*Cocos nucifera* L.) para produção de polpa celulósica (Utilization of green coconut (*Cocos nucifera* L.) husk for the production of cellulosic pulp)," *Ciência Florestal* 26(1), article 1980509821126. <https://doi.org/10.5902/1980509821126>

- Chandra, J. C. S., George, N., and Narayanankutty, S. K. (2016). "Isolation and characterization of cellulose nanofibrils from arecanut husk fibre," *Carbohydrate Polymers* 142, 158-166. <https://doi.org/10.1016/j.carbpol.2016.01.015>
- Correa, I. B., de Souza, M. B., and Secchi, A. R. (2024). "Data-driven modeling and multi-objective optimization of a continuous kraft pulping digester," *Chem. Eng. Res. Des.* 207, 505-517. <https://doi.org/10.1016/j.cherd.2024.06.026>
- Dhairiyasamy, R., Gabiriel, D., Varshney, D., and Singh, S. (2025). "Optimizing nanomaterial dosages in concrete for structural applications using experimental design techniques," *Scientific Reports* 15(1), article 22375. <https://doi.org/10.1038/s41598-025-05265-w>
- Dollie, L. (2019). *Concepts et Développements pour la Production de Cellulose Blanchie, Pure ou Oxydée à Partir de Matière Lignocellulosique à Recycler*, Ph.D. Dissertation, Université Grenoble Alpes, Grenoble, France.
- Fadjare Frempong, T., Owusu Boadi, N., and Badu, M. (2021). "Optimization of extraction conditions for polyphenols from the stem bark of *Funtumia elastica* (Funtum) utilizing response surface methodology," *AAS Open Research* 4, 46. <https://doi.org/10.12688/aasopenres.13284.2>
- Li, Q., Wang, A., Ding, W., and Zhang, Y. (2017). "Influencing factors for alkaline degradation of cellulose," *BioResources* 12(1), 1263-1272. <https://doi.org/10.15376/biores.12.1.1263-1272>
- Martin-Sampedro, R., Miranda, J., García-Fuentevilla, L. L., Hernández, M., Arias, M. E., Diaz, M. J., and Eugenio, M. E. (2015). "Influence of process variables on the properties of laccase biobleached pulps," *Bioprocess Biosyst. Eng.* 38, 113-123. <https://doi.org/10.1007/s00449-014-1249-7>
- Mayer, D. G., and Butler, D. G. (1993). "Statistical validation," *Ecological Modelling, Theoretical Modelling Aspects* 68(1), 21-32. [https://doi.org/10.1016/0304-3800\(93\)90105-2](https://doi.org/10.1016/0304-3800(93)90105-2)
- Mishra, H.P., and Jalan, A. (2021). "Analysis of faults in rotor-bearing system using three-level full factorial design and response surface methodology," *Noise Vib. Worldw.* 52, 365-376. <https://doi.org/10.1177/09574565211030711>
- Onwuakor, C. E., and Ngene, A. C. (2026). "Frontiers | Statistical optimization of glucose, sodium citrate and potassium chloride supplementation for enhanced bacteriocin production by *Lactococcus lactis* MT186647 and *Lactobacillus fermentum* MT186598 isolated from fermenting *Pentaclethra macrophylla* benth," *Front. Antibiotics* 5, article 1907088. <https://doi.org/10.3389/frabi.2026.1907088>
- Panyakaew, S., and Fotios, S. (2011). "New thermal insulation boards made from coconut husk and bagasse," *Energy Build.* 43, 1732-1739. <https://doi.org/10.1016/j.enbuild.2011.03.015>
- Pavlović, M., Lubura, J., Pezo, L., Pezo, M., Bera, O., and Kojić, P. (2023). "A novel hybrid approach for modeling and optimisation of phosphoric acid production through the integration of AspenTech, scilab unit operation, artificial neural networks and genetic algorithm," *Processes* 11(6), article 1753. <https://doi.org/10.3390/pr11061753>
- Raza, M., Farhan, A., and Abu-Jdayil, B. (2024). "Lignocellulose-based insulation materials: A review of sustainable and biodegradable solutions for energy efficiency," *Int. J. Thermofluids* 24, article 100844. <https://doi.org/10.1016/j.ijft.2024.100844>

- Rheem, S., Rheem, I., and Oh, S. (2017). "Response surface methodology using a fullest balanced model: A re-analysis of a dataset," *Korean J. Food Sci. Anim. Resour.* 37(1), 139-146. <https://doi.org/10.5851/kosfa.2017.37.1.139>
- Sampath, M. (2013). "Optimization of the extraction process of phenolic antioxidant from *Polyalthia longifolia* (Sonn.) thawaites," *Journal of Applied Pharmaceutical Science*. <https://doi.org/10.7324/japs.2013.30226>.
- Saunders, L. J., Russell, R. A., and Crabb, D. P. (2012). "The coefficient of determination: What determines a useful R^2 statistic?," *Investigative Ophthalmology & Visual Science* 53(11), 6830-6832. <https://doi.org/10.1167/iovs.12-10598>
- Sevindik, M., Gürgen, A., Krupodorova, T., Uysal, İ., and Koçer, O. (2024). "A hybrid artificial neural network and multi-objective genetic algorithm approach to optimize extraction conditions of *Mentha longifolia* and biological activities," *Sci. Rep.* 14, article 31403. <https://doi.org/10.1038/s41598-024-83029-8>
- Sivanandam, S. N., and Deepa, S.N. (2008). "Genetic algorithm optimization problems," in: *Introduction to Genetic Algorithms*, Springer, Berlin, Germany, pp. 165-209. https://doi.org/10.1007/978-3-540-73190-0_7
- Testova, L., Nieminen, K., Penttilä, P.A., Serimaa, R., Potthast, A., and Sixta, H. (2014). "Cellulose degradation in alkaline media upon acidic pretreatment and stabilisation," *Carbohydr. Polym.* 100, 185-194. <https://doi.org/10.1016/j.carbpol.2013.01.093>
- Vaillé, J., and Goupy, J. (2008). "Construire et interpréter un Plan d'expériences factoriel complet," <https://www-rocq.inria.fr/axis/modulad/archives/numero-35/Excelense-goupy-vaille-35/Plancomplet-35.pdf>.
- Wang, H., Haidn, O., Abbasi, M., Nugymanova, A., Shvab, J., and Slavinskaya, N. (2025). "Development of a genetic algorithm tool for the optimization of the methanol oxidation," *Chem. Eng. Technol.* 48, article e202400199. <https://doi.org/10.1002/ceat.202400199>
- Yates, F. (1937). *The Design and Analysis of Factorial Experiments*, Imperial Bureau of Soil Science, Harpenden, UK.
- Zhang, L., Shao, G., Jin, Y., Yang, N., and Xu, X. (2024). "Efficient hemicellulose removal from lignocellulose by induced electric field-aided dilute acid pretreatment," *Int. J. Biol. Macromol.* 261, article 129839. <https://doi.org/10.1016/j.ijbiomac.2024.129839>

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