

Cooking temperature and time optimization in kraft pulping for apus bamboo (*Gigantochloa apus* Kurz)

Abstract

Research on pulp production using apus bamboo (*Gigantochloa apus* Kurz) stem through the kraft process is conducted to address the availability of raw materials for the pulp and paper industry in Indonesia. The purpose of this study is to determine the effect of temperature and cooking time on the properties of apus bamboo pulp and to develop mathematical models and optimize the process based on the applied factors. Process optimization was conducted using response surface methodology through central composite design analysis. The kraft pulping process was performed in a micro-digester with a stem powder-to-cooking solution ratio of 1:4, utilizing 10 g of stem powder, an active alkali concentration of 17%, and a sulfidity level of 25%. The optimized variables were cooking temperature (155, 165, and 175 °C) and cooking time (60, 120, and 180 min). The increase in temperature and cooking time resulted in optimal values for yield, kappa number, hexeneuronic acid content of the pulp, as well as total solids value of the black liquor. Process optimization was achieved at a cooking temperature of 165.71 °C and a cooking time of 143.14 min due to the minimum level of kappa number or lignin dissolved. The calculated optimization conditions resulted a pulp yield of 60.22%, a kappa number of 22.96, a viscosity of 16.05 cP, a hexeneuronic acid content of 21.50 µmol/g, a brightness of 17.07%, a total solids concentration of 16.19 g/L, and a pH value of 11.85.

Keywords: non-wood pulp, sulfate process, black liquor, regression analysis, long fiber

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Introduction

The declining availability of wood over the years has raised concerns regarding the pulp and paper manufacturing process due to the decreasing supply of raw materials. Consequently, alternatives to wood have become necessary. Numerous non-wood alternative raw materials are available in large quantities, such as bamboo. Bamboo has long fibers and the advantage of being ready for harvest in 3-4 years, compared to 8-20 years for fast-growing trees. Additionally, bamboo provides a 10-30% increase in biomass per day, significantly higher than wood, which only yields 2.5%.¹

In addition to its fiber being suitable for pulp, bamboo is relatively inexpensive compared to other forest products.² Bamboo has a cellulose content of 40-50%, comparable to the cellulose content of softwoods (40-52%) and hardwoods (38-56%).³ One potential species is the apus bamboo (*Gigantochloa apus* Kurz). The community use of apus bamboo is not limited to ornamental purposes; it also provides significant economic and social benefits. Apus bamboo has a fiber length of 2.35 mm and vascular bundle frequency of 10.5 per mm².⁴ Previous research on apus bamboo pulp, utilizing the soda cooking process at a maximum temperature of 170°C for 3 hours, resulted in an average yield of 32.05% and a kappa number ranging from 22 to 49.⁵ Pulping apus bamboo using the kraft method for pulp as the base material for soundproofing composites at a temperature of 165°C for 2 hours resulted in a lower kappa number (18-41) compared to temen and haur bamboo, as well as a lower yield (48-55%) compared to temen bamboo.¹

Previously, optimizing the isothermal alkaline impregnation of poplar wood chips was conducted.⁶ This study evaluated the parameters of pulp and black liquor properties through Response Surface Methodology (RSM) analysis. The research design incorporated multiple factors and aimed to identify the optimal response through experimentation. Central Composite Design (CCD) has been used

in previous studies using *Yushania alpina* bamboo stem through an ethanol-alkali pulping with factors such as temperature, cooking time, ethanol concentration, and alkali concentration.⁷ This study aimed to determine the optimization of the kraft pulping process of apus bamboo stem to obtain a mathematical model and identify the critical points of the process based on temperature and cooking time factors. In accordance with previous studies, the cooking temperatures applied were 155, 165, and 175 °C, with durations of 60, 120, and 180 min, to enhance efficiency and minimize cellulose degradation.

Material and methods

Sample preparation

An apus bamboo stem (Figure 1) was harvested after seven years of growth, with a diameter ranging from 5.6 to 7.1 cm, in Giwangan, Yogyakarta. The collected bamboo culms were chipped and air-dried. For chemical analysis, the air-dried bamboo culms were ground and screened to pass through a number 40 mesh sieve while being retained on a number 60 mesh sieve. The 20-40 mesh fractions were retained for pulping.



Figure 1 Apus bamboo stem (left) and bamboo sawdust (right).

Chemical composition

The ethanol-toluene extractive content and hot-water solubility were determined according to the ASTM D1107-96 (2002) and ASTM D-1110-1984 standard methods, respectively. The holocellulose content was assessed by treating the extractive-free wood meal with a NaClO₂ solution.⁸ The α -cellulose content was measured by treating the holocellulose sample with 17.5% NaOH.⁹ Klason lignin was quantified by hydrolyzing carbohydrates with 72% sulfuric acid (SNI 0492:2008).

Pulp production

Wood sawdust was mixed in the desired proportions and reacted in a 125 mL stainless steel micro-digester, using 10 g of material (on an oven-dry basis) in an oil bath for each pulping trial. The pulping was conducted at different temperatures (155, 165, and 175 °C) and cooking times (60, 120, and 180 min). In all experiments, the solid-to-liquid ratio of 1:4, along with an active alkali concentration of 17% and a sulfidity level of 25%, was maintained constant. Upon completion of the pulping process, the autoclave was removed from the oil bath and cooled rapidly in cold water. The solid residue was washed and defibrated until a neutral pH was achieved. The black liquor was separated from the pulp and collected. The pulp yield was determined gravimetrically after drying to a constant weight in an oven at 105 °C. All pulping experiments were replicated (in duplicate).

Pulp and black liquor characterization

The kappa number, viscosity, and brightness of the pulp were determined according to SNI ISO 302:2014, TAPPI T230 om-08, and SNI ISO 2470-1:2014, respectively. The hexeneuronic acid content was measured using the spectrophotometric method.¹⁰ The characterization of black liquor involved determining the pH value and total solids, following SNI 06-1839-1990.

Experimental design for pulping process

In order to relate the dependent and independent variables (temperature and time) in the pulping process with the minimum possible number of experiment, a 2ⁿ central composite factor experimental design was used, making it possible to construct a second-order polynomial as well as to determine the main effects (linear, interaction, and quadratic) of the independent process variables and also formulate model equations for each response. The two process variables studied were cooking temperature (X1) and time (X2). Independent variables were normalized by using the following equation

$$X_n = \frac{X - \bar{X}}{(X_{\max} - X_{\min})/2}$$

Where X is the absolute value of the independent variable, $\bar{X}$ is the average value of the variable, and $X_{\max}$ and $X_{\min}$ are its maximum and minimum values, respectively. The analysis of variance (ANOVA) was used to identify significant effects and to check the statistical

significance of the model by the values less than 0.05. The coefficient of determination R² and lack of fit from ANOVA were used in the determination of the quality of the developed model. The developed equations were tested for adequacy and fitness by the analysis of variance. To address the non-normality in the error term for some of the responses, transformation (a mathematical conversion of response values) was required.

The values of responses enable the computation of mathematical estimation models for each response, which are then utilised to determine the ideal set of operating conditions for the independent variables and to describe the response surface's characteristics. The model coefficients were obtained using Minitab statistical version 16.4 software.

Results and discussion

Chemical components

The chemical properties of apus bamboo stem are presented in Table 1 to assess its applicability for pulp and paper production. The values for ethanol-toluene soluble and hot-water soluble extractives in this study were lower, while the holocellulose, α -cellulose, and lignin contents fell within the range reported in previous studies.^{11,12} Low extractive levels positively influence pulp yield, inter-fiber strength, and brightness. High holocellulose and α -cellulose contents indicate that the fibers will possess good strength, yield a high pulp output, and produce a brighter pulp color.¹³

Table 1 Chemical composition of apus bamboo

Chemical properties	Content (%)
Ethanol-toluene extraction	2.33 (0.20)
Hot water solubility	3.09 (0.28)
Holocellulose	69.52 (0.66)
α -cellulose	52.08 (1.06)
Lignin	24.54 (0.56)

Regression analysis

Table 2 presents the run order, the influence of two independent variables, and the observed responses for the 13 experimental runs generated. The implementation of the optimization results yielded the equations shown in Table 3. The model adequacy test (lack of fit) indicated that the model was consistent with the data, suggesting that the developed model accurately represents the data. The ANOVA of the regression model was found to be highly significant. The high R² value (>0.8) indicates that the model fitted very well with the experimental values, and the models are suitable to correlate with the experiment data. For the viscosity response, transformation (mathematical conversion of response values) was required because the non-transformed model's lack of fit (LOF) is significant (value of "prob. >F" less than 0.05), whereas an insignificant LOF is actually preferred. Therefore, the natural log model was chosen based on the statistical studies that were presented.

Table 2 A two-variable central composite design and the corresponding response for bamboo apus pulping

Run number	Real factor level		Coded factor level		Response						
	Temperature (°C)	Time (minutes)	X _A	X _B	Yield (%)	Kappa number	Viscosity (cP)	Hexeneuronic acid content(μmol/g)	Brightness (%)	Total solid (g/L)	pH value
1	155	60	-1	-1	57.20	32.13	26.98	25.86	18.67	14.64	13.38
2	155	180	-1	1	60.40	25.72	18.99	22.87	17.95	15.35	12.41
3	175	60	1	-1	63.64	22.53	21.73	11.40	18.54	16.87	13.09
4	175	180	1	1	67.17	26.68	9.25	22.97	12.29	17.00	11.43
5	150.858	120	$-\sqrt{2}$	0	63.52	32.13	40.03	22.60	18.9	15.29	12.76
6	179.142	120	$\sqrt{2}$	0	62.10	25.72	11.14	22.44	12.2	16.13	10.88
7	165	35.147	0	$-\sqrt{2}$	50.24	26.51	23.21	19.17	18.12	14.94	12.85
8	165	204.85	0	$\sqrt{2}$	69.44	25.89	17.16	10.87	14.01	17.78	11.46
9	165	120	0	0	59.16	22.56	15.36	22.42	18.61	16.29	12.46
10	165	120	0	0	59.33	21.45	18.96	21.35	17.86	16.05	11.59
11	165	120	0	0	59.68	24.65	18.45	22.91	16.89	15.42	11.67
12	165	120	0	0	57.04	23.3	16.93	24.23	17.63	15.53	11.97
13	165	120	0	0	53.99	24.24	16.9	22.59	18	15.40	11.73

Remark: *Bold letter indicates the maximum/minimum value

Based on the ANOVA results, the interaction terms, specifically the interaction between temperature and time, exhibited a substantial influence on the kappa number ($p=0.01$) and brightness ($p=0.01$). Furthermore, a strong linear dependence on the cooking temperature factor was observed for viscosity ($p<0.01$) and brightness ($p<0.01$), while the time factor significantly affected yield ($p<0.01$), viscosity ($p=0.01$), hexeneuronic acid content ($p<0.01$), and brightness ($p<0.01$). Conversely, the quadratic term for temperature had a slight effect on yield ($p=0.04$), kappa number ($p<0.01$), and brightness

($p=0.02$). A significant effect of the quadratic model for the time factor was observed in hexeneuronic acid content ($p<0.01$). The equations in Table 3 include quadratic terms and other elements involving interactions between the two independent variables, making it challenging to determine which independent variables exert the strongest and weakest effects on the dependent variables. The influential linear terms of the variables in the process were the most important in the development of most responses.

Table 3 Equation obtained for each dependent variable of pulping process

Response	Model	Lack-of-fit	R ²
Yield (%)	$775 - 8.80 X_A - 0.018 X_B + 0.0268 X_A^2 + 0.000332 X_B^2 + 0.00014 X_A X_B$	0.24	0.82
Kappa number	$861 - 9.39 X_A - 0.831 X_B + 0.02643 X_A^2 + 0.000356 X_B^2 + 0.00440 X_A X_B$	0.16	0.83
Ln (viscosity) (cP)	$23.5 - 0.232 X_A + 0.0292 X_B + 0.000664 X_A^2 + 0.000011 X_B^2 - 0.000210 X_A X_B$	0.06	0.91
Hexeneuronic acid content (μmol/g)	$231 - 1.98 X_A - 0.833 X_B + 0.00411 X_A^2 - 0.000927 X_B^2 + 0.00607 X_A X_B$	0.06	0.91
Brightness (%)	$-227.6 + 2.91 X_A + 0.396 X_B - 0.00860 X_A^2 - 0.000167 X_B^2 - 0.002304 X_A X_B$	0.19	0.93
Total solids (g/L)	$-2285 + 154 X_A + 36.8 X_B - 0.30 X_A^2 + 0.0815 X_B^2 - 0.242 X_A X_B$	0.98	0.92
pH value	$50.5 - 0.413 X_A + 0.0218 X_B + 0.00116 X_A^2 + 0.000079 X_B^2 - 0.000287 X_A X_B$	0.25	0.81

Remarks: R²: coefficient of determination; X₁: cooking temperature; X₂: cooking time

With regard to black liquor, the results confirmed the adequacy of the fitted models, as indicated by the R² value and the lack of fit (LOF) assessment (Table 3). The significance and adequacy of the model were further justified through ANOVA for total solids and pH value. The analysis revealed that the linear term for cooking time ($p=0.03$) and the quadratic term for temperature ($p<0.01$) significantly influenced the pH value. In the case of total solids, both the linear ($p<0.01$) and quadratic ($p=0.04$) terms for cooking time were significant model components.

Yield

The pulp yield obtained from the apus bamboo pulping process ranged from 50.24% to 69.44%. These values were higher than those

reported in studies of apus bamboo pulp using the soda process⁴ and the kraft process.¹ This discrepancy in values may be attributed to the pulping method, the use of a micro-digester, and the application of stem powder instead of stem chips.

The maximum yield of 69.44% was achieved at a cooking temperature of 165 °C (X_A=0) and a cooking time of 204.85 min (X_B=1.41). As both cooking time and temperature increased, the yield also increased (Figure 2). Specifically, an increase in yield was noted at 175 °C, while the highest yield was recorded at a cooking time of 180 min. The yield increased from 60 to 180 min, with level -1 (60 min) yielding between 57% and 63%, level 0 (120 min) producing a yield of 50% to 69%, and level 1 (180 min) resulting in a yield of 60% to 67%.

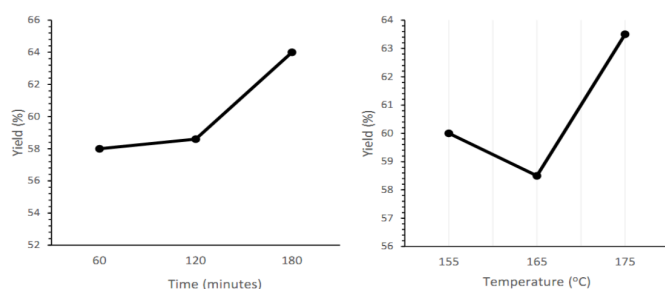


Figure 2 Effect of cooking time and temperature on pulp yield.

Cooking at high temperatures accelerates the delignification reaction, carbohydrate hydrolysis, and inhibits lignin condensation. At elevated cooking temperatures, polysaccharide degradation and lignin dissolution occur more intensively due to the increased reaction rate.¹⁴ Previously, a maximum yield of 55.76% was achieved at a cooking temperature of 160 °C and a cooking time of 180 min, while the lowest yield was recorded at a cooking temperature of 200 °C for *Yushania alpina* bamboo pulp.⁷ It should be noted that wood powder was used instead of chips for pulping in this study. Therefore, A scanning electron micrograph of the pulp obtained analysis was required to show the integrity of the fibers after the process.

Kappa number

A low kappa number indicates a relatively high level of pulp delignification. The kappa numbers obtained in this study ranged from 21.45 to 32.13. The high pulp yield observed in this experiment may be attributed to the lower lignin degradation, as indicated by the relatively high kappa number. For bleachable grades of pulp, a lignin content of 1.8% to 2.4% is necessary for hardwoods.¹⁵ In addition to time and temperature, increasing the active alkali concentration can help achieve a lower kappa number target. A high kappa number results in reduced brightness, yield, handsheet strength, and increased pulp beating energy.^{16,17} The kappa numbers obtained in this study were within the range reported in previous research on apus bamboo.¹⁵ For comparison, the kappa number for *Yushania alpina* bamboo was reported to be between 11.3 and 17.3 at a cooking temperature of 162.30 °C and a cooking time of 180 min using the soda process.⁷

The lowest kappa number obtained in this study was 21.45 at a cooking temperature of 165 °C (XA=0) and a cooking time of 120 min (XB=0). The significant interaction between these two factors demonstrates that the kappa number has an optimum value, as illustrated by the solid formed contour converging at a single point (Figure 3). Delignification occurs within a temperature range of 150 to 170 °C.¹⁸ At level -1 (155 °C), the kappa number ranged from 25.72 to 32.13, while at level 0 (165 °C), it ranged from 21.45 to 26.51, and at level 1 (175 °C), it ranged from 22.53 to 26.68. Each increase in temperature results in a lower kappa number, whereas the decrease in kappa number at lower temperatures is minimal. For the single factor of cooking time, at level -1 (60 min), the kappa number ranged from 22.53 to 32.13; at level 0 (120 min), it ranged from 21.45 to 32.13; and at level 1 (180 min), it ranged from 25.72 to 26.68. Each increase in cooking time also leads to a lower kappa number. Therefore, the optimal results for the kappa number were achieved at high operating temperatures and intermediate cooking times.

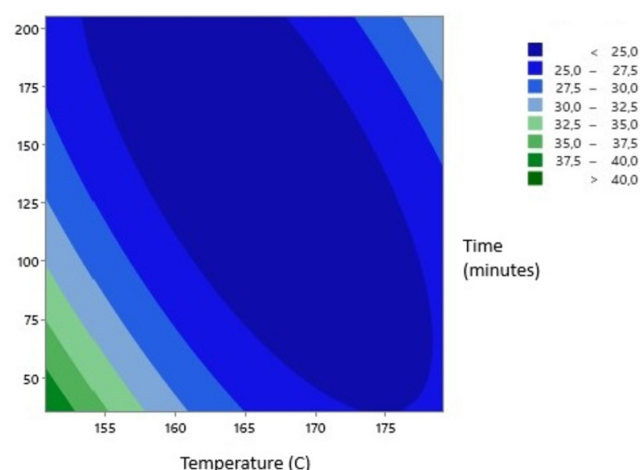


Figure 3 2D response surface plots of kappa as a function of cooking time and temperature

Viscosity

A higher viscosity value indicates a greater average degree of cellulose polymerization, which reflects the strength of the pulp and paper.¹⁹ This value is measured from the viscosity of a liquid or fluid to determine the speed of its flow. The results of the pulp viscosity tests conducted on apus bamboo during the pulping process ranged from 9.25 to 40.03 cP across all experiments. The resulting viscosity is higher than that of apus bamboo pulp produced using the soda process,²⁰ as well as that of *Acacia mangium* and *Eucalyptus pellita*,²¹ but remains within the range of *Acacia aulacocarpa* pulp values.²²

The highest pulp viscosity value recorded was 40.03 cP at a cooking temperature of 150.85 °C (XA = -1.41) and a cooking time of 120 min (XB = 0). Both temperature and time factors significantly contributed to the linear model, as indicated by the ANOVA results. The longer the cooking time, the lower the resulting pulp viscosity (Figure 4). At level -1 (60 min), the viscosity values obtained ranged from 18.99 to 26.98 cP; at level 0 (120 min), the values ranged from 15.36 to 23.21 cP; and at level 1 (180 min), they ranged from 9.25 to 21.73 cP. In addition, as the temperature increased, the pulp viscosity value decreased. At a temperature of 155 °C, the viscosity fell below 15 cP. Each increase in temperature resulted in a corresponding decrease in pulp viscosity.

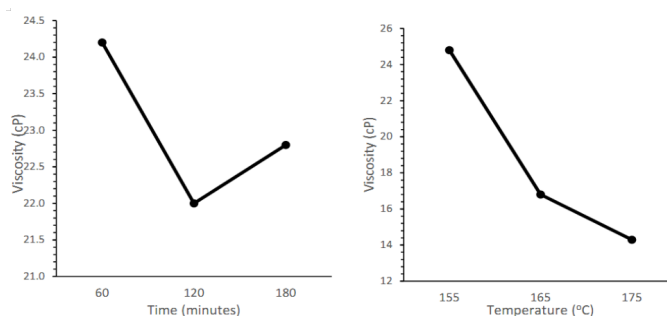


Figure 4 Effect of cooking time and temperature on pulp viscosity

Pulp with high viscosity tends to exhibit better mechanical properties.²³ The decrease in viscosity with longer cooking times is attributed to the cleavage of cellulose chains, which results in lower pulp yield and strength. Previous research indicated that high cooking temperatures corresponded to low viscosity values, with cooking temperatures of 145 °C yielding pulp viscosity units 50 to 60 dm³/

kg higher than those produced at 155 °C.²⁴ Technically, some xylan remains in the pulp fiber matrix after wood is processed to produce papermaking fibers, and this significantly influences the pulp's quality and paper's characteristics.²⁵ Due to the high hemicellulose content of bamboo, an analysis of xylan retention is required in addition to viscosity assessment for further research.

Hexeneuronic acid content

Hexeneuronic acid is formed when new reducing end groups are created, facilitating secondary peeling reactions.²⁶⁻²⁸ Furthermore, hexeneuronic acid reacts under various bleaching conditions and its reactivity is related with the amount and type of residual lignin that might be present in the bleaching filtrates.²⁹ The levels of hexeneuronic acid content (HAC) negatively affect the ease of pulp bleaching.^{17,26} The HAC levels obtained from the pulping process of apus bamboo ranged from 10.87 to 25.86 µmol/g. These HAC values in this study were lower than those reported in previous research.^{30,31}

The minimum value obtained for hexeneuronic acid content (HAC) was 10.87 µmol/g at a cooking temperature of 165 °C (XA = 0) and a cooking time of 204.85 min (XB = 1.41). As the temperature increases, the HAC decreases, particularly at the highest temperature of 175 °C (Figure 5). At level -1 (155 °C), the HAC ranged from 22.87 to 25.86 µmol/g; at level 0 (165 °C), it ranged from 10.87 to 24.24 µmol/g; and at level 1 (175 °C), it ranged from 11.40 to 22.97 µmol/g. Additionally, longer cooking times corresponded to lower HAC values, as observed at a cooking time of 180 min.

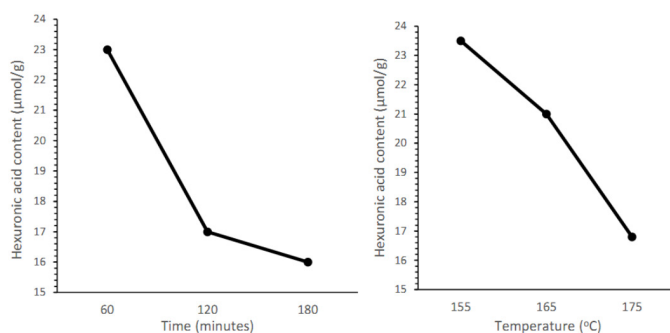


Figure 5 Effect of cooking time and temperature on hexeneuronic acid content.

Brightness

Brightness is the ability of a pulp sheet to reflect light, measured under standard conditions as an indication of its whiteness. The brightness test results obtained from the apus bamboo pulping process ranged from 12.20% to 18.90%. This range is lower than that reported for *Yushania alpina* bamboo pulp.⁷ The lignin and extractive content in wood contributes to a darker wood color, thereby affecting the brightness of the paper.^{31,32} Generally, a lower kappa number corresponds to higher brightness in the resulting paper.²⁸ However, in this study, the kappa number was relatively high, which resulted in a lower brightness level.

The results indicated a maximum pulp brightness value of 18.90% at a cooking temperature of 150.86 °C (XA = -1.41) and a cooking time of 120 min (XB = 0). As the temperature increased, the brightness level decreased, particularly at a temperature of 175 °C (Figure 6). Similarly, longer cooking times resulted in lower brightness levels, as observed at 180 min. For cooking times, at level -1 (60 min), the brightness ranged from 17.95% to 18.67%; at level 0 (120 min), it ranged from 14.01% to 18.61%; and at level 1 (180

min), it ranged from 12.29% to 18.54%. The color changes in the pulp are also influenced by the oxidation of lignin that occurs during cooking. The residual lignin is primarily responsible for the dark color of unbleached kraft pulp.³² This decrease in brightness might be attributed to the increasing formation of chromophores from the residual lignin as the temperature and cooking time increase.

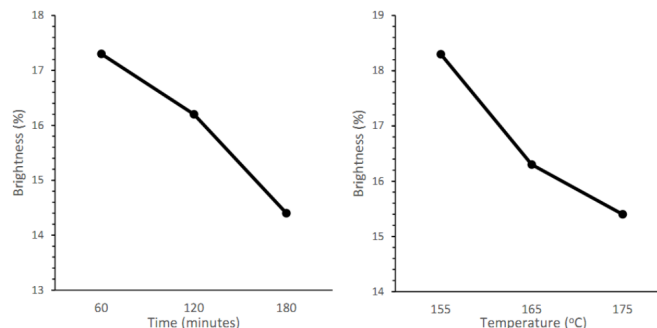


Figure 6 Effect of cooking time and temperature on pulp brightness

Total solids

Total solids refer to the total amount of solids in black liquor, which consists of suspended solids and dissolved solids. These solids contain organic compounds such as lignin, cellulose, hemicellulose, extractive substances, and other chemicals that are dissolved during the pulp cooking process. The total solids obtained from the apus bamboo pulping process ranged from 14.64 to 17.78 g/L. This total solids value is useful not only for recovery boilers but also for reclaiming pulping chemicals for reuse.³³ Separating the dissolved lignin fraction and dissolved carbohydrates in the black liquor would have a greater impact from a biorefinery perspective.

The maximum total solids value obtained in this study was 17.78 g/L at a temperature of 165 °C (XA = 0) and a cooking time of 204.85 min (XB = 1.41). High cooking temperatures resulted in increased total solids, as observed at 175 °C (Figure 7). Additionally, longer cooking times corresponded to higher total solids, particularly at 180 min (Figure 7). At level -1 (60 min), the total solids ranged from 14.64 to 15.35 g/L; at level 0 (120 min), they ranged from 14.94 to 17.78 g/L; and at level 1 (180 min), they ranged from 16.87 to 17.00 g/L. The high total solids content observed over extended periods and at elevated temperatures is attributed to the continuous decomposition and degradation of organic matter in the black liquor.

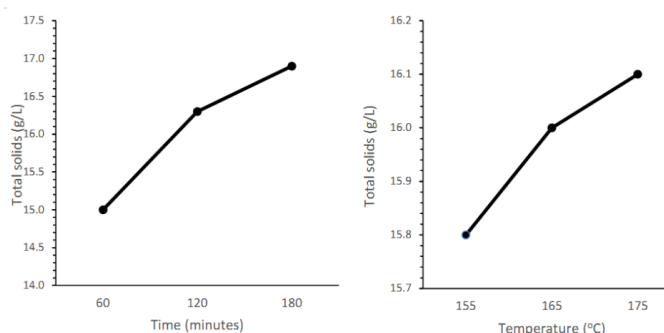


Figure 7 Effect of cooking time and temperature on total solid of black liquor.

pH value

The pH value obtained from the apus bamboo pulping process ranged from 10.88 to 13.38. This range is consistent with the pH values of black liquor derived from *Acacia mangium* and *A. aulacocarpa*.²² A

decreasing pH value indicates an increasingly intense reaction, as the stronger base of the black liquor becomes weaker due to the reaction with acidic wood components. A pH value that is too low may result in a less effective delignification reaction. It is necessary to keep pH above 11 at the end of the cook, not to risk precipitation of dissolved lignin.³⁴

The maximum pH value recorded was 13.38 at a temperature of 155 °C and a cooking time of 60 min. Longer cooking times result in lower pH values (Figure 8). At level -1 (60 min), the pH of the black liquor ranged from 12.41 to 13.38; at level 0 (120 min), it ranged from 11.46 to 12.85; and at level 1 (180 min), it ranged from 11.43 to 13.09. At high pH, lignin will dissolve because the phenolic hydroxyl groups in lignin become ionized in their salt form. Conversely, at low pH, lignin will precipitate, as the phenolic hydroxyl groups are in a non-ionized state in an acidic environment.³⁵ Higher temperatures also resulted in a lower pH (Figure 8). At elevated temperatures, the reaction with the acidic components of bamboo may become more intense, as the base in the black liquor becomes weaker.

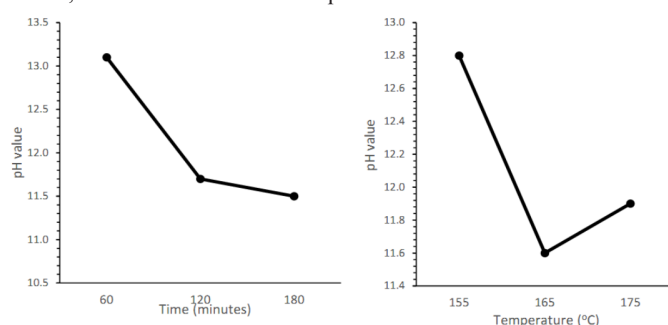


Figure 8 Effect of cooking time and temperature on pH value of black liquor.

Table 4 The calculated values of seven responses of pulps prepared by selected optimum kraft-pulping condition (cooking temperature of 165.71 °C and time of 143.14 min)

Model response	Pulping process parameters		
	Temperature (°C)	Time (minutes)	Calculated values
Yield (%)	165.71	143.14	60.22
Kappa number	165.71	143.14	22.96
Viscosity (cP)	165.71	143.14	16.05
Hexeneuronic acid content (μmol/g)	165.71	143.14	21.50
Brightness (%)	165.71	143.14	17.07
Total solids (g/L)	165.71	143.14	16.19
pH value	165.71	143.14	11.85

With increasing cooking time, the kappa number decreased. This reduction occurs because the soluble lignin has reached its optimal time limit. Consequently, extended cooking time enhances the potential for significant reductions in both lignin and sugar degradation, as indicated by the viscosity number. Therefore, a cooking temperature of 165 °C and a cooking time of 120 min are recommended for apus bamboo. When aligned with the initial hypothesis, XA (temperature factor) is appropriate at level 0, specifically 165 °C, while XB (time factor) falls between 120 and 180 min. Research conducted on *Yushania alpina* bamboo⁷ identified optimal conditions of 162.30 °C and 180 min, with temperature levels ranging from 140 °C to 220 °C and time levels from 120 to 200 min. It was reported that the optimum cooking conditions of *Phyllostachys bambusoides* modified kraft pulps were screened yield of 48.1%; kappa number of 24.1; viscosity of 1210 ml/g; and brightness of 20.35%.³⁶ In this context, the optimal

Optimization of pulping conditions

The main objective of this study was to determine the optimal maximum values for yield, viscosity, brightness, total solids, and pH value (black liquor), as well as the minimum values for kappa number and hexeneuronic acid content (HAC) from apus bamboo powder using kraft pulping. To validate the statistical experimental strategies, duplicate pulping was conducted under the predicted process conditions. Optimization can only be performed after each response has been analyzed to establish the appropriate model. The optimum conditions for each variable varied based on temperature and cooking time. Notably, for the cooking time variable, a wide range was obtained, specifically from 30 to 204 min (data not shown). Optimizing a cooking time of 204 min is technically less efficient, necessitating the exploration of shorter time alternatives.

From the variables described above, it was observed that process optimization was achieved at level 0 (central point) with a cooking temperature of 165 °C and a cooking time of 120 min. One of the variables that approached this was the kappa number, which was recorded at a cooking temperature of 165.71 °C and a cooking time of 143.14 min. The optimization aimed to minimize the kappa number, which reached a value of 22.96 at a temperature of 165.71 °C and a time of 143.14 min (Table 4). This variable was selected because the kappa number is a benchmark for delignified pulp. The target kappa number for bleachable-grade pulp is between 12 and 18 for hardwoods.¹⁵ A lower kappa number indicates a reduced lignin content in the pulp produced during the cooking process. Furthermore, the analysis results demonstrate that the kappa number serves as a limiting factor for other variables.

temperature obtained is slightly different from the temperature level determined at the central point.

Conclusion

The comparatively high cellulose content (52.08%) and low extractive content (2.33%) underscore the superiority of apus bamboo as a raw material for pulp production. In the kraft process, longer cooking times and higher cooking temperatures increased the levels of yield and total solids, while simultaneously reducing the kappa number and hexeneuronic acid content. The optimization of temperature and time for each variable was based on the kappa number, specifically at a temperature of 165.71 °C and a time of 143.14 min. Under these conditions, the process yielded 60.22%, with a kappa number of 22.96, viscosity of 16.05 cP, hexeneuronic acid content of 21.50 μmol/g, brightness of 17.07%, total solids of 16.19

g/L, and a pH value of 11.85. Compared to data obtained from the literature, it is evident that apus bamboo exhibits a comparatively high yield and low kappa number under optimal conditions. Therefore, this experiment demonstrates that apus bamboo is a potential source for pulp production.

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None.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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