Research Article

Effect of Altitude and Hydrophilic Pre-Extraction on the Phytoextract and Pyrolytic Product Distribution of Betung Bamboo (*Dendrocalamus asper*)

Yanico Hadi Prayogo*, Deded Sarip Nawawi and Naresworo Nugroho
Department of Forest Products, Faculty of Forestry and Environment, IPB University, Bogor, Indonesia

Obie Farobie
Mechanical Engineering, Faculty of Engineering and Technology, Bogor, Indonesia
Surfactant and Bioenergy Research Center (SBRC), IPB University, Bogor, Indonesia

Jajang Sutiawan and Widya Fatriasari
Research Center for Biomass and Bioproduct, National Research and Innovation Agency, Cibinong, Indonesia

* Corresponding author. E-mail: yanicopryg@apps.ipb.ac.id DOI: 10.14416/j.asep.2026.05.011
Received: 10 December 2025; Revised: 6 February 2026; Accepted: 16 March 2026; Published online: 28 May 2026
© 2026 King Mongkut's University of Technology North Bangkok. All Rights Reserved.

Abstract
Feedstock characteristics and pre-treatment strongly influence both biomass conversion processes and the resulting products. This study aims to evaluate the effects of altitude and microwave-assisted pre-extraction of *Dendrocalamus asper* (Schult. & Schult.f.) Backer on its phytoextract and pyrolytic products. Bamboo culms collected from three different elevations were subjected to microwave-assisted extraction (MAE) prior to pyrolysis. The separated extracts were characterized, and the pretreated bamboo samples were subsequently pyrolyzed. The resulting pyrolysis products were also characterized. The results show that MAE pre-treatment alters bamboo morphology, as evidenced by SEM observations indicating more pronounced macrostructural damage. However, the chemical composition of the bamboo powder remained unchanged, as demonstrated by similar FTIR spectral profiles between MAE-treated and untreated samples. Low-altitude bamboo produced extracts with higher phenolic content and stronger antioxidant activity. Altitude also influenced product distribution: increasing elevation was associated with higher syngas yields, but lower bio-oil and biochar yields. This trend was less pronounced for MAE-treated samples, which generally exhibited reduced bio-oil and biochar yields. MAE-treated bamboo also produced biochar with a more porous structure. Interestingly, bio-oil derived from MAE-treated bamboo contained higher proportions of carbohydrate derivatives, particularly the rare monosaccharide D-allose (10.46–17.31% of abundance). These findings demonstrate that both feedstock characteristics and MAE pre-treatment significantly affect the properties of phytoextracts, biochar, and bio-oil, particularly in relation to the production of high-value chemicals.

Keywords: Bamboo, Biomass conversion, Microwave-assisted extraction, Pretreatment, Pyrolysis

1 Introduction

Biorefinery is widely recognized as a sustainable strategy that enables the comprehensive utilization and conversion of biomass into a broad range of value-added products, including chemicals, food ingredients, feedstock, energy, and materials [1]. One of the major routes for biomass valorization is thermochemical conversion, particularly pyrolysis. Pyrolysis offers an efficient and environmentally friendly approach to transform biomass into fuels, chemicals, fertilizers, catalysts, and adsorbent materials [2]. This process produces distinct product phases: solid biochar, condensable liquid or gas (bio-oil), and non-condensable gas (syngas) [3], [4]. These fractions are significant as energy resources as well as

precursors for downstream chemical products [5]–[7]. Therefore, thermochemical biorefinery holds strong potential as a multiproduct conversion technology.

The pyrolytic behavior of biomass is closely governed by its lignocellulosic and extractive components. High hemicellulose content is associated with volatile formation, which contributes to bio-oil and syngas yields [8]. Conversely, the broad thermal degradation range of lignin promotes biochar generation, meaning a higher lignin fraction typically increases char yield [8]. Another research demonstrated that extractive-free bio-oil from sugarcane bagasse, sisal residue, and eucalyptus bark showed distinct profiles compared with untreated biomass, particularly in aldehyde and hydrocarbon (alkane) composition [9]. Thus, biomass selection strongly influences pyrolysis product characteristics.

Betung bamboo (*Dendrocalamus asper*, Poaceae) presents promising prospects as feedstock for bio-oil and biochar production through pyrolysis. Bamboo is well-known for its fast growth, implying excellent biomass availability. Chemically, *D. asper* contains 72.19% holocellulose, 28.05% Klason lignin, and 7.90% ethanol–benzene extractives [10]. Thermogravimetric kinetic and thermodynamic analyses have indicated its suitability as a bioenergy source [11], although previous studies did not specify the species used. To date, pyrolysis of *D. asper* has been largely limited to activated-char production [12], [13], while previous studies have mainly focused on modifying bamboo for structural applications [14].

Several studies have highlighted the impact of MAE as a pretreatment step. A previous study reported enhanced phenolic content in bio-oil derived from pine wood subjected to MAE under varying time and power conditions, using CaO as a catalyst, with optimal results obtained at high power (567 W) and short extraction duration (3 min) [15]. MAE using 16% formic acid at elevated temperatures (130–170 °C) for 30 min on bamboo powder was also shown to increase fixed carbon content and higher heating value, while reducing bio-oil yield [16]. These findings suggest that the effectiveness of MAE is highly dependent on extraction time, power, and temperature, all of which influence subsequent pyrolysis performance.

Environmental variation also affects the chemical composition of biomass and, consequently, its conversion behavior and product profile. For example, ebony wood collected from different regions exhibited varying extractive compositions [17]. As previously discussed, extractive removal in sugarcane bagasse, sisal residue, and eucalyptus bark showed that sisal, with a higher extractive content, generated bio-oil richer in alkanes, whereas sugarcane bagasse and eucalyptus produced bio-oil with a higher aldehyde fraction [9]. Another study shows that altitude, together with rainfall and other complex ecosystem factors, influences the composition of biomass, particularly hemicellulose and lignin, as well as the overall biomass yield [18], [19].

Given that the growing site influences the chemical composition of biomass, to date, there have been no studies analyzing the combined effects of variations in growing altitude and MAE pretreatment on the distribution of pyrolysis products and the characteristics of the resulting bio-oil and biochar, particularly for *D. asper* bamboo. Therefore, this study aims to investigate the effects of *D. asper* biomass sourced from three different altitudes and MAE pretreatment on pyrolysis product distribution, with particular emphasis on product yields and physicochemical characteristics.

2 Materials and Methods

2.1 *Feedstock preparation*

D. asper culms were harvested from Labuan Bajo, East Nusa Tenggara, Indonesia. The bamboo was collected from three different altitudinal sites: low altitude (Compang Liang Ndara village at 250 m a.s.l.), medium altitude (Tondong Belang village at 525 m a.s.l.), and high altitude (Golo Damu village at 822 m a.s.l.). Samples from each altitude were kept separate, and the bark was removed. The culms were then chipped, dried, ground, and sieved through a 40–60 mesh screen. The bamboo powder was analyzed for its proximate composition, including moisture and ash content. In addition, its chemical constituents were determined, including extractives, holocellulose, α-cellulose, lignin, and hemicellulose contents, with three replications for each testing sample.

2.2 *Microwave-assisted pre-extraction and characterization of phytoextracts*

The MAE pretreatment followed the method described in [15] and [16], with minor modifications, and no optimization was performed. A total of 70 g of bamboo powder was immersed in an ethanol-water mixture (1:1, v/v) at a solid-to-liquid ratio of 1:10.

Ethanol-water mixtures are effective solvent systems for MAE due to their strong microwave absorption and broad extraction capability for secondary metabolites [20], [21]. Extraction was performed at 400 W for 15 minutes, and the temperature was recorded at one-minute intervals. Each sample underwent two extraction cycles with three replications. The filtrate was separated from the solid residue, concentrated using a rotary evaporator, and the extract yield was determined. The remaining solid residue was oven-dried prior to pyrolysis. The extract was analyzed for its chemical composition by quantifying its total phenolic content using the Folin–Ciocalteu method and assessing its antioxidant activity based on DPPH radical scavenging [22]. Total phenolic content and antioxidant activity were determined in three replicates.

2.3 *MAE pretreated bamboo characterization*

Bamboo powder with and without MAE pretreatment subjected to the pre-extraction treatment was characterized for its proximate composition and morphology prior to pyrolysis. Moisture and ash content were determined gravimetrically. The ultimate analysis for determining the carbon, hydrogen, nitrogen, and sulfur content was conducted using a CHNS analyzer (Elementar, Langenselbold, Germany). The oxygen content was calculated using the equation %O = 100% − (%C + %H + %N + %S). The HHV was calculated based on the ultimate analysis results using Dulong's formula. The functional group profile of the chemical components in the bamboo powder was analyzed using the attenuated total reflectance Fourier-transform infrared (ATR-FTIR) spectroscopy (Bruker, Massachusetts, United States). In addition, the powder morphology was examined using a scanning electron microscope/SEM (JEOL, Tokyo, Japan).

2.4 *Pyrolysis*

Bamboo powder with and without the MAE pretreatment was pyrolyzed using a stainless-steel reactor equipped with a condenser, an electric heater, and a thermocouple. The pyrolysis conditions employed correspond to a typical slow pyrolysis regime. A total of 20 g of dried bamboo powder was loaded into the reactor as feedstock. Nitrogen gas was supplied at a flow rate of 100 mL min^{-1} to create an oxygen-free atmosphere. After ensuring that the system was at ambient temperature, the reactor was gradually heated to 500 °C at a heating rate of 30 °C min^{-1}. Once the reactor reached 500 °C, the temperature was held for 60 min. Only one level of temperature was used. The condensable gases were allowed to condense and collected through the liquid sampling port, while the non-condensable gases could not be collected by the pyrolysis system and were therefore discarded and not analyzed. At the end of the process, the reactor was cooled to room temperature. The bio-oil and biochar were weighed to determine their yields, and the gaseous residue fraction was calculated by difference. Pyrolysis reactions were carried out in triplicate for each sample of treated and untreated bamboo powder to ensure reproducibility. The pyrolysis kinetics were not examined in this study; instead, only the distribution of pyrolytic products was analyzed.

2.5 *Biochar characterization*

The biochar was characterized using ATR-FTIR and SEM to examine differences in its molecular structure and morphology. FTIR analysis was carried out using a Spectrum Two Universal ATR-FTIR spectrometer (Bruker, Massachusetts, United States) to evaluate the functional groups present in the biochar. The FTIR spectra were recorded in the range of 400–4000 cm^{-1}. The morphology of the biochar was examined using SEM (Hitachi SU 3500), operated at an accelerating voltage of 20 kV with magnifications of 1000× and 2500× (JEOL, Tokyo, Japan). Biochars were analyzed for their proximate profile, including moisture content, ash content, volatile matter, and fixed carbon, using three replications. The HHV was calculated based on the values obtained from the proximate analysis using the corresponding equation proposed by [23].

2.6 *Bio-oil characterization*

The chemical constituents of the bio-oil were analyzed using a gas chromatography–mass spectrometry (GC–MS) system (Agilent Technologies 7890, Agilent Inc., USA) equipped with a 5975 mass-selective detector [2]. The separation was performed on an RTX-5MS column (30 m length, 0.75 kPa pressure, 2.25 mm diameter). The injection volume was 0.5 µL, with a total flow of 35.2 mL/min and a column flow of 1.53 mL/min, using an electron ionization method. The initial injector temperature was set at 200 °C. The column oven was programmed to start at 70 °C (held for 2 min), then increased at 20 °C per minute to 180

°C and maintained for 3 min. At the end of the run, the temperature reached 250 °C at 27 minutes. Compound identification was carried out by comparing the obtained mass spectra with the National Institute of Standards and Technology (NIST) library. Additional parameters, including pH and specific gravity, were analyzed.

3 Results and Discussion

3.1 *Effect of altitude and MAE pretreatment on bamboo chemical composition and morphological*

Bamboo originating from different growing sites exhibited variations in their chemical composition. The extractive and holocellulose contents showed a similar trend, with LA bamboo having the highest levels compared with MA and HA bamboo (Table 1). A similar pattern was also observed for lignin content, where LA bamboo exhibited the highest lignin level among the three. However, the cellulose and hemicellulose contents showed a different trend. MA bamboo contained the highest cellulose content, whereas the opposite was observed for hemicellulose. Overall, the effect of increasing elevation at the growing site did not correspond to a consistent increase in the levels of each chemical component. The major components (cellulose, hemicellulose, and lignin) were not influenced by differences in growing location, whereas the composition of extractives was strongly affected by various factors such as species, site conditions, and tree part [4]–[6].

Table 1: Content of extractive, holocellulose, α-cellulose, hemicellulose, and lignin.

Bamboo	Content (%)				
	Ext.	Ho-C	α-C	Hem-C	L
LA	6.31b	79.62a	49.63a	30.00a	30.01a
MA	4.36a	78.95a	51.41b	27.54a	27.81a
HA	5.67b	79.41a	50.76ab	28.65a	28.81a

Note: Bamboo from low altitude (LA), medium altitude (MA), high altitude (HA); Ext (extractive), Ho-C (holocellulose), α-C (α-cellulose), Hem-C (hemicellulose), L (lignin); Note: Values are means of three replicates; values sharing the same letter are not significantly different (Tukey's HSD, p-value > 0.05).

The elemental composition of the bamboo powder did not undergo substantial changes as a result of the extraction pretreatment. In terms of carbon content, samples LA and HA showed an increase, whereas sample MA exhibited a slight decrease (Table 2). Meanwhile, a consistent downward trend was observed for nitrogen and sulfur across all samples. The N and S contents of the pretreated bamboo powders were lower than those of the untreated samples, indicating that the extraction pretreatment effectively reduced these elements.

Table 2: Moisture, ash, and C, H, N, S, and O contents in MAE-treated and untreated bamboo.

Parameter	Bamboo					
	LA	MA	HA	LA-E	MA-E	HA-E
MC (%)	7.42	7.65	7.89	6.54	6.13	6.22
AC (%)	2.64	1.99	1.65	2.27	1.19	1.23
C (%)	46.87	49.95	47.14	47.13	47.31	47.46
H (%)	7.00	7.27	7.45	7.28	7.35	7.36
N (%)	0.45	0.30	0.29	0.28	0.19	0.24
S (%)	0.31	0.15	0.08	0.06	0.05	0.03
O (%)	45.37	42.33	45.03	45.24	45.09	44.90
HHV (MJ/kg)	17.76	19.72	18.54	18.26	18.45	18.54

Note: moisture content (MC); ash content (AC); high heating value (MJ/kg), MAE pretreated bamboo from low altitude (LA-E), medium altitude (MA-E), high altitude (HA-E).

The FTIR spectra of bamboo powder (Figure 1) from the three elevations showed the typical absorption features expected for lignocellulosic materials [24]. A broad band around 3330–3400 cm^{-1} indicates O–H stretching from lignin, cellulose, hemicellulose and hydroxyl-containing extractive, while the peak near 2920 cm^{-1} reflects aliphatic C–H in CH, CH_2, and CH_3 groups. A distinct band at approximately 1730 cm^{-1} corresponds to C=O stretching associated with ester, carbonyl, or acetyl groups commonly found in hemicellulose and extractives. The region between 1600 and 1510 cm^{-1} exhibits aromatic C=C vibrations, which are characteristic of lignin and various benzenoid extractive components. Additional features appear at 1460–1420 cm^{-1}, associated with CH_2 and CH deformation, and at 1365–1320 cm^{-1}, which relates to C–H bending. The bands observed at 1260–1220 cm^{-1} arise from C–O stretching in lignin and hemicellulose, whereas absorption in the 1160–1030 cm^{-1} region corresponds to C–O–C and C–O vibrations typical of glycosidic linkages in cellulose, hemicellulose, and alcohol groups. Taken together, the overall spectral patterns were largely consistent across the three elevations, suggesting similar lignocellulosic composition, although minor differences in the aromatic region (1510–1600 cm^{-1}) may reflect slight variations in lignin content influenced by the respective growing environments.

After MAE pretreatment (Figure 1), the FTIR spectra of the treated bamboo displayed slight changes compared with the untreated bamboo. These slight changes were caused by the reduction of extractive

components through MAE pretreatment. A decrease in intensity was observed at peaks with wavenumbers higher than ~3300 cm^{-1}, and a reduction in the O–H peak intensity was detected, which is presumably due to the extraction of phenolic extractive compounds. A decrease in intensity was also observed in the wavenumber range of ~1700–650 cm^{-1}, which originated from the reduced intensity of various functional groups. A reduction in the intensity of the band at approximately 1730 cm^{-1} indicates the effective removal of extractive components containing carbonyl or ester groups, such as esterified phenolics. In addition, the aromatic lignin band around 1600–1510 cm^{-1} (C=C aromatic ring, C=O) showed a slight decrease in intensity, suggesting that the extraction process solubilized a portion of phenolic extractives without damaging the structural lignin. A slight intensity reduction was also observed around 1030 cm^{-1}, which is presumed to indicate a decrease in C–O alcohol-containing extractive compounds. Overall, microwave-assisted extraction pretreatment effectively reduced the extractive content, particularly polar extractives, due to the use of a polar solvent, without altering the fundamental lignocellulosic structure.

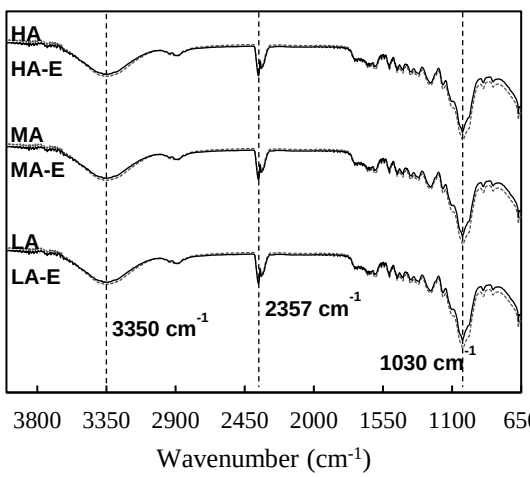


Figure 1: Infrared spectra and micrographs of bamboo with and without MAE pretreatment. Non-MAE pretreated bamboo (gray dashed line) and MAE pretreated bamboo (non-dashed line).

Microwave-assisted extraction pretreatment produced noticeable effects on the morphology of the bamboo powder. The micrographs show that structural damage occurred in samples subjected to pretreatment. This is evident from the more pronounced cracking observed in the pretreated powders compared with the untreated powders (Figure 2). Similar morphology degradation caused by microwave-assisted extraction has also been reported in moso bamboo pretreated with water as the extraction solvent [7]. In addition, other studies have described structural damage in pine and beech chips following microwave irradiation [8].

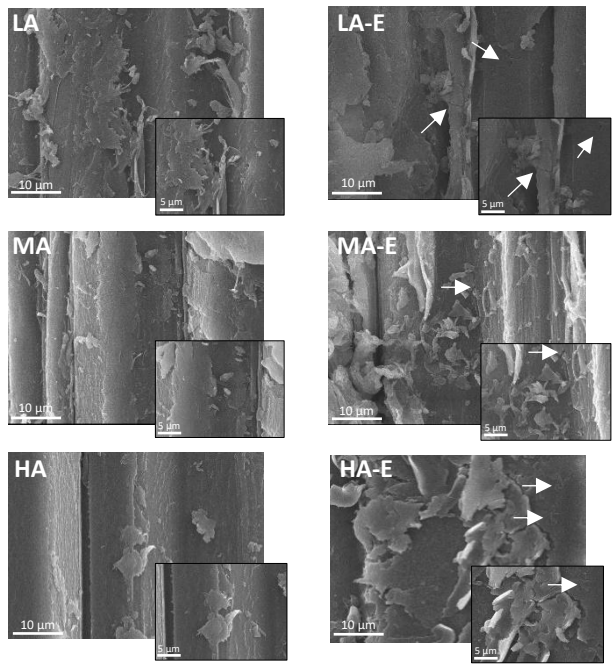


Figure 2: Micrographs of bamboo with and without MAE pretreatment. The white arrow indicates a cracked structure.

3.2 *Effect of altitude on MAE-derived bamboo phytoextracts*

Differences in growing sites affected the microwave-assisted pre-extraction process. The temperature profile during extraction showed a similar pattern for HA and LA, with both being higher than MA (Figure 3(a)). The chemical profiles of HA and LA also indicated higher extractive and lignin contents compared to MA. Lignin and other benzenoid compounds are known to be good microwave absorbers, which contributes to enhanced heat generation [25]. This phenomenon implies that HA and LA exhibited higher extraction effectiveness and produced higher yields than MA (Figure 3(b)). Accordingly, the yield increased in the order MA < LA < HA. Based on this pattern, higher growing elevation does not necessarily correspond to higher extractive content. However, the chemical characteristics of the bamboo influenced microwave

absorption, as reflected in the extraction temperature profile, which subsequently affected the extraction yield.

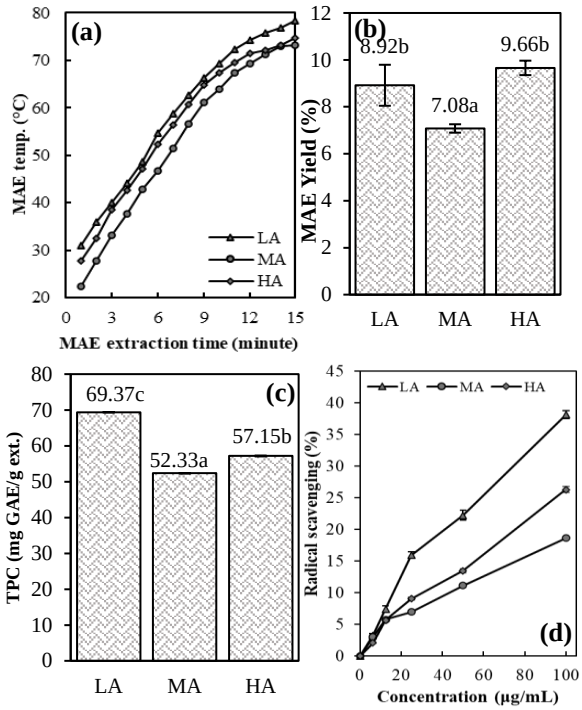


Figure 3: Relationship between MAE time and temperature (a), extraction yield (b), phenolic content (c), and DPPH radical-scavenging activity (d) of bamboo phytoextracts from different elevations. Values with the same letter are not significantly different (Tukey's HSD, p-value < 0.05).

The phenolic content of the bamboo extracts correlated with their DPPH radical-scavenging activity. Neither the phenolic content nor the radical-scavenging activity showed a trend consistent with the extraction yield. The bamboo extracts contained phenolic compounds in the range of 52–70 mg GAE/g extract (Figure 3(c)). The radical-scavenging activity of all three extracts remained below 50% at the highest concentration tested (Figure 3(d)). The trends in phenolic content and radical-scavenging activity were consistent; the LA extract, possessing the highest phenolic content, exhibited the strongest antioxidant activity, whereas the MA extract displayed the lowest radical-scavenging activity, corresponding with its minimal phenolic content. In this study, the phenolic content of the extracts was higher than the values reported for the leaves, roots, and culms of *D. asper* from Vietnam [26].

3.3 *Effects of altitude and MAE pretreatment on pyrolytic product yields*

The MAE pretreatment also influenced the yields of bio-oil, biochar, and syngas. Both biochar and bio-oil yields decreased in the pretreated samples (Figure 4(b) and (c)), whereas syngas production increased (Figure 4(a)). This behavior is closely related to the extractive components in bamboo, such as oils, resins, waxes, and phenolic compounds, which serve as important precursors for forming liquid fractions during pyrolysis. The extraction step removes these compounds from the bamboo powder as they dissolve in the extraction solvent.

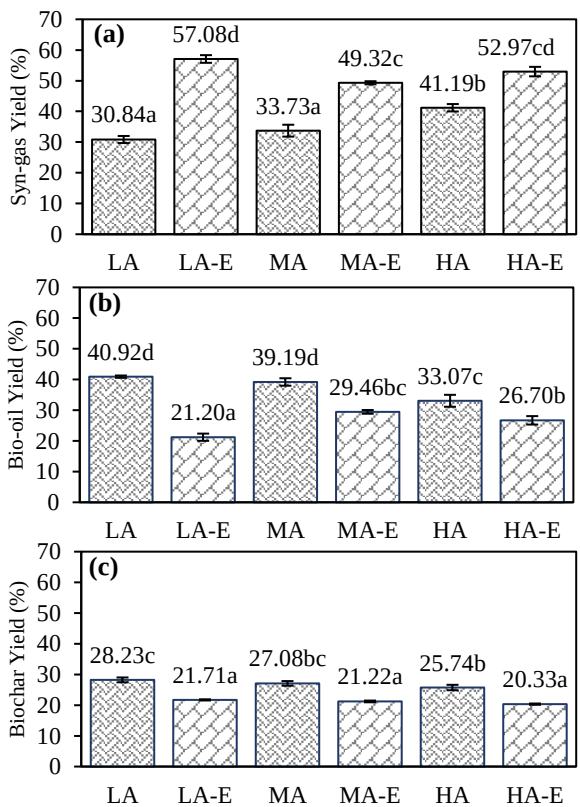


Figure 4: Product yields from the pyrolysis of *Dendrocalamus asper* with and without MAE pretreatment: syngas (a), bio-oil (b), and biochar (c). Values with the same letter are not significantly different (Tukey's HSD, p-value < 0.05).

A similar pattern was also found in the biochar yield, which decreased in the bamboo powder that underwent the MAE pretreatment. The microwave-assisted process appeared to disrupt the biomass structure. At the same time, it promotes modification of lignocellulosic components, reducing their degree of polymerization and increasing accessibility for subsequent reactions [27]. This disruption also appeared in the cracked structure of MAE pretreated bamboo (Figure 2) and made the material easier to break down during heating. Furthermore, the pretreated samples decomposed more extensively than the untreated ones, as indicated by the higher yield of syngas produced.

As these structural components degraded, they produced smaller molecular fragments that were more readily converted into syngas. This condition generally shifts product formation away from bio-oil and toward cracking and reforming reactions that generate lighter gases such as CO and CO_2, particularly those originating from hemicellulose [28]. The pretreatment likely also made the particle structure more uniform, which may have improved heat transfer during pyrolysis and encouraged secondary decomposition reactions. As a result, the conversion of solid material into gas became more efficient.

Taken together, the results in Figures 4a–c show that MAE pretreatment has a clear effect on how bamboo is transformed during pyrolysis. Both bio-oil and biochar yields declined after pretreatment, suggesting that extractives contribute significantly as volatile precursors for bio-oil, while the breakdown of the lignocellulosic matrix is driven more strongly toward gas production. Differences among the three growing elevations—lowland, mid-elevation, and highland—were noticeable in the untreated samples, where bamboo from higher elevations produced more bio-oil and biochar. However, these altitude-related differences became less apparent once the bamboo powder had been subjected to MAE pretreatment.

The mass balance closure in this study ranged between 51.84–69.16%. The values differed between pretreated and non-pretreated samples. For MAE-pretreated bamboo, the mass balance closure was 51.84% (LA-E), 57.76% (MA-E), and 56.69% (HA-E). In contrast, the non-MAE-pretreated bamboo showed mass balance closure values of 69.16% (LA), 66.27% (MA), and 58.81% (HA). These relatively low mass balance values are attributed to limitations of the pyrolysis reactor, which was unable to fully recover the gases produced during the process.

3.4 *Impact of altitude and MAE on biochar characteristics*

Biochar exhibited higher HHV values compared to bamboo powder, and MAE pretreatment had a significant effect on increasing volatile matter and decreasing fixed carbon content. Biochar derived from non-pretreated bamboo showed higher fixed carbon values and was significantly different compared to biochar from pretreated bamboo (Table 3). The opposite trend was observed for the volatile matter parameter. This phenomenon affected the HHV values, where LA and HA biochars exhibited higher HHV values and were significantly different compared to LA-E and HA-E. However, no significant difference in HHV values was observed between MA and MA-E biochars.

Table 3: The proximate characteristics of biochar.

Biochar	MC (%)	VM (%)	AC (%)	FC (%)	HHV (MJ/kg)
LA	7.09a	10.98c	8.79c	80.24b	30.02b
MA	7.75b	10.48a	6.80b	82.72d	30.84cd
HA	6.99a	10.48a	5.38a	84.14e	31.35e
LA-E	8.02b	14.07c	9.85d	76.08a	29.02a
MA-E	7.74b	13.44b	5.05a	81.51c	30.88d
HA-E	8.16b	14.27c	5.36a	80.37b	30.61c

Note: Values are means of three replicates; values sharing the same letter are not significantly different (Tukey's HSD, p-value > 0.05); volatile matter (VM); fixed carbon (FC).

Bamboo subjected to MAE pretreatment also produced biochar with functional-group profiles distinct from those of untreated samples. The biochar derived from MAE-treated bamboo exhibits characteristic peaks at approximately ~3700 cm^{-1}, ~3100 - 2780 cm^{-1}, ~1056 cm^{-1}, and ~1009 cm^{-1} (Figure 5). The peaks at ~3716 cm^{-1} correspond to O–H stretching of alcohols/phenols. The peaks at ~3100–2780 cm^{-1} correspond to C–H stretching of alkenes, alkanes, and aldehyde, respectively. In addition, the peaks near ~1056 cm^{-1} and ~1009 cm^{-1} are C-O stretching and consistent with features previously reported in the literature [29]. The biochar from extracted bamboo shows sharper peaks at ~1056 cm^{-1} and ~1009 cm^{-1} with lower transmittance values. In addition, the ~3716 cm^{-1} and ~3100–2780 cm^{-1} peaks are more pronounced in the MAE-treated biochar, suggesting that MAE promotes the formation or retention of structures enriched in alkene characteristics. Based on the FTIR spectra, a noticeable change was observed at the peak around 860 cm^{-1}. The biochar derived from the treated bamboo no longer exhibited the sharp peak seen in the

biochar from the untreated sample. This reduction is likely related to the more extensive lignin degradation that occurred in the MAE-treated bamboo, which may have decreased the degree of aromatic substitution in its structure.

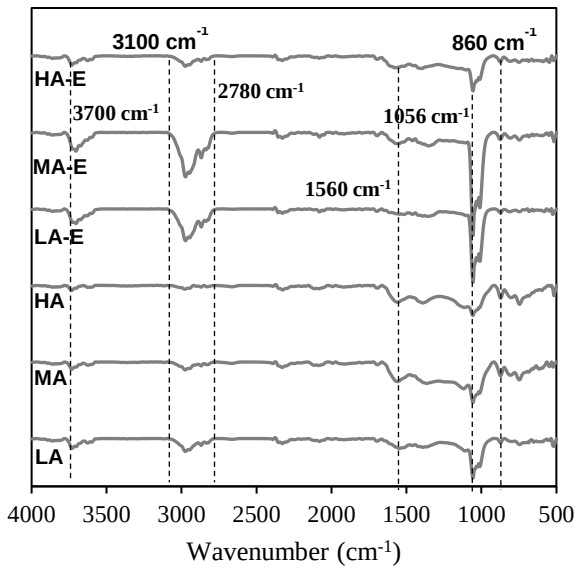


Figure 5: IR spectra profile of biochar from bamboo with and without MAE treatment.

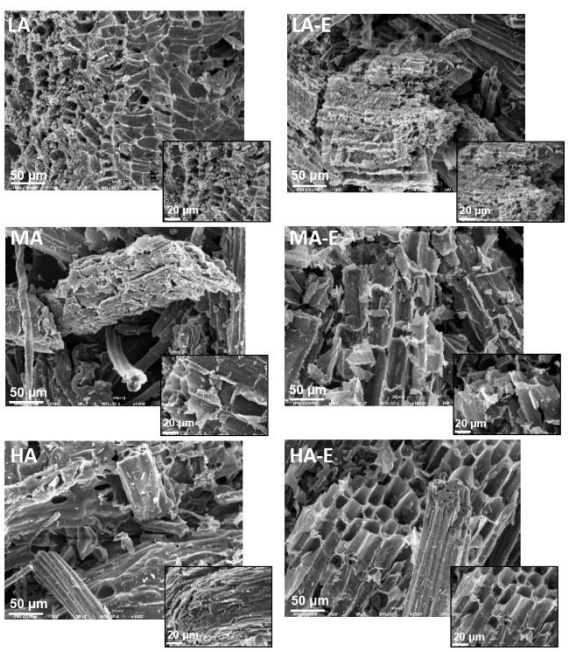


Figure 6: Micrograph of biochar from bamboo with and without MAE treatment.

The biochar exhibited a noticeably more porous structure than the surface of the original bamboo (Figure 6). All biochar samples developed clear pore networks. Overall, the surface of the biochar appeared rougher and more textured than that of both the treated and untreated bamboo powders. The micrographs observed in this study are consistent with previous reports on bamboo-derived biochar, which typically show the formation of porous and rough surfaces as a result of slow pyrolysis [29]. Comparing the biochar produced from treated and untreated bamboo, the LA-E, MA-E, and HA-E samples displayed more extensive porosity and a rougher surface texture. The MAE pre-treatment seemed to intensify structural degradation, leading to more visible cracks, peeling of cell walls, increased pore development, and greater fragmentation of the cellular structure.

3.5 *Impact of altitude and MAE on bio-oil characteristics*

Bio-oil from bamboo without MAE treatment was dominated by phenolic compounds, which appeared at a higher relative abundance (Table 4). Phenolic compounds showed the highest abundance in all three bio-oils from untreated bamboo (LA, MA, and HA). In addition, several other highly abundant compounds were substituted phenolics, such as 3-methylphenol, 2-methoxyphenol, 4-ethylphenol, creosol, and catechol. These phenolic compounds are derivatives or degradation products of lignin, as indicated by their substitution patterns that resemble lignin structures [30].

In contrast to the bio-oil from untreated bamboo, the pretreated bamboo produced bio-oil with higher sugar content. D-allose appeared at abundances above 10% in all three bio-oils and was the most abundant compound compared to all other components. Phenolic compounds, on the other hand, decreased in concentration in the bio-oil from treated bamboo. Several compounds that were not detected in the bio-oil from untreated bamboo, such as p-xylene, 2(5H)-furanone, cis-1,2-cyclohexanediol, pentanal, and DL-norvaline, were detected in the bio-oil from pretreated bamboo. D-allose is a rare monosaccharide formed from cellulose degradation. Other studies have also reported that pretreatment using hydrochloric acid washing, which alters the microstructure of the feedstock, can increase the percentage of D-allose and ketone compounds in bio-oil up to 15% [31]. Another study also showed that microwave pretreatment of

pine sawdust increased the ketone and aromatic hydrocarbon content in the resulting bio-oil [15], a trend also observed in the LA-E, MA-E, and HA-E bio-oils, which contained xylene.

In general, differences in growing elevation did not affect the compound composition of the bio-oil. However, the MAE pre-treatment showed a noticeable influence on the bio-oil composition. Four groups of compounds showed relatively large changes in their percentage abundance: ketones, furans, phenols and phenolic compounds, and carbohydrates and their derivatives (Figure 7). Ketones, furans, and carbohydrates increased in abundance after MAE treatment, while phenols and phenolic compounds decreased in the bio-oil from treated bamboo. Non-phenolic aromatic compounds also showed a lower relative abundance compared to the bio-oil from untreated bamboo.

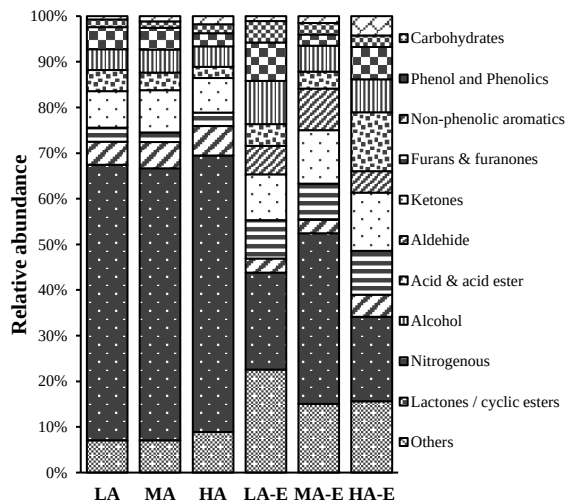


Figure 7: Chemical groups distribution of bio-oil.

Table 4: Major chemical components in bio-oil derived from untreated and pretreated bamboo.

RT (mins)	Identified Compound	MW (g/mol)	SI (%)	Relative abundance (%)					
				LA	MA	HA	LA-E	MA-E	HA-E
6.777	Phenol	94.05	97	8.6	7.38	7.84	1.48	2.37	1.99
8.283	Phenol, 3-methyl-	107.1	97	5.44	3.97	5.1	0	0	0
12.403	Phenol, 2,6-dimethoxy-	154.0	95	5.32	6.59	5.71	3.18	4.8	3.1
9.694	Phenol, 4-ethyl-	107.1	98	4.86	4.5	5.52	1.32	2.56	0
8.552	Phenol, 2-methoxy-	109.0	98	4.76	4.91	4.27	2.45	3.38	3.13
10.189	Catechol	110.0	97	3.65	4.03	3.8	1.37	3.13	1.58
5.366	Benzene, 1,3-dimethyl-	91.10	96	3.37	0	3.38	0	0	0
14.643	D-Allose	60.05	96	3.3	3.35	4.41	17.31	10.46	10.94
7.965	Phenol, 2-methyl-	108.1	96	3.1	2.54	2.85	0	2.89	0
11.388	Phenol, 4-ethyl-2-methoxy-	137.0	93	2.98	2.68	2.75	1.18	1.62	1.14
10.143	Creosol	123.0	96	2.6	2.55	2.73	2.54	2.82	2.63
7.531	1,2-Cyclopentanedione, 3-methyl-	112.1	96	2.58	2.88	2.52	2.26	3.03	2.58
5.864	2-Cyclopenten-1-one, 2-hydroxy-	98.05	94	0.77	0.62	0	2.43	3.71	3.93
9.702	Benzoic acid	122.0	87	0.33	0.18	0	0.85	0	6.09
5.369	o-Xylene	91.05	95	0	3.38	0	0	0	0
5.371	p-Xylene	91.05	92	0	0	0	2.8	1.95	3.43
5.708	2(5H)-Furanone	55.05	96	0	0	0	2.79	3.9	4.26
5.778	cis-1,2-Cyclohexanediol	70.05	80	0	0	0	1.9	1.94	2.97
7.966	DL-Norvaline, N-[(phenylmethoxy)carbonyl]-	43.00	74	0	0	0	2.74	0	0
8.627	2-Heptanamine, 5-methyl-	44.05	83	0	3.06	1.72	0	0	0
8.632	Pentanal	44.05	84	0	0	0	2.39	4.13	2.8

Note: retention time (RT); similarity index (SI); molecular weight (MW).

Table 5: The pH and specific gravity of bio-oil.

Bio-oil	pH	Specific gravity
LA	3.01c	1.05a
MA	2.57b	1.04a
HA	2.82c	1.04a
LA-E	2.24a	1.13b
MA-E	2.26a	1.16b
HA-E	2.27a	1.15b

Note: Values are means of three replicates; values sharing the same letter are not significantly different (Tukey's HSD, p-value < 0.05).

Bio-oil produced from MAE-pretreated bamboo exhibited lower pH values and higher specific gravity compared to that from untreated bamboo. In general, differences in growing altitude did not show a clear trend. The most pronounced effect was associated with MAE pretreatment, as bio-oil derived from treated bamboo showed higher acidity and specific gravity than that from non-MAE-treated bamboo (Table 5). This behavior is consistent with the chemical composition of the LAE-E, MA-E, and HA-E bio-oils, which showed higher relative abundances

of acids, acid esters, and other oxygenated compounds such as aldehydes and ketones. These oxygen-rich components are known to contribute to increased acidity and density of bio-oil.

An interesting observation is the increase in D-allose concentration in the bio-oil derived from treated bamboo. D-allose is a C-3 epimer of D-glucose as a result of cellulose degradation via pyrolysis. Chen *et al*., elucidated the formation of carboxylic acids, furan derivatives, anhydrous saccharides, and low-molecular-weight compounds as dominant pyrolysis products via pyrolysis-gas chromatography/mass spectrometry and Fourier-transform infrared spectroscopy [32]. D-allose was actually formed with relatively low abundance in the bio-oil obtained from non-pretreated bamboo, indicating that, naturally, the pyrolysis products of *D. asper* culms are indeed able to generate D-allose. Prado *et al*.,reported that bio-oil from açaí stems (*Euterpe oleracea* Mart./palmwood) contained D-allose with an abundance of 1.8%, whereas bio-oil from cocoa husks (*Theobroma cacao* L., hardwood—non-stem) did not contain D-allose [33]. In addition, a study on catalytic pyrolysis showed a decrease in D-allose abundance in Ni/Al_2O_3-catalytic bio-oil compared to non-catalytic bio-oil from teak wood (hardwood), although no explanation regarding the mechanism was provided [34].

Another study converting microcrystalline cellulose via Al_1–Fe_5 nano-catalytic pyrolysis reported a significant increase in D-allose concentration up to 50.69%, attributed to the presence of Fe^{3+} ions that enhanced acidic oxidation sites while simultaneously promoting β-O-4 glycosidic bond cleavage in cellulose during the pyrolysis process. This facilitated the conversion of cellulose to glucose and promoted isomerization of the –OH group at the C-3 position of glucose to form D-allose [35]. Based on this mechanism and its correlation with the results of the present study, hydrophilic MAE removes extractives that act as physical barriers and induces disruption in biomass morphology, resulting in a cellulose structure that is more accessible to degradation. Consequently, the pyrolysis conversion pathway shifts from a lignin degradation pathway toward a more cellulose-dominated degradation pathway, inducing further degradation of D-glucose derived from cellulose depolymerization and facilitating epimerization of D-glucose into D-allose.

D-allose is a high-value monosaccharide with a sweetness level of approximately 80% relative to sucrose, low caloric content, and proven non-toxicity [36]. In addition, D-allose has been reported to exhibit potential anticancer and antitumor properties [36], making it an attractive candidate for applications in both the food and pharmaceutical sectors.

The production of D-allose via the conversion of cellulose or lignocellulosic biomass through non-catalytic pyrolysis represents a practical approach for transforming abundant, low-cost biomass into high-value products. This approach is particularly promising in regions where lignocellulosic resources are readily available and may contribute to the development of biomass-based industries.

Despite this potential, commercial implementation will require the development of optimization strategies to produce bio-oil with a higher D-allose content. Such optimization would improve process efficiency while simultaneously reducing production costs. Furthermore, because bio-oil consists of a complex mixture of carbohydrate-derived compounds, simple and efficient purification technologies are needed to isolate D-allose at high purity. Simplifying the downstream purification steps would reduce overall costs and enhance the economic feasibility of the process. The biomass-to-D-allose conversion pathway can be developed into a sustainable and economically viable process, capable of supporting broad applications in the food, health, and specialty chemical industries.

4 Conclusions

Altitude was found to influence the chemical composition of bamboo, which in turn affected the characteristics of phytoextracts produced by MAE. The MAE pretreatment also modified bamboo morphology and altered the distribution of pyrolysis products. As a result, MAE-pretreated bamboo generated higher syngas yields, biochar with a rougher surface, and bio-oil with a chemical profile that differed from that of untreated bamboo. While the pyrolysis products of untreated bamboo showed a clear linear response to elevation, such a trend was not observed in MAE-treated samples. In addition, MAE shifted the chemical composition of the bio-oil by increasing carbohydrate-derived compounds and reducing phenolic components. Among these compounds, D-allose, a rare monosaccharide with recognized bioactive potential, was detected at a higher relative abundance in bio-oil obtained from MAE-pretreated bamboo. These findings indicate that MAE pretreatment not only alters pyrolysis behavior

but also provides a promising approach for promoting the formation of value-added rare sugars.

Acknowledgments

This project was funded by the Dana Masyarakat IPB for the 2025 Fiscal Year through the Young Lecturer Research Scheme (Penelitian Dosen Muda) with grant number 11604/IT3.D10/PT.01.03/P/B/2025. The authors thank Muhammad Rafi Sugiarto, Nasya Fadilah, and Ade Pera Amydha Sudrajat Herawati Pendi for their assistance throughout the course of this research. The authors also thank the Collaborative Research Center for Biomass and Bamboo Bioproducts for providing betung bamboo samples and acknowledge the facilities and services provided by the Integrated Laboratory for Bioproducts (ILaB) BRIN through the E-Layanan Sains BRIN, Indonesia.

Author Contributions

Y.H.P: conceptualization, reviewing and editing, investigation, methodology, writing an original draft, reviewing and editing, research design, data analysis, data curation, funding acquisition, project administration; D.S.N: conceptualization, reviewing and editing, methodology, research design; O.F: conceptualization, reviewing and editing, methodology, research design; J.S: reviewing and editing, investigation; W.F: reviewing and editing, data analysis, data curation; N.N: conceptualization, reviewing and editing, investigation, methodology. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

References

[1] O. Bédué, *Features of First Generation Biorefineries*. Switzerland: EPFL Press, 2013, doi: 10.1201/b15443-4.

[2] W. Jerzak, E. Acha, and B. Li, "Comprehensive review of biomass pyrolysis: Conventional and advanced technologies, reactor designs, product compositions and yields, and techno-economic analysis," *Energies*, vol. 17, no. 20, 2024, doi: 10.3390/en17205082.

[3] Y. Li, R. Gupta, Q. Zhang, and S. You, "Review of biochar production via crop residue pyrolysis: Development and perspectives," *Bioresource Technology*, vol. 369, 2023, doi: 10.1016/j.biortech.2022.128423.

[4] A. Amrullah and O. Farobie, "Conversion and rate behavior of brown macroalgae in pyrolysis: Detailed effects of operating parameters," *Heliyon*, vol. 9, no. 7, 2023, Art. no. e18350, doi: 10.1016/j.heliyon.2023.e18350.

[5] W. N. R. W. Isahak, M. W. M. Hisham, M. A. Yarmo, and T. Y. Yun Hin, "A review on bio-oil production from biomass by using pyrolysis method," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 8, pp. 5910–5923, 2012, doi: 10.1016/j.rser.2012.05.039.

[6] M. P. C. Volpi, J. C. G. Silva, A. Hornung, and M. Ouadi, "Review of the current state of pyrolysis and biochar utilization in Europe: A scientific perspective," *Clean Technologies*, vol. 6, no. 1, pp. 152–175, 2024, doi: 10.3390/cleantechnol6010010.

[7] N. Zhou *et al.*, "Syngas production from biomass pyrolysis in a continuous microwave assisted pyrolysis system," *Bioresource Technology*, vol. 314, 2020, Art. no. 123756, doi: 10.1016/j.biortech.2020.123756.

[8] M. del C. Recio-Ruiz *et al.*, "An integrated approach to the valorization of pyrolysis products from lignocellulosic residues and by-products," *Biomass and Bioenergy*, vol. 196, 2025, Art. no. 107676, doi: 10.1016/j.biombioe.2025.107676.

[9] T. Q. S. Sampaio, F. S. Cunha, L. M. A. Campos, and C. A. M. Pires, "Evaluation of the influence of hydrophilic extractives on the formation of bio-oil from the micro-pyrolysis of biomass waste," *Journal of Analytical and Applied Pyrolysis*, vol. 178, 2024, Art. no. 106417, doi: 10.1016/j.jaap.2024.106417.

[10] R. A. Murda *et al.*, "Changes in chemical composition of Betung bamboo (*Dendrocalamus asper*) after alkali immersion treatment under various immersion times," *Journal of Sylva Lestari*, vol. 10, no. 3, pp. 358–371, 2022, doi: 10.23960/jsl.v10i3.599.

[11] Y. Li *et al.*, "Pyrolysis kinetics and thermodynamic parameters of bamboo residues

and its three main components using thermogravimetric analysis," *Biomass and Bioenergy*, vol. 170, 2023, Art. no. 106705, doi: 10.1016/j.biombioe.2023.106705.

[12] T. W. Widayati, D. Jaya, A. Danujatmiko, and B. D. Trimulyo, "Characterization of activated carbon from pyrolysis process of bamboo base waste (*Dendrocalamus asper*)," *CHEMICA: Jurnal Teknik Kimia*, vol. 7, no. 1, p. 63, 2020, doi: 10.26555/chemica.v7i1.15876.

[13] W. Astuti, R. M. Ramadhan, and V. A. Octaviany, "Synthesis of activated carbon from petung bamboo stems (*Dendrocalamus asper*) using microwave-assisted pyrolysis (MAP) process for biogas storage," *Jurnal Bahan Alam Terbarukan*, vol. 11, no. 1, pp. 58–67, 2022, doi: 10.15294/jbat.v11i1.36939.

[14] I. Sumardi, A. Z. Hikmatiar, L. Melani, A. Darwis, A. Hadiyane, and A. A. Sembada, "Revealing changes in the physical, mechanical, and chemical properties of Betung bamboo (*Dendrocalamus asper*) under heating and smoking treatment," *Journal of the Indian Academy of Wood Science*, vol. 22, no. 2, pp. 324–336, 2025, doi: 10.1007/s13196-025-00387-0.

[15] J. Liang, X. Xu, Z. Yu, L. Chen, Y. Liao, and X. Ma, "Effects of microwave pretreatment on catalytic fast pyrolysis of pine sawdust," *Bioresource Technology*, vol. 293, 2019, Art. no. 122080, doi: 10.1016/j.biortech.2019.122080.

[16] L. Dai, Y. Wang, Y. Liu, and R. Ruan, "Microwave-assisted pyrolysis of formic acid pretreated bamboo sawdust for bio-oil production," *Environmental Research*, vol. 182, 2020, Art. no. 108988, doi: 10.1016/j.envres.2019.108988.

[17] M. Rafi *et al.*, "Untargeted metabolomics analysis of *Diospyros celebica* Bakh. from three different geographical origins in Sulawesi island using UHPLC-Q-Orbitrap HRMS," *Wood Science and Technology*, vol. 57, no. 1, pp. 211–228, 2023, doi: 10.1007/s00226-022-01440-8.

[18] R. Musule *et al.*, "Chemical composition of lignocellulosic biomass in the wood of *Abies religiosa* across an altitudinal gradient," *Journal of Wood Science*, vol. 62, no. 6, pp. 537–547,2016, doi: 10.1007/s10086-016-1585-0.

[19] M. Golian, D. Tančinová, J. Lakatošová, M. Mrvová, J. Gažo, and P. Borsányi, "Effect of altitude on biomass production and essential oil composition of selected medicinal plants," *Industrial Crops and Products*, vol. 233, 2025, Art. no. 121475, doi: 10.1016/j.indcrop.2025.121475.

[20] S. Kasemsukphaisan and S. Maksup, "Phytochemical profiling, antioxidant, and antityrosinase activities of bamboo leaves in Thailand," *Applied Science and Engineering Progress*, vol. 16, no. 1, 2022, Art. no. 6229, doi: 10.14416/j.asep.2022.09.002.

[21] H. López-Salazar, B. H. Camacho-Díaz, M. L. A. Ocampo, and A. R. Jiménez-Aparicio, "Microwave-assisted extraction of functional compounds from plants: A review," *BioResources*, vol. 18, no. 3, pp. 6614–6638, 2023, doi: 10.15376/biores.18.3.Lopez-Salazar.

[22] Y. H. Prayogo, W. Syafii, R. K. Sari, I. Batubara, and Danu, "Pharmacological activity and phytochemical profile of acacia heartwood extracts," *Scientia Pharmaceutica*, vol. 89, no. 3, Art. no. 37, 2021, doi: 10.3390/scipharm89030037.

[23] J. Parikh, S. A. Channiwala, and G. K. Ghosal, "A correlation for calculating HHV from proximate analysis of solid fuels," *Fuel*, vol. 84, no. 5, pp. 487–494, 2005, doi: 10.1016/j.fuel.2004.10.010.

[24] S. G. Kostryukov, H. B. Matyakubov, Y. Yu, A. S. Kozlov, and M. K. Pryanichnikova, "Determination of lignin, cellulose, and hemicellulose in plant materials by FTIR spectroscopy," *Journal of Analytical Chemistry*, vol. 78, no. 6, p. 718–727, 2023, doi: 10.1134/S1061934823040093.

[25] W. Wang, X. Zhao, S. Liu, L. Cai, S. Q. Shi, and Y. Ni, "Effect of various microwave absorbents on the microwave-assisted lignin depolymerization process," *ACS Sustainable Chemistry & Engineering*, vol. 8, no. 31, pp. 11624–11633, 2020, doi: 10.1021/acssuschemeng.0c04658.

[26] N. Tran, T. Khanh, V. Thi, D. Chi, and N. T. An, "Evaluation of antioxidant capacity in *Dendrocalamus asper* extracts cultivated in agricultural fields of An Giang Province, Vietnam," *Journal of Xi'an Shiyou University, Natural Science Edition*, vol. 19, no. 6, 2023.

[27] X. Zhang, Y. Zhang, S. Zhang, L. Yao, and Y. Hao, "Lignocellulosic biomass pyrolysis: A review on the pretreatment and catalysts," *Fuel Processing Technology*, vol. 279, 2025, Art. no.

108352, doi: 10.1016/j.fuproc.2025.108352.
[28] R. Valdmanis and M. Zake, "Selective microwave pretreatment of biomass mixtures for sustainable energy production," *Energies*, vol. 18, no. 14, Jul. 2025, doi: 10.3390/en18143677.
[29] S. S. Sahoo, V. K. Vijay, R. Chandra, and H. Kumar, "Production and characterization of biochar produced from slow pyrolysis of pigeon pea stalk and bamboo," *Cleaner Engineering and Technology*, vol. 3, 2021, Art. no. 100101, doi: 10.1016/j.clet.2021.100101.
[30] M. B. Figueirêdo, I. Hita, P. J. Deuss, R. H. Venderbosch, and H. J. Heeres, "Pyrolytic lignin: a promising biorefinery feedstock for the production of fuels and valuable chemicals," *Green Chemistry*, vol. 24, no. 12, pp. 4680–4702, 2022, doi: 10.1039/d2gc00302c.
[31] C. F. Linares, J. Quintero, L. Martínez, and G. González, "A new antacid drug from activated carbon modified with calcium carbonate," *Materials Letters*, vol. 61, no. 11–12, pp. 2362–2364, 2007, doi: 10.1016/j.matlet.2006.09.012.
[32] L. Chen, Y. Liao, Z. Guo, Y. Cao, and X. Ma, "Products distribution and generation pathway of cellulose pyrolysis," *Journal of Cleaner Production*, vol. 232, pp. 1309–1320, 2019, doi: 10.1016/j.jclepro.2019.06.026.
[33] R. M. L. Prado, R. Surculento, V. Luis, and L. Henrik, "Pyrolysis of açai stems (*Euterpe oleracea* Mart.) and cocoa husks (*Theobroma cacao* L.) residues for the generation of added-value products in rural areas," *Biomass Conversion and Biorefinery*, vol. 15, no. 11, pp. 16793–16804, 2025, doi: 10.1007/s13399-024-06325-3.
[34] M. Bhattacharyya, K. Prasad, and R. Purkayastha, "Catalytic upgradation of pyrolytic products by catalytic pyrolysis of sawdust using a synthesized composite catalyst of NiO and Ni(II) aluminates," *Renewable Energy*, vol. 221, 2024, Art. no. 119658, doi: 10.1016/j.renene.2023.119658.
[35] Y. Zhang, G. Qu, Z. Li, J. Zhou, R. Xu, and J. Li, "Effective catalytic conversion of cellulose pyrolysis into D-Allose via Al1-Fe5," *Molecular Catalysis*, vol. 569, 2024, Art. no. 114506, doi: 10.1016/j.mcat.2024.114506.
[36] X. Tang, Y. Ravikumar, G. Zhang, J. Yun, M. Zhao, and X. Qi, "D-allose, a typical rare sugar: properties, applications, and biosynthetic advances and challenges," *Critical Reviews in Food Science and Nutrition*, vol. 65, no. 14, pp. 2785–2812, 2025, doi: 10.1080/10408398.2024.2350617.