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Effect of Temperature and N-Doping on the Distribution of Bamboo Waste Pyrolysis Products Using Quartz Tube Furnace

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ABSTRACT: This study investigates the effect of temperature and nitrogen doping (N-Doping) on the pyrolysis of bamboo waste to optimize the distribution of biochar, bio-oil, and gas products. Bamboo waste as raw material was applied to pyrolysis in a quartz tube furnace reactor at temperatures of 300°C, 400°C, 500°C, and 600°C under two atmospheric conditions: pyrolysis with nitrogen (PN) and pyrolysis without nitrogen (PWN). The results showed that the maximum bio-oil yield achieved of 55.32% at 500°C under pyrolysis with nitrogen (PN), while the maximum bio-oil yield achieved of 52 % at 500°C under pyrolysis without nitrogen (PWN). Nitrogen doping can increase bio-oil production by preventing oxidation and reducing secondary reactions. In addition, PWN conditions produced higher biochar yields due to partial oxidation. Gas yields increased at higher temperatures in both conditions, which was caused by thermal cracking and reforming processes. These findings emphasize the importance of using nitrogen doping and controlled temperature under atmospheric conditions to maximize the efficiency and product quality of bamboo waste pyrolysis. The results provide valuable insights into sustainable biomass conversion strategies, contributing to the development of renewable energy and increasing the value of bamboo waste.

Keywords: bamboo waste; biochar biomass; n-doping; pyrolysis

1. Introduction

Bamboo is one of the abundant natural resources with wide applications in various sectors, especially in tropical regions such as Indonesia. In 2021, total bamboo production in Indonesia increased significantly, reaching 50.1 million stems (BPS-Statistics, 2022). In addition, bamboo has a relatively fast growth cycle, which is around 20.32 cm to 50 cm per day depending on the species (Yadav & Mathur, 2021). One of the locations of this study is Mojorejo Village, East Java, which has a bamboo planting area of 15 hectares (Muslih et al., 2020). The high compressive strength and sustainability of bamboo have made it a popular choice in construction and design (Linh, 2024), It is increasingly utilized in modern architecture and interior design due to its aesthetic appeal and sustainability, The rapid growth cycle of bamboo (3-5 years) ensures a continuous supply of raw material (Rashmi Sarmah & Neog, 2024). Its cultivation helps conserve forests and promotes sustainable economic development (Chaudhary et al., 2024). However, the intensive use of bamboo generates significant biomass waste, including culm fragments and production residues. Effective management of this waste is essential for optimizing its value. Therefore, a sustainable and value-added approach is needed to utilize bamboo waste, one of which is through the pyrolysis process.

Pyrolysis is a thermochemical conversion method that can be used to process biomass into high-value products, such as biochar (solid residue), bio-oil (liquid product), and gas (volatile product) (Mufandi et al., 2020). This process is carried out at high temperatures in conditions without oxygen or with very limited oxygen, resulting in products that can be used for various applications (Somerville & Deev, 2020; Tong et al., 2020). Biochar has great potential for use in soil amendment, pollutant adsorption, and carbon emission mitigation (Aini et al., 2023). While bio-oil can be used as liquid fuel or industrial chemical raw material (Gautam & Chaurasia, 2020). Pyrolysis gas is rich in compounds such as carbon monoxide (CO), methane (CH_4), and hydrogen (H_2) that can be used as fuel for heat energy purposes (Kryshtopa et al., 2021; Zhang et al., 2023). Pyrolysis has advantages over other conversion methods due to its flexibility in producing a wide range of products that can be tailored to needs (Jerzak et al., 2024; Wang et al., 2017b).

The distribution of pyrolysis products is greatly influenced by process parameters, such as temperature, residence time, heating rate, and reaction atmosphere.

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Among these parameters, temperature has the most significant effect on pyrolysis yield, because temperature determines the thermochemical decomposition mechanism of lignocellulosic biomass components (Treedet et al., 2020). Lignocellulosic biomass, such as bamboo waste, consists of three main components: hemicellulose, cellulose, and lignin. At low temperatures hemicellulose degrades to produce light volatile compounds, such as carbon dioxide (CO_2) and organic acids (Wang et al., 2021). Cellulose begins to decompose at medium temperatures (300–400°C) through a depolymerization process, producing energy-rich bio-oil (Jamilatun et al., 2022). Lignin, which is more thermally stable, decomposes at high temperatures (>400°C), producing biochar rich in aromatic carbon and volatile compounds such as phenols. Therefore, selecting the appropriate temperature is very important to optimize the distribution of pyrolysis products according to the desired application.

In addition, the addition of nitrogen gas or N-doping also has an important role in determining the distribution and quality of pyrolysis products (Kasera et al., 2022). Pyrolysis is generally carried out in an inert gas, such as nitrogen, to prevent oxidation reactions that can reduce the yield of volatile products, such as bio-oil, and increase the formation of carbon dioxide from the oxidation of volatile compounds or solid carbon (Chen et al., 2016). Nitrogen helps stabilize volatile compounds produced during devolatilization and prevents secondary reactions, such as oxidation or thermal cracking, which can reduce bio-oil yield. In contrast, in conditions without atmospheric control (without nitrogen), the presence of residual oxygen can trigger partial oxidation of volatile compounds and solid carbon, producing more gas but reducing the quality of bio-oil and biochar. Therefore, evaluation of the effect of atmospheric nitrogen on the distribution of pyrolysis results is very important, especially in relation to biomass conversion efficiency.

Bamboo waste has great potential to be processed through pyrolysis because of its supporting chemical characteristics. The high cellulose and hemicellulose content allows bamboo waste to produce significant amounts of bio-oil, while the lignin content also supports the formation of biochar with good carbon stability (Chaturvedi et al., 2024). In addition, bamboo waste has low ash and water content, which makes it an efficient raw material for thermochemical processes, as it minimizes the energy required for water evaporation and reduces ash residue. However, research on bamboo waste pyrolysis, especially those discussing the effect of atmospheric nitrogen on yield distribution, is still very limited. Most previous studies have focused more on other biomass, such as hardwood, agricultural residues, or industrial wood waste, so further studies specifically on bamboo waste are needed. Several previous studies have shown that nitrogen atmosphere plays an important role in increasing pyrolysis efficiency (Nan et al., 2020). N-doped carbon materials exhibit improved catalytic performance for reactions like NO oxidation, with a conversion rate increase from 47.3% to 54.7% when nitrogen is incorporated (Deng et al., 2025). The simultaneous activation and nitrogen doping during biomass pyrolysis can significantly increase the specific surface area and nitrogen content of biochar (Wang et al., 2024). However, these studies mostly used biomass other than bamboo, so the results cannot be generalized to bamboo waste which has unique chemical characteristics. In addition, there are still few studies that discuss the comparison of pyrolysis with and without nitrogen, especially in relation to the distribution of biochar, bio-oil, and gas results.

This study aims to evaluate the effect of temperature and nitrogen atmosphere on the pyrolysis results of bamboo waste. The focus in this study is to understand how these two parameters (Pyrolysis with Nitrogen (PN) and Pyrolysis Without Nitrogen (PWN) affect the distribution of biochar, bio-oil, and gas products, as well as the mechanisms underlying these changes. By comparing pyrolysis conditions with and without nitrogen at various temperatures, this study can provide new insights into the optimization of bamboo waste pyrolysis to produce high-value products.

2. Materials and Methods

2.1. Raw Materials

Bamboo waste as the main raw material in this study was obtained from the Kampung Bambu Group (Deling Studio) in Mojorejo Village, Ponorogo, East Java. Meanwhile, nitrogen gas as the inner gas was obtained from CV. Gasindo, Ponorogo Regency, East Java. The supporting equipment such as an oven with a oven memmert UN 55 and a grinder type miller DE200G was supported by the chemistry laboratory at Département of agro-industrial technology, Universitas Darussalam Gontor.

2.2. Bamboo Waste Preparation

The initial processing of bamboo waste before the pyrolysis process includes drying, shredding, and weighing. Bamboo waste is dried in direct sunlight for 8 hours and 1.5-2 hours using an oven at a temperature of 80 C to reduce its water content to below 10%. This drying stage is very important, because high water content can affect pyrolysis products and significantly increase energy consumption during the pyrolysis process. Materials with high water content tend to reduce the calorific value of pyrolysis products because some of the energy is spent on evaporating water. The next stage shredded bamboo waste to a small size to facilitate the process of inserting bamboo waste into the reactor. Furthermore, the characteristics of bamboo waste are tested using parameters such as water content, ash content, lignin composition, cellulose, and hemicellulose. This characterization provides important information about the chemical and physical properties of raw materials.

2.3. Pyrolysis Equipment and Procedures

A total of 50 grams of bamboo waste was placed into a quartz tube furnace reactor for the pyrolysis process. The pyrolysis was conducted at four different temperature variations: 300°C, 400°C, 500°C, and 600°C. The study also investigated the effect of nitrogen doping by introducing two pyrolysis conditions: pyrolysis with nitrogen (PN) and pyrolysis without nitrogen (PWN). In the PN process, nitrogen gas (N_2) was used as an inert carrier at a flow rate of 500 mL/min to establish an oxygen-free environment, prevent unwanted oxidation reactions, and facilitate the decomposition of organic matter into bio-oil, syngas, and biochar. This flow rate aligns with values commonly reported in similar pyrolysis studies, where nitrogen effectively scavenges residual oxygen and supports efficient thermal decomposition (Ngo & Kim, 2014). The absence of nitrogen in the PWN condition served as a control to evaluate the role of inert gas in influencing the reaction kinetics, product distribution, and overall efficiency of the pyrolysis process. The quartz tube furnace reactor configuration employed in this study is shown in Figure 1 and the research stages can be seen in Figure 2.

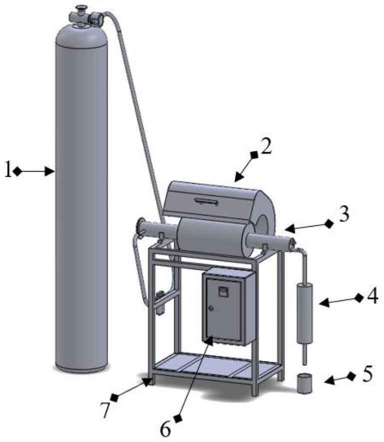

Figure 1. The quartz tube furnace reactor configuration

Based on Figure 1, the pyrolysis apparatus consists of several key components: a nitrogen gas tank (1), a reactor cover (2), a reactor with a bamboo waste sample holder (3), a condenser (4), a bio-oil storage container (5), an electrical control system (6), and a support stand (7). The quartz tube furnace reactor used in this study has specific dimensions: a length of 700 mm, a diameter of 60 mm, a stand height of 600 mm, and a stand width of 500 mm. The sample holder within the reactor has a length of 300 mm. The reactor is equipped with a heating jacket designed to minimize heat loss and ensure consistent temperature throughout the pyrolysis process. Additionally, the reactor features a condenser for efficient cooling and condensation of the volatile products, facilitating the collection of bio-oil. The nitrogen gas flow into the reactor is precisely controlled using a rotameter, which ensures accurate and steady gas flow during the pyrolysis process.

The calculation of pyrolysis product yields followed the methodology outlined in previous research (Jamilatun et al., 2022) with no significant modifications. The pyrolysis products: biochar, bio-oil, and gas were quantified using Equations (1) through (3), which determine the percentage yield of each product based on their respective weights relative to the initial biomass feedstock. These equations are standard in pyrolysis studies and are expressed in Eq 1 to 3.

$$Y_{bio-oil} = \frac{W_{bio-oil}}{W_{bamboo\,waste}} x100\% \tag{1}$$

$$Y_{biochar} = \frac{W_{bio-char}}{W_{bamboo\,waste}} x100\% \tag{2}$$

$$Y_{gas} = \frac{W_{gas}}{W_{bamboo\,wate}} x100\% \tag{3}$$

where Y_b, Y_c, and Y_g are yields of bio-oil (wt.%), biochar (wt.%), and gas (wt.%), respectively. W_m, W_b, and W_c, respectively, are the sample weight of bagasse (g), liquid product (g), and biochar (g).

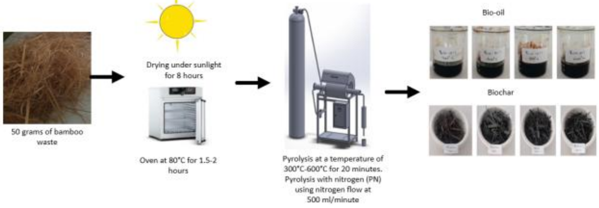

Figure 2. the research stages

3. Results and Discussion

3.1. Characteristics of Bamboo Waste

Bamboo waste has great potential to be processed into biochar, bio-oil, and gas through the pyrolysis process. In this study, the characteristics of bamboo waste are shown in Table 1. The nitrogen content in bamboo waste (0.18%) makes bamboo waste an ideal raw material for producing biochar with a high carbon content. Low nitrogen levels also minimize the risk of nitrogen oxide (NOx) release, thereby improving carbon stability and biochar quality, especially for soil amendment applications (Wang et al., 2017a). The relatively low water content of bamboo waste (5.50%) is another advantage, because the low water content will reduce the energy required for water evaporation during the initial stage of pyrolysis, thereby increasing overall energy efficiency (Qian et al., 2015). In addition, low water content also reduces the formation of water vapor in the gas product, which can affect the composition and calorific value of the pyrolysis gas.

The ash content in bamboo waste of 2.62% shows that this material has a low mineral content, thus producing biochar with higher carbon purity. This is important for various applications, such as pollutant adsorption, soil amendment, or raw material for composite materials. The low ash content also reduces the mineral residues remaining after pyrolysis, which further improves the quality of biochar (Wang et al., 2014). Meanwhile, the high content of cellulose (54.27%) and hemicellulose (26.32%) contributed significantly to the pyrolysis results. Cellulose is the main component that plays a role in producing bio-oil with high energy content, while hemicellulose increases the amount of volatile gas in the early stages of pyrolysis, which can be used as a source of heat energy to support the sustainability of the process (Yang et al., 2016).

In addition, the relatively low lignin content (5.94%) still plays an important role in the formation of carbon-rich biochar. Lignin degrades at high temperatures and produces biochar with good carbon stability, as well as porosity that supports optimal absorption. The high carbon stability of biochar makes it ideal for a variety of environmental applications, including carbon emission mitigation and soil quality improvement (Tripathi et al., 2016). The low lignin content in bamboo waste is mainly caused by the biological characteristics of bamboo as a monocotyledonous plant with rapid growth and a lignocellulose structure dominated by cellulose and hemicellulose. The low lignin content is in line with the research results from (Hu et al., 2019) on bamboo pyrolysis, where the lower proportion of lignin indicates that bamboo is mostly composed of cellulose and hemicellulose,

The chemical and physical characteristics of bamboo waste indicate that this material is very suitable to be processed through the pyrolysis process with optimal results. With the right temperature and pyrolysis time settings, bamboo waste can produce high-value products such as biochar, bio-oil, and gas.

Table 1. Characteristics of bamboo waste

No	Characteristics	Bamboo Waste
1	Nitrogen (%)	0.18
2	Water content (%)	5.50
3	Ash content (%)	2.62
4	Cellulose (%)	54.27
5	Hemicellulose (%)	26.32
6	Lignin (%)	5.94

3.2. Effect of Temperature on The Distribution of Bamboo Waste Pyrolysis Product Using Quartz Tube Furnace Reactor

The results of the study on the effect of temperature on the distribution of bamboo waste pyrolysis can be seen in Figure 3. The results of this study indicate that temperature plays an important role in determining the yield of each product including biochar, bio-oil, and gas through the thermochemical decomposition of lignocellulose in bamboo waste. The Increasing of temperature generally causes a decrease in biochar yield, an increase in gas yield, and a peak in bio-oil yield at a certain temperature before finally decreasing. At 300°C, the biochar yield was 28%, bio-oil was 38%, and gas was 34%. With increasing temperature to 400°C, the biochar yield decreased slightly to 26%, while the bio-oil yield increased significantly to 50%, followed by a decrease in gas to 23%. At 500°C, the bio-oil yield peaked at 52%, while the biochar yield increased slightly to 27%, and the gas yield reached again to 21%. At 600°C, the bio-oil yield began to decline to 47%, while the gas yield increased sharply to 29%, and the biochar yield dropped to 24%. These changes indicate the dynamics of biomass degradation at various pyrolysis temperatures

The effect of temperature on biochar shows a decrease as the pyrolysis temperature increases. This is because at higher temperatures, lignocellulosic components, such as cellulose, hemicellulose, and lignin, are degraded more intensely, so that more volatile materials are released as gas and biochar (Jamilatun et al., 2020). The increase in bio-oil yields up to 500°C is associated with the maximum decomposition of hemicellulose and cellulose. However, at temperatures >500°C, bio-oil begins to decompose into light gases due to thermal cracking. The decrease in bio-oil yield also reflects the occurrence of secondary reactions, such as gas reformation or polymerization. Meanwhile, the increase in gas yield at high temperatures reflects the thermal reformation reaction and further decomposition of bio-oil and biochar.

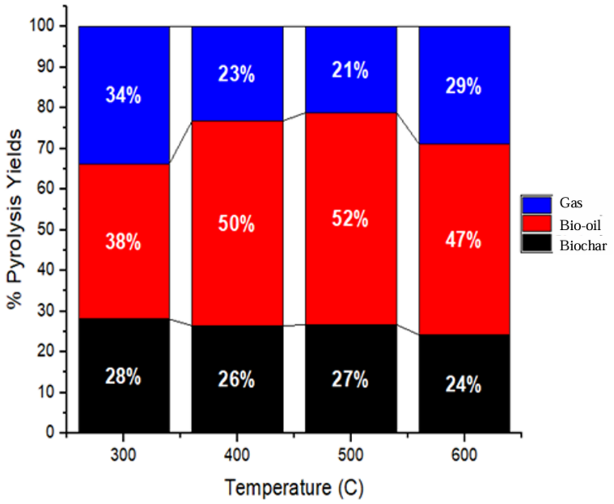

Figure 3. Effect of temperature on the distribution of pyrolysis products (biochar, bio-oil, and gas)

The biomass process mechanism occurs in three main stages, namely dehydration, devolatilization, and reformation or further cracking (Jamilatun et al., 2017; Vamkuka, 2012; Vuppaladadiyam et al., 2023). The temperatures < 200°C is the dehydration stage where free water and bound water in biomass are evaporated. This stage does not involve major chemical reactions, but preparation of the material for subsequent thermal decomposition. In the devolatilization stage, thermal decomposition occurs in lignocellulose components such as hemicellulose, cellulose, and lignin. Hemicellulose is the first component to degrade, producing volatile compounds, such as carbon dioxide (CO_2), carbon monoxide (CO), organic acids, and other light compounds. The main reactions that occur are decarboxylation and decarboxylation. Cellulose produces bio-oil rich in organic compounds, such as organic acids, furfural, and volatile hydrocarbons. The main reaction is depolymerization into monomers such as glucose, followed by thermal cracking. Lignin decomposes more slowly than hemicellulose and cellulose, producing complex aromatic compounds, phenols, and biochar. The main reaction involves aromatic condensation which produces aromatic carbon-rich biochar. The final stage is reforming and further cracking, which volatile compounds produced from devolatilization undergo further cracking, producing light gases such as hydrogen (H_2), methane (CH_4), carbon monoxide (CO), and carbon dioxide (CO_2). In addition, the bio-oil produced begins to decompose back into gas, which causes a decrease in bio-oil yield at high temperatures (Mufandi et al., 2023).

Bio-oil yield increased significantly in PN atmosphere compared to PWN, especially at temperatures of 300–500°C. At a temperature of 300°C, the bio-oil yield in PN is 40.67%, while in PWN it is only 11.19%. At 400°C, bio-oil yield reached 44.64% in PN and 27.70% in PWN. The most significant increase was seen at 500°C, where the bio-oil yield in PN reached 55.32%, compared to 16.52% in PWN.

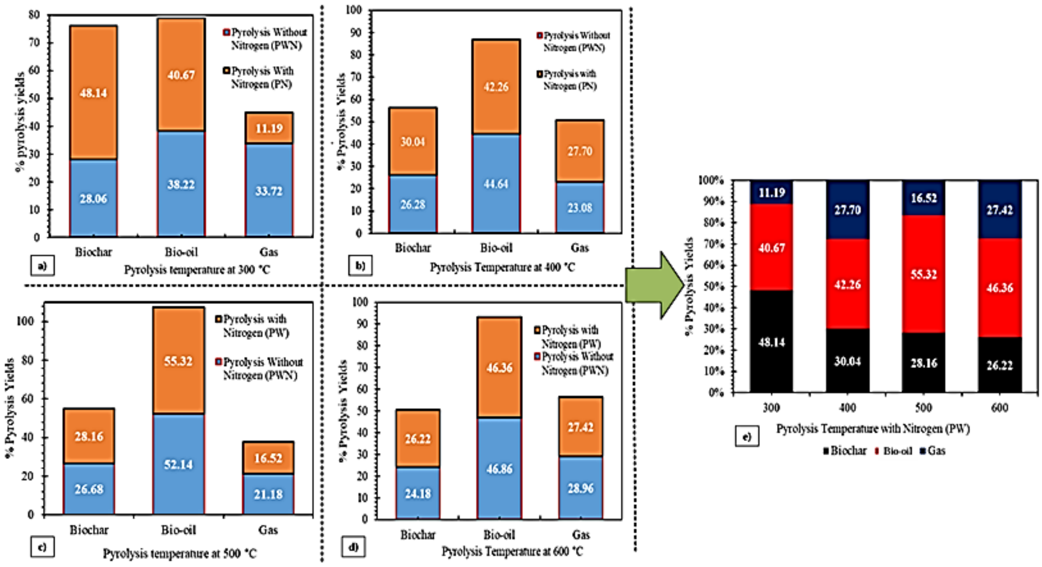

Figure 4. Effect of pyrolysis with nitrogen (PN) and pyrolysis without nitrogen (PWN)

3.3. Effect of N-Doping on The Distribution of Pyrolysis from Bamboo Waste

Figure 4 shows the effect of N-Doping on the pyrolysis results of bamboo waste at various temperatures (300°C, 400°C, 500°C, and 600°C). In this study, there are two main conditions compared between pyrolysis with nitrogen (PN) and pyrolysis without nitrogen (PWN) to evaluate the role of atmospheric nitrogen in influencing the distribution of pyrolysis results and the mechanism of chemical reactions that occur. The pyrolysis products observed include biochar, bio-oil, and gas. According to Figure 4, the biochar yield in PN conditions was lower than PWN. At 300°C, the biochar yield in PN was 28.06%, while in PWN it reached 48.14%. Similar patterns were seen at 400°C (30.04% in PN vs. 42.26% in PWN), 500°C (28.16% in PN vs. 26.68% in PWN), and 600°C (26.22% in PN vs. 24.18% in PWN). The decrease in biochar yield in nitrogen atmosphere indicates that the presence of nitrogen supports a more efficient devolatilization reaction, so that more biomass is decomposed into volatile compounds (bio-oil and gas). In addition, nitrogen prevents partial oxidation of carbon that occurs in nitrogen-free (PWN) conditions, which can increase the amount of solid residue (biochar) due to the reaction of carbon with oxygen remaining in the gas nitrogen inert. These results are consistent with the research result from (Aladin et al., 2020) which stated that an inert atmosphere (such as nitrogen) facilitates the decomposition of lignocellulose into volatile compounds.

However, at 600°C, the bio-oil yield in PN decreased to 46.36%, although it was still higher than PWN (27.42%). The increase in bio-oil yield in nitrogen atmosphere is due to the prevention of thermal oxidation reactions that occur in PWN. Nitrogen as an inert atmosphere prevents volatile compounds from being oxidized into light gases, so that more volatile compounds are condensed into bio-oil (Jamilatun et al., 2020; Treedet et al., 2020). Additionally, a nitrogen atmosphere reduces secondary reactions, such as thermal cracking and polymerization, which normally convert bio-oil to gas or solid carbon under nitrogen-free conditions.

Gas yield was higher in PN conditions compared to PWN at high temperatures (>500°C). At a temperature of 300°C, the gas yield in PN is 33.72%, while in PWN it is only 11.19%. At 400°C, the gas yield in PN increased to 27.70%, compared with 23.08% in PWN. At 500°C, the gas yield in PN is 21.18%, slightly higher than PWN (16.52%). At temperature of 600°C, the gas yield in PN reached 28.96%, higher than PWN (27.42%). At high temperatures, nitrogen atmosphere enhances gas production through devolatilization and thermal cracking mechanisms. Nitrogen also promotes the reformation of volatile compounds into light gases, such as CO, CO_2, CH_4, and H_2, through secondary reactions at high temperatures.

The observed trends in this study align with findings from other biomass pyrolysis research. For instance, (Mohamed et al., 2013) reported a slight increase in bio-oil yield, from 45.65% at a nitrogen flow rate of 150 cm³/min to 46.02% at 200 cm³/min. This indicates that increasing the nitrogen flow rate enhances gas velocity, facilitating the faster removal of hot vapours, reducing their residence time, and minimizing secondary reactions. Similarly, (Saif et al., 2020) observed a maximum bio-oil yield of 45 wt% at 500 °C with a nitrogen flow rate of 200 cm³/min. Temperature was identified as the most significant factor affecting product distribution. Higher temperatures reduced bio-char yield while increasing gas yield. Bio-oil yield increased with temperature up to 500 °C but declined at higher temperatures due to secondary cracking reactions, which fevered the formation of gaseous products. The comparative mechanism analysis between pyrolysis with nitrogen and without nitrogen in the distribution of pyrolysis results can be seen in Table 2.

Tabel 2. Comparative mechanism analysis of pyrolysis with nitrogen (PN) and without nitrogen (PWN)

No	Pyrolysis with Nitrogen (PN)	Pyrolysis Without Nitrogen (PWN)
1	The nitrogen atmosphere prevents oxidation reactions of carbon and volatile compounds.	Carbon oxidation produces a larger amount of biochar residue, resulting in a higher biochar yield.
2	The devolatilization mechanism is more dominant, producing high amounts of bio-oil and gas with high calorific value.	Volatile compounds are more easily decomposed into gas due to thermal oxidation and cracking reactions.
3	Volatile compounds are better protected from secondary reactions, so that the bio-oil yield is more optimal.	Partial oxidation of volatiles can significantly reduce the yield of bio-oil.

4. **Conclusions**

This study highlights the significance of nitrogen doping (N-doping) in enhancing bio-oil yield and quality during bamboo waste pyrolysis. The findings demonstrate that N-doping prevents oxidation and reduces secondary cracking reactions, leading to optimized product yields, particularly bio-oil. The maximum bio-oil yield of 55.32% was achieved at 500°C under N-doping conditions, emphasizing the role of controlled pyrolysis parameters in improving the efficiency of biomass conversion processes. The results of this study have practical implications for improving the product pyrolysis. Future research should investigate alternative doping gases and further optimize pyrolysis parameters, such as heating rates and residence times, to maximize efficiency and product quality.

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Statement

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CRediT authorship contribution statement

Ilham Mufandi: Supervision, Conceptualization, Writing – review & editing, Writing – original draft, and Conceptualization. **Muhammad Nur Kholis**: Methodology, and Validation, **Mahmudah Hamawi**: Resources and Data curation **Much Taufik Ardani**: Investigation and formal analysis. **Hafidha Ayu Kusuma**: Project administration, and Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data may be shared upon request.

References

Aladin, Modding, B., T. S., & F. C. D. (2020). Effect of nitrogen gas flowing continuously into the pyrolysis reactor for simultaneous production of charcoal and liquid smoke. *The 2nd International Seminar on Science and Technology (ISST-2)*, 1–5.

Aini, N., Mufandi, I., Jamilatun, S., & Rahayu, A. (2023). Exploring cacao husk waste – Surface modification, characterization, and its potential for removing phosphate and nitrate ions. *Journal of Ecological Engineering, 24*(12), 282–292.

BPS-Statistics. (2022). *Statistics of forestry production 2021*. BPS-Statistics Indonesia.

Chaturvedi, K., Singhwane, A., Dhangar, M., Mili, M., Gorhae, N., Naik, A., Prashant, N., Srivastava, A. K., & Verma, S. (2024). Bamboo for producing charcoal and biochar for versatile applications. *Biomass Conversion and Biorefinery, 14*(14), 15159–15185.

Chaudhary, U., Malik, S., Rana, V., & Joshi, G. (2024). Bamboo in the pulp, paper and allied industries. *Advances in Bamboo Science, 7*, 100069.

Chen, W., Yang, H., Chen, Y., Chen, X., Fang, Y., & Chen, H. (2016). Biomass pyrolysis for nitrogen-containing liquid chemicals and nitrogen-doped carbon materials. *Journal of Analytical and Applied Pyrolysis, 120*, 186–193.

Deng, W., Zhang, Y., Hu, M., Wang, R., & Su, Y. (2025). Optimization of nitrogen-doped sludge char preparation and mechanism study for catalytic oxidation of NO at room temperature. *Journal of Environmental Sciences, 150,* 503–514.

Gautam, N., & Chaurasia, A. (2020). Study on kinetics and bio-oil production from rice husk, rice straw, bamboo, sugarcane bagasse and neem bark in a fixed-bed pyrolysis process. *Energy, 190,* 116434.

Hu, J., Yan, Y., Evrendilek, F., Buyukada, M., & Liu, J. (2019). Combustion behaviors of three bamboo residues: Gas emission, kinetic, reaction mechanism and optimization patterns. *Journal of Cleaner Production, 235,* 549–561.

Jamilatun, S., Budhijanto, Rochmadi, & Budiman, A. (2017). Thermal decomposition and kinetic studies of pyrolysis of *Spirulina platensis* residue. *International Journal of Renewable Energy Development, 6*(3), 193–201.

Jamilatun, S., Mufandi, I., Evitasari, R. T., & Budiman, A. (2020). Effects of temperature and catalysts on the yield of bio-oil during the pyrolysis of *Spirulina platensis* residue. *International Journal of Renewable Energy Research, 10*(2), 678–686.

Jamilatun, S., Pitoyo, J., Amelia, S., Ma'arif, A., Hakika, D. C., & Mufandi, I. (2022). Experimental study on the characterization of pyrolysis products from bagasse (*Saccharum officinarum* L.): Bio-oil, biochar, and gas products. *Indonesian Journal of Science and Technology, 7*(3), 565–582.

Jerzak, W., Acha, E., & Li, B. (2024). Comprehensive review of biomass pyrolysis: Conventional and advanced technologies, reactor designs, product compositions and yields, and techno-economic analysis. *Energies, 17*(20).

Kasera, N., Kolar, P., & Hall, S. G. (2022). Nitrogen-doped biochars as adsorbents for mitigation of heavy metals and organics from water: A review. *Biochar, 4*(1), 17.

Kryshtopa, S., Kryshtopa, L., Panchuk, M., Smigins, R., & Dolishnii, B. (2021). Composition and energy value research of pyrolysis gases. *IOP Conference Series: Earth and Environmental Science, 628*(1), 012008.

Linh, H. C. T. (2024). Application of bamboo materials in the field of interior architecture design—Modern landscape. In C. Ha-Minh, C. H. Pham, H. T. H. Vu, & D. V. K. Huynh (Eds.), *7th International Conference on Geotechnics, Civil Engineering and Structures (CIGOS 2024)* (pp. 132–140). Springer Nature Singapore.

Mohamed, A. R., Hamzah, Z., Daud, M. Z. M., & Zakaria, Z. (2013). The effects of holding time and the sweeping nitrogen gas flowrates on the pyrolysis of EFB using a fixed–bed reactor. *Procedia Engineering, 53,* 185–191.

Mufandi, I., Suntivarakorn, R., Treedet, W., & Singbua, P. (2023). Analisis termogravimetri dan dekomposisi termal pada produksi bio-oil dari daun tebu menggunakan proses pirolisis cepat. *Eksergi, 20*(2), 82.

Mufandi, I., Treedet, W., Singbua, P., & Suntivarakorn, R. (2020). Efficiency of bio-oil production from napier grass using circulating fluidized bed reactor with bio-oil scrubber. *KKU Research Journal, 20*(December), 94–107.

Muslih, M., Etica, U., Rosanti, E., Hastuti, E. W., & Mubarok, W. (2020). Pengembangan sentra produksi kemasan berbasis anyaman bambu melalui pemberdayaan karang taruna dan PKK untuk peningkatan ekonomi masyarakat di Desa Mojorejo Kecamatan Jetis Kabupaten Ponorogo. *Engagement: Jurnal Pengabdian Kepada Masyarakat, 4*(2), 343–362.

Nan, H., Xiao, Z., Zhao, L., Yang, F., Xu, H., Xu, X., & Qiu, H. (2020). Nitrogen transformation during pyrolysis of various N-containing biowastes with participation of mineral calcium. *ACS Sustainable Chemistry & Engineering, 8*(32), 12197–12207.

Ngo, T.-A., & Kim, J. (2014). Fast pyrolysis of pine wood chip in a free fall reactor: The effect of pyrolysis temperature and sweep gas flow rate. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 36*(11), 1158–1165. https://doi.org/10.1080/15567036.2011.631089

Qian, K., Kumar, A., Zhang, H., Bellmer, D., & Huhnke, R. (2015). Recent advances in utilization of biochar. *Renewable and Sustainable Energy Reviews, 42,* 1055–1064. https://doi.org/10.1016/j.rser.2014.10.074

Sarmah, R., & Neog, D. (2024). Bamboo as a potential eco-friendly composite – A review. *Journal of Physics: Conference Series, 2818*(1), 012031. https://doi.org/10.1088/1742-6596/2818/1/012031

Saif, A. G. H., Wahid, S. S., & Ali, M. R. O. (2020). Pyrolysis of sugarcane bagasse: The effects of process parameters on the product yields. *Materials Science Forum, 1008,* 159–167. https://doi.org/10.4028/www.scientific.net/MSF.1008.159

Somerville, M., & Deev, A. (2020). The effect of heating rate, particle size and gas flow on the yield of charcoal during the pyrolysis of radiata pine wood. *Renewable Energy, 151,* 419–425. https://doi.org/10.1016/j.renene.2019.11.036

Tong, W., Cai, Z., Liu, Q., Ren, S., & Kong, M. (2020). Effect of pyrolysis temperature on bamboo char combustion: Reactivity, kinetics and thermodynamics. *Energy, 211,* 118736. https://doi.org/10.1016/j.energy.2020.118736

Treedet, W., Suntivarakorn, R., Mufandi, I., & Singbua, P. (2020). Bio-oil production from Napier grass using a pyrolysis process: Comparison of energy conversion and production cost between bio-oil and other biofuels. *International Energy Journal, 20*(2), 155–168.

Tripathi, M., Sahu, J. N., & Ganesan, P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and Sustainable Energy Reviews, 55,* 467–481. https://doi.org/10.1016/j.rser.2015.10.122

Vamvuka, D. (2012). Bio-oil, solid and gaseous biofuels from biomass pyrolysis processes—An overview.

International Journal of Energy Research, 33(4), 23–40. https://doi.org/10.1002/er

Vuppaladadiyam, A. K., Varsha, S. S., Sikarwar, V. S., Ahmad, E., Pant, K. K., Pandey, A., Bhattacharya, S., Sarmah, A., & Leu, S.-Y. (2023). A critical review on biomass pyrolysis: Reaction mechanisms, process modeling and potential challenges. *Journal of the Energy Institute, 108*, 101236. https://doi.org/10.1016/j.joei.2023.101236

Wang, J., Minami, E., Asmadi, M., & Kawamoto, H. (2021). Thermal degradation of hemicellulose and cellulose in ball-milled cedar and beech wood. *Journal of Wood Science*, *67*(1), 32. https://doi.org/10.1186/s10086-021-01962-y

Wang, N., Chang, Z.-Z., Xue, X.-M., Yu, J.-G., Shi, X.-X., Ma, L. Q., & Li, H.-B. (2017a). Biochar decreases nitrogen oxide and enhances methane emissions via altering microbial community composition of anaerobic paddy soil. *Science of The Total Environment*, *581–582*, 689–696. https://doi.org/10.1016/j.scitotenv.2016.12.181

Wang, S., Dai, G., Yang, H., & Luo, Z. (2017b). Lignocellulosic biomass pyrolysis mechanism: A state-of-the-art review. *Progress in Energy and Combustion Science*, *62*, 33–86. https://doi.org/10.1016/j.pecs.2017.05.004

Wang, Yan, Yin, R., & Liu, R. (2014). Characterization of biochar from fast pyrolysis and its effect on chemical properties of the tea garden soil. *Journal of Analytical and Applied Pyrolysis*, *110*, 375–381. https://doi.org/10.1016/j.jaap.2014.10.006

Wang, Yurou, Guo, W., Chen, W., Xu, G., Zhu, G., Xie, G., Xu, L., Dong, C., Gao, S., Chen, Y., Yang, H., Chen, H., & Fang, Z. (2024). Co-production of porous N-doped biochar and hydrogen-rich gas from simultaneous pyrolysis-activation-nitrogen doping of biomass: Synergistic mechanism of KOH and NH3. *Renewable Energy*, *229*, 120777. https://doi.org/10.1016/j.renene.2024.120777

Yadav, M., & Mathur, A. (2021). Bamboo as a sustainable material in the construction industry: An overview. *Materials Today: Proceedings*, *43*, 2872–2876. https://doi.org/10.1016/j.matpr.2021.01.125

Yang, H., Huan, B., Chen, Y., Gao, Y., Li, J., & Chen, H. (2016). Biomass-based pyrolytic polygeneration system for bamboo industry waste: Evolution of the char structure and the pyrolysis mechanism. *Energy & Fuels*, *30*(8), 6430–6439. https://doi.org/10.1021/acs.energyfuels.6b00732

Zhang, Y., Liang, Y., Li, S., Yuan, Y., Zhang, D., Wu, Y., Xie, H., Brindhadevi, K., Pugazhendhi, A., & Xia, C. (2023). A review of biomass pyrolysis gas: Forming mechanisms, influencing parameters, and product application upgrades. *Fuel*, *347*, 128461. https://doi.org/10.1016/j.fuel.2023.128461