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Optimization of Biochar Production from Lemongrass Solid Waste at Different Pyrolysis Temperatures

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ABSTRACT

The waste from refining lemongrass oil has not been utilized properly. The potential waste produced can reach 2-3 tons per week. This waste optimization is carried out to reduce the impact of environmental pollution by converting waste into biochar using a pyrolysis process. This research aims to examine the chemical characteristics of biochar from lemongrass solid waste using a pyrolysis process at different temperatures. This research used a completely randomized design (CRD) with three replications. The pyrolysis process was carried out at temperatures 200, 250, 300, and 350°C for 60 minutes. Pyrolysis temperature significantly affects yield, proximate composition, pH, electrical conductivity (EC), cation exchange capacity (CEC), organic C, and total N. At a temperature of 200°C, the pyrolysis process produced functional groups and carbon minerals, as well as the highest yield of 26.57% (char) compared to other temperatures, and nutrient composition of 8.89% C, 1.37% N, 9.04% P, 31.09% K, 8.98% S, 33.41% Ca, 4.30% Cl, 1.08% Mn, 2.10% Fe, and 7.35% Si. Lemongrass waste has the potential to be used as biochar for soil ameliorants. Biochar has been shown to have the potential for sustainable agricultural practices and contribute to waste management and environmental sustainability.

1. INTRODUCTION

One benefit of biochar, produced during the carbonization process in biomass power plants, is that it is a material that improves soil fertility and has a long-lasting, resistant quality. Biochar contains high carbon, which is influenced by the type of biomass used. Biochar is derived from two syllables: "bio," representing biomass or renewable organic material, and "char," referring to charcoal produced from organic waste. Biochar serves as a soil amendment, enhancing soil quality by improving its physical, chemical, and biological properties [1]. Biochar can be formed through pyrolysis or burning organic waste without oxygen (O_2) at high temperatures. Pyrolysis is a thermal decomposition process that breaks down organic compounds at high temperatures (400°C to 800°C) in the absence of oxygen (O_2), with a duration of up to 4 hours [2, 3].

The absence of oxygen prevents the materials from burning completely, resulting in a carbon-rich substance known as biochar. The structure of biochar is unique and plays a significant role in its various applications. It possesses numerous negative charges on its surface, along with various functional groups. These functional groups are specific arrangements of atoms that can interact with other substances. Biochar has a large specific surface area, meaning it has many surfaces available for interactions relative to its mass. It also has a large pore volume, creating spaces within its structure where other substances can be held. Another crucial property of biochar is its high cation exchange capacity. Cations are positively charged ions, and biochar's ability to exchange these ions makes it valuable in soil amendments. It can attract and hold essential nutrients like calcium, magnesium, and potassium, preventing them from being washed away and making them available to plants.

Biochar's physicochemical qualities are determined mainly by the type of raw material used. Other influencing factors include particle size, temperature, and production method [4-6]. The temperature at which pyrolysis takes place [7], the length of the procedure, and the kind of apparatus employed can all affect the finished product. A critical element in the pyrolysis process is temperature. Biochar produced at higher temperatures has a more porous structure and a higher carbon content. On the other hand, some advantageous volatile molecules may also be lost at very high temperatures.

Another consideration is the size of the biochar particle [8]. Smaller particles are generally more reactive than larger ones because they have a higher surface area. Biochar's unique properties can differ greatly based on several variables. One important factor influencing the finished attributes is the kind of raw material utilized. The procedures used to process different feedstocks will change, resulting in variances in the final biochar.

Pyrolysis, a process of heating biomass under low-oxygen conditions, is a common method for biochar production. Biochar consists of aromatic carbon rings, so it is more durable and long-lasting and functions as a carbon store in the soil. Carbon-rich compounds, such as biochar, have recently been used as alternative and cost-effective adsorbents to remove or inactivate pesticides and other inorganic and organic toxins in soil [9] and water systems [10]. The large surface area causes the high adsorption of contaminants into biochar. Biochar contains phenol and carboxyl groups and a high carbon content (22-52%). The biochar material's cellulose and lignin structure will naturally provide a porous structure, making the material used as an adsorption medium.

The process employed to produce biochar significantly influences both the quantity generated and the properties of the final product. Ancient farmers originally utilized the earth-hole method to create biochar, a technique characterized by burying burning biomass in pits lined with soil. However, this method often suffered from uncontrollably spreading fires due to the insulating properties of the soil walls, uneven temperatures within the pit, and inefficient combustion, all of which reduced the effectiveness of the process. Not only did this method release substantial amounts of CO_2, but it also yielded a relatively low amount of charcoal. Similarly, the drum method, which is more widely used, faces challenges such as the need to carefully manage the fire to avoid producing either ash or partially combusted material. This is due to either extinguishing the fire too quickly or adding an excessive amount of biomass [11].

In response to these inefficiencies, the Kon-Tiki method was developed. This innovative approach utilizes a steel furnace with a top diameter of 1.50 meters, a height of 0.90 meters, and wall slopes measuring 63.50 meters, designed to allow biomass to burn continuously and gradually as it is vertically stacked in the furnace [12, 13].

A significant amount of organic waste is generated by the citronella distillation factory at BSIP TRO Laing Solok, estimated at 8 tons per month. This figure is only a portion of the total waste produced in the region, as Solok City is home to several distilleries operated by various farmer groups, suggesting that the collective waste output likely exceeds this amount. The composition of the lemongrass solid waste includes 68.68% holocellulose, 51.17% cellulose, 17.51% hemicellulose, and 25.06% lignin. This waste not only poses an environmental challenge but also offers an opportunity for sustainable waste management.

By converting citronella waste into biochar through pyrolysis, this material can be repurposed to enhance soil fertility, improve soil structure, and increase carbon sequestration. Such practices contribute to sustainable farming and reduce the environmental impact of citronella distillation activities. This research aims to explore the chemical properties of biochar derived from lemongrass solid waste at varying temperatures, evaluating its potential as a soil amendment material.

2. MATERIAL AND METHODS

2.1 Experimental design

The research was conducted from June to August 2023 at the Soil Chemistry and Physics Laboratory, Department of Soil, Faculty of Agriculture, Universitas Andalas, Padang, Indonesia. This study employed a completely randomized design (CRD) in which all experimental units were equally likely to receive any of the treatments, thus minimizing bias and enhancing the reliability of the results.

The experiment included four levels of pyrolysis temperature as the primary treatment variable: 200℃, 250℃, 300℃, and 350℃. Each temperature level constituted a distinct treatment condition, offering a spectrum of thermal environments to evaluate their effects on biochar properties. The selection of these specific temperatures was informed by preliminary investigations and existing literature, which suggest that biochar characteristics can significantly vary across different pyrolysis temperatures.

Each treatment was replicated three times, resulting in a total of twelve experimental units. Replication is a critical aspect of experimental design as it accounts for natural variability among the experimental units, thereby providing a more precise estimation of treatment effects. The decision to use three replications was based on prior similar studies and practical considerations, including the availability of time, materials, and laboratory facilities.

2.2 Biochar production and its analysis

Biochar was produced from fragrant lemongrass solid waste sourced from the dried fragrant lemongrass recovery industry at BSIP TRO Laing Solok. This particular biomass was selected based on its availability, low economic value, and potential for high-quality biochar production due to its lignocellulosic content. The use of agricultural waste provides a sustainable feedstock for biochar production and addresses waste management issues in the industry.

Figure 1 presents the steps of biochar production. Firstly, the dry lemongrass waste was chopped into 4 cm lengths to ensure consistent heating and carbonization during pyrolysis. Each biochar production batch involved 100 g of the prepared lemongrass waste. This specific quantity was standardized across all treatments to ensure consistency in the experimental setup and allow for accurate biochar comparisons under different conditions.

The pyrolysis process was carried out using an LMF-10D fiber muffle furnace ceramic. This equipment was selected for its precision in temperature control and ability to maintain an oxygen-free environment, which is critical for producing high-quality biochar. The temperatures of 200°C, 250°C, 300°C, and 350°C were meticulously controlled and maintained for 60 min.

Following pyrolysis, the resultant biochar is examined to describe its chemical and physical characteristics. Proximate analysis was the first step in the characterization process, and it involved figuring out the fixed carbon, moisture content, volatile matter, and ash content. Understanding the biochar's thermal stability and energy content is crucial for its possible uses in soil amendment and carbon sequestration. These characteristics play a significant role in this process.

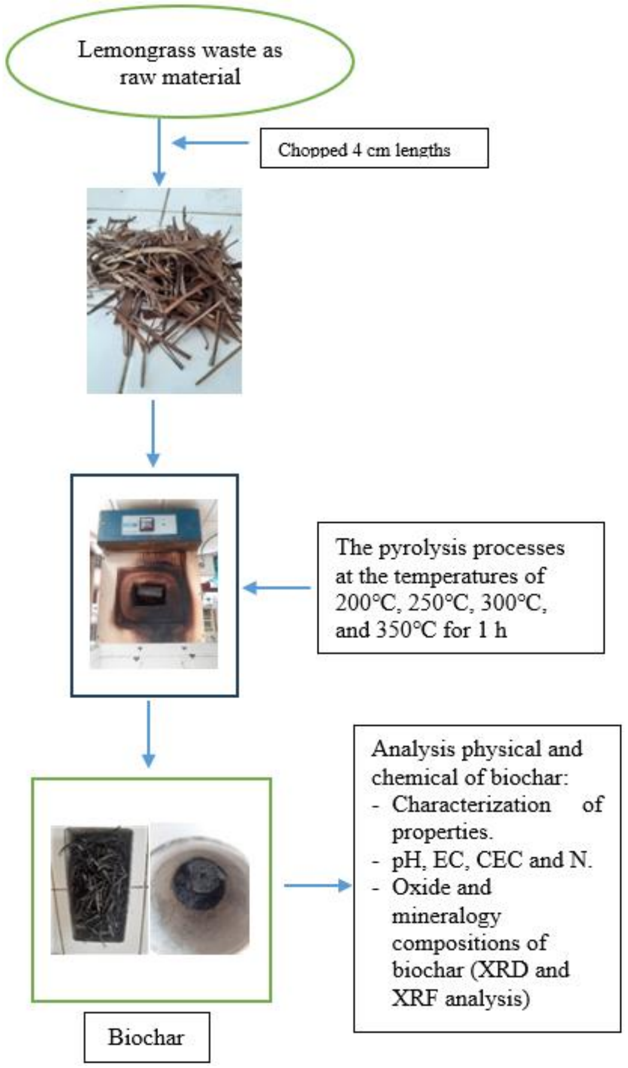

Figure 1. The steps of biochar production

The biochar's pH, total nitrogen (N) concentration, electrical conductivity (EC), and cation exchange capacity (CEC) were also assessed. X-ray diffraction (XRD) and X-ray fluorescence (XRF) studies were used to assess the oxide and mineralogical compositions of the biochar, respectively. While XRF supplied a quantitative investigation of the elemental composition of the biochar, XRD offered extensive insights into the mineral phases and crystalline structure of the material [14, 15].

2.3 Statistics analysis

The data collected from the various analyses of biochar characteristics were subjected to thorough statistical analysis to determine the effects of different pyrolysis temperatures on the properties of the biochar. Statistical analysis using Microsoft Excel 2016, SPSS 16, and Statistics 8 software on biochar production and characteristics. The primary statistical method used was the analysis of variance (ANOVA). It allows for detecting significant differences in biochar properties resulting from the different pyrolysis temperatures. The analysis was conducted at a significance level of 5% ($p < 0.05$) and 1% ($p < 0.01$), indicated by the F test.

3. RESULTS AND DISCUSSION

As shown in Figure 2(a), the pyrolysis temperature significantly impacts the yield of biochar produced from solid waste lemongrass. Notably, a temperature of 200°C produced the highest biochar output of 26.57%, while 350°C produced the lowest yield of 15.29%. The breakdown of different chemicals within the raw material, which results in their conversion into gaseous forms, is the cause of this yield decline with rising temperatures. There are four main stages to the actual pyrolysis process. Hemicellulose undergoes pyrolysis when water evaporates at temperatures between 180°C and 300°C. After that, cellulose is subjected to pyrolysis at temperatures between 260°C and 350°C. Finally, lignin pyrolysis happens at 300°C or higher. This staged breakdown procedure highlights the complex link between heat and biomass conversion and clarifies how temperature affects charcoal yield [16].

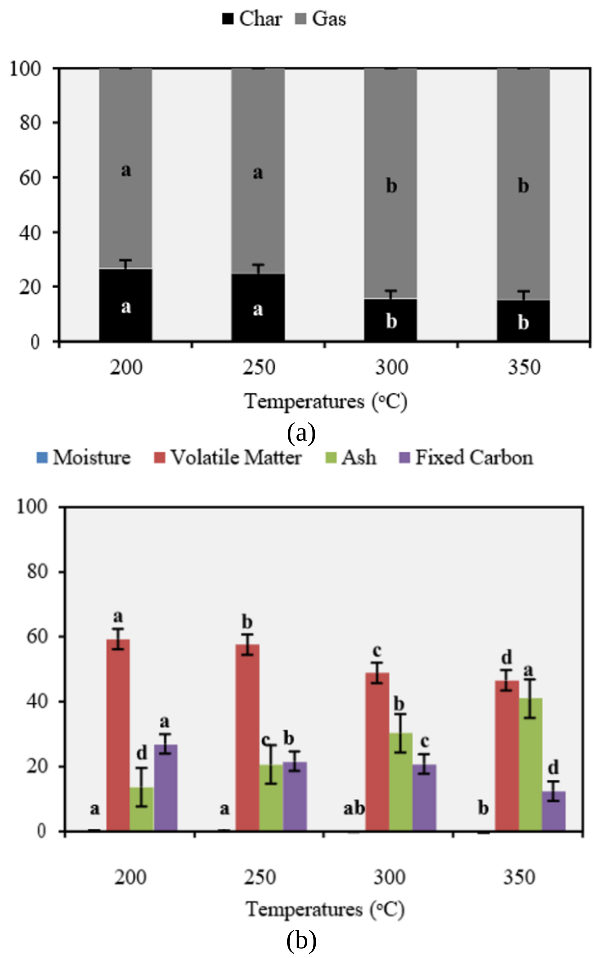

Figure 2. Effect of pyrolysis temperature on (a) biochar yield and (b) proximate of biochar from lemongrass solid waste

A decrease in liquid yield and increased gas yield were observed at higher temperatures. The reduction in both liquid and gas yields at lower temperatures is attributed to the incomplete decomposition of the raw materials, indicating that pyrolysis was not fully completed. At higher temperatures, the decrease in liquid and char yields, coupled with an increase in gas yield, can be attributed to the secondary cracking of pyrolysis vapors as well as solid char. The type of biomass determines pyrolysis yield. Using 4 different agricultural wastes, Biswas et al. [17] found that variation in liquid yield may be due to differences in the components present in each type of biomass.

Previous studies on the production of biochar from maize cobs and grape shoots under varying pyrolysis conditions—specifically at temperatures of 350°C and 500°C and pressures of 0.1 MPa and 0.5 MPa for 60 minutes—consistently indicate that higher pyrolysis temperatures reduce the yield of biochar while also lowering the H/C and O/C ratios [18]. These findings are corroborated by the research of Khater et al. [19], which also recorded a decline in biochar yield with increased pyrolysis temperatures. Moreover, Khater et al. [19] noted that the characteristics of the biochar varied according to the type of biomass used and the specific pyrolysis conditions applied, further underscoring the complexity of biochar production dynamics.

The analysis of Figure 2(b) demonstrates that the pyrolysis temperature highly influences the water content (0.23) of lemongrass distillation waste biochar. It is predicted that as temperatures rise, more water will evaporate during the pyrolysis process, lowering the water content of biochar. The analysis's findings indicate that the pyrolysis temperature influences the ash concentration at 200°C (13.61%). The amount of ash content and the temperature and duration of pyrolysis often correlate directly.

Biochar's water-holding capacity can be optimized through controlled water content during pyrolysis, leading to significant implications for soil water management. Research indicates that biochar derived from wheat straw made at 550°C (B550) exhibited the largest mean weight diameter, most water-stable aggregates, and highest available water content, with increases of 235%, 39%, and 166% compared to the control [18]. By optimizing biochar production at specific temperatures and incorporating it into soil management practices, such as irrigation systems, the soil's water-holding capacity can be improved, contributing to more efficient water use and enhanced soil moisture conservation in various agricultural and environmental applications.

The process's operating temperature influences the amount of volatile biochar that results from pyrolysis. As the temperature of pyrolysis rose, the amount of volatile matter dropped. The volatile matter value was 59.28% at 200°C, while at 350°C, the minimum volatile matter level was recorded at 46.62%. A drop in volatile matter content during pyrolysis resulted from the progressive breakdown of cellulose, hemicellulose, and lignin. The temperature ranges for cellulose decomposition are 200°C to 400°C, for hemicellulose decomposition are 300°C to 450°C, and for lignin decomposition are around 450°C. Biochars with sorbed volatile organic compounds (VOCs), mainly consisting of short-chain aldehydes, furans, and ketones, were produced at lower pyrolysis temperatures (≤350°C). Higher temperature biochars (>350°C) components were usually longer-chain hydrocarbons and sorbed aromatic compounds. Sorbed volatile organic compounds decreased due to oxygen being present during pyrolysis [20].

Decreased pyrolysis temperatures typically produce more amorphous biochar with decreased electrical conductivity and alkalinity. It usually has more significant concentrations of volatile matter, labile carbon, net negative charge, and moisture content [21].

The pyrolysis temperature significantly influences the yield and quality of the resulting biochar. The yield of biochar generally decreases as the pyrolysis temperature rises. For instance, studies show that the accelerated breakdown of organic materials into volatile chemicals and synthesis gas at higher pyrolysis temperatures (400-600°C) reduces biochar yields [18, 19]. In particular, as pyrolysis temperature rises, the yield of biochar produced from rice husk reduces; the maximum output was recorded at the lowest temperature of 250°C [18]. Similarly, the maximum amount of biochar was produced by pyrolyzing teff husk at 400°C, but the yield decreased at higher temperatures [21]. However, the biochar quality tends to improve at greater pyrolysis temperatures, especially its energy value and carbon content. For instance, biochar heated to 600°C showed increased porosity and maximum carbon content, increasing its energy content [19]. High values were also found in the energy content of biochar made from food waste, and bio-oil produced at 450-550°C had an energy content of approximately 80% that of diesel [21]. Furthermore, at greater pyrolysis temperatures, the elemental composition of biochar, including the concentration of SiO_2, increases while the calorific value and concentrations of other elements, such as hydrogen and carbon, drop [18]. A high biochar output and energy value were obtained under the ideal pyrolysis conditions for poultry litter, which include a temperature of 300°C [22]. This highlights the significance of adjusting pyrolysis parameters for various feedstocks. Higher pyrolysis temperatures, therefore, typically result in less biochar produced. Still, they also improve the quality and energy content of the biochar, making it better suited for some uses based on the intended result.

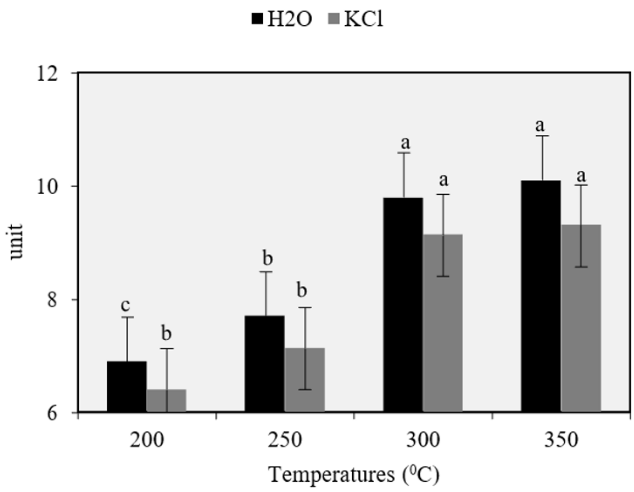

Figure 3. Effect of pyrolysis temperature on pH of biochar from lemongrass solid waste

Figure 3 shows that pyrolysis temperature significantly influenced the pH value of biochar, where at the temperature of 200°C, the pH H_2O value was 6.90, increased to 10.10 at a temperature of 350°C. As the temperature increases, weak biochar bonds, such as hydroxyl bonds in the biochar structure, are broken. While most biochar is alkaline, biochar with a pH of 6.90 can be produced at lower pyrolysis temperatures, such as 200°C. At this temperature, the carboxylic and phenolic functional groups will break off; raising the temperature to 300°C and 350°C will break COOH and –OH [23]. Acidity levels can be raised by acetic acid and other acids generated during the pyrolysis process, which promotes the breakdown of cellulose and acidic extractive compounds [24].

As shown in Figure 4(a), the pyrolysis temperature substantially impacted the values of electrical conductivity (EC) and cation exchange capacity (CEC). While the EC value rose with the pyrolysis temperature, the CEC value decreased as the pyrolysis temperature climbed. At 200°C, EC and CEC measured values were 0.87 dS m^{-1} and 226.67 cmol (+) kg^{-1}, respectively. According to Intani et al. [25], the rise in the EC value might be explained as increased salts in the biochar formed as the pyrolysis temperature was raised. Several investigations have demonstrated that when pyrolysis temperature rises, the biochar's CEC falls. The formation of aromatic carbon and the removal of surface functional groups are responsible for the drop in CEC [26].

The temperature significantly influences OC, IOC and N, where the value of OC, IOC and N decreased as the temperature increased. This finding aligns with the results of other studies [27, 28]. Figure 4(b) shows that the highest value of OC, IOC and N, namely 8.89%, 0.09% and 1.372% respectively, were obtained at temperature of 200°C.

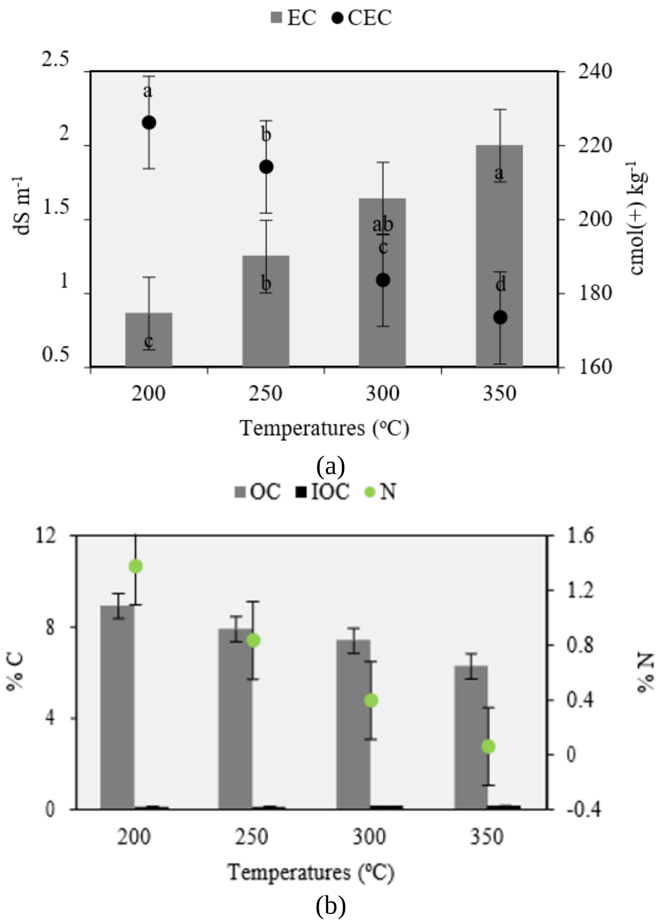

Figure 4. Effect of pyrolysis temperature on (a) EC and CEC and (b) OC, IOC, and total N of biochar from lemongrass solid waste

The XRD analysis on biochar from lemongrass solid waste with a pyrolysis temperature of 200°C as the best biochar found that the biochar's diffraction pattern matches the carbon compounds' diffraction pattern (Figure 5(a)). This indicates that the main component in biochar is carbon, which aligns with the characteristics of organic materials carbonized at high temperatures. On the other hand, the chemical composition of biochar also shows the presence of other elements such as phosphorus, potassium, and calcium (XRF), but this confirms that carbon is the main component of the biochar. Biochar has a structural property dominated by carbon, which can benefit agricultural applications or other uses, such as increased nutrient availability, increased soil capacity, and improved water retention [23]. In addition, the high carbon content in biochar can be utilized for carbon sequestration in soil, thereby reducing greenhouse gas emissions [29]. Therefore, increasing carbon sequestration in soil is essential to mitigate climate change and improve soil fertility and health [30, 31]. Previous studies have also indicated that biochar, as a carbon-rich organic amendment, is frequently employed to sequester carbon and maintain soil productivity [32]. Biochar can increase agricultural productivity and support sustainable agricultural practices and environmental conservation by improving soil structure, enhancing water and nutrient retention, and encouraging beneficial microbial activity [30, 33, 34].

The chemical composition of the best biochar citronella solid waste at 200°C with the XRF method is presented in Figure 5(b). The nutrient composition from highest to lowest is Ca > K > P > S > Si > Cl > Fe > Mn > Zn > Cu > Ni with values of 33.409%, 31.090%, 9.043%, 8.984%, 7.350%, 4.303%, 2.102%, 1.084%, 0.791%, 0.674%, 0.016%, respectively. The nutritional content of biochar produced from the solid waste of lemongrass at a temperature of 200°C can be useful for agriculture. These temperatures also produce biochar with desirable physical and chemical properties, including high volatile matter content, low air content, and balanced pH levels, making it an effective soil amendment.

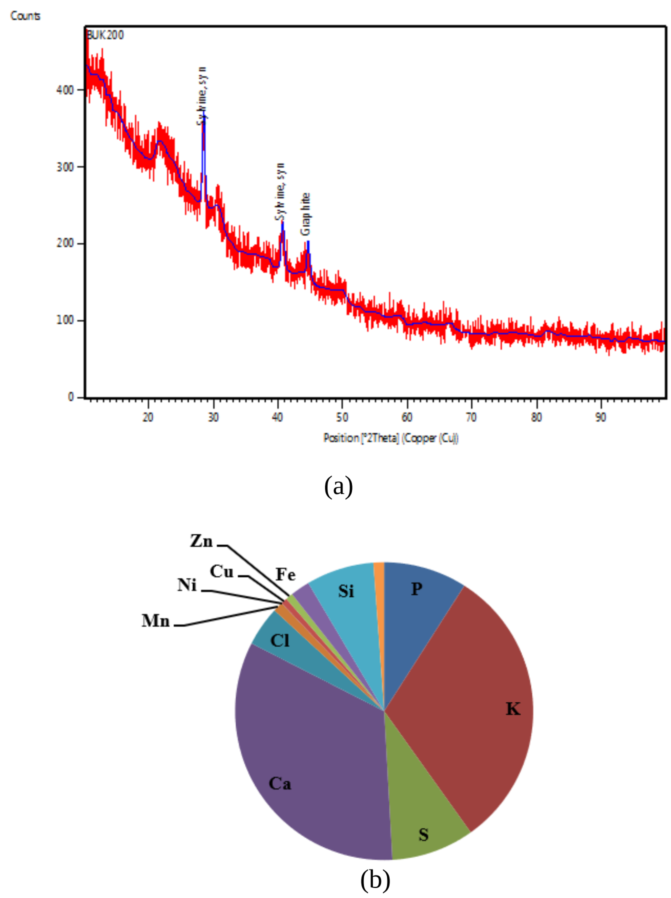

Figure 5. Biochar from lemongrass solid waste with pyrolysis temperature of 200°C on mineral (a) and oxide composition (b) by XRD and XRF

Table 1 shows the characteristics of biochar resulting from a pyrolysis process with different temperatures. With a high

CEC value, biochar can be used to improve the physical and chemical properties of the soil. It is expected to retain more nutrients in soil and decrease nutrient leaching.

The CEC of biochar is a critical parameter for its application in soil amendment and pollutant adsorption. Several trends emerge when comparing biochar produced at 200℃ to those produced at higher temperatures. According to study [35], the CEC of biochar from shredded cotton stalks decreases as the pyrolysis temperature increases. Specifically, the CEC ranges from 38.02 cmol/kg at 200℃ to 24.39 cmol/kg at 500℃, indicating that lower temperatures favor higher CEC retention [35]. This trend is consistent with findings from Danso-Boateng et al. [36], who observed that increasing the hydrothermal carbonization (HTC) temperature generally decreases the zeta potential magnitude of hydrochars, which correlates with a reduction in CEC [37]. Additionally, Jindo and Sonoki's research on biochar stability shows that while higher temperatures (e.g., 500℃ and above) produce more stable biochars with higher carbon content, these biochars tend to have lower CEC due to the loss of functional groups that contribute to cation exchange [38]. Therefore, biochar produced at 200℃ retains a higher CEC than those produced at higher temperatures, making it more effective for applications requiring high cation exchange capacity, such as soil fertility enhancement and pollutant adsorption. However, it is important to balance this with the stability and carbon content requirements of the specific application, as higher temperature biochars offer greater longevity and carbon sequestration potential [35, 38].

Table 1. Lemongrass biochar characteristics under different temperature pyrolysis process

Temp. (℃)	pH H_2O	EC	CEC	OC	N
		cmol(+)kg^{-1}		%	
200	6.90 c	0.87 c	226.27 a	8.89 a	1.372 a
250	7.70 b	1.25 b	214.27 b	7.89 b	0.831 b
300	9.80 a	1.64 ab	183.60 c	7.38 c	0.392 c
350	10.10 a	2.00 a	173.40 d	6.27 d	0.056 d

Note: The same letter within the same column indicate no statistically significant difference at the 5% level.

Utilizing biochar as soil amendments [34] improves soil fertility and increases the effectiveness of fertilizers when mixed due to their nutrient retention capacity and high nutrient content. The high silica content in rice husk biochar enhances nutrient retention, turgidity, and plant structure [39]. The high calcium content in biochar is beneficial for plant growth. calcium is essential for plant growth and development because it has an important structural function in forming plant tissues, thereby increasing their growth. In addition, calcium strengthens plant tissues, making them more resistant to various stressors, including biotic and abiotic factors [40]. Biochar also contains 1.155% of other elements not explicitly listed. These may include minor or trace elements that can have an additional impact on plant growth and health.

Furthermore, mineral elements including Na, K, Ca, Fe, and Mg are abundant in biochar. The mineral components found in lemongrass biochar produced at 200℃ via pyrolysis include 33.41% Ca, 1.08% Mn, 2.10% Fe, and 7.35% Si, as shown in Figure 5(b).

Specific surface area is one more physicochemical attribute of soil that can benefit from the application of biochar.

The pores of biochar vary widely in size, from nanometres to tens of micrometres. Pore distribution, which makes the assumption that a model with similar interactions and regularly formed pores can replicate the complicated pore structure found in real solids, can be used to evaluate the internal structure of biochar. One important factor in describing the structural variability of biochar is the distribution of pore sizes. Its porosity and surface area are strongly correlated, with micropores accounting for the majority of this attribute [41].

Previous studies have shown that biochar derived from different agricultural wastes, such as compost, rice husks, sugarcane bagasse, and maize cobs, enhanced soil microbial counts and decreased mancozeb and heavy metal concentrations. Additionally, it lowers pesticide levels, pollutants, and soil quality, promoting sustainable agriculture and preserving human health [42].

Significant levels of ash may harm the overall quality of biochar. This is mainly because the ash's mineral component clogs the pores in the structure of the biochar. Biochar loses some of its surface area, which lowers its efficiency. The investigation's conclusions show that the pyrolysis temperature significantly influences the amount of bound carbon produced. Higher pyrolysis temperatures lead to higher rates of carbon sequestration. Rising temperatures and the presence of a catalyst speed up the process of converting raw materials into biochar and optimize the breakdown process into biochar.

4. CONCLUSIONS

Biochar derived from lemongrass solid waste can be optimized by pyrolysis temperature, with the maximum yield occurring at 200℃ (26.57%) and the minimum yield at 350℃ (15.29%). Temperature significantly impacts the water content, ash content, volatile matter content, and bound carbon in biochar. At 200℃, biochar has the highest CEC value and the essential nutrient composition. Lemongrass solid waste biochar's high pH value and nutrient composition can increase soil fertility, support sustainable agricultural practices, and overcome waste pollution. Future research may focus on enhancing the pyrolysis process to handle larger quantities of citronella waste, evaluating commercial-scale biochar production's economic feasibility and environmental impacts, and developing efficient technologies to integrate biochar applications into broader agricultural and environmental management strategies.

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