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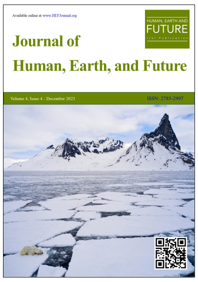

Influence of Pyrolysis Temperature and Time on Biochar Properties and Its Potential for Climate Change Mitigation

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Abstract

The thermochemical conversion of disposable bamboo chopstick (DBC) wastes into biochar is a practical strategy for converting waste into resources. This study aimed to investigate the effects of pyrolysis temperature and holding time on the physicochemical properties of DBC biochar and its potential for climate change mitigation. Properties affecting the biochar efficiency and potential for application were analyzed: moisture content (MC), volatile matter (VM), fixed carbon (FC), ash, pH, and carbon (C), hydrogen (H), nitrogen (N), and oxygen (O) content. Six different pyrolysis conditions were studied, with temperatures of 400 °C, 450 °C, and 500 °C and holding times of 20 and 60 min, at a constant heating rate. The results demonstrated that temperature and holding time significantly affected the physicochemical properties and performance of the biochar. Increases in %C, %FC, %N, and pH and reductions in %MC, %VM, %H, and %O were found when the temperature was increased at different holding times. The aromaticity increased and the polarity decreased significantly with increasing temperature and holding time. The results showed that temperature interacts significantly with holding time, and these two factors jointly affect the contents of MC, ash, FC, C, H, N, and O (R^2 of 0.997) and pH (R^2 of 0.999). The DBC biochar obtained via pyrolysis at 450 °C and 500 °C for 20 and 60 min could be applied for climate change mitigation. The best DBC biochar was obtained at a pyrolysis temperature of 500 °C and a holding time of 20 min. This biochar showed good hydrophobicity, tremendous stability, the highest C (88.06%) and FC (76.49%) values, and the lowest ash (2.62%) and VM (19.23%) contents.

Keywords: Pyrolysis Conditions; Biochar; Wooden Biomass; Climate Change Mitigation; Carbonization.

1. Introduction

Lignocellulosic biomass is the most readily renewed resource in the world. Furthermore, it is abundant in various areas around the world. Many previous studies have indicated that lignocellulosic biomass, both wood- and non-wood-based biomasses, is a carbon-neutral renewable resource that has enormous potential to produce environmentally friendly materials and products such as biofuels, green composites, and biochar [1, 2]. Biochar is a solid black carbonaceous material that is usually produced from slow pyrolysis [3]. Pyrolysis is the process by which a biomass substrate is thermochemically converted within a temperature range of 300 °C to 700 °C under oxygen-limited or oxygen-free conditions [4, 5]. According to the meta-analysis literature, biochar is recognized as a potential material for achieving environmental sustainability due to its unique properties and diverse applications, which include agricultural applications that can reduce greenhouse gas emissions [6–8] and achieve carbon capture and storage [9, 10], in addition to achieving increases in soil fertility and enhancing crop productivity [11, 12]. Moreover, biochar has the potential to be applied as a catalyst [13], an adsorbent [14], and for energy storage [15].

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Although biochar has many functions and roles, many studies in the meta-analysis literature also clearly state that both the biochar application regime (rate, frequency, and particle size) and its versatility and effectiveness depend on its quality and properties [16–18]. Biochar has been reported to be a material with various properties and quality levels [3, 19, 20], especially in terms of its morphological and physicochemical properties [21–23]. The properties of biochar depend on the type of biomass feedstock used and the pyrolysis conditions [24–26].

It has been widely observed that biochar can be produced from many types of lignocellulosic biomasses, such as rice husk [27], wheat straw [28], shell and peel [29], herbaceous [30], tree branches and bark [31], paper sludge [32], and manure [33, 34]. Recently, researchers have given considerable attention to wood-based feedstocks due to their abundant availability and favorable characteristics [25, 35, 36], especially wood wastes, which generate and drive a circular economy. Single-use or disposable bamboo chopsticks (DBCs) constitute a large proportion of urban waste worldwide because they are used for food consumption in Asian cultures. DBC feedstocks have the potential to be converted into biochar, providing added value to waste streams.

Although many pyrolysis conditions can affect biochar properties, a meta-analysis of the literature performed by Ippolito et al. [37], Wang et al. [38], and Guizani et al. [39] showed that temperature and holding times are considered strong factors that directly influence biochar properties, the breakdown of lignocellulosic feedstocks and chemical bonds, and the physical and chemical structure of the resultant biochar [32, 40, 41]. A comprehensive review of the literature on biochar shows that the properties of biomass feedstocks change with the techniques and conditions employed in the pyrolysis process [42–44]. High temperatures enable the formation of micropores, increase pore structure, and provide large surface areas [45, 46]; in contrast, high ash content and low yields are observed [14, 47, 48]. Additionally, biochar prepared at high temperatures is highly hydrophobic, with high carbon contents, orderly and organized carbon layers, high stability, and persistency [49]. Due to these characteristics, biochar has been used to combat climate change.

The effect of different pyrolysis temperatures on biochar properties has been widely studied for various feedstocks, including agricultural residues [50, 51], wood chips and branches [52, 53], and mixed wood wastes [54]. At a high temperature (500 °C), the carbon content in Neem wood biochar was 75.80% [55], that in pineapple leaf biochar was 60.79% [56], that in rice straw biochar was 61.98% [57], and that in corn stover biochar was 64.50% [51]. In contrast, at low temperatures (350 °C), low specific surface areas were observed in biochar derived from groundnut shell (13.44 m^2/g) [58], bamboo (2.72 m^2/g) [59], mulberry wood (16.6 m^2/g) [60], sugar cane leaves (125 m^2/g) [61], and orange pomace (1.2 m^2/g) [5]. Moreover, Domingues et al. [62] reported that biochar derived from chicken manure decreases in carbon content when increasing pyrolysis temperature while increasing in eucalyptus sawdust biochar. On the contrary, when the temperature rises, cation exchange capacity decreases in chicken manure biochar and eucalyptus sawdust biochar, while coffee husk biochar increases.

Similarly, the influence of holding times has been studied. During the pyrolysis of various feedstocks at 600 °C [63], it was found that wheat straw biochar had a fixed carbon content of 48.2% and an ash content of 14.8%. After pyrolysis for 0.5 hours and a 4-hour holding time, the ash content increased to 16.3% and the fixed carbon content increased to 68.1%. In contrast, ash content decreased in platane wood biochar when the holding time was extended from 0.5 hr (3.8%) to 4 hr (3.0%), and the fixed carbon increased from 80.3 to 88.7%. However, Uroić Štefanko & Leszczynska [64] reported that increasing temperature from 400 °C to 700 °C with prolonged holding time has generated aromatic structures with more stability in biochar. Wang et al. [65] reported that at the same pyrolysis temperature, the surface area of tobacco stem biochar increased as the prolonged holding time from 1.5 to 3 hours. Furthermore, at the same holding time (1.5 hr), the temperature was varied, resulting in only a slight decrease in pore size, all of which were classified as macropores.

According to the literature, numerous studies have focused on both factors, but the impact of these factors on biochar properties has been analyzed separately in most studies [66–68]. Studies showing the combined effect of these two factors on biochar properties are limited. Moreover, wood-based biochar can have substantially different properties, and some biochar does not follow the trends reported in the literature [49, 69, 70] because the wood-based feedstocks can have complex structures and differing properties, and their lignocellulosic compositions affect the biochar properties [53, 71, 72]. There are limited studies of these factors with disposable wooden chopsticks as the feedstock. Consequently, extensive research into wood-based biochar production is still needed.

Accordingly, understanding the pyrolysis reaction conditions, including temperature and holding time, is very challenging and fills knowledge gaps related to the properties of biochar, notably that produced from wood biomass, which has complex structures and compositions and varying elemental contents. It is crucial to evaluate the comprehensive impact of pyrolysis temperature and holding time, which influence the morphology and physicochemical properties that are important for climate change mitigation applications involving using biochar as a soil amendment. In this study, the physicochemical properties of biochar produced under different pyrolysis temperatures and holding times from disposable bamboo chopstick feedstock, which are waste materials in urban areas, were examined. Investigating the interaction of temperature and holding time in the production process, which affects biochar properties, could be beneficial for fine-tuning biochar properties by modifying practical synthesis and production conditions. This can allow for the targeted production of biochar that meets application requirements.

2. Material and Methods

2.1. Analysis of Feedstock and Biochar Properties

Disposable bamboo chopsticks (DBCs) are an urban waste from daily consumption used as a feedstock for producing biochar. The DBC feedstock and biochar were analyzed for fundamental properties that were used to identify the quality of biochar and its essential properties for its use to mitigate climate change applications: moisture content (MC), volatile matter (VM), ash, fixed carbon (FC), pH, and elemental composition [1, 20, 73]. The proximate analysis, including MC, VM, ash, and FC contents, was carried out by thermogravimetric (TGA) analysis [9], which was conducted following the American Society for Testing and Materials standard (ASTM). Based on the ASTM D7582 method, the MC, VM, ash, and FC were analyzed for feedstock characterization, and the ASTM D3172-D3175 method was used for biochar [74].

The elemental contents of carbon (C), hydrogen (H), and nitrogen (N) were analyzed by the Elemental Analyzer (CHN; LECO, Truspec CHN Analyzer, Condition: 950, 850 °C, O_2 (HP), He (UHP)) using the ASTM D 5373-16 method [75]. The O content was evaluated by calculating the difference between the percentages in the principal elements and ash; in that case, the material has a low sulfur content: ($O = 100 - C - H - N - ash$) [49, 76]. The elemental composition results were used to calculate atomic ratios of H/C, O/C, and (O+N)/C, which classified biochar and its quality following the European Biochar Certificate (EBC) [77] and the International Biochar Initiative (IBI) [64]. Moreover, these atomic ratios were used to predict carbon sequestration potential [78]. The pH was tested using the 9045D method based on the United States Environmental Protection Agency (USEPA) [79, 80].

2.2. Designed Pyrolysis Process

Since the DBC feedstock has a dry appearance, removing moisture from the feedstock before entering the process is unnecessary. Eighty pairs of DBC feedstock, weighing approximately 5.65 g/pair, were pyrolyzed at specified pyrolysis temperatures and holding times. The pyrolysis reactor was a muffle furnace with a digital temperature regulator (detection accuracy < 10 °C.(

As described in previous literature, woody biomass is diverse and complex in composition and structure. Lignocellulose is degraded in a specified temperature range via thermochemical reactions that continuously occur during pyrolysis [81–84]. In the thermochemical reactions of lignocellulosic biomass, the first two components that decompose are hemicellulose, which decomposes at a temperature of 200–315 °C [85], and cellulose, which decomposes at a temperature of 300–375 °C [86]. Lignin is a complex macromolecule with various chemical bonds; therefore, the decomposition of various functional groups with different thermal stabilities occurs over a wide temperature range. Lignin has been reported to be the primary precursor in biochar production [87], and lignin degradation occurs at temperatures ranging from 250 °C to 900 °C, depending on the type of biomass and holding time employed in the process [85, 88]. However, most of the thermal degradation of lignin begins with repolymerization at 350 °C, and bonds between monomers break at a temperature of 500 °C [12, 89]. It has been widely observed that increasing temperatures cause decreased biochar yield, while temperatures exceeding 500 °C result in a significant increase in the ash content of DBC biochar [49].

In this study, pyrolysis temperatures of 400 °C, 450 °C, and 500 °C were employed, which is the temperature range corresponding to the degradation of lignocellulosic biomass in biochar production and provides low ash content. Additionally, the feedstock has very low humidity and is small; therefore, pyrolysis at high temperatures can lead to a high ash content and low productivity. Pyrolysis was performed at each temperature with holding times of 20 and 60 min, and the process was conducted at a constant heating rate of 20 °C/min for each condition. Therefore, the study included six pyrolysis conditions, each with four replicates. The concept and approach are shown in Figure 1.

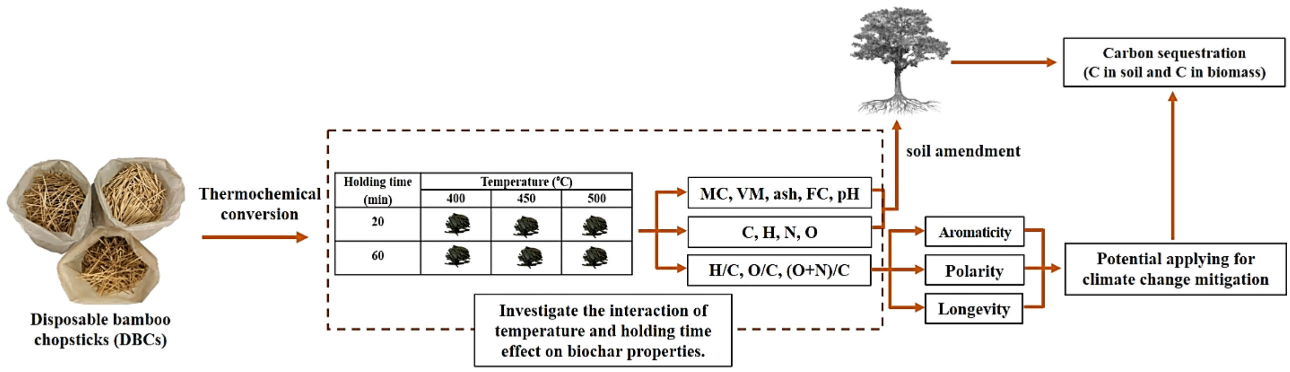


Figure 1. Designed biochar pyrolysis production and analyzed its properties and potential for climate change mitigation purposes

When the pyrolysis process was completed in each condition, biochar samples were stored in a desiccator to prevent oxidation or moisture uptake that might occur before further analysis. The samples were ground to approximately 2-3 sieve particle sizes and kept in a sealed airtight container; then, the samples were analyzed for the target properties.

2.3. Statistical Analysis

The physicochemical properties of feedstock and biochar were derived from four replicated measurements. The data were presented as the mean ± standard deviation (SD). All statistical analyses were conducted with the Social Science Statistical Package (SPSS) software (v.28.0.0.0). Data on the properties of feedstock and biochar were analyzed with variance analysis (ANOVA). Variations between biochar produced under different conditions of temperature and holding time were analyzed using one-way ANOVA, and significant differences between means were determined using Turkey's post hoc test ($p < 0.05$). ANOVA was employed as a factorial experiment based on a completely randomized design to determine significant differences among treatments between pyrolysis temperatures and holding times.

3. Results and Discussion

3.1. Characteristics of DBC Feedstocks

The analysis results of the proximate and elemental compositions of DBC feedstock are presented in Table 1. The results showed that the DBC had a high VM content (85.16%), a low MC (3.83%), and a low ash content (0.77%). All wood biomass typically has an acidic pH because all wood species are naturally acidic, caused by free acids and acidic groups, especially acetic acid and acetyl groups [31, 36, 55]. Therefore, the DBC feedstock was strongly acidic, with a pH of 5.07.

Table 1. The results of proximate analysis and the elemental compositions of disposable bamboo chopsticks

Proximate analysis (%)				Elemental compositions (%)			
VM	**MC**	**Ash**	**FC**	**C**	**H**	**N**	**O**
85.16±2.153	3.83±0.235	0.77±0.055	10.24±2.127	45.37±0.145	6.18± 0.147	0.30± 0.019	48.08±0.136

Remark: Data presented as mean ± SD with a harmonic mean sample size of 4.0.

The contents of FC and C in the feedstock are the critical properties that can be used to evaluate the suitability of biomass conversion to biochar. Most wood biomass had FC and C contents ranging from 9.5% to 28.1% and 43.9% to 52.1%, respectively [48]. The results showed that the DBC feedstock had an FC content of 10.24% and a C content of 45.37%, while the FC and C contents of bamboo have been reported differently. Hernández-Mena et al. [46] reported that bamboo (*D. giganteus* Munro) had an FC content of 17.75% and a C content of 39%. Sucipta et al. [72] reported that Ampel bamboo (*Bambusa vulgaris*) contained an FC of 9.41% and C of 39.75%, while bamboo (*Bambusoideae*) had an FC of 16.03% and C of 46.98% [69]. The DBC feedstock contained a low ash composition (0.77%) compared with bamboo, which contained differences of 2.57% [46] and 8.69% in Ampel bamboo [72]. The difference in such chemical composition, even in bamboo feedstock, is caused by its structure, age, species, and part of the plant, affecting the composition of lignin, cellulose, hemicellulose, and other extractions [31, 36, 53].

3.2. The VM, MC, Ash, FC, and pH of DBC Biochar Obtained from Various Pyrolysis Conditions

The lignocellulose composition in the DBC feedstock was transformed into biochar with different thermochemical reactions. The reaction pathways during pyrolysis were fragmentation of the lignocellulosic components, depolymerization, and biochar formation [10, 71]. The physical change and chemical reaction continuously coincide in the pyrolysis process; hence, the biochar consists of aromatic-aliphatic groups, residual VM, and ash, with varying morphological structures [22, 85, 87].

Table 2. The proximate analysis and pH of disposable bamboo chopsticks obtained from different pyrolysis temperatures at 20 and 60 min of holding times

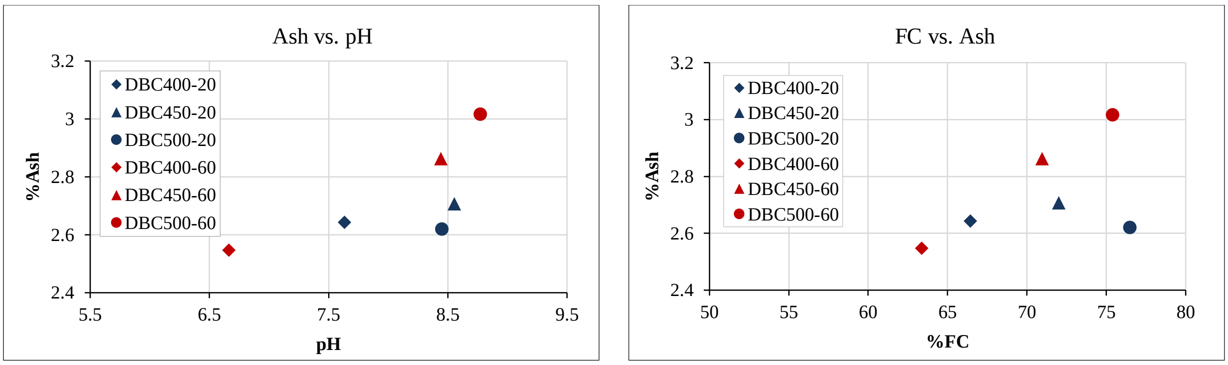
Properties	DBC400-20	DBC450-20	DBC500-20	DBC400-60	DBC450-60	DBC500-60
%MC	2.18±0.033^b	2.69±0.042^a	1.66±0.043^c	4.58±0.017^x	2.77±0.057^y	2.19±0.102^z
%VM	28.72±0.395^a	22.59±0.222^b	19.23±0.217^c	29.48±0.550^x	23.40±0.667^y	19.38±0.599^z
%Ash	2.64±0.037^b	2.71±0.019^a	2.62±0.008^b	2.55±0.017^z	2.86±0.031^y	3.02±0.031^x
%FC	66.45±0.356^c	72.01±0.205^b	76.49±0.249^a	63.39±0.531^z	70.97±0.666^y	75.41±0.587^x
pH	7.63±0.025^c	8.55±0.012^a	8.45±0.022^b	6.66±0.034^z	8.44±0.008^y	8.77±0.045^x

Remark: Data presented as mean ± SD with a harmonic mean sample size of 4.0. The letters (a, b, and c) represent statistically significant differences between the data set of 20 min of holding times. In contrast, the letters (x, y, and z) represent statistically significant differences between the data set of 60 min of holding times.

The first phase of the process is to expel moisture and volatile substances from the biomass structure; hence, more moisture is expelled from the DBC feedstock when the temperature rises (Table 2). Initially, the VM content and tarry vapors (such as CO, CO_2, C_xH_y, $C_xH_yO_z$, H_2O, HCN, and NH_3), which are associated with cellulose and hemicellulose contents [15, 60, 83], were excreted from feedstocks [23], which resulted in the majority of mass loss [45, 88], inducing bond rupture and the generation of hydroperoxide, -COOH and -CO groups [13, 35, 40]. The results showed that increasing the pyrolysis for 20 min of holding time from 400 °C to 500 °C significantly decreased the MC and VM contents of DBC biochar from 2.18% to 1.66% and 28.72% to 19.23%, respectively. Similarly, for 60 min of holding time, the MC and VM contents markedly decreased from 4.58% to 2.19% and 29.48% to 19.38%, respectively. However, Askeland et al. [30] reported increased MC in biochar produced at higher temperatures.

A further increase in the pyrolysis temperature decreases the release of carbon-rich compounds ($C_xH_yO_z$), whereas other volatile compounds, such as CO, CO_2, and HCN, are continuously released [3, 43, 45]. The VM content represented the degree of thermal alteration related to its chemical composition [61, 76, 79]. Some previous studies indicated that the VM content of biochar had a strong positive relationship with labile C, irrespective of biochar feedstock [20, 66, 70]. Due to an increased temperature, VM is continuously released, leading to an increase in the remaining FC content [10, 21, 23]. Accordingly, as the holding time and temperature increased, the FC content of DBC biochar markedly increased. As observed, increasing the temperature from 400 °C to 500 °C for 20 min of holding time showed that the FC contents significantly increased from 66.45% to 76.49% and from 63.39% to 75.41% for 60 min. Furthermore, pyrolysis of DBC feedstock at high temperatures (500 °C) at both 20- and 60-min holding times gave DBC biochar the highest FC and the least VM and MC content. With the high FC content, increasing the pyrolysis temperature and time could enhance the stability of biochar.

Naturally, the ash content increased when the temperature and time increased due to the accumulation of minerals, an increased concentration of inorganic elements, and the volatilization of VM [14, 34, 55, 63]. However, the results indicated that the ash content was only slightly affected at a low holding time. On the other hand, there was a significant increase in ash content as the temperature increased for a holding time of 60 min, aligning with the study by Uroić Štefanko & Leszczynska [64], who indicated that ash content and its formation were proportional to the nutrient and mineral levels in feedstock. Therefore, the ash content in biochar derived from wood-based feedstocks is lower than that in non-wood-based feedstocks. However, Wijitkosum [52] found that corn cob biochar had an ash content (0.96%) lower than krachid biochar (*Streblus ilicifolius* (Vidal) Corner.) (3.60%), while ash content in rain tree biochar (*Samanea saman* (Jacq.) Merr.) (0.99%) was lower than cassava rhizome biochar (5.02%). Moreover, this study found that prolonged holding times simultaneously increased the ash contents and pH values of DBC biochar. A highly positive correlation was found between the ash content and pH values (Figure 2). Ash correlated with pH at a low level (R^2 = 0.129) when pyrolysis occurred at different temperatures for 20 min. On the other hand, at a holding time of 60 min, ash contents and pH values were correlated at a high level (R^2 = 0.968). In addition, the FC was positively correlated with ash. A lower level of correlation (R^2 = 0.038) was observed in pyrolysis at different temperatures for 20 min compared with pyrolysis for 60 min (R^2 = 0.998).



(a) (b)

Figure 2. The relationship between the ash contents and pH (a) and between FC and ash contents (b) of DBC biochar pyrolysis at different conditions

The findings from previous studies, commonly known as biochar, were alkaline and obtained from wooden-based and nonwooden feedstock [28, 71, 74]. According to the pH in this study, the DBC biochar obtained from different pyrolysis conditions was neutral (pH 6.66) to strongly alkaline (pH 8.77). Wijitkosum [52] reported that biochar obtained from corn cob, cassava rhizome, and rice husk at 450-550 °C were alkaline (9.54, 10.40, and 7.48, respectively). Boraah et al. [55] reported that biochar derived from old wood furniture and neem wood increased alkalinity when temperatures increased. However, under the same pyrolysis conditions, it was found that biochar from old wood furniture had a higher pH than that from neem wood. In addition, the present result observed that at the same pyrolysis condition, the DBC biochar with lower pH also has lower ash content, consistent with the report by Zhang et al. [47] and Yuan et al. [80].

Tag et al. [5] reported that wood-based biochar had an average lower pH than non-wood-based biochar, even with similar pyrolysis conditions. The low pH of wood-based biochar is caused by cellulose and hemicellulose, which decompose during the thermal conversion of biomass feedstock and yield organic acids, affecting the pH of the final product [29, 31, 82]. Neutral DBC biochar was obtained from pyrolysis at 400 °C for 60 min; when the temperature rose to 500 °C, the biochar was strongly alkaline. However, pyrolysis for 20 min showed that the DBC biochar had a pH ranging from 7.63 to 8.55, classified as slightly alkaline to strongly alkaline. These results suggested that DBC biochar was more alkaline when the temperature rose, regardless of the holding time. This result is probably caused by an increased concentration of fundamental elements inherited from feedstock, such as alkali and alkali earth metals [12, 42, 76]. At the same time, acidic surface functional groups decreased during carbonization [26, 27, 31]. Both mechanisms coincide, increasing biochar alkalinity as the pyrolysis temperature increases [42, 54, 63]. Furthermore, the pH of wooden biochar correlated with the pH of the feedstock, which could be used to predict the pH of biochar. However, such relationships did not appear in low-temperature pyrolysis [24, 28].

3.3. Elemental Compositions of DBC Biochar Obtained from Various Pyrolysis Conditions

The temperature still significantly affected the elemental composition of DBC biochar, even if the holding time was set for 20 min or 60 min (Table 3).

Table 3. The elemental composition and pH of disposable bamboo chopsticks obtained from different pyrolysis temperatures at 20 and 60 min of holding times

Elements	DBC400-20	DBC450-20	DBC500-20	DBC400-60	DBC450-60	DBC500-60
%C	77.54±0.253^{c}	81.01±0.243^{b}	88.06±0.146^{a}	74.57±0.300^{z}	80.39±0.168^{y}	83.57±0.346^{x}
%H	4.56±0.023^{a}	4.23±0.015^{b}	3.32±0.026^{c}	4.58±0.053^{x}	4.18±0.010^{y}	3.82±0.017^{z}
%N	0.31±0.025^{c}	0.40±0.013^{b}	0.51±0.028^{a}	0.37±0.018^{z}	0.44±0.016^{y}	0.49±0.029^{x}
%O	14.95±0.266^{a}	11.66±0.268^{b}	5.49±0.189^{c}	17.82±0.247^{x}	12.05±0.189^{y}	9.03±0.317^{z}

Remark: Data are presented as mean ± SD with a harmonic mean sample size of 4.0. The letters (a, b, and c) represent statistically significant differences between the data set of 20 min of holding times. In contrast, the letters (x, y, and z) represent statistically significant differences between the data set of 60 min of holding times.

This study showed that increasing pyrolysis temperature and time caused C in DBC biochar to increase significantly. As the temperature increased from 400 °C to 500 °C, the C content of biochar obtained from pyrolysis at 20 min increased from 77.54% to 88.06% and from 74.57% to 83.57% when pyrolysis occurred at 60 min. This result confirmed the observation by Domingues et al. [62] that the C content of wooden biochar increases significantly from 67.6% to 86.3% when the pyrolysis temperature increases from 350 °C to 750 °C. Likewise, Tomczyk et al. [82] found that the biochar C content significantly increased from 62.2 to 92.4% when the pyrolysis temperature was elevated. Sbizzaro et al. [59] indicated that bamboo culm biochar produced at 350 °C had a C content of 68.46% and increased to 73.75% at 550 °C. Furthermore, if the temperature exceeds 450 °C, the aliphatic C will disappear or change to aromatic C [33], and the aromatic ring structure has high stability [17, 25, 42].

The temperature increased from 400 °C to 500 °C with 20 min of holding time, slightly decreasing the H content from 4.56% to 3.32%, while the O content dramatically decreased to 5.49% when the temperature reached 500 °C. Upon increasing the holding time to 60 min, the H content slightly decreased from 4.58% to 3.82%, and the O content interestingly decreased from 17.82% to 9.03%. The decrease in H and O contents is likely due to three crucial reactions: dehydration, the decomposition of the oxygenated bonds, and the release of low-molecular-weight byproducts containing H and O [29, 58, 86]. Likewise, some of the elemental contents of C and H were formed as organic functional groups and then appeared at the biochar surface [9, 37, 56]. Furthermore, during the reaction, there was a change in structure and higher C formation, which means that biochar had a more aromatic structure [21, 23, 26]. At the same time, the loss of H and O functional groups, such as -OH and -COOH, indicates more hydrophobic structures of biochar [32, 50, 80]. The mechanism of such reactions is complex and has a relationship between the elemental composition, such as C, H, and O, and the composition of VM, FC, and ash [30, 79].

Previous studies reported that the N content decreased with increasing temperature [38, 41, 59, 82]. Conversely, the N content of DBC biochar increased from 0.31% to 0.51% and from 0.37% to 0.49% when the temperature rose from 400 °C to 500 °C at 20 min and 60 min, respectively. At the same time, some studies reported that the N content increased with increasing pyrolysis temperature [17, 30, 53]. Zhang et al. [27] indicated that the N content of biochar was more affected by the feedstock type than the pyrolysis condition, notably in wooden feedstock, where the wood structure contains N resistant to degradation as the temperature rises [16, 33]. In this case, Tu et al. [57] reported that the N content of woody plant-based biochar decreased from 0.54% to 0.10% when the temperature increased from *400* °C to 700 °C. In contrast, Kloss et al. [28] found that a temperature increases from *400* °C to *525* °C increased the content of N in biochar obtained from poplar wood (*Populus tremula*) and spruce wood (*Picea abies*). The increasing N content was caused by dehydration, decarbonization, aromatization reactions, and especially heterocyclic N formation [9, 42]. In contrast, a reduction in N content could be attributed to the decomposition and volatilization of N compounds in feedstock [26, 67, 68].

3.4. Pyrolysis Temperature and Holding Times Affect the Properties of DBC Biochar

The results indicated that temperature and holding time both affected the DBC biochar properties (Table 4). The distinct composition of DBC biochar resulted from a slow pyrolytic conversion of the biomass feedstock. The pyrolysis process causes VM and ash contents to be significantly and dramatically reduced compared to feedstock (85.16% VM and 0.77% ash). Moreover, the FC content in DBC biochar increased significantly from the feedstock (10.24%) when DBC underwent pyrolysis.

Table 4. The proximate analysis and pH of disposable bamboo chopstick biochar produced from different pyrolysis conditions

Treatments	%MC	%VM	%Ash	%FC	pH
DBC400-20	2.18±0.033^{c}	28.72±0.395^{a}	2.64±0.037^{d}	66.45±0.356^{e}	7.63±0.025^{d}
DBC450-20	2.69±0.042^{b}	22.59±0.222^{b}	2.71±0.019^{c}	72.01±0.205^{c}	8.55±0.012^{b}
DBC500-20	1.66±0.043^{d}	19.23±0.217^{c}	2.62±0.008^{d}	76.49±0.249^{a}	8.45±0.022^{c}
DBC400-60	4.58±0.017^{a}	29.48±0.550^{a}	2.55±0.017^{e}	63.39±0.531^{f}	6.66±0.034^{e}
DBC450-60	2.77±0.057^{b}	23.40±0.667^{b}	2.86±0.031^{b}	70.97±0.666^{d}	8.44±0.008^{c}
DBC500-60	2.19±0.102^{c}	19.38±0.599^{c}	3.02±0.031^{a}	75.41±0.587^{b}	8.77±0.045^{a}

Remark: Data are presented as mean ± SD with a harmonic mean sample size of 4.0. The letters (a, b, c,…n) represent statistically significant differences between the data set at p<0.05.

Although the MC, ash contents, and pH did not clearly show a statistically significant difference in each pyrolysis condition, statistically significant differences were found in some conditions. In contrast, a statistically significant difference was found in FC content. An analysis of the impact of temperature and holding time on biochar properties found that each factor affected MC, VM, FC, and pH at $p < 0.05$. Temperature robustly interacted with time ($p < 0.05$) and together interacted significantly, affecting the MC (R^2 of 0.997), FC (R^2 of 0.990), and pH (R^2 of 0.999). Temperature and time strongly interact to influence the biochar ash ($p < 0.001$), with an adjusted R^2 of 0.999.

On the other hand, the results showed that temperature and time did not interact with each other to affect the VM content. This is consistent with the findings of the Table 4 analysis. Previous research by Enders et al. [76] indicated that VM content depends purely on feedstock type rather than pyrolysis temperature. The present findings are consistent with the results of other studies; temperature and time increases clearly showed an effect on the increase in pH, ash, and FC of biochar [37, 41, 57]. Increasing pyrolysis temperature virtually decreases VM and MC contents; when temperatures reach 500 °C, the VM and MC contents drop dramatically. Although many previous studies reported increased holding time and decreased MC and VM contents [63, 68], this study observed prolonged holding time at the same temperature and increased MC and VM contents, which aligns with the study Ahmad et al. [44].

The DBC biochar had statistically significant differences in %C, %H, %N, and %O after the feedstock had undergone pyrolysis at 20 min and 60 min of holding time and different temperatures (Table 5). All DBC biochars had an increased C content from feedstock (45.37%), ranging from 74.57% to 88.06%, and H (3.32%–4.58%) and O (5.49%–17.82%) contents were lower compared to feedstock (6.18% H and 48.08% O). The DBC biochar had a higher N content (0.31%–0.49%) than the feedstock (0.30%), with the highest (DBC500–20) and lowest (DBC400–20) values found in biochar obtained from pyrolysis at 20 min of holding time.

Table 5. The elemental composition of disposable bamboo chopstick biochar produced from different pyrolysis conditions

Treatments	%C	%H	%N	%O
DBC400-20	77.54±0.253^{e}	4.56±0.023^{a}	0.31±0.025^{d}	14.95±0.266^{b}
DBC450-20	81.01±0.243^{c}	4.23±0.015^{b}	0.40±0.013^{c}	11.66±0.268^{c}
DBC500-20	88.06±0.146^{a}	3.32±0.026^{d}	0.51±0.028^{a}	5.49±0.189^{e}
DBC400-60	74.57±0.300^{f}	4.58±0.053^{a}	0.37±0.018^{c}	17.82±0.247^{a}
DBC450-60	80.39±0.168^{d}	4.18±0.010^{b}	0.44±0.016^{b}	12.05±0.189^{c}
DBC500-60	83.57±0.346^{b}	3.82±0.017^{c}	0.49±0.029^{a}	9.03±0.317^{d}

Remark: Data are presented as mean ± SD with a harmonic mean sample size of 4.0. The letters (a, b, c,…n) represent statistically significant differences between the data set at p<0.05.

The results likely follow the same trend as the FC content; the C content of DBC biochar obtained from different pyrolysis conditions is significantly different. In contrast, the elemental contents of H, N, and O were not statistically significant in each pyrolysis condition. However, it is worth noting that the difference between the highest and lowest values of the elemental composition of biochar that was pyrolyzed at 20 min is wider than the biochar obtained from pyrolysis at 60 min.

The thermal decomposition process affects the elemental composition changes in DBC feedstock, and the properties of DBC biochar are shown in the results of the above analysis. The apparent impact of increasing temperature and time on changes in C, H, and O of wooden-based biochar was observed, consistent with previous studies [5, 31, 32, 66]. In contrast to N content, the correlation between N content and temperature and time could not be determined [14, 17]. Considering the interaction between temperature and holding time ($p < 0.05$), it was discovered that both factors had a significant interaction; therefore, they concertedly affected the elemental composition of DBC biochar (R^2 of 0.997). Furthermore, each factor affects ($p < 0.05$) the elemental composition of the biochar content.

Previous research presented the temperature and time that affect the properties of biochar [2, 30, 68], and the influence of each factor was reported [4, 38, 45]. This finding indicated that temperature strongly interacted with time and together influenced DBC biochar properties; the results are in line with Anupam et al. [15], who reported that temperature interacted with time, with the temperature (0.91) being more prominent than the holding time (0.63). The present research findings support the complexity of the thermochemical conversion of lignocellulosic biomass to biochar, which affects the properties of biochar. Biochar is a highly diverse material with an endothermic process for the decomposition and conversion of biomass into biochar and other products.

3.5. Suitable Pyrolysis Conditions for Producing High-quality Biochar Derived from Disposable Bamboo Chopstick Waste

With the various types of feedstocks and the complexity of the production process, designing a suitable pyrolysis process to control the excellent quality of biochar is challenging [11, 39]. Typically, biochar quality is strongly influenced by temperature and holding time and is determined by the C content and the atomic ratios of H/C, O/C, and (O+N)/C, representing the degree of carbonization, aromaticity, polarity, and stability of biochar, respectively [11, 57].

Increased temperature (from 400 °C to 500 °C) at 20 min and 60 min (Table 6) dramatically decreased the atomic ratio of H/C, O/C, and (O+N)/C. The atomic ratio of H/C and O/C decreased, implying that the DBC biochar became increasingly aromatic and carbonaceous. At the same temperature (Table 6), it was found that more extended holding time provided DBC biochar with higher atomic ratios of O/C and (O+N)/C. On the other hand, the results showed that when the time was extended, the H/C was higher when compared with each temperature, except for biochar pyrolyzed at 450 °C.

Table 6. The aromaticity, polarity, and stability of DBC biochar obtained from different pyrolysis conditions

Properties	DBC400-20	DBC450-20	DBC500-20	DBC400-60	DBC450-60	DBC500-60
H/C	0.71	0.63	0.45	0.74	0.62	0.55
O/C	0.15	0.11	0.05	0.21	0.14	0.11
(O+N)/C	0.15	0.11	0.05	1.29	0.94	0.76

Remark: Data presented as a sample size of 4.0.

Increasing pyrolysis temperature had an effect on the degree of aromaticity (H/C ratio) and the degree of polarity (O/C ratio). The result is consistent with numerous previous studies [35, 40, 59, 64]. However, prolonged holding time increased the H/C ratio in this study, which is in contrast to the results of Wang et al. [67], which reported that the H/C ratio decreased as the holding time and temperature. The result found that increased pyrolysis temperature and prolonged time result in an even more hydrophobic character of DBC biochar due to more polar surface functional groups being removed. Similar observations are found in the previous literature [14, 40, 47, 51]. Low-temperature pyrolysis (400 °C) for both 20 and 60 min provided lower-quality biochar products compared to the other production at other pyrolysis conditions due to H/C > 0.7, even if the O/C (<0.4) and C contents (>50%) meet the standard requirements of the EBC [77] and the IBI [78]. This finding could indicate that 400 °C was the pyrolysis temperature that resulted in the incomplete formation of aromatic carbon. Shafizadeh & Sekiguchi [84] stated that only 2.5% of the aromatic carbon structure occurs at 400 °C. The O/C ratio of DBC400-20 and DBC400-60 was less than 0.4 in this study because the C content increased while the H and O contents decreased as the temperature increased. The present results are consistent with the studies of Guizani et al. [39], which indicated that at a pyrolysis temperature higher than 300 °C, the cracking of the residual O and H in biochar caused the atomic ratios of H/C and O/C to decrease. Based on the study results, selecting the appropriate production pyrolysis conditions that produce high-quality biochar for effective use is possible. The analysis results indicated that pyrolysis at 500 °C for 20 min is the best condition for producing DBC biochar, which had the highest contents of C (88.06%) and FC (76.49%) while having the lowest ash (2.62%) and VM (19.23%) contents. The DBC biochar obtained from this condition showed the highest carbonization, aromaticity, and recalcitrance values. At the same time, it showed the lowest polarity and the highest hydrophobicity. Such important properties are critical and most beneficial for applying biochar for environmental and agricultural purposes.

3.6. Predicting the Potential of DBC Biochar for Climate Change Mitigation

Using biochar in agricultural areas plays a role in mitigating climate change in two ways: reducing greenhouse gas emissions [1, 6, 51] and sequestering carbon in biomass and soil [9, 73]. In general, its durability and physicochemical properties in the soil environment determine the critical factors of biochar for this role. In this case, ash content, pH, C, and the atomic ratios of H/C, O/C, and (O+N)/C were considered [42].

The greenhouse gas reduction potential of biochar is in the order of N_2O, followed by CH_4 and CO_2 [1]. Mechanisms for controlling greenhouse gas emissions from biochar are quite complex and are carried out through soil microbial activities and plant mechanisms in the soil environment [6, 16]. The high aromaticity of biochar causes less organic C to inhibit methanogenesis, thus helping to control CH_4 emissions from the soil [1, 7]. Amending soil with alkaline biochar to elevate soil pH to neutral and alkaline levels was reported to be an appropriate condition for chemical reactions in the soil, including reduced CH_4 emissions [16]. However, in the event of the reduction of N_2O emissions, Ji et al. [7] and Cayuela et al. [8] indicated that it is not a direct result of soil pH changes but a result of other biochar properties intrinsically connected to pH and induced support mechanisms to reduce N_2O emissions. A meta-analysis of the literature by Lyu et al. [1] indicated that in the case of CO_2, the difference in the impact of biochar on CO_2 in both positive and negative directions is reported. Considering the aromaticity and persistence of DBC biochar, DBC450-20, DBC450-60, DBC500-20, and DBC500-60 had high aromaticity ($H/C < 0.7$), high stability, and persistence with a half-life of more than 1,000 years ($O/C < 0.2$).

Moreover, DBC450-20, DBC450-60, DBC500-20, and DBC500-60 were moderately alkaline to strongly alkaline and could be applied to acidic soil and reduce CH_4 emissions. All DBC biochar contained a high C content of 80.39% to 88.06% and a low ash content of 2.62% to 3.02%. With these properties, DBC biochar produced under all four conditions has the potential to be used to reduce greenhouse gas emissions. In contrast, DBC biochar obtained at 400 °C did not show the potential for this purpose. Furthermore, selecting suitable biochar for soil and climatic conditions is also a key factor affecting the direction and magnitude of mitigation. A previous literature review found that long-term studies assessing the potential and mechanisms of greenhouse gas emissions in the field are rare. Basic mechanisms and key influencing factors related to the impact on greenhouse gas emissions after long-term use are still challenging to understand and exhibit complexity, especially in tropical soils. In addition, findings from past research do not have a definite direction, such as the duration and age of biochar influencing greenhouse gas emissions, which are reported differently [6, 8, 16]. Therefore, future research will include field experiments on the selected DBC biochar (DBC450-20, DBC450-60, DBC500-20, and DBC500-60) to assess the potential for greenhouse gas emission reductions and their mechanisms in tropical soil.

4. Conclusion

Pyrolysis of DBC feedstock at different temperatures at 400 °C, 450 °C, and 500 °C for 20 min and 60 min holding times significantly affected the physicochemical properties of DBC biochar. Increasing the pyrolysis temperature from 400 °C to 500 °C significantly increased the C, FC, N, and ash contents. In contrast, VM, MC, H, and O contents dramatically decreased. Such changes gave the same trend as pyrolysis at different times. The C and FC contents of DBC biochar were completely different under all pyrolysis conditions. The H, N, O, ash, and MC contents showed statistically significant differences under certain pyrolysis conditions.

Additionally, increasing temperature and time increased the aromaticity, hydrophobicity, and stability of DBC biochar while decreasing its polarity. It could be concluded that temperature significantly interacts with time ($p < 0.05$); these two factors together influenced the elemental composition (C, H, N, and O) of biochar and the MC, ash, and FC contents of biochar under different pyrolysis conditions. In contrast, no such relationship was found for the VM content; therefore, the VM content obtained from different pyrolysis conditions is the result of each factor. Prolonged holding times simultaneously increased the ash contents and pH values of DBC biochar. The study concluded that pyrolysis at 450 °C and 500 °C for 20 min and 60 min provided good-quality DBC biochar with a high potential to reduce greenhouse gas emissions and C sequestration.

5. Declarations

5.1. Data Availability Statement

The data presented in this study are available in the article.

5.2. Funding

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5.3. Institutional Review Board Statement

Not applicable.

5.4. Informed Consent Statement

Not applicable.

5.5. Declaration of Competing Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the author.

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