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# Aromaticity, polarity, and longevity of biochar derived from disposable bamboo chopsticks waste for environmental application

Saowanee Wijitkosum [a,*], Thavivongse Sriburi [b]

[a] Environmental Research Institute, Chulalongkorn University, Bangkok, 10330, Thailand
[b] Pa-deng Biochar Research Center, Phetchaburi, 76170, Thailand

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ABSTRACT

Transforming disposable bamboo chopstick (DBC) wastes into biochar is an effective way to achieve waste-to-resource conversion. This research focused on the elemental and chemical composition of biochar and revealed how these properties affect biochar performance in real-world applications, particularly with respect to climate change mitigation. This research is aimed at examining the effect of pyrolysis temperature on the aromaticity, polarity, and longevity of DBC biochar. The DBC feedstock was pyrolyzed at different temperatures of 400 °C, 450 °C, 500 °C, and 550 °C with a holding time of 20 min at a constant heating rate of 20 °C $min^{-1}$. The chemical composition, including carbon (C), hydrogen (H), nitrogen (N), oxygen (O), volatile matter (VM), ash, and fixed carbon (FC) contents, were analyzed. The aromaticity, polarity, and longevity of biochar are presented by the atomic ratios of H/C, O/C, (O + N)/C, and C/N, and these ratios are used to determine the potential of biochar for use in climate change mitigation applications. The findings demonstrated that DBC biochar produced at various pyrolysis temperatures contained C contents ranging from 77.54% to 88.06%, ash contents ranging from 2.62% to 2.99%, and a half-life of over 1000 years ($O/C < 0.2$). Pyrolysis temperature significantly affected biochar properties, as supported by the results for the FC/ash ratio (>10); the ash, FC, C, and N contents increased with increasing temperature; in contrast, the VM, H, and O contents decreased. The results revealed that DBC wastes are the potential feedstock to produce good-quality biochar that could be applied for environmental purposes. Furthermore, the research demonstrated that the best-performing DBC biochar was produced at 500 °C, which had the highest C content, aromaticity, and longevity and the lowest polarity as represented by the values of O/C, H/C, and (O + N)/C, and this biochar could be applied for climate change mitigation purposes.

## 1. Introduction

Biochar is an eco-friendly carbon-rich product and is an organic material produced from lignocellulosic biomass through a pyrolysis process at temperatures ranging from 300 °C to 700 °C [1,2]. Slow pyrolysis, thermochemical decomposition under oxygen-limited conditions, has been identified as an appropriate process for producing biochar, forming a stable carbonaceous, homogeneous

* Corresponding author. Environmental Research Institute, Chulalongkorn University, Bangkok, 10330, Thailand.
*E-mail address:* saowanee.w@chula.ac.th (S. Wijitkosum).

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structure and resulting in high yield [3–5]. Studie in the literature revealed that biochar had gained widespread attention due to its effective use in various applications, including soil improvement [6,7], absorption [8,9], wastewater treatment [10], carbon sequestration, reduction of greenhouse gas emissions [11–13], and crop yield and productivity increases [14,15]. The unique properties that make it useful in various applications are its liming capacity, high porosity, large surface area, and high ion exchange capacity [16–18]. Moreover, biochar has a high carbon content, and its principal component contains hydrogen, nitrogen, oxygen, and plant macronutrients such as nitrogen, phosphorous, and potassium [5,19,20].

However, using biochar for various purposes depends on the biochar properties, including morphology, physical properties, and physicochemical properties [21–23]. One of the primary uses of biochar is as a soil amendment; such applications must take into account biochar pH, cation exchange capacity, and porosity [24,25]. Similarly, for removing soil and water contamination, biochar adsorption mechanisms must be considered [9,26–28]. Biochar chemical composition, aromaticity, polarity, and longevity affect its utility for environmental and agricultural purposes [24,29–31], especially in terms of its potential for application in climate change mitigation and long-term remediation of soil ecosystems [32–34].

The meta-literature indicates that biochar properties depended on feedstock and pyrolysis conditions [21,35,36]. Previous studies reported that biochar could be produced from various lignocellulosic biomass feedstock types, both wooden and non-wooden [4,32,37], such as agricultural waste and residues [15,38,39], sewage and sludge [1], animal manure [34], and wood and woodchips [2,36,40]. Studies on converting wood-based wastes that have the potential to produce biochar have also been widely reported [5,41–43]. Disposable wooden chopsticks (DWCs) have been widely used worldwide, and most DWC wastes are destined for landfills and incinerators, which presents problems related to waste disposal and results in unsustainable natural resource consumption. Therefore, the thermochemical conversion of these wastes to biochar is an efficient way to produce sustainable material that is more environmentally and financially viable for many applications [22,42]. Moreover, the conversion of carbon in biomass to fixed carbon in biochar reduces the amount of $CO_2$ in the atmosphere and leads to the possibility of carbon neutralization [6,44].

With respect to pyrolysis conditions, temperature, time, and heating rate determine the unique properties of different biochar [38,45]. However, many studies have noted that feedstock, temperature, and time are important factors that significantly affect the properties of biochar [36,46,47]. Additionally, in the case of the same feedstock type, the properties of biochar are significantly affected by the temperature [20,48,49]. However, wooden feedstocks have complex structures and compositions; as a result, the various components of the biomass break down at different temperatures, which makes the biochar properties highly diverse, even when produced from the same feedstock [41,43,50].

It has been widely observed that biochar is a special material with unique characteristics and typically differs in properties, impacting its performance in real-world applications [25,35,51]. Accordingly, biochar production research continues to be significant and necessary to advance applications and seek suitable conditions to produce good-quality and high-efficiency biochar. Furthermore, understanding the relevance of biochar properties and pyrolysis temperatures can lead to targeted biochar design for specific applications. This study aimed to integrate the utilization of wood-based wastes, e.g., disposable bamboo chopsticks, with biochar production and evaluate the properties of the resultant biochar for climate change mitigation purposes based on the aromaticity, polarity, and longevity of the biochar.

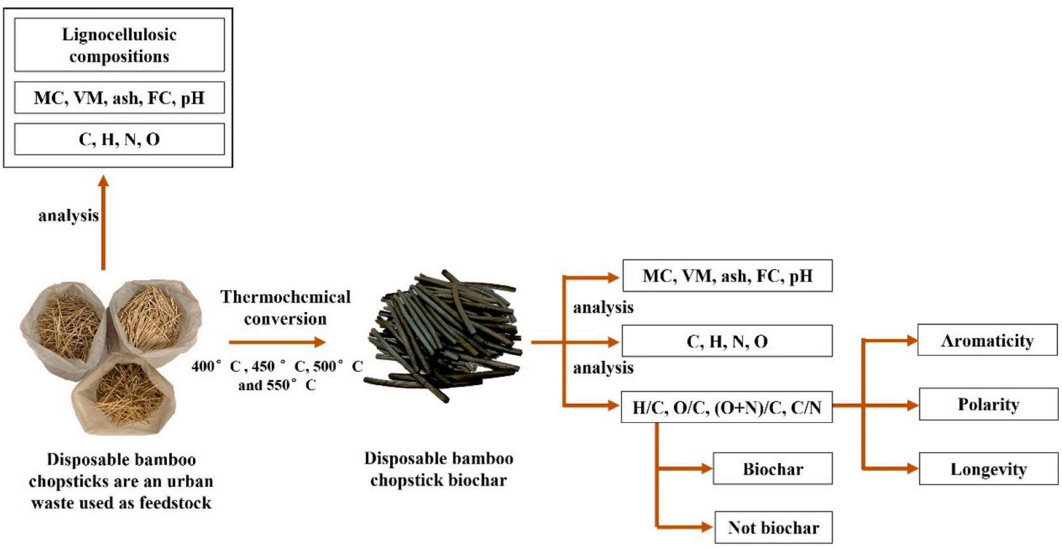


**Fig. 1.** Biochar production and analysis of feedstock and biochar.

## 2. Material and methods

### 2.1. Biochar production process

The waste from disposable bamboo chopsticks is a feedstock for biochar production. Most are made from *Dendrocalamus membranaceus* Munro. Lignocellulosic biomass contains cellulose, hemicellulose, and lignin as the main components, which have different proportions in each plant type [25], in which each composition responds to different thermal decomposition temperatures. Hemicellulose decomposes at 200–300 °C [52,53], and cellulose decomposes at 300–375 °C [34,54]. Lignin is a complex phenylpropanoid polymer with considerable structural heterogeneity [55]; therefore, it continuously decomposes in a temperature range of 250–500 °C. The carbonization stage will be complete at 500–600 °C [19,35]. Therefore, in this study, the temperature of the process was set to be evaluated based on incomplete (400 °C and 450 °C) and complete (500 °C and 550 °C) pyrolysis conditions. The process was held a constant holding time of 20 miniuts, and a heating rate of 20 °C $min^{-1}$ was set for each pyrolysis temperature process. The pyrolysis reactor was a muffle furnace with a digital temperature regulator (detection accuracy $<$10 °C).

After the pyrolysis process was finished, the samples were left in the reactor until the product reached room temperature. Biochar samples were stored in tightly closed containers at room temperature. The samples were ground into approximately 2–3 sieve particle sizes and examined for their elemental composition analysis and proximate analysis without further treatment (Fig. 1).

### 2.2. Feedstock and biochar characterization

The lignocellulosic compositions of DBCs were analyzed according to the Technical Association of the Pulp and Paper Industry (TAPPI) Standard, including the holocellulose, alpha-cellulose (TAPPI T203), lignin (TAPPI T222), and ash (TAPPI T211). Hemicellulose was determined by using the difference between the content of holocellulose and alpha-cellulose.

The properties of feedstock and biochar were analyzed, including volatile matter (VM), ash, fixed carbon (FC), carbon (C), hydrogen (H), nitrogen (N), and oxygen (O). The proximate analysis of VM, ash, and FC contents was based on the American Society for Testing and Materials standard (ASTM), using the ASTM D7582 for feedstock and the ASTM D3172-3175 method for biochar. The C, H, and N contents were analyzed using the ASTM D5373-16 method by the Elemental Analyzer (CHN; LECO, Truspec CHN analyzer, Condition: 950, 850 °C, $O_2$ (HP), He (UHP)). The bamboo had a very low sulfur content (0.023%–0.05%) [5,17]; hence, the O content was calculated from the difference in the percentage of ash and elemental C, H, and N contents, following the ASTM. The atomic ratio of O/C, H/C, and (O + N)/C of biochar was calculated to evaluate aromaticity, polarity, and longevity [56,57] and evaluated the product as biochar [58]. The C/N ratio was calculated to predict the potential of biochar for greenhouse gas reduction [59].

### 2.3. Statistical data analysis

The properties of feedstock and biochar were derived from four replicates, and the data were presented as mean ± standard deviation (SD). Variations between properties produced at different temperatures were analyzed using one-way ANOVA, and significant differences between means were determined using Turkey's Post hoc test ($p < 0.05$). Statistical analyses were performed with the Social Science Statistical Package (SPSS) software v.28.0.0.0.

## 3. Results and discussion

### 3.1. Characteristics of disposable bamboo chopstick feedstock

The results revealed (Table 1) that DBCs mainly comprised 37.54% cellulose, 22.45% hemicellulose, 22.52% lignin, and 11.29% extractives.

Lignin is a complex phenolic polymer with many benzene rings [35], containing high C and low O contents [14,18] and providing impermeability, structural support, and oxidative stability [50]. Therefore, lignin has been identified as a significant factor influencing biomass utilization [17,55], notably biochar production [35,37]. However, the recent literary works of Tomczyk et al. [21] showed that cellulose and lignin composition are considered important reasons for the differences in biochar properties and structures. The DBCs had a high proportion of such components and a low ash content, showing potential as a feedstock for producing biochar. Furthermore, the chemical linkage between cellulose-lignin and cellulose-hemicellulose and their physical arrangement within the biomass structure may influence biochar distribution [20,34].

Table 2 showed that the DBCs had a high VM content of 85.16%, which made them easy to ignite. The low MC (3.83%) is

**Table 1**
Chemical compositions of the structure of disposable bamboo chopsticks.

| Lignocellulosic components (%) | | | | |
|---|---|---|---|---|
| Cellulose | Hemicellulose | Lignin | Extractives | Ash |
| 37.54 ± 0.159 | 22.45 ± 0.150 | 22.52 ± 0.109 | 11.29 ± 0.264 | 0.08 ± 0.004 |

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

**Table 2**
Proximate analysis and the pH of bamboo chopsticks.

| Proximate analysis (%) | | | | |
|---|---|---|---|---|
| DM | VM | MC | Ash | FC |
| 96.17 ± 0.235 | 85.16 ± 2.153 | 3.83 ± 0.235 | 0.77 ± 0.055 | 10.24 ± 2.127 |

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

advantageous because it does not necessitate pretreatment before pyrolysis. The MC value was lower than the MC of bamboo, which is 7.1–10.7% [8,37,42]. It is worth noting that the ash content in the DBC feedstock was lower than that in bamboo, based on Hernandez-Mena et al. [42] (2.57%), Wang et al. [37] (2.10%), and Sahoo et al. [36] (1.58%). The FC content in woody biomass varies depending on plant type; therefore, the FC of DBC was 10.24% different from that of other wooden feedstocks, such as 15.2% for beech wood [49], 35% of tree bark *(Pinus pinaster), and 19% of applewood* [45].

Generally, more than 90% of the fundamental elements of lignocellulosic biomass, which are important components of plant structures, are C, H, and O, which can be divided into organic and inorganic phases [29,32]. In contrast, N is a minor component [4, 59]; as a result, the DBCs (Table 3) comprise a C content of 45.37%, an H content of 6.18%, and an O content of 48.08% while having a low N content (0.30%). The DBCs have low N content because bamboo trunks are used to make the chopsticks, which are low in protein and chlorophyll and contain N components [59]. Most of the C, H, and O components are in the organic phase; therefore, the H/C and O/C of biomass can predict the trend in structural change in the lignocellulosic biomass [27,30]. The atomic O/C ratio of biomass has the following order: cellulose (approximately 0.83) > hemicellulose > lignin (0.33) [52]. The result showed that DBCs had an atomic ratio of 1.63 H/C, O/C 0.79, and C/N 51.81.

### 3.2. Properties of DBC biochar obtained at different pyrolysis temperatures

Pyrolysis temperature is an important factor determining biochar properties (Table 4) since it governs the extent of cleavage of chemical bonds within crucial components of the lignocellulosic components. It can be observed that all DBC biochar had lower VM, H, and O contents than the feedstock while having higher ash, FC, C, and N contents.

An FC/ash ratio greater than 10 in biochar indicated that temperature affected biochar properties [48]. Accordingly, the DBC biochar had a high ratio of FC/ash (25.14–28.01), which supports the fact that the compositions of VM, ash, FC, C, H, N, and O are significantly affected by temperature. Previous results from Enders et al. [29], Kim et al. [40], Wijitkosum [22], and Sun et al. [34] supported the relationship between the ash and FC content of biochar and revealed that temperature affects ash content. Moreover, the ash content of a feedstock, which mainly consists of alkali and alkaline earth metallic species, is detrimental to the formation of biochar FC. Therefore, the FC content of the biochar increases as the temperature rises in feedstocks with low ash content and decreases in feedstocks with high ash. This result showed that increasing the pyrolysis temperature of the DBC feedstock, which had a low ash content (0.77%), increased the FC of biochar. Moreover, the FC content of DBC biochar obtained at different temperatures showed a statistically significant difference.

The FC content of DBC biochar obtained from different temperatures (400–550 °C) ranged from 66.45% to 78.13%. Meta-literature analysis by Tan et al. [50] reported that biochar produced from slow pyrolysis contains FC contents ranging from 30% to 98%, depending on temperature and feedstock types. Because an equilibrium state is reached in the reaction chamber, the pyrolysis process is quenched before reaction completion; hence, the chemical transformation of biochar is complex [26,53,57]. As the temperature increased, the VM content gradually decreased while the ash content increased as organic components were volatilized. The VM content is released at a higher temperature from the porous structure of the DBC feedstock. DBC-550, which was produced at the highest temperature (550 °C), had the highest FC of 78.13% and an ash content of 2.99% while having the lowest VM of 11.69%. In contrast, the highest VM content was found in DBC-400 (28.72%); however, DBC-450 and DBC-500 did not show significantly different VM contents.

These results arise from the thermal decomposition of the lignocellulosic composition of the DBC feedstock, which had different chemical structures; the DBC biochar generation process and structure obtained at each temperature are different. For the primary reaction, cellulose, hemicellulose, and lignin underwent depolymerization, fragmentation, and rearrangement [2,24]. The decomposition of cellulose, hemicellulose, and lignin also depends on the content of these organic components in the biomass feedstock [34, 38]. Heat drives volatile compounds and gases from biomass feedstocks, including $CO_2$, CO, $H_2O$, and hydrocarbons [3,10,18]. Subsequently, the primary decomposition products underwent cracking and condensation reactions to form non-condensable gases and biochar [50]. Furthermore, the degradation of cellulose and lignin and the dehydration of the hydroxyl groups increase

**Table 3**
Elemental compositions and the atomic ratio of bamboo chopsticks.

| Elemental compositions | | | | Atomic molar ratio | | |
|---|---|---|---|---|---|---|
| C | H | N | O | H/C | O/C | C/N |
| 45.37 ± 0.145 | 6.18 ± 0.147 | 0.30 ± 0.019 | 48.08 ± 0.136 | 1.63 ± 0.042 | 0.79 ± 0.005 | 51.81 ± 1.832 |

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

**Table 4**
The properties of DBC biochar obtained from different pyrolysis temperatures.

| Parameters | DBC-400 | DBC-450 | DBC-500 | DBC-550 |
|---|---|---|---|---|
| % VM | 28.72 ± 0.395[a] | 22.59 ± 0.222[b] | 19.23 ± 0.217[b] | 11.69 ± 6.169[c] |
| %Ash | 2.64 ± 0.037[c] | 2.71 ± 0.019[b] | 2.62 ± 0.008[c] | 2.99 ± 0.005[a] |
| % FC | 66.45 ± 0.356[d] | 72.01 ± 0.205[c] | 76.49 ± 0.249[b] | 78.13 ± 0.441[a] |
| %C | 77.54 ± 0.253[d] | 81.01 ± 0.243[c] | 88.06 ± 0.146[a] | 86.30 ± 0.233[b] |
| %H | 4.56 ± 0.023[a] | 4.23 ± 0.015[b] | 3.32 ± 0.026[d] | 3.73 ± 0.006[c] |
| %N | 0.31 ± 0.025[c] | 0.40 ± 0.013[b] | 0.51 ± 0.028[a] | 0.49 ± 0.010[a] |
| %O | 14.95 ± 0.266[a] | 11.66 ± 0.268[b] | 5.49 ± 0.189[d] | 6.49 ± 0.230[c] |

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

significantly at higher temperatures [7,20], which results in reduced H and O content during the carbonization process [17,18]. The O content was correlated with VM, FC, and ash [48]. N in the organic phase of lignocellulose is transformed to heterocyclic N, accompanied by aromatization of C. Graphitic-N might also be formed at increased temperature [1,54,59].

The DBC biochar, as a wood-based biochar, had very high %C ranging from 77.54% to 88.06% and exhibited significant differences in each pyrolyzed biochar. All DBC biochar is classified as class 1 biochar by IBI, which has greater than 60% C content [58]. The results showed that with increasing temperature, the DBC biochar had progressively higher C content, resulting from the removal of dissociated bonds between C and functional groups on the surface of the biomass, including –OH, aliphatic C–O, and aliphatic C–H groups [9,19,33,47]. The aromatization process begins at approximately 350 °C and continues at higher temperatures [40,49]. The aromatic C–H deformation increased until the temperature reached 500 °C [43]. Amorphous carbons, the main biochar component, are structured as aromatic rings, giving biochar its characteristic stability [26,32]. Therefore, DBC biochar had the highest C content when the temperature was raised to 500 °C. However, as the temperature reached 550 °C, a decrease in C content (86.30%) was observed. The results are consistent with those of Chatterjee et al. [16], which revealed that when the temperature reached a certain point, the C in biochar decreased; corn stover biochar had C content that decreased at a temperature of 800 °C, and C in switchgrass biochar decreased when the temperature reached 700 °C.

A significant increase in the C and N contents of DBC biochar was accompanied by a decrease in the H and O contents at increased carbonization temperatures from 400 °C to 550 °C. The DBC biochar dramatically decreased in O content when the temperature reached 500 °C. A similar decrease in the H and O contents of wood-based biochar and agro-based biochar has been reported in Wang et al. [37] for bamboo, in Zhang et al. [2] for oak and pine wood, in Chatterjee et al. [16] for switchgrass, corn stover, and sugarcane bagasse, and in Enders et al. [29] for sawdust and hazelnut shells. The results showed that the N content of DBC biochar increased with increasing temperature, in line with results for the pyrolysis of bamboo in Sahoo et al. [36] and sawdust and rice husk in Pariyar et al. [24]. However, Jindo et al. [38] and Pariyar et al. [24] reported that the N content of biochar decreased when temperature increased.

### 3.3. *Aromaticity, polarity, and longevity of DBC biochar obtained from different pyrolysis temperatures*

The study found that the atomic ratio of H/C and O/C of DBC feedstock dramatically decreased when it was thermochemically converted to biochar. Because cellulose, hemicellulose, and lignin have different C and O contents, the atomic O/C ratio can reflect compositional variations during the process. Moreover, during pyrolysis, O is released at a greater rate than H, with the final product of biochar characterized by a decreased atomic H/C and O/C ratio with a low O content [14,22,57]. Therefore, the results in Table 5 showed that with an increase in temperature from 400 °C to 550 °C, the H/C and O/C ratios of DBC biochar decreased from 0.71 to 0.52 and 0.14 to 0.06, respectively, which can be attributed to the loss of H and O content during the process, leading to greater aromaticity. It is worth noting that when the temperature increases to values greater than 500 °C, the H/C and O/C ratios increase.

The atomic ratios of H/C and O/C are widely recognized factors determining the characteristics of biochar. The H/C ratio reflects that biochar has converted carbon structures from hydrocarbons into aromatic rings [6,29,47]; it is used to evaluate aromaticity and predict its longevity [5,66]. The atomic ratio of H/C decreases substantially as the pyrolysis temperatures rise, indicating that depolymerization procedures are occurring, which implies increased oxidation resistance [3,10]. In biochar with an atomic H/C ratio lower than 0.7, this indicates the experience of the aromatization processes mainly at pyrolysis temperatures greater than 400 °C [13,16,27]; it has better fused aromatic ring structures [43,58], making it highly stable and resistant in the soil ecosystem [1,19,39].

**Table 5**
The atomic ratio of DBC biochar obtained from different pyrolysis temperatures.

| Parameters | DBC-400 | DBC-450 | DBC-500 | DBC-550 |
|---|---|---|---|---|
| O/C | 0.14 ± 0.003[a] | 0.11 ± 0.003[b] | 0.05 ± 0.002[d] | 0.06 ± 0.002[c] |
| H/C | 0.71 ± 0.004[a] | 0.63 ± 0.003[b] | 0.45 ± 0.003[d] | 0.52 ± 0.002[c] |
| (O + N)/C | 0.15 ± 0.003[a] | 0.11 ± 0.003[b] | 0.05 ± 0.001[d] | 0.06 ± 0.002[c] |
| C/N | 295.69 ± 1.223[a] | 238.06 ± 1.129[b] | 202.71 ± 1.135[c] | 205.16 ± 1.222[c] |

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

Accordingly, the results found that pyrolysis of DBC feedstock at a temperature ≥450 °C provided DBC biochar which had a high degree of aromaticity with an atomic ratio of H/C lower than 0.7. The results indicated that DBC-500 had the highest condensed aromaticity and showed the highest stability and persistence when applied to the soil.

The low values of the H/C ratio are caused by the composition of cellulose, hemicellulose, and lignin in woody feedstocks; it was observed that wood-based biochar had a lower H/C ratio than herbaceous biochar, agricultural residue biochar, and animal manure biochar [33,41,47]. It is worth noting that Wijitkosum and Jiwnok [12] reported that rice husk biochar obtained from the CTRHBRSP, which is a patented furnace (400–500 °C), had the H/C ratio of 0.27, which was lower than DBC biochar. However, Wijitkosum [41] reported that krachid (*Streblus ilicifolius* (Vidal) Corner.) biochar and corn cob biochar obtained from the CTBRSPP patented furnace (400–500 °C) had H/C ratios of 0.02 and 0.04, respectively. In this case, the residential time, heating rate, and type of furnace (reactor) were significant factors [17,21,53]. Due to the thermal degradation of the lignocellulosic biomass, the process is endothermic, for which substantial heat is necessary to raise and maintain the reaction temperature. Therefore, transferring heat from the pyrolysis reactor to the biomass feedstock is necessary to influence the biomass pyrolysis reactions and product distribution [26,59].

The O/C ratio is also used to evaluate the degree of biochar oxidation [41,44,56]. Furthermore, the O/C and (O + N)/C represent the degree of polarity with polar functional groups of biochar [5,27,31], reflecting the hydrophobicity of biochar. Biochar produced at a temperature lower than 450 °C generally has higher water-soluble organic compound content, especially in low molecular weights [46,51]. In addition, biochar also accumulates aliphatic and aromatic compounds in its pores and on the surface, and when the temperature rises, the concentration of these compounds will be diminished and removed [28]. The O/C ratio decreased when the temperature increased due to the decarboxylation reaction, which implies the high carbonization and formation of solid C structures in biochar [57]. Therefore, the results indicated that DBC-400 showed lower hydrophobicity performance and higher polarity than other DBC biochar. Similarly, the DBC-500 also became highly hydrophobicity due to the high loss of O content and low protection of O-containing functional groups. As another point, lowering the O/C ratio indicates highly fused aromatic rings of biochar; therefore, the atomic ratio of O/C also reflects the stability of biochar by comparing carbon materials using the spectrum of the O/C ratio between biomass and graphite, which is a position continuum ranging from 0 (graphite) to 0.6 (biomass) [31]. Previous research by Pariyar et al. [24] reported that biochar obtained from pyrolysis between 500 °C and 599 °C would typically have a half-life of 100–1000 years (O/C of 0.2–0.6). On the other hand, the present research found that DBC biochar produced at 400 °C–550 °C had a low O/C ratio (<0.20), which was highly stable (half-life >1000 years).

Depending on the feedstock and pyrolysis conditions, the C/N ratio can be highly variable, ranging from 6.5 to 640 [14]. The C/N ratio of DBC biochar ranged from 202.71 to 295.69 and was affected by the temperature. However, in pyrolysis in the same temperature range, Wijitkosum [41] indicated that biochar produced from wood had a C/N ratio (101.13–132.47) higher than biochar derived from agricultural waste (38.94–65.08). Similar observations from previous research reported that C/N ratios of biochar produced from rice and maize straw were 50 and 70, respectively [15]. Sun et al. [34] observed that biochar produced from sludge, animal manure, and aquatic plants had a lower C/N ratio, which was less than 30 and not suitable for decreased $N_2O$ emission from agriculture. The (O + N)/C and C/N ratios decreased with increasing temperature; as a result, the highest values of the (O + N)/C and C/N ratios were found in DBC-400; however, DBC-500 presented the lowest value.

The present research indicated that pyrolysis of DBC feedstock at temperatures higher than 450 °C provided DBC biochar with high aromaticity and persistence while showing hydrophobic performance. The results are in line with Tomczyk et al. [21], Crombie et al. [13], and Ippolito et al. [32]. Considering the potential of biochar for practical applications, it is well known that highly stable biochar is in high demand from the point of view of climate change mitigation and is also a feature that supports higher agricultural benefits. In this case, the biochar properties for the mentioned purposes can be determined by the persistence of biochar in the soil environment (H/C ratio as aromaticity index), polarity ((O + N)/C ratio as a polarity index), and hydrophobicity (O/C as a hydrophilicity index). At the same time, the C/N ratio was also an index that could indicate the potential of biochar for utilization to reduce greenhouse gas emissions from agricultural areas [11].

Furthermore, biochar with high aromaticity increases adsorption capacity and the potential for C sequestration [25]. The results indicated that all DBC biochar with a high C/N ratio reduced the mineralization intensity of soil nitrogen when applied to the soil and, therefore, could reduce greenhouse gas emissions. However, Bakshi et al. [33] suggested that the atomic ratio of H/C is intrinsically more accurate than O/C. From this study, it could be indicated that DBC biochar produced from temperatures of 450–550 °C had high performance, although the biochar obtained at 400 °C has an O/C ratio of less than 0.2, while the H/C is still higher than 0.7.

## 4. Conclusions

The study results showed that disposable bamboo chopstick waste, as a wood-based lignocellulosic biomass, was a potential feedstock to produce biochar due to its low ash and MC contents and high FC and C contents. The pyrolysis of DBC feedstock at different temperatures of 400 °C, 450 °C, 500 °C, and 550 °C provided biochar of good quality. The analysis results indicated that pyrolysis temperature plays a significant role in defining the characteristics of DBC biochar, including C, H, N, and O, VM, FC, ash contents, and the atomic ratios of H/C, O/C, (O + N)/C, and C/N. The degree of carbonization increased with pyrolysis temperature; therefore, DBC biochar became progressively more aromatic and carbonaceous as the temperature increased. In addition, increasing pyrolysis temperature increases the longevity and decreases the polarity of DBC biochar. Biochar is utilized for climate change mitigation due to its aromaticity, polarity, and stability, and the best performing DBC biochar was produced at high temperatures (450 °C, 500 °C, and 550 °C) and had high C contents and a high C/N ratio and a low atomic ratio of O/C, H/C and (O + N)/C.

## Author contribution statement

Saowanee Wijitkosum: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Thavivongse Sriburi: Conceived and designed the experiments.

## Data availability statement

Data will be made available on request.

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## 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.

## References

[1] H.-B. Kim, S.-H. Kim, E.-K. Jeon, D.-H. Kim, D.C. Tsang, D.S. Alessi, E.E. Kwon, K. Baek, Effect of dissolved organic carbon from sludge, Rice straw and spent coffee ground biochar on the mobility of arsenic in soil, Sci. Total Environ. 636 (2018) 1241–1248, https://doi.org/10.1016/j.scitotenv.2018.04.406.
[2] Y. Zhang, Z. Ma, Q. Zhang, J. Wang, Q. Ma, Y. Yang, X. Luo, W. Zhang, Comparison of the physicochemical characteristics of biochar pyrolyzed from moso bamboo and rice husk with different pyrolysis temperatures, Bioresources 12 (3) (2017) 4652–4669.
[3] H. Huang, N.G. Reddy, X. Huang, P. Chen, P. Wang, Y. Zhang, Y. Huang, P. Lin, A. Garg, Effects of pyrolysis temperature, feedstock type and compaction on water retention of biochar amended soil, Sci. Rep. 11 (1) (2021) 7419, https://doi.org/10.1038/s41598-021-86701-5.
[4] M.E. Doumer, G.G.C. Arízaga, D.A. da Silva, C.I. Yamamoto, E.H. Novotny, J.M. Santos, L.O. dos Santos, A. Wisniewski Jr., J.B. de Andrade, A.S. Mangrich, Slow pyrolysis of different Brazilian waste biomasses as sources of soil conditioners and energy, and for environmental protection, J. Anal. Appl. Pyrol. 113 (2015) 434–443, https://doi.org/10.1016/j.jaap.2015.03.006.
[5] Q. Fang, B. Chen, Y. Lin, Y. Guan, Aromatic and hydrophobic surfaces of wood-derived biochar enhance perchlorate adsorption via hydrogen bonding to oxygen-containing organic groups, Environ. Sci. Technol. 48 (1) (2014) 279–288, https://doi.org/10.1021/es403711y.
[6] H.P. Schmidt, C. Kammann, N. Hagemann, J. Leifeld, T.D. Bucheli, M.A. Sánchez Monedero, M.L. Cayuela, Biochar in agriculture–A systematic review of 26 global meta-analyses, GCB Bioenergy 13 (11) (2021) 1708–1730, https://doi.org/10.1111/gcbb.12889.
[7] T.M. Maaz, W.C. Hockaday, J.L. Deenik, Biochar volatile matter and feedstock effects on soil nitrogen mineralization and soil fungal colonization, Sustainability 13 (4) (2021) 2018, https://doi.org/10.3390/su13042018.
[8] J.-H. Park, J.J. Wang, S.-H. Kim, S.-W. Kang, C.Y. Jeong, J.-R. Jeon, K.H. Park, J.-S. Cho, R.D. Delaune, D.-C. Seo, Cadmium adsorption characteristics of biochars derived using various pine tree residues and pyrolysis temperatures, J. Colloid Interface Sci. 553 (2019) 298–307, https://doi.org/10.1016/j.jcis.2019.06.032.
[9] T.G. Ambaye, M. Vaccari, E.D. van Hullebusch, A. Amrane, S. Rtimi, Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater, Int. J. Environ. Sci. Technol. 18 (2021) 3273–3294, https://doi.org/10.1007/s13762-020-03060-w.
[10] X. Wang, Z. Guo, Z. Hu, J. Zhang, Recent advances in biochar application for water and wastewater treatment: a review, PeerJ 8 (2020), e9164, https://doi.org/10.7717/peerj.9164.
[11] Q. Zhang, J. Xiao, J. Xue, L. Zhang, Quantifying the effects of biochar application on greenhouse gas emissions from agricultural soils: a global meta-analysis, Sustainability 12 (8) (2020) 3436, https://doi.org/10.3390/su12083436.
[12] S. Wijitkosum, P. Jiwnok, Effect of biochar on Chinese kale and carbon storage in an agricultural area on a high rise building, AIMS Agriculture and Food 4 (1) (2019) 177–193, https://doi.org/10.3934/agrfood.2019.1.177.
[13] K. Crombie, O. Mašek, A. Cross, S. Sohi, Biochar–synergies and trade-offs between soil enhancing properties and C sequestration potential, GCB Bioenergy 7 (5) (2015) 1161–1175, https://doi.org/10.1111/gcbb.12213.
[14] G. Bonanomi, F. Ippolito, G. Cesarano, B. Nanni, N. Lombardi, A. Rita, A. Saracino, F. Scala, Biochar as plant growth promoter: better off alone or mixed with organic amendments? Front. Plant Sci. 8 (2017) 1570, https://doi.org/10.3389/fpls.2017.01570.
[15] M. Ghorbani, P. Konvalina, R.W. Neugschwandtner, M. Kopecký, E. Amirahmadi, J. Moudrý, L. Menšík, Preliminary findings on cadmium bioaccumulation and photosynthesis in rice (*Oryza sativa* L.) and maize (*Zea mays* L.) using biochar made from C3- and C4-originated straw, Plants 11 (2022) 1424, https://doi.org/10.3390/plants11111424.
[16] R. Chatterjee, B. Sajjadi, W.-Y. Chen, D.L. Mattern, N. Hammer, V. Raman, A. Dorris, Effect of pyrolysis temperature on physicochemical properties and acoustic-based amination of biochar for efficient $CO_2$ adsorption, Front. Energy Res. 8 (2020) 85, https://doi.org/10.3389/fenrg.2020.00085.
[17] W. Suliman, J.B. Harsh, N.I. Abu-Lail, A.-M. Fortuna, I. Dallmeyer, M. Garcia-Perez, Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties, Biomass Bioenergy 84 (2016) 37–48, https://doi.org/10.1016/j.biombioe.2015.11.010.
[18] O. Oginni, K. Singh, Influence of high carbonization temperatures on microstructural and physicochemical characteristics of herbaceous biomass derived biochars, J. Environ. Chem. Eng. 8 (5) (2020), 104169, https://doi.org/10.1016/j.jece.2020.104169.
[19] J. Chen, D. Zhang, H. Zhang, S. Ghosh, B. Pan, Fast and slow adsorption of carbamazepine on biochar as affected by carbon structure and mineral composition, Sci. Total Environ. 579 (2017) 598–605, https://doi.org/10.1016/j.scitotenv.2016.11.052.
[20] H. Zhang, R. Voroney, G. Price, Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations, Soil Biol. Biochem. 83 (2015) 19–28, https://doi.org/10.1016/j.soilbio.2015.01.006.
[21] A. Tomczyk, Z. Sokołowska, P. Boguta, Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects, Rev. Environ. Sci. Biotechnol. 19 (2020) 191–215, https://doi.org/10.1007/s11157-020-09523-3.
[22] S. Wijitkosum, Repurposing disposable bamboo chopsticks waste as biochar for agronomical application, Energies 16 (2) (2023) 771, https://doi.org/10.3390/en16020771.
[23] J.M. De la Rosa, P. Campos, A. Diaz-Espejo, Soil biochar application: assessment of the effects on soil water properties, plant physiological status, and yield of super-intensive olive groves under controlled irrigation conditions, Agronomy 12 (2022) 2321, https://doi.org/10.3390/agronomy12102321.

[24] P. Pariyar, K. Kumari, M.K. Jain, P.S. Jadhao, Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application, Sci. Total Environ. 713 (2020), 136433, https://doi.org/10.1016/j.scitotenv.2019.136433.
[25] A. El-Naggar, S.S. Lee, J. Rinklebe, M. Farooq, H. Song, A.K. Sarmah, A.R. Zimmerman, M. Ahmad, S.M. Shaheen, Y.S. Ok, Biochar application to low fertility soils: a review of current status, and future prospects, Geoderma 337 (2019) 536–554, https://doi.org/10.1016/j.geoderma.2018.09.034.
[26] M. Ghorbani, P. Konvalina, M. Kopecký, L. Kolář, A meta-analysis on the impacts of different oxidation methods on the surface area properties of biochar, Land Degrad. Dev. (2022) 1–14.
[27] I.J. Schreiter, W. Schmidt, C. Schüth, Sorption mechanisms of chlorinated hydrocarbons on biochar produced from different feedstocks: conclusions from single- and bi-solute experiments, Chemosphere 203 (2018) 34–43, https://doi.org/10.1016/j.chemosphere.2018.03.173.
[28] B. Chen, D. Zhou, L. Zhu, Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures, Environ. Sci. Technol. 42 (14) (2008) 5137–5143, https://doi.org/10.1021/es8002684.
[29] A. Enders, K. Hanley, T. Whitman, S. Joseph, J. Lehmann, Characterization of biochars to evaluate recalcitrance and agronomic performance, Bioresour. Technol. 114 (2012) 644–653, https://doi.org/10.1016/j.biortech.2012.03.022.
[30] D.B. Wiedemeier, S. Abiven, W.C. Hockaday, M. Keiluweit, M. Kleber, C.A. Masiello, A.V. McBeath, P.S. Nico, L.A. Pyle, M.P. Schneider, Aromaticity and degree of aromatic condensation of char, Org. Geochem. 78 (2015) 135–143, https://doi.org/10.1016/j.orggeochem.2014.10.002.
[31] M. Elmquist, G. Cornelissen, Z. Kukulska, Ö. Gustafsson, Distinct oxidative stabilities of char versus soot black carbon: implications for quantification and environmental recalcitrance, Global Biogeochem. Cycles 20 (2) (2006), https://doi.org/10.1029/2005GB002629.
[32] J.A. Ippolito, L. Cui, C. Kammann, N. Wrage-Mönnig, J.M. Estavillo, T. Fuertes-Mendizabal, M.L. Cayuela, G. Sigua, J. Novak, K. Spokas, Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review, Biochar 2 (2020) 421–438, https://doi.org/10.1007/s42773-020-00067-x.
[33] S. Bakshi, C. Banik, D.A. Laird, Estimating the organic oxygen content of biochar, Sci. Rep. 10 (2020), 13082, https://doi.org/10.1038/s41598-020-69798-y.
[34] H. Sun, H. Lu, L. Chu, H. Shao, W. Shi, Biochar applied with appropriate rates can reduce N leaching, keep N retention and not increase $NH_3$ volatilization in a coastal saline soil, Sci. Total Environ. 575 (2017) 820–825, https://doi.org/10.1016/j.scitotenv.2016.09.137.
[35] V. Dhyani, T. Bhaskar, A comprehensive review on the pyrolysis of lignocellulosic biomass, Renew. Energy 129 (2018) 695–716, https://doi.org/10.1016/j.renene.2017.04.035.
[36] S.S. Sahoo, V.K. Vijay, R. Chandra, H. Kumar, Production and characterization of biochar produced from slow pyrolysis of pigeon pea stalk and bamboo, Cleaner engineering and technology 3 (2021), 100101, https://doi.org/10.1016/j.clet.2021.100101.
[37] Y. Wang, B. Zhong, M. Shafi, J. Ma, J. Guo, J. Wu, Z. Ye, D. Liu, H. Jin, Effects of biochar on growth, and heavy metals accumulation of moso bamboo (Phyllostachy pubescens), soil physical properties, and heavy metals solubility in soil, Chemosphere 219 (2018) 510–516, https://doi.org/10.1016/j.chemosphere.2018.11.159.
[38] K. Jindo, H. Mizumoto, Y. Sawada, M.A. Sanchez-Monedero, T. Sonoki, Physical and chemical characterization of biochars derived from different agricultural residues, Biogeosciences 11 (23) (2014) 6613–6621, https://doi.org/10.5194/bg-11-6613-2014.
[39] G. Enaime, M. Lübken, Agricultural waste-based biochar for agronomic applications, Appl. Sci. 11 (2021) 8914, https://doi.org/10.3390/app11198914.
[40] K.H. Kim, J.-Y. Kim, T.-S. Cho, J.W. Choi, Influence of pyrolysis temperature on physicochemical properties of biochar obtained from the fast pyrolysis of pitch pine (Pinus rigida), Bioresour. Technol. 118 (2012) 158–162, https://doi.org/10.1016/j.biortech.2012.04.094.
[41] S. Wijitkosum, Biochar derived from agricultural wastes and wood residues for sustainable agricultural and environmental applications, ISWCR 10 (2022) 335–341, https://doi.org/10.1016/j.iswcr.2021.09.006.
[42] L.E. Hernandez-Mena, A. Pécoraa, A.L. Beraldob, Slow pyrolysis of bamboo biomass: analysis of biochar properties, Chem. Eng. 37 (2014) 115–120, https://doi.org/10.3303/CET1437020.
[43] M.U. Jamal, A.J. Fletcher, Design of experiments study on scottish wood biochars and process parameter influence on final biochar characteristics, Bioenerg. Res. (2023), https://doi.org/10.1007/s12155-023-10595-6.
[44] M. Ghorbani, R.W. Neugschwandtner, G. Soja, P. Konvalina, M. Kopecký, Carbon fixation and soil aggregation affected by biochar oxidized with hydrogen peroxide: considering the efficiency of pyrolysis temperature, Sustainability 15 (2023) 7158, https://doi.org/10.3390/su15097158.
[45] A. Lataf, M. Jozefczak, B. Vandecasteele, J. Viaene, S. Schreurs, R. Carleer, J. Yperman, W. Marchal, A. Cuypers, D. Vandamme, The effect of pyrolysis temperature and feedstock on biochar agronomic properties, J. Anal. Appl. Pyrol. 168 (2022), https://doi.org/10.1016/j.jaap.2022.105728.
[46] M. Ghorbani, E. Amirahmadi, R.W. Neugschwandtner, P. Konvalina, M. Kopecký, J. Moudrý, K. Perná, Y.T. Murindangabo, The impact of pyrolysis temperature on biochar properties and its effects on soil hydrological properties, Sustainability 14 (2022), 14722, https://doi.org/10.3390/su142214722.
[47] P. Tu, G. Zhang, G. Wei, J. Li, Y. Li, L. Deng, H. Yuan, Influence of pyrolysis temperature on the physicochemical properties of biochars obtained from herbaceous and woody plants, Bioresour. Bioprocess. 9 (2022) 131, https://doi.org/10.1186/s40643-022-00618-z.
[48] K.T. Klasson, Biochar characterization and a method for estimating biochar quality from proximate analysis results, Biomass Bioenergy 96 (2017) 50–58, https://doi.org/10.1016/j.biombioe.2016.10.011.
[49] C. Guizani, M. Jeguirim, S. Valin, M. Peyrot, S. Salvador, The Heat Treatment Severity Index: a new metric correlated to the properties of biochars obtained from entrained flow pyrolysis of biomass, Fuel 244 (2019) 61–68, https://doi.org/10.1016/j.fuel.2019.01.170.
[50] H. Tan, C. Lee, P. Ong, K. Wong, C. Bong, C. Li, Y. Gao, A review on the comparison between slow pyrolysis and fast pyrolysis on the quality of lignocellulosic and lignin-based biochar, IOP Conf. Ser. Mater. Sci. Eng. (2021), https://doi.org/10.1088/1757-899X/1051/1/012075.
[51] S. Joseph, A. Cowie, L. Zwieten, N. Bolan, A. Budai, W. Buss, M. Cayuela, E. Graber, J. Ippolito, Y. Kuzyakov, Y. Luo, Y. Ok, K. Palansooriya, J. Shepherd, S. Stephens, Z. Weng, J. Lehmann, How biochar works, and when it doesn't: a review of mechanisms controlling soil and plant responses to biochar, Glob. Change Biol. Bioenergy 13 (2021) 1731–1764, https://doi.org/10.1111/gcbb.12885.
[52] P. Kumar, D.M. Barrett, M.J. Delwiche, P. Stroeve, Methods for pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production, Ind. Eng. Chem. Res. 48 (8) (2009) 3713–3729, https://doi.org/10.1021/ie801542g.
[53] B. Babu, Biomass pyrolysis: a state-of-the-art review, Biofuels, Bioproducts and Biorefining: Innovation for a sustainable economy 2 (5) (2008) 393–414, https://doi.org/10.1002/bbb.92.
[54] J. Paz-Ferreiro, A. Nieto, A. Méndez, M.P.J. Askeland, G. Gascó, Biochar from biosolids pyrolysis: a review, Int. J. Environ. Res. Publ. Health 15 (5) (2018) 956, https://doi.org/10.3390/ijerph15050956.
[55] R. Vanholme, K. Morreel, J. Ralph, W. Boerjan, Lignin engineering, Curr. Opin. Plant Biol. 11 (3) (2008) 278–285, https://doi.org/10.1016/j.pbi.2008.03.005.
[56] S. Schimmelpfennig, B. Glaser, One step forward toward characterization: some important material properties to distinguish biochars, J. Environ. Qual. 41 (4) (2012) 1001–1013, https://doi.org/10.2134/jeq2011.0146.
[57] K.A. Spokas, Review of the stability of biochar in soils: predictability of O: C molar ratios, Carbon Manag. 1 (2) (2010) 289–303, https://doi.org/10.4155/cmt.10.32.
[58] International Biochar Initiative (IBI), Standardized Product Definition and Product Testing Guidelines for Biochar that Is Used in Soil, 2015. https://biochar-international.org/wp-content/uploads/2020/06/IBI_Biochar_Standards_V2.1_Final2.pdf.
[59] W.-J. Liu, W.-W. Li, H. Jiang, H.-Q. Yu, Fates of chemical elements in biomass during its pyrolysis, Chem. Rev. 117 (9) (2017) 6367–6398, https://doi.org/10.1021/acs.chemrev.6b00647.