Available online at www.ijournalse.org

Emerging Science Journal

(ISSN: 2610-9182)

Vol. 8, No. 3, June, 2024

Taking Advantage of Disposal Bamboo Chopsticks to Produce Biochar for Greenhouse Crop Cultivation

Saowanee Wijitkosum [1*], Thavivongse Sriburi [2], Luechai Krutnoi [3]

[1] *Environmental Research Institute, Chulalongkorn University, Bangkok 10330, Thailand.*

[2] *Pa-deng Biochar Research Center, Phetchaburi 76170, Thailand.*

[3] *Chula Unisearch, Chulalongkorn University, Bangkok 10330, Thailand.*

Abstract

Biochar is a value-added product that can be used for many purposes, particularly for environmental and agricultural purposes. In this study, pyrolysis at 450–500 °C was used to upgrade urban waste such as disposable bamboo chopsticks (DBCs) into biochar. The properties of DBC biochar were analyzed, and the biochar was subsequently used to cultivate Romaine lettuce to assess its potential as a soil amendment. Its properties, including specific surface area (SSA), pore size, pore volume, pH, cation exchange capacity (CEC), contents of carbon (C), hydrogen (H), nitrogen (N), oxygen (O), macronutrient content, and the atomic ratio of H/C, O/C, (O+N)/C, and C/N, were analyzed. The experimental pots consisted of four treatments, each with ten replicates: unamended soil (TC), soil amended with 10% (w/w) vermicompost (TV), soil amended with 10% vermicompost mixed with 1.5% biochar (TVB1.5), and soil amended with 10% vermicompost mixed with 2.5% biochar (TVB2.5). Fundamental physicochemical soil properties and plant yield (plant height, leaf width, number of leaves, and fresh weight) were investigated. The results indicated that the DBC biochar was neutral (pH 6.80) and had a high CEC (10.86 cmol/kg), 66.80% C, 3.76% H, 25.93% O, and 0.61% N. It had mesopores (39.077 Å), a large SSA (0.542 m^2/g), and a pore volume of 0.005 cc/g. The biochar exhibited high aromaticity and hydrophobicity. Based on these results, the DBC biochar has the potential to be used as a soil amendment: it significantly enhances soil quality and increases plant yields. The application of 2.5% biochar resulted in the highest yield.

Keywords:

Upcycling;

Biochar;

Soil Amendment;

Waste-to-Resource;

Enhanced Yield.

Article History:

Received: 18 January 2024

Revised: 04 May 2024

Accepted: 09 May 2024

Published: 01 June 2024

1- Introduction

Worldwide, waste generation rates are increasing, especially in urban areas. With rapid population growth and urbanization, municipal waste generation is expected to increase to 2.2 billion tons by 2025 [1]. Asia produces more than 1 million tons of municipal solid waste (MSW) daily, and this value is expected to reach 1.8 million tons by 2025 [2]. One important waste from urban areas is single-use wood chopsticks, which are highly used in this region. Single-use wood chopsticks are produced from several types of wood, such as bamboo, cottonwood, birch, poplar, and spruce; these types of wood are lignocellulosic biomasses that have the potential to be reused and upcycled [3]. Due to the properties of disposable bamboo chopsticks (DBCs), such as low moisture content, low ash content, high volatile matter content, and high carbon content, they have the potential to be converted into biochar [4]. The transformation of these wastes into valuable materials seems to be a good solution for waste management and the sustainable consumption of natural resources. Driving a waste-to-resource management system provides enormous potential to promote the idea of a circular economy [5]. Moreover, lignocellulosic biomasses are advantageous for biochar production due to their low sulfur and nitrogen contents and lack of net emissions of atmospheric CO_2 [6, 7].

---

[*] **CONTACT**: saowanee.w@chula.ac.th; w.m.saowanee@gmail.com

DOI: http://dx.doi.org/10.28991/ESJ-2024-08-03-07

Biochar is a porous carbonaceous solid material with a high degree of aromatization and high resistance to decomposition when applied to soil ecosystems [8, 9]. Biochar is recognized as an environmentally friendly soil amendment with diverse properties; however, the fundamental characteristics of biochar make it suitable for use as a soil amendment include its large surface area, high porosity, highly stable carbon availability, alkalinity, high exchange cation capacity, and essential plant nutrients [4, 10-12]. Previous studies have reported that biochar can be produced from various biomass feedstocks, including wood-based and nonwood-based feedstocks [13, 14]. A meta-literature analysis indicated that various lignocellulosic biomass wastes, including agricultural residue, agricultural byproducts, and urban wastes, have received increased amounts of attention and are considered potential feedstocks for conversion into biochar, both in terms of their availability and properties [8, 12, 15].

Slow pyrolysis is generally used to produce biochar, in which a substrate is heated under oxygen-free or oxygen-limited conditions [16 ,17]. Several factors influence the biochar production process, such as temperature, residential time, heating rates, and reactor types, which affect the resultant biochar properties [18-20]. A systematic review of meta-analyses of published works by Ippolito et al. [21] and Tomczyk et al. [22] indicated that feedstock types influence biochar properties; wood-based biochar has high carbon and fixed carbon contents with various porosities but low nutrient contents compared to those of biochar derived from sewage sludge and animal manure. In contrast, the pyrolysis temperature affects biochar properties when the same type of feedstock is used. Huang et al. [23] indicated that wood-based biochar had 66.40% carbon and 19.80 m^2/g specific surface area when pyrolyzed at 300 °C, and these values increased to 83.29% carbon and 73.10 m^2/g specific surface area when the temperature reached 600 °C. However, in wooden feedstocks, some previous studies have noted that wood-based biochar has diverse properties, including morphological and physicochemical properties, due to the complex structures and compositions of the wooden feedstock [24-26].

A meta-analysis of the literature by Tomczyk et al. [22] indicated that feedstocks with high lignin contents are likely to provide greater biochar yields, but some studies have reported that the use of biochar derived from wood is not in line with the above trends. Moreover, numerous studies have reported that an increase in pyrolysis temperature increases biochar alkalinity and decreases N content [18, 27, 28]. In contrast, it has been reported that the opposite results were obtained for certain types of wood biochar [3, 13, 29]. Under the same pyrolysis condition, Kloss et al. [29] reported that increasing the pyrolysis temperature from 400 °C to 525 °C increased the N content in biochar obtained from poplar wood (*Populus tremula*) and spruce wood (*Picea abies*). In contrast to the result, Tu et al. [13] reported that biochar derived from the same types of woody feedstock had decreased N content from 4.41% to 1.49% when the temperature rose from 300 °C to 700 °C. At the same pyrolysis temperature (450–500 °C), Wijitkosum [14] demonstrated that biochar derived from a rain tree (*Samanea saman* (Jacq.) Merr.) had a specific surface area of 31.17 m^2/g, while krachid (*Streblus ilicifolius* (Vidal) Corner.) presented of 151.27 m^2/g. Zama et al. [30] reported that mulberry wood biochar had a specific surface area of 16.56 m^2/g from 350 °C and increased to 31.45 m^2/g from 450 °C. Bamboo is used in various ways and has received attention for its use as a feedstock for producing biochar. However, previous research reported that the variable properties of bamboo feedstock were also observed, particularly the fixed carbon content. Different values of fixed carbon content in bamboo were reported as 16.03% in bamboo (*Bambusoideae*) [31], 9.41% in Ampel bamboo (*Bambusa vulgaris*) [32], and 17.75% in bamboo (*D. giganteus* Munro) [33]. With many of those observations in mind, the conversion of wood-based feedstock into biochar still needs to be studied in more detail in the interest of its application.

A study on biochar application showed that the ultimate goal of biochar research is to enable the application of biochar for agricultural and environmental purposes, that is, as a soil amendment for directly improving soil and increasing crop productivity [20, 34, 35] and for indirect purposes such as carbon sequestration and reducing greenhouse gas emissions [36]. Wang et al. [37] and Palansooriya et al. [38] reported that biochar can improve soil properties and increase crop yield efficiency, both when used individually and when incorporated with compost and fertilizer [34, 39, 40], over short- and long-term cultivation [41-43]. Moreover, biochar was applied in various soil issues, including low-fertility soil [44], salt-affected soil [45, 46], and weathered [47]. According to the literature review, biochar application in agriculture has been studied in pots [48], greenhouses [49], and fields [36, 37, 50]. Its application in cultivating various plants, such as rice, field crops, and horticulture plants, has been reported [34, 42, 51]. Previous studies by Hou et al. [52], Liu et al. [53], and Hardy et al. [54] reported that the effect of biochar on soil and plant yield relies on the mechanism of biochar in the soil environment, which involves the relative effects of different biochar types and application rates on plant nutrient responses [39, 52, 55]. The biochar application rate is variable, and the range of application is wide, partly due to cultivation conditions (such as area location, container size, and cultivation pattern) and biochar properties and their effects [47, 56, 57].

Although a large body of literature has reported that biochar significantly promotes plant growth, increases plant productivity, and improves soil quality, some previous studies have reported the negative effects of biochar on plant yield [58, 59]. In addition, some studies have reported that biochar does not affect plant growth [60]. In addition, meta-analysis literature by Ye et al. [61] reported that in short planting time (1 yr), biochar effectively enhanced crop yields when fertilizer was combined. On the other hand, Wijitkosum & Sriburi [62] stated that using a cassava stem biochar alone (at all rates) for maize cultivation increased the fresh weight of seeds more than those obtained from plots cultivated with fertilizer alone. The significant factors influencing these results were considered in terms of biochar quality and properties, suitable biochar for soil resources (size and type), and application rates [63, 64]. As previously described, various properties and factors influence biochar and its utilization. Furthermore, this diversity strongly motivates researchers to attain the mechanistic understanding needed to produce optimized biochar and application patterns for specific crops and soil systems. Therefore, research on the potential of biochar and its use as a soil amendment is still needed, particularly for biochar derived from wood-based feedstocks, which are more diverse than non-wood feedstocks. For the reasons mentioned above, this study aimed to exploit DBC waste, an abundant waste in urban areas, and convert it into biochar, which can be utilized as a soil amendment. Although DBC is a biomass that has the potential to produce biochar, assessments of the performance of biochar obtained from DBC as a soil amendment are rare. Accordingly, the feasibility of applying DBC biochar as a soil amendment to grow Romaine lettuce in greenhouse plantations was investigated. The efficiency of biochar application at different rates mixed with vermicompost was analyzed and compared to that of vermicompost. The results confirmed the efficiency and potential of DBC biochar for soil amendment and an appropriate application rate for crop cultivation. The results can help guide the management of DBC waste and provide a way to upscale biochar production.

2- Material and Methods

2-1- Experimental Design

The experiments were designed with a completely randomized block design (CRBD); the plants were cultivated in plastic pots and placed in the greenhouse to establish an urban agricultural prototype. The experimental set was established to assess the feasibility of using biochar produced from disposable bamboo chopsticks as a soil amendment combined with vermicompost. The biochar application rate was taken from previous research by Wijitkosum & Jiwnok [48], who reported that the biochar application rate clearly affects crop yield during urban crop cultivation on a high-rise building. Therefore, four experimental treatments, each with ten replicates, were set up: 1) unamended soil as a control treatment (TC), 2) soil amended with 10% (w/w) vermicompost (TV), 3) soil amended with 10% vermicompost mixed with 1.5% biochar (TVB1.5), and 4) soil amended with 10% vermicompost mixed with 2.5% biochar (TVB2.5).

The planting materials (soil, vermicompost, and biochar) were thoroughly mixed on trays at the specified application rates and incubated under a clear polyvinyl chloride (PVC) sheet for 30 days; then, the mixed materials were placed in the experimental pots. The experimental pots consisted of black plastic pots with twelve drainage holes and a pot volume of approximately 2.26 liters, a width of 6 inches, a 4-inch bottom diameter, and a height of 5 inches.

Lactuca sativa L. var. Longifolia, or Romaine lettuce, a highly valuable plant, was selected for the evaluation of the potential of DBC biochar as a soil amendment for urban farming. Romaine plants are a variety of lettuce plants that have leaves that are longer than they are wide, and they typically have an upright growth habit, forming an elongated head so that they can be planted in a limited area [49, 63]. Romaine lettuce was seeded and grown in peat moss blocks for 14 days [64], and healthy plants aged 14 days were subsequently planted in the experimental pots with one plant per pot and covered with rice straw. All the plants in the experimental pots were placed in the greenhouse and watered by sprinkler irrigation once daily. The planting period was 60 days, after which the plants were harvested.

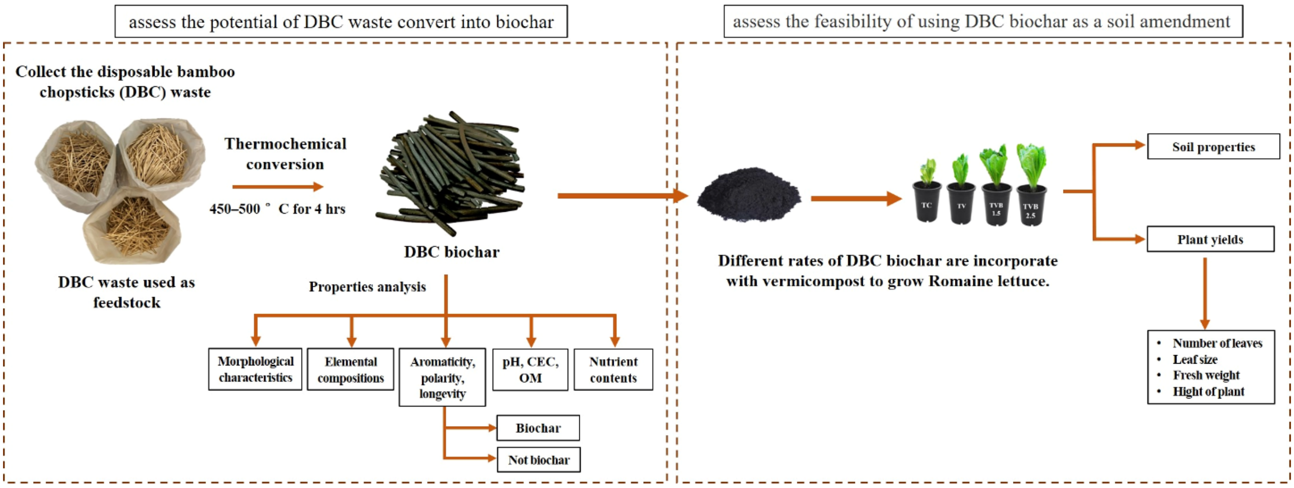


Figure 1. The conceptual research framework

2-2- Biochar Preparation and Property Analysis

DBC biochar was obtained from disposable bamboo chopsticks by pyrolysis at 450–500 °C for 4 hrs using a prototype local-design furnace. The biochar samples were kept and stored in a tightly closed container at room temperature before analysis of the essential properties of the soil amendments and characterization of their morphology. The samples were ground to approximately 2-3 sieve particle sizes and subjected to laboratory analysis without any treatment. The analysis methods followed the standard product definitions and product testing guidelines for biochar used in the soil [65].

The biochar pH was measured in deionized water and 1 m KCL solution using the 9045D method based on the United States Environmental Protection Agency [66]. The cation exchange capacity (CEC) was determined at pH 7 using ammonium acetate extraction. The organic matter (OM) content was analyzed using the Walkley and Black method. The elemental compositions of carbon (C), hydrogen (H), and nitrogen (N) were analyzed following the ASTM D5373-16 method using an elemental analyzer (CHN; LECO, Truspec CHN analyzer; conditions: 950, 850 °C; O_2 (HP); He (UHP)). Following the ASTM, the oxygen (O) content was determined by the difference in the percentage of ash and the elemental C, H, and N contents [67]. DBC was evaluated to determine whether the product was produced as biochar by calculating the atomic ratio of H/C, O/C, (O+N)/C, and C/N of the biochar to evaluate aromaticity, polarity, and longevity [68-70]. The macronutrient contents, including total nitrogen (N), total phosphorous (P_2O_5), and total potassium (K_2O), were analyzed. The distillation apparatus was used to analyze the total N via the Kjeldahl method. The spectrophotometric molybdovanadophoshate method was used to analyze the total P_2O_5, and the total K_2O was analyzed using the flame photometric method [71].

The morphology and structure of the DBC biochar were characterized using scanning electron microscopy (SEM) on a JEOL JSM-6610LV, Oxford X-Max 50, scanning electron microscope to determine the porosity morphology and characteristics. Energy dispersive X-ray spectroscopy (EDS) was used to analyze the qualitative and quantitative elemental compositions of the DBC biochar. The specific surface area was analyzed by the Brunauer–Emmett–Teller (BET) method, and the Barrett–Joyner–Halenda (BJH) method was used for the analysis of the total pore volume and the average pore diameter [72].

2-3- Properties of the Untreated Soil and Vermicompost

The soil used in this study was clay loam soil with a pH of 6.80, CEC of 16.30 cmol/kg, and an organic C content of 1.26%. The untreated soil had the following macronutrients: total N of 1.38 mg/kg, available P of 223 mg/kg, and available K of 234 mg/kg.

Vermicompost is obtained by the bioconversion of organic waste into biofertilizer through the intestines of earthworms, which act as biological reactors [73, 74]. In the present study, vermicompost was obtained from *Eudrilus eugeniae* [75]. It was slightly acidic with a pH of 6.10, an electrical conductivity (EC) of 1.57 dS/m, a CEC of 15.30 cmol/kg, and a C/N ratio of 28.87. The vermicompost contained an OM content of 19.40%, a total N of 3.9 g/kg, a total P_2O_5 of 7.00 g/kg, and a total K_2O of 23.20 g/kg.

2-4- Analysis of Plant Yield and Postcultivation Soil Properties

After harvesting, plant yield and soil samples were collected for analysis. The Romaine lettuce yield was evaluated by the height of the plant, width of the leaf, number of leaves, and fresh weight. The height of the plant was measured from the base of the root boundary to the highest leaf tip. The number of leaves was counted for every leaf per plant. The roots were cut off before being weighed per plant, after which the fresh weight was recorded.

Soil samples from all the experimental pots were sampled, and their physicochemical properties were analyzed. This study focused on examining the ability of DBC biochar to apply a soil amendment; therefore, the analyzed soil properties, including pH, CEC, and macronutrients (N, P, and K), were necessary. The soil properties were analyzed using the principles and procedures for using the soil survey laboratory data method [76]. A hydrometer was used to analyze the soil texture. The soil pH was measured using a pH meter with 1:1 (v/v) soil:water and CEC (ammonium acetate method). The Kjeldahl method with a distillation apparatus was used to analyze the total N [77], and the Bray II method with 0.1 N HCl and NH_4F was used to analyze the available P [78]. The available K was analyzed by extraction with 1 M NNH_4OAc at pH 7.0 via an atomic absorption spectrophotometer (AAS), and the K content was determined via the atomic emission method [79].

2-5- Statistical Data Analysis

The data on Romaine lettuce yield obtained from different experimental treatments are displayed as the mean ± SD and were derived from ten replicates. Analysis of variance (ANOVA) and Duncan’s new multiple range test (DMRT) were used to analyze the mean variance and compare statistically significant differences ($p < 0.05$). The Statistical Package of the Social Science (SPSS) software was used to analyze the statistical data. Postcultivated soil properties are reported as the mean (average) values.

3- Results and Discussion

3-1- Characteristics of Biochar Obtained from Disposable Bamboo Chopsticks and its Use as a Soil Amendment

The thermochemical conversion of lignocellulosic biomass, such as DBC waste, into biochar by pyrolysis at 450-500 °C changes the structure and properties of the biomass. Lignocellulosic components, such as cellulose, hemicelluloses, lignin, and other extracts, are degraded and decomposed at different temperatures, affecting biochar properties [5, 6, 8, 11]. Key biochar factors that improve soils and support plant growth include pH; CEC; the contents of C, H, N, and O; specific surface area; porosity; aromaticity; polarity; and hydrophobicity. The physicochemical properties and nutrient contents of the DBC biochar are shown in Table 1.

Table 1. Physicochemical properties and nutrient contents of DBC biochar

pH	CEC (cmol/kg)	OM (%)	Nutrient contents (g/kg)		
			total N	total P_2O_5	total K_2O
6.80± 1.064	10.86± 5.857	8.77± 1.874	0.54± 0.010	1.79± 0.155	3.06± 0.800

Remark: Data are shown as the mean ± SD with a harmonic mean sample size = 4.00.

The DBC biochar was neutral with a pH of 6.80; the pH was higher than that of the DBC feedstock, which had a pH of 3.96. Biochar can have diverse pH values, ranging from strongly acidic to strongly alkaline, depending on the feedstock type and pyrolysis process applied. Štefanko & Leszczynska [24] reported that alkaline biochar is often derived from manure and agricultural lignocellulosic waste. Conversely, acidic biochar is derived from wood-based feedstocks [3, 13, 19, 26]. The thermochemical conversion process increased the pH as acidic surface functional groups were lost during pyrolysis, and the functional groups were replaced by neutral or basic fused aromatic moieties [5, 18, 66]. Therefore, biochar obtained at high pyrolysis temperatures (>450 °C) and long residence times has high pH values [18, 24]. The DBC biochar had a CEC of 10.86 cmol/kg, which was influenced by the pyrolysis temperature; biochar produced at high temperatures (>450 °C) had a high CEC value due to the specific functional groups formed during pyrolysis that can affect the surface properties of the biochar [28]. However, Wijitkosum [3] reported that CEC increases with increasing temperature and decreases when the temperature reaches 500 °C. Moreover, the CEC of biochar depends on the feedstock type [25, 47], among which wood-based biochars have higher CEC values than other biochars [14].

Elemental analysis (Table 2) revealed that the DBC biochar had 66.80% C, 3.76% H, 25.93% O, and 0.61% N. These elemental compositions originated from the composition of lignocellulose in the biomass feedstock; pyrolysis dissociated bonds between C and functional groups on the surface of the biomass feedstock, including -OH, aliphatic C-O and aliphatic C-H groups [22, 72]. Degradation and disintegration occur at different temperatures depending on the structure, bonding strength, and composition of the lignocellulosic biomass [8, 19, 24]. An increase in temperature drives volatile compounds and gases (CO_2, CO, H_2O, and volatile hydrocarbons) out of the biomass feedstock, and the aromatization process begins at approximately 350 °C and continues at higher temperatures. The content of aromatic structures increases when the temperature exceeds 400 °C, and aromatic C–H deformation increases until the temperature reaches 500 °C [6, 20, 26]. Therefore, the DBC biochar had higher C content than feedstock. In the end, amorphous carbons, which have an aromatic ring structure, are formed as the main component of biochar, making biochar a stable carbon material that can endure in the soil environment [4, 6, 10, 15].

Table 2. The physicochemical properties and nutrient contents of DBC biochar

Elemental compositions (%)				Atomic ratios			
C	H	N	O	H/C	O/C	(O+N)/C	C/N
66.80 ± 1.421	3.76 ± 1.117	0.61 ± 0.028	25.93 ± 0.030	0.675	0.291	0.300	127.76

Remark: Data on elemental compositions are shown as the mean ± SD with a harmonic mean sample size = 4.00. The atomic ratios are shown as the means with a harmonic mean sample size = 4.00.

The DBC biochar has lower H and O contents than feedstock due to the degradation of cellulose and lignin and the dehydration of hydroxyl groups during carbonization [3, 7, 8], which is consistent with Sucipta et al. [32] and Hernandez-Mena et al. [33]. The N content of the feedstock was transformed from an organic phase to heterocyclic N structures, and this transformation was accompanied by the aromatization of C [19, 32]. However, the N content in biochars has been reported to both increase [3, 29, 32] and decrease [13, 33] compared to feedstock. The O content in biochar indicates the concentration of O-containing functional groups and surface hydrophilicity and hydrophobicity [6, 9]. Accordingly, decreasing H/C and O/C resulted from removing H- and O-containing functional groups with increasing temperature, and the biochar exhibited high aromaticity and low polarity [20, 36]. The results (Table 2) showed that DBC biochar had an H/C of 0.675 and an O/C of 0.291, which indicated that the DBC biochar was characterized as biochar and presented high persistence potential in the soil environment. Biochar with an H/C ratio lower than 0.7 had a highly fused aromatic ring structure and condensed aromaticity [65, 69, 70]. Likewise, the O/C ratio reflects the degree of biochar oxidation and stability and is close to 0.2, indicating high stability [4].

The polarity of biochar can be evaluated from the (O+N)/C ratio along with O/C [4, 68]. The results showed that DBC had low polarity with an (O+N)/C of 0.30. The polarity of biochar results from the diminished and eliminated water-soluble organic compound content, especially at low molecular weights, from its pores and surface [68], which occurs at a temperature higher than 450 °C [26]. Although the C/N ratio was not significant enough to directly indicate that biochar can be used for soil amendment, it was used to infer benefits for the soil microbes due to the relative concentrations of essential chemical constituents needed for the growth and metabolic reactions of the microbial population [27, 43, 54].

The DBC biochar had a nutrient content of total N of 0.54 g/kg, a total P_2O_5 of 1.79 g/kg, a total K_2O of 3.06 g/kg, and an OM content of 8.77%. The feedstock type influences and determines the nutrient content of biochar rather than the pyrolysis conditions applied [14, 18, 25]. The wood-based feedstock had a low nutrient content, while the agricultural residual-based feedstock had higher nutrient content [11, 21]. The highest contents were found in manure-based feedstocks [23, 52]. However, temperature affects nutrient content through thermal degradation; a high temperature decreases N content due to the loss of volatile compounds in the feedstock and the relatively small loss of alkali nutrients in the gaseous phase [7]. In contrast, the P and K contents increased with pyrolysis temperature [22]. Accordingly, if a high amount of plant nutrients is expected in biochar, choosing manure and wastewater sludges for the feedstock is often considered.

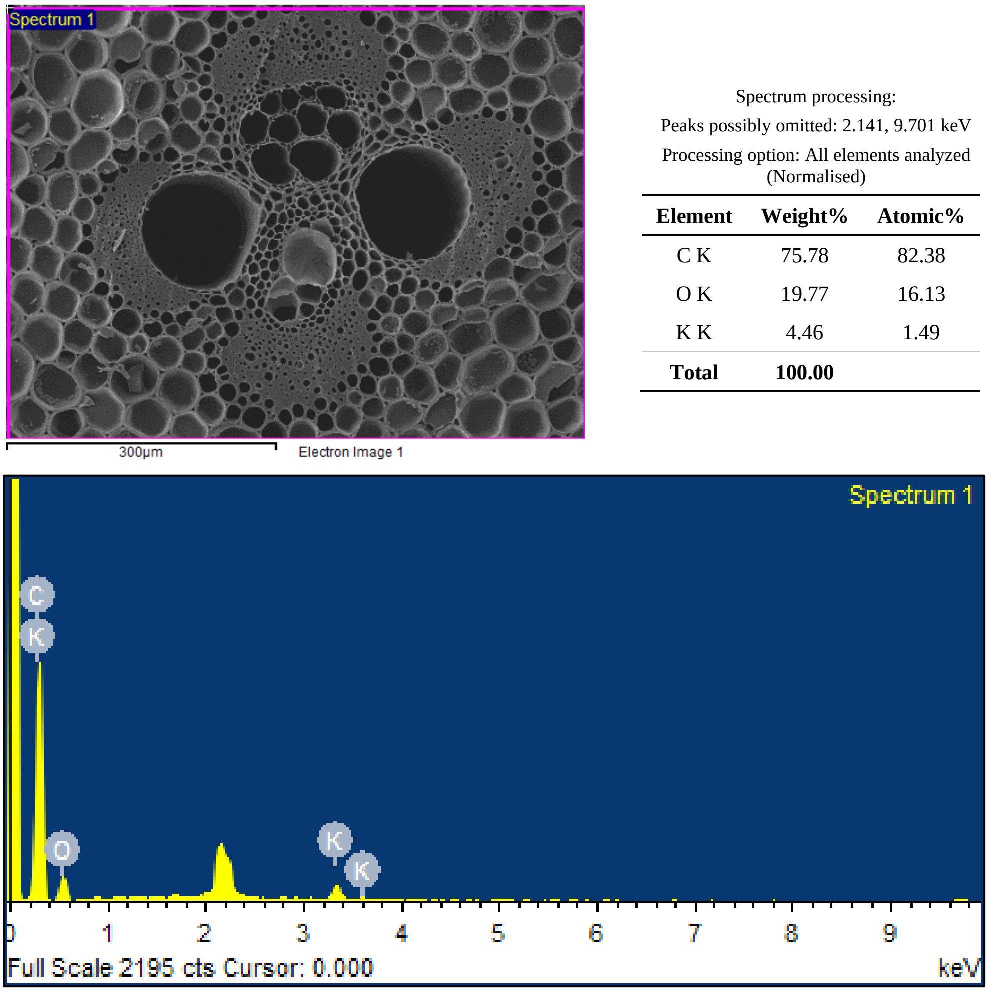
Physical property analysis revealed that the DBC biochar had a specific surface area of 0.542 m^2/g, a pore volume of 0.005 cc/g, and an average pore diameter of 39.077 Å. The physical and morphological properties of biochar derived from wooden feedstock have been reported to be different, although it is a similar wood type, such as bamboo. Sahoo et al. [31] reported that bamboo biochar obtained from pyrolysis at 500 °C had a specific surface area of 225.33 m^2/g, a pore volume of 0.18 cm^3/g, and an average pore diameter of 2.37 nm. The morphology of the biochar (specific surface area, pore volume, and pore size) is influenced mainly by its feedstock, while the pyrolysis temperature plays a role in making its physical properties favorable [13, 16, 26]. Compared with the other biochar types, wood-based biochar has the greatest specific surface area [14, 16] because it contains more lignin and cellulose than the other feedstock types and has a lower content of nondecomposable components [20, 72]. Moreover, the lignocellulosic biomass in the feedstock and inorganic minerals, including alkali and alkali earth metals, influence pore development during pyrolysis [21].

Channel structures increase the SSA and pore volume during pyrolysis, during which pore-blocking substances are removed or thermally cracked, increasing the externally accessible surface area [28, 34]. Simultaneously, cellulose and lignin are progressively degraded, and vascular bundles or channel structures are formed [17, 19]. An increase in biochar porosity is caused by the decomposition of lignin and aromatic condensation reactions as the temperature increases [6,15]. A higher pore volume leads to a high capillary force, increasing the hydrophobicity of the biochar [23, 24]. Furthermore, wood-based biochar acts as a soil amendment and could promote more favorable soil physical characteristics than biochar derived from another feedstock [21].

Scanning electron microscopy and electron dispersive X-ray analysis (Figure 2) provided information about the surface structure and mineral distribution of the DBC biochar, revealing that C, O, and K were the significant elements found in the DBC biochar. This result demonstrated that C formed the main skeleton along with O in the DBC biochar. The O might have originated from oxygen-containing functional groups (e.g., -COOH and -OH) or oxygen-containing metal mineral particles.

3-2- Plant Yields from Different Experimental Treatments

Romaine lettuce plants were harvested from the different experimental treatment groups; the yields are shown in Figure 3 and Table 3. The cultivation of lettuce in soil amended with vermicompost mixed with biochar at every rate markedly promoted plant growth compared with that in soil amended with vermicompost. The results showed that the tallest plants (57.88 cm) were found in the TVB2.5 pot, and their heights significantly differed from those of plants in the other pots. The plant height obtained from the pots amended with vermicompost (26.28 cm) was not significantly different from that obtained from the unamended soil (24.60 cm).



Spectrum processing:
Peaks possibly omitted: 2.141, 9.701 keV
Processing option: All elements analyzed (Normalised)

Element	Weight%	Atomic%
C K	75.78	82.38
O K	19.77	16.13
K K	4.46	1.49
Total	**100.00**	

Figure 2. SEM and EDS images of the pore structure and elemental composition of DBC biochar

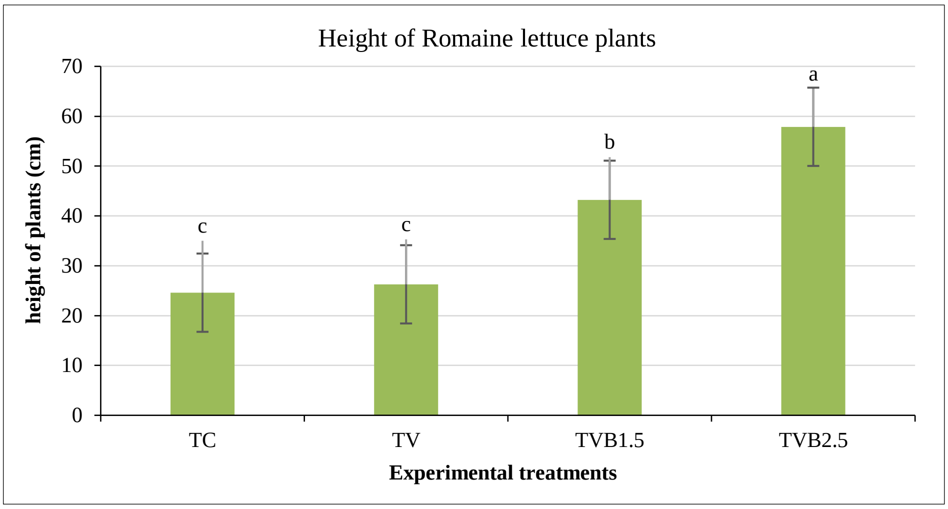


Figure 3. The height of Romaine lettuce plants obtained from different experimental treatments

Table 3. Plant yield obtained from different experimental treatments

Treatments	Number of leaves (leave/plant)	Width of leaf (cm)	Fresh weight (gram/plant)
TC	6.00 ± 1.31^{bc}	3.51 ± 0.35^{b}	6.25 ± 1.49^{c}
TV	6.75 ± 1.49^{b}	3.53 ± 0.28^{b}	7.63 ± 1.77^{c}
TVB1.5	7.00 ± 2.51^{b}	4.19 ± 0.68^{ab}	9.63 ± 4.96^{b}
TVB2.5	9.38 ± 2.33^{a}	4.46 ± 0.45^{a}	13.75 ± 3.65^{a}

Remark: Data are shown as the mean ± SD with a harmonic mean sample size = 10.00. The letters a, b, and c represent statistically significant differences between the experimental treatments at $p < 0.05$.

Moreover, amending soil with vermicompost mixed with biochar increased the number of plant leaves and the leaf size, and the TVB2.5 treatment had the highest values (9 leaves/plant and 4.46 cm/leaf). The number of Romaine lettuce leaves obtained from the TVB2.5 experimental pots was significantly greater than that obtained from the other experimental pots. In contrast, the number of leaves did not significantly differ from that in the other pots. The Romaine lettuce leaves obtained from the TVB2.5 pot were significantly larger than those obtained from the other pots, except for those obtained from the TVB1.5 pot, and the smallest leaves were found in the TC pot. In addition, the leaves obtained from the TV pot (3.53 cm) were the same size as those obtained from the control pot (3.51 cm).

The fresh weight results showed that cultivation in soil amended with vermicompost mixed with biochar at the highest rate (2.5%) markedly increased the plant weight compared with that obtained from the other amended and unamended soils. The romaine lettuce plants obtained from the TVB1.5 treatment group were significantly heavier than those obtained from the TV and TC treatment groups, while the weight of the lettuce plants in these two groups did not significantly differ.

3-3- Postcultivation Soil Physicochemical Properties

The physicochemical properties of the soil before planting (after 30 days of incubation) showed that the soil pH was neutral, ranging from 6.70 to 6.80, and the soil in the experimental pots of the TV, TVB1.5, and TVB2.5 groups had the same pH values (6.70). The soil had a cation exchange capacity of 16.30-17.50 cmol/kg. The soil in the TVB2.5 treatment had the highest CEC value, and the control pot had the lowest CEC. Macronutrient analysis (for N, P, and K) revealed that the soil had a total N content ranging from 1.34-1.73%, available P ranging from 223-281 mg/kg, and available K ranging from 204-245 mg/kg.

After lettuce cultivation, the soil properties changed in all the experimental treatments, as presented in Table 4. The pH of the soil increased in all the experimental treatments postcultivation, reaching neutral to slightly alkaline values (pH of 7.05-7.52). The soil in the TC pots had the highest pH values, which were slightly alkaline. The CEC ranged from 10.50 to 22.0 cmol/kg, with the highest values found in the TVB2.5 pots and the lowest in the TC pots. Moreover, the soil in the TV pots (21.40 cmol/kg) had higher CEC values than did that in the TVB1.5 pots (18.40 cmol/kg). The total N ranged from 1.25 to 1.60 g/kg, with the TV pot having the highest total N and the TC having the lowest total N. The postcultivation soil had available P and available K values ranging from 213.00 to 256.25 mg/kg and from 369.00 to 515.00 mg/kg, respectively. The TC soil had the lowest available P and available K, while the highest values were found in TVB2.5. The soil in the TVB1.5 group had a greater available K content than that found in the TV pots.

Table 4. The physicochemical properties of postcultivated soil from different experimental treatments

Treatments		pH	CEC (cmol/kg)	Total N (g/kg)	Available P (mg/kg)	Available K (mg/kg)
TC	Pre	6.80	16.30	1.38	223.00	234.00
	Post	7.52	10.50	1.42	213.00	369.00
TV	Pre	6.70	16.80	1.34	247.00	245.00
	Post	7.37	21.40	1.60	249.50	441.00
TVB1.5	Pre	6.70	16.90	1.73	269.00	204.00
	Post	7.05	18.40	1.25	234.88	470.00
TVB2.5	Pre	6.70	17.50	1.34	281.00	240.00
	Post	7.25	22.00	1.47	256.25	515.00

Remark: Data are shown as the means with a harmonic mean sample size = 10.00.

The analysis of changes in soil properties indicated that the postcultivation soil in all the experimental pots had an increase in pH and available K compared to those in the untreated soil. An analysis of changes in pH showed that the increase in TC was greatest (10.59%), and the increase in pH was lowest in the TVB1.5 pot (3.68%). The TC treatment was the only treatment in which the CEC decreased. The TVB2.5 pot had the highest increase in CEC (34.97%) and available P (14.91%). An analysis of the changes in total N content showed that the TC and TVB1.5 pots had a decrease in total N, with the TC pot having the highest rate of decrease (11.59%). In contrast, the TV pot had the highest increase (15.94%). The TC pot had the lowest increase in available K in the soil after cultivation (57.69%), while the highest increase was found in TVB2.5 (120.09%). Moreover, the increase in available K in TVB1.5 (100.85%) was greater than that in TV (88.46%).

Mixing vermicompost and biochar improved or adjusted the soil substrate physicochemical properties. The soil properties changed after incubating for 30 days compared to those of untreated soil because soil microbial activities led to oxidation–reduction and hydrolysis reactions [77]. In the case of postincubation soil, the CEC increased via two mechanisms: adsorption of organic acids by biochar and oxidation of the biochar surface [12, 30]. Moreover, previous research by Dumroese et al. [64] showed that an appropriate proportion of different substrates affects the C/N ratios and enhances crop growth. Therefore, the postcultivation soil properties changed compared to those of the preplanting soil (soil after incubation). The CEC in postcultivation soil dramatically decreased by 35.58% in the TC group, and the greatest change was in the TV pots (27.38%), followed by TVB2.5 (25.71%) and TVB1.5 (8.88%). The available P in postcultivation soil decreased in every experimental group except for TV, which increased by only 1.01%; the highest decrease was found in TVB1.5 (12.68%). In contrast, after cultivation, the available K in the soil increased in all the experimental treatments; that in TVB1.5 markedly increased by 130.39%, followed by that in TVB2.5 (114.58%), TV (80.00%), and TC (57.69%).

3-4- Effect and Performance of DBC Biochar as a Soil Amendment on Plant Yield and Soil Properties

The results indicated that biochar derived from DBC feedstock had morphological and fundamental physicochemical properties that can be used for cultivation, as indicated by its large surface area (0.542 m^2/g), mesoporous structure (39.077 Å), high CEC value (10.86 cmol/kg), high C content (66.80%), high OM content (8.77%), high C/N ratio (127.76), low atomic ratio (H/C) (0.675), high O/C (0.291), and high (O+N)/C (0.30). The analytical results of the Romaine lettuce growth and yield indicated that DBC biochar could significantly increase plant growth (plant height) and crop yield (fresh weight) compared to those of plants grown without soil unamended (TC) or cultivated with amendment soil with vermicompost alone (TV). The Romaine lettuce yield was consistent with the postcultivation soil properties. The properties of the precultivation soil in which the biochar was mixed for 30 days, as evidenced, were changed by the mechanism of DBC biochar in the soil. The soil in the TVB1.5 and TVB2.5 pots had higher nutrient contents (total N and available P) than did the soil in the TV pots. Furthermore, TVB1.5 and TVB2.5 had high CEC values, which affects nutrient availability and uptake [13, 48, 52]; thus, soil mixed with DBC biochar and vermicompost creates a soil environment that promotes plant growth beginning at an early stage.

DBC biochar enhanced the Romaine lettuce yield by providing a suitable soil environment for plant growth both directly and indirectly. Regarding the promotion of plant nutrients in the soil, biochar acts through direct and indirect mechanisms [18, 44, 55]. Soil nutrients are directly increased due to the nutrient content of biochar, which directly releases nutrients such as PO^{4}_{3-}, NH^{4+}, K^+, Mg^{2+}, and Ca^{2+}, and pH strongly influences the release of these nutrients from biochar [40, 48]. Although the nutrient levels in DBC are not very high, vermicompost supplements the nutrient content; moreover, biochar functions can increase nutrient availability through various mechanisms in the soil [13, 40, 55, 57]. As evidenced by the postcultivation soil results, the soil amended with DBC biochar and vermicompost had higher nutrient contents than did the soil amended with only vermicompost, except for the total N content. Several important indirect mechanisms involve changes in pH and CEC in the soil and alterations in the biochemical processes of soil microbes [41, 46, 53]. DBC biochar has a large surface area (0.542 m^2/g), providing abundant reactive adsorption sites [30, 56, 58]. A large surface area combined with the presence of many active functional groups on SSA, such as hydroxyl, carboxyl, and sulfonic acid groups, is effective for microbial cell adhesion and proliferation [35, 38], providing additional opportunities for microbial colonization and nutrient fixation. Furthermore, DBC biochar and vermicompost could improve soil microbial activities by providing accessible sources of available nutrients and C and N [27, 43, 52]. Nutrients can be retained in the soil through this mechanism and improve vermicompost use efficiency, increasing crop growth and yields. Moreover, Zhang et al. [41] reported that biochar improved K availability in soil by increasing the number and metabolic activity of Azotobacter and Pseudomonas and effectively alleviated K deficiency in plants, supporting the present results.

With its pore structure, biochar provides habitat for soil microbes, while the biochar pH creates favorable habitat conditions for microbial activity and communities in soil ecosystems [37, 38]. An altered soil pH can effectively shape microbial populations through their diversity and abundance [37, 54]. Not only does it provide habitat, but with its highly dense mesoporous DBC biochar, it also stores dissolved substances and water, supporting microbial activity. Additionally, DBC biochar provides carbon sources and nutrients for microorganisms [54], as the high C/N value of DBC biochar allows soil microbes to obtain more N and enhance their activities, such as N fixation. However, Dumroese et al. [64] indicated that a high C/N ratio (> 100) might be problematic for plant growth because of the immobilization of N by microorganisms. In contrast, the results of the present study showed that this phenomenon would not be a problem because DBC biochar and vermicompost have sufficiently high total N contents to support plant growth. Moreover, applying DBC biochar with vermicomposts encourages specific microbes to form microbial communities [27]. With the mechanism described above, applying DBC biochar to the soil enhances the persistence, survival, and colonization of microbes, which play a crucial role in soil biochemical processes and nutrient and carbon cycling [35, 46], making the soil fertile and supporting plant growth.

An increase in the soil pH in the TV, TVB1.5, and TVB2.5 pots was influenced by both DBC biochar and vermicompost, particularly in the DBC biochar, which has liming potential. Similar results were reported by Wang et al. [37], Wu et al. [45], and Hafez et al. [50]. The increase in soil pH following biochar addition was caused by the ash in the biochar, which contains oxides, hydroxides, and carbonates of alkaline metals [56]. Consequently, the negatively charged functional groups (-COOH, -OH) bind H^+ ions from the soil solution, which decreases the activity of H^+ ions and increases the soil pH [17]. As mentioned above, biochar application might have resulted in the neutralization of soil pH by a series of proton-consuming reactions, as supported by many studies [50, 66]. Simultaneously, vermicompost addition increases soil pH due to the decomposition of organic matter to produce organic acids such as humic acid and phosphoric acid, which reduce the concentration of H^+ [73, 74]. However, some studies have reported the opposite results, indicating that using biochar in the soil causes a decrease in soil pH [34, 55, 56]. Similarly, Demir [49] reported that applying vermicompost to sandy clay loam soil under water addition causes the soil pH to decrease. This situation resulted from complex chemical reactions in the soil involving soil microorganisms and abiotic elements, as supported by a meta-analysis by Dai et al. [12], which indicated that the ability of biochar to increase plant yield was significantly related to biochar-specific functionality and soil conditions. Moreover, irrigation systems also affect chemical reactions in the soil [47, 49], and the biochar application rate affects the buffering capacity of the soil [46, 66]. This is an additional reason why the 2.5% DBC biochar application rate increased the soil pH more than the biochar application rate did (1.5%). In addition, the buffering capacity, due to the biochar application rate, causes the change in soil pH to be variable and unpredictable; it is another reason that soil pH changes in many studies are variable and not entirely consistent in the same direction.

DBC biochar and vermicompost influenced the soil CEC, as presented in the results showing that soil amended with DBC biochar and vermicompost and soil with vermicompost alone increased the soil CEC postincubation and postcultivation. The increase in soil CEC with DBC biochar application was explained by two potential mechanisms. Biochar directly increases the soil CEC by increasing the number of exchange sites on soil particles via the high charge density on the surface of biochar, which results in a high degree of oxidation of soil organic matter and a high surface area for cation adsorption sites [10, 42, 56, 72]. A high quantity of oxygen-containing functional groups on the biochar surface, which contributes to negative soil charges, could also increase the soil CEC [34, 60, 47]. In addition, biochar indirectly inhibits the mineralization of native soil organic matter, a large source of cation exchange sites [39, 47]. Additionally, an increase in soil CEC is positively correlated with the application rate [42, 44]; this is an additional reason why the soil in the TVB2.5 experimental pot had a higher CEC than that in the TVB1.5 pot. For vermicompost (TV), a high CEC and increasing pH could increase the soil CEC [48, 74].

Due to its biochar properties, high CEC, and large surface area, along with its many porous structures, biochar benefits plants by increasing the absorption of cationic nutrients, including ammonium (NH^{4+}), K^+, calcium (Ca^{2+}), and magnesium (Mg^{2+}), from the soil to plant roots by releasing H+ to balance charges in the soil [38, 51, 57]. Additionally, increased soil CEC acts as a buffer, preventing the chemical structure of the soil from changing in unfavorable ways. The hydrophobicity of DBC prevents water from entering the internal pore structure. This may increase water retention in the soil [9,23]. Moreover, the ability of biochar to increase water retention can reduce nutrient loss, improve crop productivity, and reduce nutrient leaching rates [10, 53, 55]. Improving the physical properties of the resulting soil increases plant growth and supports root elongation; with better root architecture, roots can continuously take up soluble nutrients in the soil for plant growth [39, 44, 52, 57]. As a result, higher Romain lettuce yields were observed in the TVB1.5 and TVB2.5 pots.

Although this plant was cultivated in pots and watered by sprinklers, which may reduce nutrient loss from vermicompost, DBC biochar, which has a high CEC, a stabilizing chemical structure, and many porous characteristics, allows it to retain more nutrients from vermicompost [18, 45, 53] and supports reduced nutrient loss and leaching from the soil [10, 34]. This is a reason to support the evidence that experimental pots mixed with DBC biochar still contain greater amounts of nutrients than soil mixed with fertilizer alone. Nutrient leaching and loss from cultivated areas are major problems for agriculture in the field, and many studies have reported that the properties of biochar can help correct nutrient leaching [40, 43, 53, 54]. The positive impact of biochar on soil nutrient retention is more prominent during long-term cultivation or multiple-season planting, as reported by Zhang et al. [41], who conducted a four-year study on the application of biochar to acidic soil and citrus growth. Adekiya et al. [42] applied biochar for cocoyam cultivation in sandy loam soil during a two-year cultivation regime. Additionally, Wijitkosum & Sriburi [71] applied biochar once during two cycles of maize cultivation. Although this study involved only one season of Romaine lettuce cultivation, the results sufficiently indicate that the positive impacts of DBC biochar application persist in the soil after planting, as indicated by the quantity of nutrients remaining in the soil after cultivation, and the soil amended with DBC biochar had a higher nutrient content than the soil with vermicompost.

Considering the characteristics and mechanisms of DBC in the soil, as discussed above, Romaine lettuce plants growing in soil were mixed with biochar and vermicompost, increasing the CEC and nutrient content (N, P, and K) of the soil; thus, the plants were allowed to grow and produce significantly greater yields than were those growing in soil mixed with vermicompost alone. Although the total N content in the soil amended with vermicompost was greater in the postcultivation soil than in the control soil, this difference did not cause a greater number of leaves or leaf size than the yield obtained from planting in the amended soil with DBC biochar. The opposite results were obtained for total N in the soil after cultivation in this study; for example, Wijitkosum & Jiwnok [48] reported that the highest total N content in postcultivation soil was found in the soil in which the highest percentage of rice husk biochar was applied mixed with vermicompost. However, the crop yield results obtained from both studies are in the same direction.

Applying biochar to the soil has been shown to significantly increase the effectiveness of N, P, and K from fertilizer, which are the macronutrients for plant growth [11, 34, 59, 61]. Therefore, soil amended with DBC biochar mixed with vermicompost had a greater plant yield than soil amended with only vermicompost. These findings are consistent with numerous previous studies, such as a study by Wang et al. [40], who reported that the combined application of biochar and compost provides significant benefits for grain yield and nutrient cycling. Wijitkosum & Jiwnok [48], who reported that using rice husk biochar at 2.0% and 2.5% mixed with vermicompost at 20% helps improve soil properties and increases Chinese kale productivity more than using vermicompost alone (20%). Similarly, Regmi et al. [59] demonstrated that hardwood biochar mixed with fertilizer increases Viola growth and flowering. For cultivation in pots under a greenhouse, the amount of watered significantly affects yields, as supported by the report by Demir [49]. Irrigation level affects soil aeration, root growth, and plant nutrient uptake [52, 54, 57]. Therefore, this cultivation of Romaine lettuce plants under sprinkler irrigation did not negatively impact the biochar mechanism in the pot soil or plant growth.

Moreover, biochar application at appropriate rates combined with fertilizer also further increased the yield. These results are consistent with previous studies examining different plants, such as rice [45, 50, 53], maize [39, 62, 71], citrus [41], cocoyam [42], grape [57], and oat [60]. The results showed that low rates of DBC biochar (1.5%) combined with vermicompost still increase lettuce yield, particularly fresh weight, more than those obtained from pots cultivated with vermicompost alone. However, some previous research reported that a low biochar application rate is insufficient to increase crop yields [48, 61, 62]. Furthermore, Regmi et al. [59] reported that the fertilizer-added biochar application rate did not impact flowering and flower polyphenol concentrations. On the contrary, a high biochar application rate harms plant growth; as shown in a report by Bai et al. [58], it was found to be harmful to the germination rate, shoot length, and root growth of rice and corn. The present study indicated that applying 2.5% DBC biochar mixed with vermicompost provides the best results for determining the yield and soil properties of Romain lettuce. The soil and plant results demonstrated that DBC biochar derived from disposable bamboo chopstick waste can be used for crop cultivation. When used as a soil amendment, it had a positive effect on plant growth, supported the growth of cultivated plants, and increased yields.

4- Conclusion

This research goal is to find ways to exploit abundant urban waste that has not yet been upcycled, such as disposable bamboo chopsticks, by converting such waste into biochar for use as a soil amendment for growing household crops. Experimenting with household cultivation as a greenhouse by planting Romaine lettuce in the pots took place based on two frameworks: evaluating the potential of DBC waste for upcycling into biochar and its feasibility for use as a soil amendment in household vegetable growing. The conversion of disposable bamboo chopstick wastes into biochar promotes the upgrading of wastes into resources through the pyrolysis process, which increases the value of waste. The physicochemical properties and morphology of the DBC biochar showed that disposable bamboo chopsticks can be good feedstocks. The DBC feedstock characteristics changed through the pyrolysis process: the pH, CEC, specific surface area, pore volume, and C content increased while the O and H content and pore size decreased. The DBC had good physicochemical properties and morphology: it had a high C content and CEC value with a large specific surface area and mesopores, indicating that the biochar-amended soil was suitable for cultivation, enhanced plant growth, and improved soil properties. Due to the low nutrient content of DBC, 10% vermicompost was applied in combination with DBC for cultivation. The results demonstrated that DBC biochar positively impacted the yield of soil and Romaine lettuce. Amending soil with DBC biochar at 1.5% and 2.5% mixed with vermicompost increased the plant yield and soil quality compared to applying vermicompost alone. The study also showed that Romaine lettuce productivity increased according to the rate of biochar application. The application of 2.5% DBC biochar mixed with vermicompost had the greatest effect on the height of the plant, number of leaves, leaf size, and fresh weight. Therefore, this application rate was recommended for Romaine lettuce in pot cultivation.

5- Declarations

5-1- Author Contributions

Conceptualization, S.W.; methodology, S.W., T.S., and L.K.; validation, S.W. and L.K.; formal analysis, S.W.; investigation, S.W.; resources, T.S.; data curation, S.W.; writing—original draft preparation, S.W.; writing—review and editing, S.W.; visualization, S.W. and T.S.; supervision, S.W.; project administration, S.W.; funding acquisition, S.W. All authors have read and agreed to the published version of the manuscript.

5-2- Data Availability Statement

Data sharing is not applicable to this article.

5-3- Funding

The research was financially supported by the Thailand Science Research and Innovation Fund (fundamental fund), a basic research plan to drive the BCG economy under the project Urban Organic Waste Upcycling for Agricultural and Environmental, Chulalongkorn University (CUFRB65_BCG (36) 214_54_01).

5-4- Institutional Review Board Statement

Not applicable.

5-5- *Informed Consent Statement*

Not applicable.

5-6- *Conflicts of Interest*

The authors declare that there is no conflict of interest 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 authors.

6- References

[1] The World Bank. (2019). Solid Waste Management. The World Bank, Washington, United States. Available online: http://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management (accessed on May 2024).

[2] Hoornweg, D., & Bhada-Tata, P. (2012). What a waste: a global review of solid waste management. The World Bank, Washington, United States.

[3] Wijitkosum, S. (2023). Repurposing Disposable Bamboo Chopsticks Waste as Biochar for Agronomical Application. Energies, 16(2), 771. doi:10.3390/en16020771.

[4] Wijitkosum, S., & Sriburi, T. (2023). Aromaticity, polarity, and longevity of biochar derived from disposable bamboo chopsticks waste for environmental application. Heliyon, 9(9). doi:10.1016/j.heliyon.2023.e19831.

[5] Ghodake, G. S., Shinde, S. K., Kadam, A. A., Saratale, R. G., Saratale, G. D., Kumar, M., Palem, R. R., AL-Shwaiman, H. A., Elgorban, A. M., Syed, A., & Kim, D. Y. (2021). Review on biomass feedstocks, pyrolysis mechanism and physicochemical properties of biochar: State-of-the-art framework to speed up vision of circular bioeconomy. Journal of Cleaner Production, 297, 126645. doi:10.1016/j.jclepro.2021.126645.

[6] Qin, F., Zhang, C., Zeng, G., Huang, D., Tan, X., & Duan, A. (2022). Lignocellulosic biomass carbonization for biochar production and characterization of biochar reactivity. Renewable and Sustainable Energy Reviews, 157, 112056. doi:10.1016/j.rser.2021.112056.

[7] Jafri, N., Wong, W. Y., Doshi, V., Yoon, L. W., & Cheah, K. H. (2018). A review on production and characterization of biochars for application in direct carbon fuel cells. Process Safety and Environmental Protection, 118, 152–166. doi:10.1016/j.psep.2018.06.036.

[8] Mukherjee, A., Patra, B. R., Podder, J., & Dalai, A. K. (2022). Synthesis of Biochar from Lignocellulosic Biomass for Diverse Industrial Applications and Energy Harvesting: Effects of Pyrolysis Conditions on the Physicochemical Properties of Biochar. Frontiers in Materials, 9. doi:10.3389/fmats.2022.870184.

[9] Mao, J., Zhang, K., & Chen, B. (2019). Linking hydrophobicity of biochar to the water repellency and water holding capacity of biochar-amended soil. Environmental Pollution, 253, 779–789. doi:10.1016/j.envpol.2019.07.051.

[10] Shaaban, M., Van Zwieten, L., Bashir, S., Younas, A., Núñez-Delgado, A., Chhajro, M. A., Kubar, K. A., Ali, U., Rana, M. S., Mehmood, M. A., & Hu, R. (2018). A concise review of biochar application to agricultural soils to improve soil conditions and fight pollution. Journal of Environmental Management, 228, 429–440. doi:10.1016/j.jenvman.2018.09.006.

[11] Agegnehu, G., Srivastava, A. K., & Bird, M. I. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance: A review. Applied Soil Ecology, 119, 156–170. doi:10.1016/j.apsoil.2017.06.008.

[12] Dai, Y., Zheng, H., Jiang, Z., & Xing, B. (2020). Combined effects of biochar properties and soil conditions on plant growth: A meta-analysis. Science of the Total Environment, 713, 136635. doi:10.1016/j.scitotenv.2020.136635.

[13] Tu, P., Zhang, G., Wei, G., Li, J., Li, Y., Deng, L., & Yuan, H. (2022). Influence of pyrolysis temperature on the physicochemical properties of biochars obtained from herbaceous and woody plants. Bioresources and Bioprocessing, 9(1), 131. doi:10.1186/s40643-022-00618-z.

[14] Wijitkosum, S. (2022). Biochar derived from agricultural wastes and wood residues for sustainable agricultural and environmental applications. International Soil and Water Conservation Research, 10(2), 335–341. doi:10.1016/j.iswcr.2021.09.006.

[15] Dhyani, V., & Bhaskar, T. (2018). A comprehensive review on the pyrolysis of lignocellulosic biomass. Renewable Energy, 129, 695–716. doi:10.1016/j.renene.2017.04.035.

[16] Amalina, F., Razak, A. S. A., Krishnan, S., Sulaiman, H., Zularisam, A. W., & Nasrullah, M. (2022). Biochar production techniques utilizing biomass waste-derived materials and environmental applications – A review. Journal of Hazardous Materials Advances, 7. doi:10.1016/j.hazadv.2022.100134.

[17] El-Gamal, E., Saleh, M., Elsokkary, I., Rashad, M., & Abd El-Latif, M. M. (2017). Comparison between Properties of Biochar Produced by Traditional and Controlled Pyrolysis. Alexandria Science Exchange Journal: An International Quarterly Journal of Science Agricultural Environments, 38(July-September), 412–425. doi:10.21608/asejaiqjsae.2017.3720.

[18] Wang, K., Peng, N., Lu, G., & Dang, Z. (2020). Effects of Pyrolysis Temperature and Holding Time on Physicochemical Properties of Swine-Manure-Derived Biochar. Waste and Biomass Valorization, 11(2), 613–624. doi:10.1007/s12649-018-0435-2.

[19] Zhao, S. X., Ta, N., & Wang, X. D. (2017). Effect of temperature on the structural and physicochemical properties of biochar with apple tree branches as feedstock material. Energies, 10(9), 1293. doi:10.3390/en10091293.

[20] Li, L., Long, A., Fossum, B., & Kaiser, M. (2023). Effects of pyrolysis temperature and feedstock type on biochar characteristics pertinent to soil carbon and soil health: A meta-analysis. Soil Use and Management, 39(1), 43–52. doi:10.1111/sum.12848.

[21] Ippolito, J. A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizabal, T., Cayuela, M. L., Sigua, G., Novak, J., Spokas, K., & Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. Biochar, 2(4), 421–438. doi:10.1007/s42773-020-00067-x.

[22] Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Reviews in Environmental Science and Biotechnology, 19(1), 191–215. doi:10.1007/s11157-020-09523-3.

[23] Huang, H., Reddy, N. G., Huang, X., Chen, P., Wang, P., Zhang, Y., Huang, Y., Lin, P., & Garg, A. (2021). Effects of pyrolysis temperature, feedstock type and compaction on water retention of biochar amended soil. Scientific Reports, 11(1), 7419. doi:10.1038/s41598-021-86701-5.

[24] Uroić Štefanko, A., & Leszczynska, D. (2020). Impact of Biomass Source and Pyrolysis Parameters on Physicochemical Properties of Biochar Manufactured for Innovative Applications. Frontiers in Energy Research, 8, 138. doi:10.3389/fenrg.2020.00138.

[25] Kazemi Shariat Panahi, H., Dehhaghi, M., Ok, Y. S., Nizami, A. S., Khoshnevisan, B., Mussatto, S. I., Aghbashlo, M., Tabatabaei, M., & Lam, S. S. (2020). A comprehensive review of engineered biochar: Production, characteristics, and environmental applications. Journal of Cleaner Production, 270, 122462. doi:10.1016/j.jclepro.2020.122462.

[26] Krzesińska, M. (2017). Anisotropy of skeleton structure of highly porous carbonized bamboo and yucca related to the pyrolysis temperature of the precursors. Journal of Analytical and Applied Pyrolysis, 123, 73–82. doi:10.1016/j.jaap.2016.12.024.

[27] Tan, H., Lee, C. T., Ong, P. Y., Wong, K. Y., Bong, C. P. C., Li, C., & Gao, Y. (2021). A Review on The Comparison Between Slow Pyrolysis and Fast Pyrolysis on the Quality of Lignocellulosic and Lignin-Based Biochar. IOP Conference Series: Materials Science and Engineering, 1051(1), 012075. doi:10.1088/1757-899x/1051/1/012075.

[28] Suliman, W., Harsh, J. B., Abu-Lail, N. I., Fortuna, A. M., Dallmeyer, I., & Garcia-Perez, M. (2016). Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. Biomass and Bioenergy, 84, 37–48. doi:10.1016/j.biombioe.2015.11.010.

[29] Kloss, S., Zehetner, F., Dellantonio, A., Hamid, R., Ottner, F., Liedtke, V., Schwanninger, M., Gerzabek, M. H., & Soja, G. (2012). Characterization of Slow Pyrolysis Biochars: Effects of Feedstocks and Pyrolysis Temperature on Biochar Properties. Journal of Environmental Quality, 41(4), 990–1000. doi:10.2134/jeq2011.0070.

[30] Zama, E. F., Zhu, Y. G., Reid, B. J., & Sun, G. X. (2017). The role of biochar properties in influencing the sorption and desorption of Pb(II), Cd(II) and As(III) in aqueous solution. Journal of Cleaner Production, 148, 127–136. doi:10.1016/j.jclepro.2017.01.125.

[31] Sahoo, S. S., Vijay, V. K., Chandra, R., & Kumar, H. (2021). Production and characterization of biochar produced from slow pyrolysis of pigeon pea stalk and bamboo. Cleaner Engineering and Technology, 3, 100101. doi:10.1016/j.clet.2021.100101.

[32] Sucipta, M., Putra Negara, D. N. K., Tirta Nindhia, T. G., & Surata, I. W. (2017). Characteristics of Ampel bamboo as a biomass energy source potential in Bali. IOP Conference Series: Materials Science and Engineering, 201(1), 12032. doi:10.1088/1757-899X/201/1/012032.

[33] Hernandez-Mena, L. E., Pecora, A. A. B., & Beraldo, A. L. (2014). Slow pyrolysis of bamboo biomass: Analysis of biochar properties. Chemical Engineering Transactions, 37, 115–120. doi:10.3303/CET1437020.

[34] Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., Kirkham, M. B., Chowdhury, S., & Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. Biochar, 2(4), 379–420. doi:10.1007/s42773-020-00065-z.

[35] Bolan, S., Hou, D., Wang, L., Hale, L., Egamberdieva, D., Tammeorg, P., Li, R., Wang, B., Xu, J., Wang, T., Sun, H., Padhye, L. P., Wang, H., Siddique, K. H. M., Rinklebe, J., Kirkham, M. B., & Bolan, N. (2023). The potential of biochar as a microbial carrier for agricultural and environmental applications. Science of the Total Environment, 886. doi:10.1016/j.scitotenv.2023.163968.

[36] Rafiq, M. K., Bachmann, R. T., Rafiq, M. T., Shang, Z., Joseph, S., & Long, R. L. (2016). Influence of pyrolysis temperature on physico-chemical properties of corn stover (zea mays l.) biochar and feasibility for carbon capture and energy balance. PLoS ONE, 11(6), 156894. doi:10.1371/journal.pone.0156894.

[37] Wang, C., Chen, D., Shen, J., Yuan, Q., Fan, F., Wei, W., Li, Y., & Wu, J. (2021). Biochar alters soil microbial communities and potential functions 3–4 years after amendment in a double rice cropping system. Agriculture, Ecosystems & Environment, 311, 107291. doi:10.1016/j.agee.2020.107291.

[38] Palansooriya, K. N., Wong, J. T. F., Hashimoto, Y., Huang, L., Rinklebe, J., Chang, S. X., Bolan, N., Wang, H., & Ok, Y. S. (2019). Response of microbial communities to biochar-amended soils: a critical review. Biochar, 1(1), 3–22. doi:10.1007/s42773-019-00009-2.

[39] Omara, P., Aula, L., Oyebiyi, F. B., Eickhof, E. M., Carpenter, J., & Raun, W. R. (2020). Biochar application in combination with inorganic nitrogen improves maize grain yield, nitrogen uptake, and use efficiency in Temperate Soils. Agronomy, 10(9), 1241. doi:10.3390/agronomy10091241.

[40] Wang, L., Yu, B., Ji, J., Khan, I., Li, G., Rehman, A., Liu, D., & Li, S. (2023). Assessing the impact of biochar and nitrogen application on yield, water-nitrogen use efficiency and quality of intercropped maize and soybean. Frontiers in Plant Science, 14(1171547). doi:10.3389/fpls.2023.1171547.

[41] Zhang, M., Riaz, M., Xia, H., Li, Y., Wang, X., & Jiang, C. (2022). Four-year biochar study: Positive response of acidic soil microenvironment and citrus growth to biochar under potassium deficiency conditions. Science of the Total Environment, 813, 152515. doi:10.1016/j.scitotenv.2021.152515.

[42] Adekiya, A. O., Agbede, T. M., Olayanju, A., Ejue, W. S., Adekanye, T. A., Adenusi, T. T., & Ayeni, J. F. (2020). Effect of Biochar on Soil Properties, Soil Loss, and Cocoyam Yield on a Tropical Sandy Loam Alfisol. Scientific World Journal, 2020. doi:10.1155/2020/9391630.

[43] Sun, Z., Hu, Y., Shi, L., Li, G., Pang, Z., Liu, S., Chen, Y., & Jia, B. (2022). Effects of biochar on soil chemical properties: A global meta-analysis of agricultural soil. Plant, Soil and Environment, 68(6), 272–289. doi:10.17221/522/2021-PSE.

[44] El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., Zimmerman, A. R., Ahmad, M., Shaheen, S. M., & Ok, Y. S. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. Geoderma, 337, 536–554. doi:10.1016/j.geoderma.2018.09.034.

[45] Wu, L., Zhang, S., Chen, M., Liu, J., & Ding, X. (2021). A sustainable option: Biochar addition can improve soil phosphorus retention and rice yield in a saline–alkaline soil. Environmental Technology & Innovation, 24, 102070. doi:10.1016/j.eti.2021.102070.

[46] Yuan, Y., Liu, Q., Zheng, H., Li, M., Liu, Y., Wang, X., Peng, Y., Luo, X., Li, F., Li, X., & Xing, B. (2023). Biochar as a sustainable tool for improving the health of salt-affected soils. Soil & Environmental Health, 1(3), 100033. doi:10.1016/j.seh.2023.100033.

[47] Domingues, R. R., Sánchez-Monedero, M. A., Spokas, K. A., Melo, L. C. A., Trugilho, P. F., Valenciano, M. N., & Silva, C. A. (2020). Enhancing cation exchange capacity ofweathered soils using biochar: Feedstock, pyrolysis conditions and addition rate. Agronomy, 10(6), 824. doi:10.3390/agronomy10060824.

[48] Wijitkosum, S., & Jiwnok, P. (2019). Effect of biochar on Chinese kale and carbon storage in an agricultural area on a high-rise building. AIMS Agriculture and Food, 4(1), 177–193. doi:10.3934/AGRFOOD.2019.1.177.

[49] Demir, Z. (2019). Effects of Vermicompost on Soil Physicochemical Properties and Lettuce (Lactuca sativa Var. Crispa) Yield in Greenhouse under Different Soil Water Regimes. Communications in Soil Science and Plant Analysis, 50(17), 2151–2168. doi:10.1080/00103624.2019.1654508.

[50] Hafez, E. M., Gowayed, S. M., Nehela, Y., Sakran, R. M., Rady, A. M. S., Awadalla, A., Omara, A. E. D., & Alowaiesh, B. F. (2021). Incorporated biochar-based soil amendment and exogenous glycine betaine foliar application ameliorate rice (Oryza sativa l.) tolerance and resilience to osmotic stress. Plants, 10(9), 1930. doi:10.3390/plants10091930.

[51] Doulgeris, C., Kypritidou, Z., Kinigopoulou, V., & Hatzigiannakis, E. (2023). Simulation of Potassium Availability in the Application of Biochar in Agricultural Soil. Agronomy, 13(3), 784. doi:10.3390/agronomy13030784.

[52] Hou, J., Pugazhendhi, A., Sindhu, R., Vinayak, V., Thanh, N. C., Brindhadevi, K., Lan Chi, N. T., & Yuan, D. (2022). An assessment of biochar as a potential amendment to enhance plant nutrient uptake. Environmental Research, 214, 113909. doi:10.1016/j.envres.2022.113909.

[53] Liu, Y., Li, H., Hu, T., Mahmoud, A., Li, J., Zhu, R., Jiao, X., & Jing, P. (2022). A quantitative review of the effects of biochar application on rice yield and nitrogen use efficiency in paddy fields: A meta-analysis. Science of the Total Environment, 830, 154792. doi:10.1016/j.scitotenv.2022.154792.

[54] Hardy, B., Sleutel, S., Dufey, J. E., & Cornelis, J. T. (2019). The Long-Term Effect of Biochar on Soil Microbial Abundance, Activity and Community Structure Is Overwritten by Land Management. Frontiers in Environmental Science, 7, 110. doi:10.3389/fenvs.2019.00110.

[55] Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M. L., Graber, E. R., Ippolito, J. A., Kuzyakov, Y., Luo, Y., Ok, Y. S., Palansooriya, K. N., Shepherd, J., Stephens, S., Weng, Z., & Lehmann, J. (2021). How biochar works, and when it doesn’t: A review of mechanisms controlling soil and plant responses to biochar. GCB Bioenergy, 13(11), 1731–1764. doi:10.1111/gcbb.12885.

[56] Alkharabsheh, H. M., Seleiman, M. F., Battaglia, M. L., Shami, A., Jalal, R. S., Alhammad, B. A., Almutairi, K. F., & Al-Saif, A. M. (2021). Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. Agronomy, 11(5), 993 10 3390 11050993. doi:10.3390/agronomy11050993.

[57] Chang, Y., Rossi, L., Zotarelli, L., Gao, B., Shahid, M. A., & Sarkhosh, A. (2021). Biochar improves soil physical characteristics and strengthens root architecture in Muscadine grape (Vitis rotundifolia L.). Chemical and Biological Technologies in Agriculture, 8(1). doi:10.1186/s40538-020-00204-5.

[58] Bai, X., Zhang, S., Shao, J., Chen, A., Jiang, J., Chen, A., & Luo, S. (2022). Exploring the negative effects of biochars on the germination, growth, and antioxidant system of rice and corn. Journal of Environmental Chemical Engineering, 10(3), 107398. doi:10.1016/j.jece.2022.107398.

[59] Regmi, A., Poudyal, S., Singh, S., Coldren, C., Moustaid-Moussa, N., & Simpson, C. (2023). Biochar Influences Phytochemical Concentrations of Viola cornuta Flowers. Sustainability (Switzerland), 15(5), 3882. doi:10.3390/su15053882.

[60] Schulz, H., Dunst, G., & Glaser, B. (2014). No effect level of co-composted biochar on plant growth and soil properties in a greenhouse experiment. Agronomy, 4(1), 34–51. doi:10.3390/agronomy4010034.

[61] Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B., & Sabir, M. (2020). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. Soil Use and Management, 36(1), 2–18. doi:10.1111/sum.12546.

[62] Wijitkosum, S., & Sriburi, T. (2021). Applying cassava stems biochar produced from agronomical waste to enhance the yield and productivity of maize in unfertile soil. Fermentation, 7(4), 277. doi:10.3390/fermentation7040277.

[63] Simko, I., Hayes, R. J., Mou, B., & McCreight, J. D. (2015). Lettuce and Spinach. CSSA Special Publications, Madison, United States. doi:10.2135/cssaspecpub33.c4.

[64] Dumroese, R. K., Heiskanen, J., Englund, K., & Tervahauta, A. (2011). Pelleted biochar: Chemical and physical properties show potential use as a substrate in container nurseries. Biomass and Bioenergy, 35(5), 2018–2027. doi:10.1016/j.biombioe.2011.01.053.

[65] International Biochar Initiative (IBI). (2015). Standardized Product Definition and Product Testing Guidelines for Biochar that Is Used in Soil. International Biochar Initiative (IBI), Washington, United States.

[66] Yuan, J. H., Xu, R. K., & Zhang, H. (2011). The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresource Technology, 102(3), 3488–3497. doi:10.1016/j.biortech.2010.11.018.

[67] ASTM D 5373-14e1 (2016) Standard Test Methods for Determination of Carbon, Hydrogen and Nitrogen in Analysis Samples of Coal and Carbon in Analysis Samples of Coal and Coke. ASTM International, Pennsylvania, United States. doi:10.1520/D5373-14E01.

[68] Fan, Q., Sun, J., Chu, L., Cui, L., Quan, G., Yan, J., Hussain, Q., & Iqbal, M. (2018). Effects of chemical oxidation on surface oxygen-containing functional groups and adsorption behavior of biochar. Chemosphere, 207, 33–40. doi:10.1016/j.chemosphere.2018.05.044.

[69] Klasson, K. T., Boihem, L. L., Uchimiya, M., & Lima, I. M. (2014). Influence of biochar pyrolysis temperature and post-treatment on the uptake of mercury from flue gas. Fuel Processing Technology, 123, 27–33. doi:10.1016/j.fuproc.2014.01.034.

[70] Schimmelpfennig, S., & Glaser, B. (2012). One Step Forward toward Characterization: Some Important Material Properties to Distinguish Biochars. Journal of Environmental Quality, 41(4), 1001–1013. doi:10.2134/jeq2011.0146.

[71] Wijitkosum, S., & Sriburi, T. (2019). Increasing the Amount of Biomass in Field Crops for Carbon Sequestration and Plant Biomass Enhancement Using Biochar. Biochar - An Imperative Amendment for Soil and the Environment, IntechOpen, London, United Kingdom. doi:10.5772/intechopen.82090.

[72] Leng, L., Xiong, Q., Yang, L., Li, H., Zhou, Y., Zhang, W., Jiang, S., Li, H., & Huang, H. (2021). An overview on engineering the surface area and porosity of biochar. Science of the Total Environment, 763, 144204. doi:10.1016/j.scitotenv.2020.144204.

[73] Hussain, N., & Abbasi, S. A. (2018). Efficacy of the vermicomposts of different organic wastes as “clean” fertilizers: State-of-the-art. Sustainability (Switzerland), 10(4), 1205. doi:10.3390/su10041205.

[74] Manyuchi, M., Chitambwe, T., Phiri, A., Muredzi, P., & Kanhukamwe, Q. (2013). Effect of vermicompost, vermiwash and application time on soil physicochemical properties. International Journal of Chemical and Environmental Engineering, 4(4), 216-220.

[75] Elbl, J., Maková, J., Javoreková, S., Medo, J., Kintl, A., Lošák, T., & Lukas, V. (2019). Response of microbial activities in soil to various organic and mineral amendments as an indicator of soil quality. Agronomy, 9(9), 485. doi:10.3390/agronomy9090485.

[76] Ditzler, C., Scheffe, K., & Monger, H. C. (2017). Soil survey manual: Soil science division staff. Goverment Printing Office: Washington, United States.

[77] Bremner, J. M. (2016). Inorganic Forms of Nitrogen. Methods of Soil Analysis, 1179–1237, Agronomy Monographs, Madison, United States. doi:10.2134/agronmonogr9.2.c33.

[78] Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. Soil Science, 59(1), 39–45. doi:10.1097/00010694-194501000-00006.

[79] Estefan, G. (2013). Methods of soil, plant, and water analysis: a manual for the West Asia and North Africa region. International Center for Agricultural Research in the Dry Areas (ICARDA), Beirut, Lebanon.