https://doi.org/10.33263/Materials24.477490

ISSN: 2668-5728 https://materials.international

Materials International

Volume 2, Issue 4, Pages 0477-0490
2020

Received: 20.07.2020
Accepted: 25.09.2020
Published: 10.10.2020

Article

Applying Rice Husk Biochar for Carbon Sequestration in Building-Integrated Agriculture for Sustainable Urban Agriculture

Saowanee Wijitkosum [1,*], Preamsuda Jiwnok [2]

[1] Environmental Research Institute, Chulalongkorn University, Phayathai Road, Pathumwan, Bangkok 10330, Thailand
[2] Chula Unisearch, Chulalongkorn University, Phayathai Road, Pathumwan, Bangkok 10330, Thailand
* Correspondence: w.m.saowanee@gmail.com, saowanee.w@chula.ac.th; Scopus ID: 55165365500

Abstract: The porous structure of biochar and its high chemically stable carbon content make it useful for carbon sequestration in soil agriculture. The physical and chemical characteristics of biochar can improve the soil functions and enhance crop yields. Incorporating biochar as a soil amendment increases its potential to become an important bio-sequestration agent and makes the agricultural sector a key contributor to climate change mitigation. The research aimed to assess carbon storage in roof-top farming using biochar as a soil amendment. Rice husk biochar (RHB) obtained through a pyrolysis process using an innovative retort invented by the research team for an in-situ use. Seven soil supplementation treatments were assayed, as: (i) 20% by weight (wt.%) organic fertilizer (worm casting), (ii–iv) RHB (1.5, 2.0, or 2.5 wt.%), and (v–vii) 20 wt.% worm casting with RHB (1.5, 2.0, or 2.5 wt.%); plus (viii) non-supplemented soil as the control. The highest amount of carbon in the form of biomass and carbon in the soil was found when using soil supplemented with worm casting plus 2.5 wt.% RHB, with a positive impact on the amount of carbon sequestered within the soils in a roof-top agricultural area and food security in an urban area.

Keywords: rice husk biochar; soil amendment; carbon sequestration; urban agriculture; building-integrated agriculture.

1. Introduction

Increasing global urbanization and population growth contribute to the declining levels of natural resources and increased pollution crisis and climate change, which compromise the quality of life. Improving environmental and socio-economic sustainability is a major issue and has gotten attention in many cities, especially in food security, food safety, and recycling urban wastes. Urban agriculture can make an important contribution to household food security in developing countries, especially in times of crisis or food shortages.

Biochar is a form of charcoal with highly stable material, comprised of more than 65% carbon, and is produced from the biomass through a pyrolysis process conducted under a limited supply of oxygen and at a relatively low temperature of 350–700 °C

Cite This Article: Wijitkosum, S.; Jiwnok, P. Applying Rice Husk Biochar for Carbon Sequestration in Building-Integrated Agriculture for Sustainable Urban Agriculture. Mat Int **2020**, 2, 0477-0490. https://doi.org/10.33263/Materials24.477490

[1-4]. Biochar is seen as shown as a potential material in agronomy, environment, and energy [1,6-10] due to the physical and chemical properties of biochar [8,11-14]. The important physical properties of biochar include high average pore diameter, high surface area, and total pore volume, and high ion exchange capacity [3,5,8,15-16]. The stable carbon form of the biochar, which is a high constant C content, made the biochar to remain in the soil for a long time [15], preventing the carbon from returning to the atmosphere (e.g., like carbon dioxide or methane) within a short period [17-18]. Rather, the residence time of biochar in soils ranges from hundreds to thousands of years [10-12].

Many types of feedstocks are used to produce biochar, such as crop residues, hardwoods, softwoods, dungs, and agro-industrial wastes. Biochar can be used either as a single type or in combination with biochar produced from various types of feedstocks. Rice husk is a type of natural fiber obtained from the original sheath of rice grains. Once paddy is harvested, rice husk forms 20% of the crop's volume. Moreover, rice husk decomposes slowly due to the rich silica content and the high ash content [7]. Therefore, rice husk becomes a popular agro-industrial waste material for the production of biochar. Application of biochar in soil has been shown to have a clear effect on improving the soil fertility [19-22] and soil quality [23-16], increasing the crop productivity [27-31], increasing the efficiency of fertilizer use [30,32], and decontamination of pollutants, such as pesticides, heavy metals, and hydrocarbons [33-34]. Furthermore, the unique feature of biochar, a solid filled with stable carbon elements, is used as a measure to solve climate change problems. Therefore, applying biochar in agriculture provides an opportunity for long-term soil carbon sequestration as well as increase indirect carbon sequestration in plant biomass.

Previous studies showed that incorporating biochar as a soil amendment plays an important role in bio-sequestration, which makes the agricultural sector a key contributor to climate change mitigation [6,17,35-37]. The agricultural sector is also a carbon sink area since it stores carbon in various forms, and its cultivated areas are scattered all over the globe. Thus, these farming areas have the potential to be utilized effectively for carbon sequestration [6]. Moreover, the Food and Agriculture Organization (FAO) of the United Nations (UN) has suggested the use of agricultural areas for carbon sequestration to reduce greenhouse gas (GHG) emissions [39-40]. Bio- sequestration appears to be a suitable and viable means of mitigation for long-term climate objectives [41-42]. Many countries have an attempt to establish agriculture for food security at the urban scale [43-44] in the long term, such as Bologna, Chicago, Shanghai, Hong Kong, Montreal, Toronto, Vancouver, Taipei, and Tokyo [43] Food production and consumption in urban areas has become a global concern due to the increasing numbers of people living in and moving to urbanized living spaces, which threatens food security [45]. As for the environmental aspect, food consumed in the urban areas is usually transported a long distance from its source(s) of production, processing, and storage, which raises concerns about food-mile-derived GHG emissions [46]. The application of biochar for food security, carbon sequestration, and reducing GHG emission purposes leads to sustainable agriculture in the long run.

Building-Integrated Agriculture (BIA) is a type of urban agriculture that allows people to grow plants on the top of or inside buildings. It is considered as an environmentally sustainable method by reducing food-miles [47], decreasing land usage and water consumption for agricultural purposes, and enhancing crop yields [48]. Therefore, the integration of bio-sequestration with BIA is a compelling approach to battle climate change at the urban scale since it would help to increase carbon sequestration within soils and biomass, reduce food- miles, and improve food security. The most popular plants for BIA or roof-top greenhouse are short-lived food plants, especially vegetables that both root vegetables such as radish, beetroot, and leaf vegetables such as Chinese cabbage, Cantonese vegetables, Romaine Lettuce, pak choi, etc. Pak choi (*Brassica rapa* subsp. *chinensis*) is suitable for planting on BIA because it has naturally shallow-rooted, takes up little space, and easy to cultivate. Pak choi grows well in warm climates but can grow under different environmental conditions.

Bangkok, the capital city of Thailand, is facing several environmental problems, such as land-use changes, urban heat islands, and a rapid increase in the population, especially in the inner Bangkok area. According to the World Bank's report [49] entitled "East Asia's Changing Urban Landscape: Measuring a Decade of Spatial Growth", the Bangkok urban area dominated the urban growth of Thailand and is the fifth-largest urban area in East Asia. This research aimed to explore the use of rice husk biochar to increase plant biomass for the carbon sequestration purpose in building-integrated agriculture. This study aimed to establish a good example for the development of urban areas to prepare for and adapt to urban climate change in the future. Compared to traditional farming, this research provided an insight into an innovative agricultural method that leads to sustainable agriculture in an urban area in the long run.

2. Materials and Methods

2.1. Urban agricultural on roof-top: the design process and agricultural area preparation.

This pilot study aimed to explore the possibility of using rice husk biochar (RHB) in BIA for carbon sequestration and plant biomass enhancement on the roof-top of high- rise buildings by using a university campus as a model. The study was carried out on the roof-top of a building at Chulalongkorn University located in central Bangkok, Thailand.

The floor of the roof-top was covered with a 0.3 mm thick PVC-coated Kunilon polyester fabric with a smooth texture which was thick, scratch-resistant, and highly durable. Its elasticity allowed the fabric to withstand direct sunlight and rainfall as well as stress resistance. The fabric was waterproof on both sides, preventing water damage to both the structure and surface area of the building and could last up to 5-7 years, given the conditions. As the experimental site was on the 14th-floor roof-top of a research building at Chulalongkorn University, an open greenhouse with a steel frame was built. The greenhouse was 2 m high and covered with a shade net (50% shade) to protect the crops from strong wind and direct sunlight, which would otherwise impact the plant growth.

2.2. Experimental design.

This experiment consisted of eight treatments: (i) un-supplemented soil as a control treatment (TC), (ii) soil plus worm casting at 20% wt% (TM20), (iii–v) soil plus RH biochar at 1.5 wt.% (TB1.5); 2.0 wt.% (TB2.0); and 2.5 wt.% (TB2.5), and (vi–viii) soil plus worm casting at 20 wt.% and plus RH biochar at 1.5 wt.% (TMB1.5); 2.0 wt.% (TMB2.0); and 2.5 wt.% (TMB2.5).

Pak choi was used in this experiment. The study was conducted using a completely randomized experimental design. Each treatment had four replications giving a total of 32 experimental plots. Each plot was planted in a UPVC treatment box of 0.3 x 0.6 x 0.3 m in size and was placed with a 0.15 m space between them. There were eight plots per treatment box.

2.3. Soil sampling and soil character analysis.

The soil in the experimental plots was analyzed prior to the experiment. The samples were selected at random from areas scattered throughout each plot. The samples were considered as composite samples in the soil analysis. The soil samplings were analyzed for their physical and chemical characteristics using the method developed by the Soil Survey Staff (2014). The analyzed characteristics included pH (pH meter with 1:1 (v/v) soil:water), soil texture (hydrometer method), bulk density (BD; core method), cation exchange capability (CEC; ammonium acetate method), electrical conductivity (EC; EC meter with 1:5 (v/v) soil: Water), organic matter (OM; Walkley and Black method), total nitrogen (Total N; Kjeldahl method), and available phosphorous (avail. P; Bray II method) (Bray II determine by spectrophotometer).

Moreover, the exchangeable potassium (exch. K), exchangeable calcium (exch. Ca), and exchangeable magnesium (exch. Mg) were also determined by ammonium acetate extraction followed by atomic absorption spectrophotometry (AAS).

2.4. Organic fertilizer (worm casting).

The organic fertilizer used in this study was worm castings produced by *Eudrilus eugeniae*, an earthworm species that is easily cultivatable, grows and reproduces quickly. They produce decent sized worm casting and are commonly found in tropical countries [50]. Therefore, using the worm castings as fertilizer in this study was in accordance with the parameters given by the Organic Fertilizer Standard of the Thai Department of Agriculture in 2005 [51].

2.5. Production of RH biochar and analysis of its characteristics.

Rice husk is rich in potassium and silicon and can be used as a soil amendment for improving soil properties [25,52]. Many researchers indicated that pyrolysis temperature has a significant effect on the physical and chemical properties of biochar [ex. 3,8,14,16,52-53]. The preparation of RH biochar in this study considered the influence of pyrolysis temperature on the production and the properties of biochar. Furthermore, the production of good quality biochar with a simple and low-cost process is also an important factor affecting the use of biochar. Therefore, the production of biochar in this study was an emphasis on using affordable technology and utilizes locally available materials with Controlled Temperature Rice Husk Biochar Retort for Slow Pyrolysis Process (CTRHBRSP; patent number 1601001281). The patented retort complied with the standard set by the FAO [54]. It had a controlled temperature between 400-500 °C under the slow pyrolysis condition. The yields of RH biochar from the CTRHBRSP was 45% of the total feedstock, representing a conversion ratio of feedstock to biochar yield of 1:0.45 (88 kg:40 kg). The products from the retort included biochar and gas.

The CTRHBRSP was a cuboid design with double layers (Figure 1). The outer layer was made from concrete blocks with four smoke chimneys. The inner layer was divided into four parts for the installation of four sets of kilns, which were 200 litter steel drums. Each part was supported by a removable steel rebars-each set of the kiln connected to a smoke chimney at the top of the retort. A heat exchanger was placed in the middle of each kiln secured by steel heat exchanger support. The research team had conducted several design experiments regarding the amount and the size of air intake holes. The results indicated that the retort with five intake holes of different sizes, at the bottom on each side, allowed the retort to reach the controlled pyrolysis condition and gave a substantial amount of biochar. Moreover, the retort is equipped with a thermometer to monitor the heat throughout the process.

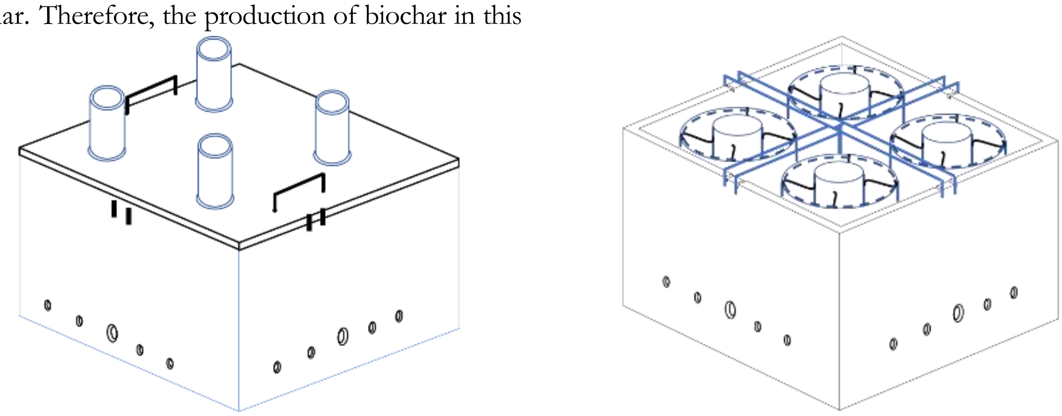

Figure 1. The Controlled Temperature Rice Husk Biochar Retort for Slow Pyrolysis Process.

The physiochemical characteristics of the RH biochar were analyzed following the Standardized Product Definition and Product Testing Guidelines for Biochar that is used in Soil [55]. The samples were randomly selected from the ground RH biochar and analyzed for their physical properties, chemical properties, and composition. The physical properties included the specific surface area, analyzed by the Brunauer-Emmett-Teller (BET) method [9,13], and the total pore volume and average pore diameter, analyzed by the Barrett- Joyner- Halenda (BJH) method [56]. An Autosorb-1 Surface area and pore size analyzer were used to measure the surface areas, total pore volume, and average pore diameter.

Morphological characterization was carried out using scanning electron microscopy (SEM) with the JEOL JEM-5410LV SEM machine to determine the surface morphology and surface characteristics [9,13]. The chemical properties of the soil were determined in terms of the pH (pH meter with 1:2 (v/v) char : water), EC (EC meter with 1:5 (v/v) char : water), CEC (leaching method), OM (Walkley and Black method), total N (Kjeldahl method), total P (P_2O_5; vanadomolybdophosphoric acid colorimetric method), and total K (K_2O_5; AAS). The composition of the RHB was analyzed as total carbon (total C; Shimadzu TOC Tcvh), total oxygen (O), total organic carbon (TOC; Shimadzu TOC Tcvh), and molar hydrogen to TOC ratio (H/C_{org} Ratio). The carbon, hydrogen, nitrogen (CHN) were measured using a Carbon, Hydrogen Nitrogen Analyzer (Leco CHN628 model). The oxygen content was calculated from the residual difference of the biomass.

2.6. Productivity and carbon sequestration of pak choi.

During the harvesting period (49 days), pak choi plants were uprooted from the soil and washed for data collection, including productivity, biomass (BM), and carbon sequestration. Each pak choi plant was measured for the whole plant weight (fresh weight; FW). The plants were then cut and separated by parts: leaves, stems, and roots., Each part was measured (length and FW) and then cut into small pieces and dried in an oven at 70°C for 48 h or until the dry weight (DW) was obtained. The moisture content (MC) (wt%) of the biomass was estimated using the FW/DW ratio [57-58], and the carbon sequestration in the biomass (C_{BM}) [37,59] was derived from carbon concentration (CC) in each part of biomass (Eq.3).

$$MC\% = \frac{(FW-DW)\times 100}{DW} \quad (1)$$

$$BM = \frac{100 \times FW}{100+ MC} \quad (2)$$

$$C_{BM} = \frac{\%CC\times BM}{100} \quad (3)$$

2.7. Carbon sequestration in soil.

The amount of carbon stored within the soil was calculated by Eq. (4). This is adapted from previous reports [37-38,60].

$$C_S = CC \times A \times BD \times D \times 10^{-6} \quad (4)$$

where C_S is the carbon storage in soil (tonC/h), CC is the carbon concentration of the mineral soil (wt.%), A is the area (ha) and BD of the soil (g/cm^3), respectively, and D is the depth of the measured soil layer (cm). In this research, the soil was collected at 15 cm depth, which is the level of carbon deposition in the topsoil.

2.8. Carbon sequestration in pak choi grown on the roof-top.

The amount of carbon sequestered in each of the pak choi experimental plot consisted of the carbon concentration of the plant biomass (C_{BM}) and carbon concentration of the soil (C_S), as shown in Eq. (5),

$$C_{BIA_{rf}} = C_{BM} + C_S \quad (5)$$

2.9. Statistical analysis.

Data from the experiment and field samples were compiled and processed for statistical analysis using analysis of variances (ANOVA). Comparisons between means were tested for significance using Tukey's multiple comparison test in the Statistical Package of the Social Science (SPSS) software version 22. Significance was accepted at the $p < 0.05$ level.

3. Results

3.1. Characteristics of the soil and worm casting.

The pre- experimental soil analysis results revealed that the soil in the experimental plots was a medium alkaline clay soil (26% of sand, 20% of silt, 54% of clay) and with a very high CEC level of 67.40 cmol/kg. The soil had a low EC level (0.20 dS/m), which did not affect plant growth. However, the soil had fairly low fertility, low organic matter (1.21%), and low primary element of macronutrients (0.16 wt.% of total N, 15.00 mg/kg of avail. P, 207.00 mg/kg of exch. K). It contained high secondary elements, which exch. Ca was 22,207 mg/kg, and exch. Mg was 1,011 mg/kg. It also contained fine particles with low soil compactness, as shown in the low bulk density level of 0.90 g/cm^3.

Characteristics of the worm casting indicated that the compost was slightly acidic (pH 6.7). It contained moderate CEC of 55 cmol/kg, low EC level (2.63 dS/m), and a high %OC of 22.67. Worm casting had high OM (39.10), and a high level of soil nutrients (1.87% of total N, 1.85% of total P_2O_5, 0.47% of K_2O_5).

3.2. Characteristics of the RH biochar.

The physical analysis of RH biochar (Figure 2) indicated that a high specific surface area (41.43 m^2/g) and porous structure (0.034 cm^3/g), which varied in pore diameter (32.73 Å of the average pore). The results showed that the amount of Total C was equal to TOC indicated that RH biochar contained solely organic carbon. The H/C_{org} and O/C_{org} molar indicated that the RH biochar was of highly stable carbon and suitable for use as a soil amendment and soil carbon storage. The RH biochar was slightly alkaline with low EC and very high CEC.

According to the analysis of nutrient content in RH biochar, the results revealed that RH biochar had a very high OM and nutrients content.

Table 1 shows details from the properties and characteristics analysis of RH biochar properties and compositions.

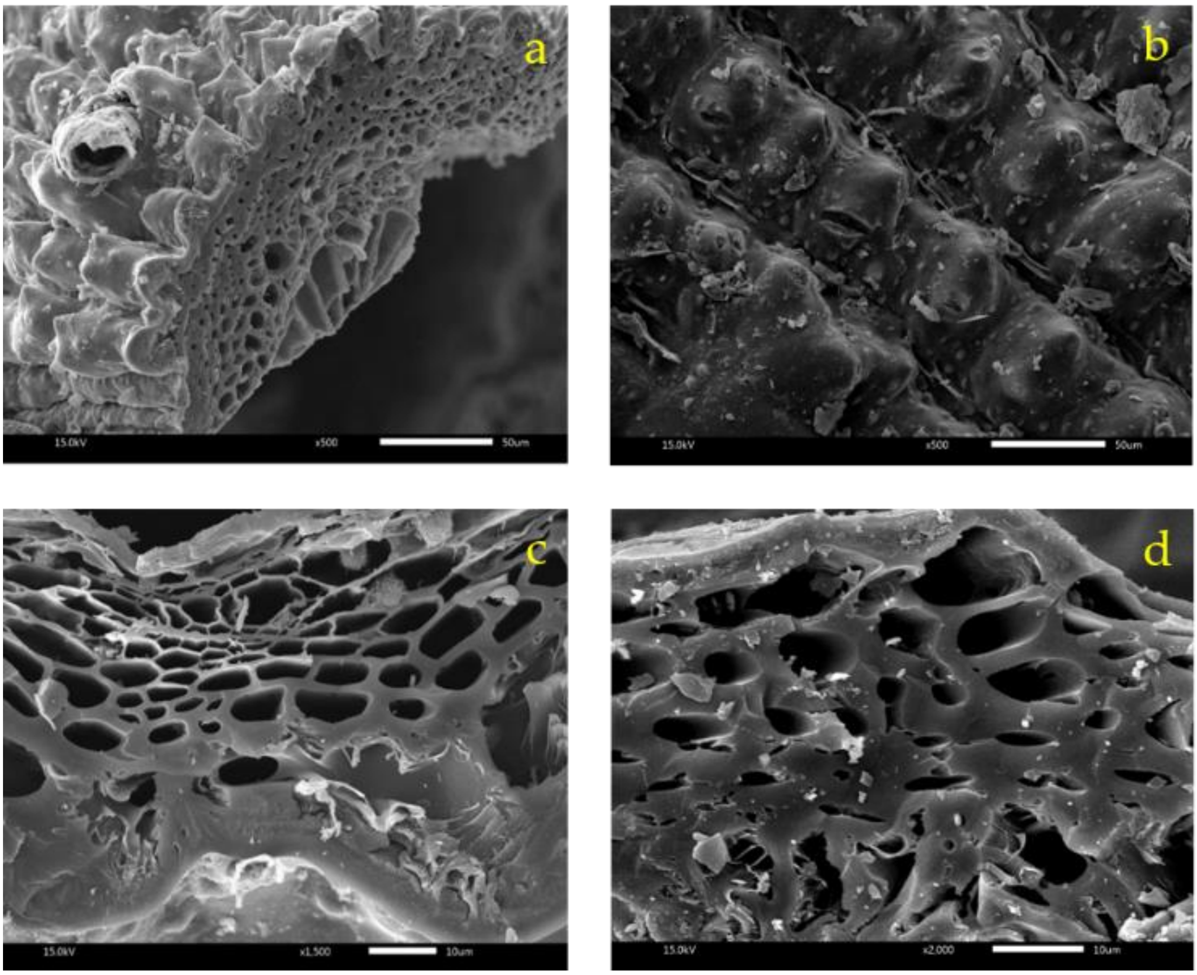

Figure 2. Scanning Electron Microscopy (SEM) images showing a surface at a magnitude of 500x (a and b) and morphology at a magnitude of 1500x (c) and 2000x (d) of RH biochar.

Table 1. Properties and characteristics of RH biochar.

Parameter	Unit	RHB
Composition		
: TC	%	47.67
: TOC	%	47.67
: H	%	2.22
: N	%	1.06
: O	%	28.87
: O/C ratio	Molar	0.45
: H/C ratio	Molar	0.27
: Ash	%	20.18
Chemical properties		
: pH	-	7.90
: EC	dS/m	0.35
: CEC	cmol/kg	17.34
: OM	%	13.10
: Total N	%	0.51
: Total P_2O_5	%	0.29
: Total K_2O	%	1.02

3.3. The productivity of the pak choi

The plants grown in TMB2.0 had the highest FW of both shoots (14.40 t/ha) and roots (4.76 t/ha), while those from the untreated soil (TC) had the lowest FW of shoots (9.12 t/ha) and roots (2.83 t/ha). The FW of roots in TMB2.0 and TMB 2.5 was significantly higher than in the other treatments. The FW of shoots in TMB2.0 was significantly higher than those from TC and TB1.5, but no other differences in the FW of shoots or roots between treatments were significant (Figure 3).

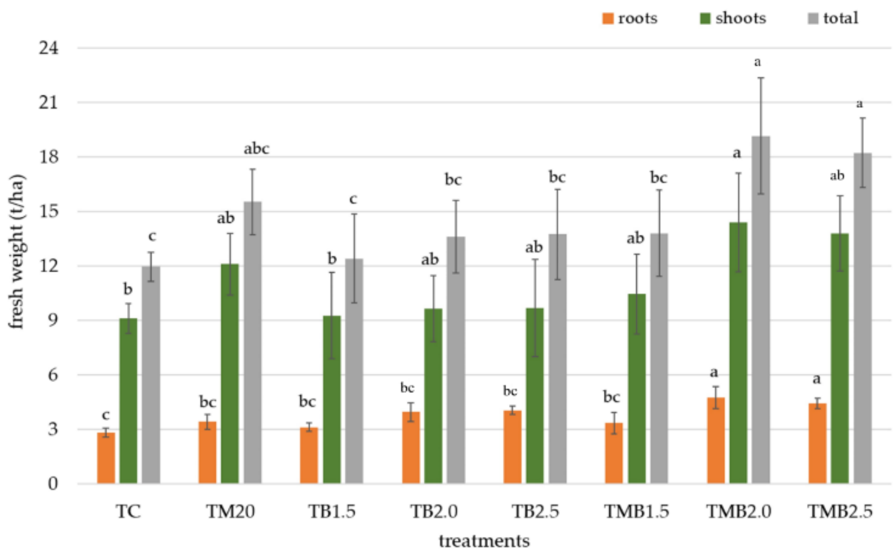

Figure 3. Fresh weight of the roots and shoots of pak choi grown in the eight different treatments for 49 d. Data are shown as the mean ± 1SD, derived from four replicates. The letters a, b, and c refer to a significant difference between treatments at the 0.05 level ($p<0.05$).

3.4. Biomass of pak choi.

The highest total biomass of pak choi was achieved in the soil with 20 wt% worm casting plus 2.0 wt% RHB (TMB2.0), as well as the highest biomass of both shoots and roots. The total biomass in TMB2.0 was significantly higher than those grown with different levels of RHB alone or with worm casting but with a lower level of RHB (TMB1.5), as well as in the untreated soil. The shoot biomass of TMB2.0 was significantly higher than that for TC and TB1.5, while the roots biomass in TMB2.0 was higher than TM20, TMB1.5, TB1.5, and TC. The biomass of pak choi is described in Figure 4.

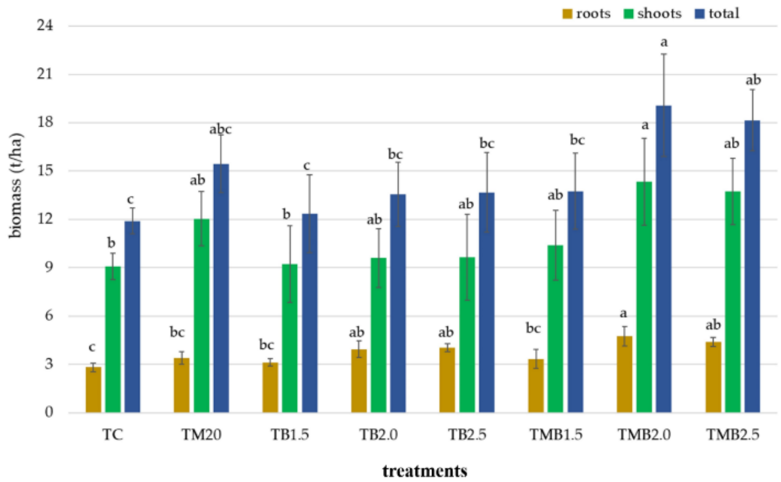

Figure 4. Total, roots, and shoots biomass of pak choi grown in the different soil treatments for 49 d. Data are shown as the mean ± 1SD, derived from four replicates. The letters a, b, and c refer to a significant difference between treatments at the 0.05 level ($p<0.05$).

3.5. Carbon sequestration in pak choi cultivation.

With respect to carbon sequestration by the growing pak choi（Figure 5）, TMB2.0 gave the highest carbon storage in the total biomass and shoots (total = 6.74 tC/ha, shoot = 5.23 tC/ha), followed by those in TMB2.5, TM20, TMB1.5, TB2.5, TB2.0, TB1.5, and TC, respectively.

The results indicated that the total amount of carbon storage in the biomass of pak choi in all treatments with the addition of RHB and worm casting (TMB2.5, TMB2.0, and TMB1.5) were higher than those with RHB alone (TB2.5, TB2.0, and TB1.5), and those without RHB (TC). The amount of carbon storage in the roots grown in TMB2.5 was the highest (1.53 tC/ha). Several noteworthy results were that soil incorporated with RHB at the lowest amount (TB1.5) produced the same amount of carbon storage in the roots as the soil incorporated with worm casting and that the carbon storage in pak choi root biomass increased with increasing amounts of RHB added into the soil (TB2.5 > TB2.0 > TB1.5).

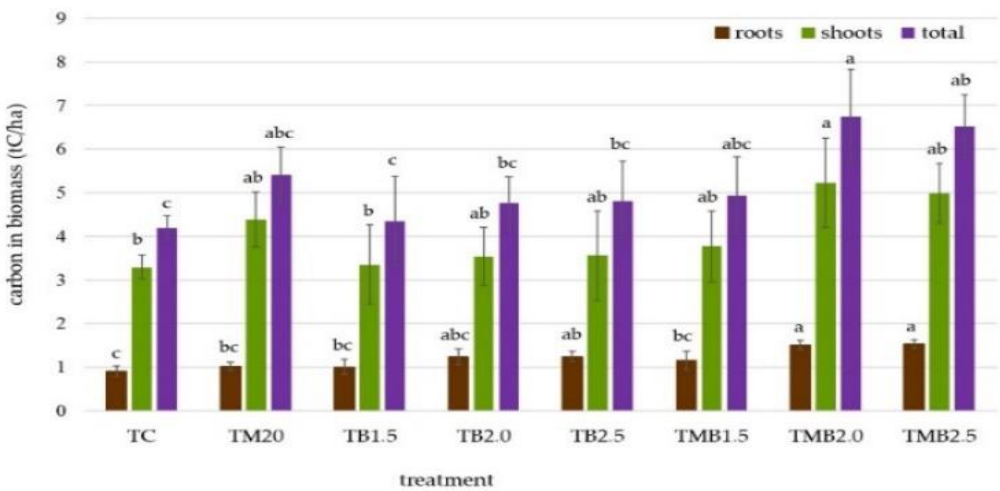

Figure 5. Carbon storage in different parts of pak choi biomass grown in different treatments for 49d.

Data are shown as the mean ± 1SD, derived from four replicates. The letters a, b, and c refer to a significant difference between treatments at the 0.05 level ($p<0.05$).

3.6. Carbon sequestration in BIA.

The carbon sequestration in BIA consists of two parts; carbon storage in the soil and carbon storage in the plant biomass. The results found that the amount of carbon storage in the soil was the highest in the soil with incorporated RHB and worm casting (TMB2.5, TMB2.0, and TMB1.5), as expected. The amount of carbon storage in the soil increased with higher amounts of added RHB, and was significantly higher than in TC, TB1.5, and TB2.0, but not with TM20 and TB2.5.

Overall, the amount of carbon sequestration in these agricultural plots increased with increasing amounts of added RHB (TMB2. 5 > TMB2.0 > TBM1.5 and TB2.5 > TB2.0 > TB1.5), where TMB2.5 gave the highest amount of carbon storage, which was significantly higher than the other treatments, while the lowest was the untreated soil.

The result indicated that incorporating RHB as a soil amendment increased its potential to become an important bio-sequestration (Table 2).

Table 2. Amount of sequestered carbon in the different pak choi cultivation treatments after 49 d of cultivation.

Treatment	Amount of sequestered carbon in pak choi experimental areas (tC/ha)		
	Within biomass	Within soil	Within plots
TC	c4.199 ± 0.279	c24.074 ± 3.002	d28.273 ± 3.043
TM20	abc5.406 ± 0.643	a35.580 ± 1.083	ab40.986 ± 1.407
TB1.5	c4.353 ± 1.031	c25.901 ± 1.113	d30.253 ± 2.074
TB2.0	bc4.769 ± 0.597	bc27.653 ± 2.588	cd32.422 ± 2.853
TB2.5	bc4.807 ± 0.925	ab34.221 ± 4.766	bc39.028 ± 4.776
TMB1.5	abc4.928 ± 0.889	a37.357 ± 3.147	ab42.285 ± 2.641
TMB2.0	a6.739 ± 1.087	a38.381 ± 3.906	ab45.120 ± 2.935
TMB2.5	ab6.514 ± 0.725	a41.751 ± 4.323	a48.265 ± 4.373

Data are shown as the mean ± 1SD, derived from four replicates. The a, b, and c, refers to significant difference between treatments at the 0.05 level ($p<0.05$).

3.7. Discussion.

3.7.1. Rice husk biochar mixed in soil that affects the productivity and biomass of pak choi.

Increasing production and biomass of pak choi was obtained in RHB supplemented soil. The RHB pyrolysis at 400-500 °C resulted in a rich content of high stability carbon, mostly in the form of amorphous carbon in which the carbon atoms were attached in aromatic rings [1,4-5]. The H/C_{org} ratio of the RHB was low (less than 0.7), which reflected its stability [5,8,55]. These chemical properties enabled the carbon in the RHB to be very stable [5,8,14] and generated a highly porous structure [22,28,53]. Moreover, the use of an appropriate temperature during the pyrolysis increased the porosity on the biochar's surface and led to an increased level of surface ions, giving the high ion exchange capacity and CEC [1,5,24,32].

The RHB possessed weak alkalinity (pH 7.9), due to the type of feedstock and pyrolysis condition [16,32], and a high level of macro-nutrients, which contributed to the increased nutrient levels in the soil and so improved the soil fertility. Overall, these physical and chemical characteristics and formations of this RHB made it suitable as a soil amendment agent [2,32] to improve soil properties [23,30], increase plant growth [22,28,30,32], plant biomass [6,37], and carbon storage in the soil [4,29,37]. The addition of worm casting enhanced the obtained pak choi biomass numerically, but not significantly.

Likewise, the addition of RHB showed a dose-dependent numerical increase in the obtained biomass, but this was only significantly higher than the control at higher RHB levels (TMB2. 0 and TMB2. 5), and no supplemented soil resulted in significantly higher biomass than the others. This result is consistent with the previous report that adding RHB to soil increased the stem size and leaf length of the Chinese kale [37] and the water spinach [52]. Moreover, evaluation of the effect of RHB on the growth of pak choi white (Tropical Type) over two seasons revealed that the aboveground biomass increased with biochar addition up to 25 t/ha in both crop cycles [26]. The control (0 t/ha) and the soil treated with RHB at 50 t/ha did not give significantly different pak choi growth in both crop cycles. Thus, it is likely to be an upper limit on the application of biochar and crop productivity.

Many studies indicated that incorporating biochar as a soil amendment increases both productivity and biomass. Wijitkosum and Sriburi [6] studied the effect of soil amendment with cassava stems biochar (CSB) on maize biomass, where the total biomass of maize grown over two crop cycles was the highest when incorporating 30 t/ha of CSB into the soil, yielding a maize biomass product of 16.26 t/ha in the first crop cycle and 15.55 t/ha in the second cycle. Likewise, the addition of bamboo biochar or rice straw biochar (RSB) in rice paddy fields over two crop cycles both had positive effects on the rice growth, but the application of RSB significantly increased the rice yield and stem height over two successive years. Overall, previous research results had indicated that incorporating biochar produced from diverse types of feedstocks into the soil increased the plant yields, biomass, and productivity as well as affecting the carbon mineralization and nutrients in the soil [27,61].

This research indicated that mixing 20 wt.% worm castings with an appropriate amount of RHB (2.0 wt%) into the soil increased the pak choi plant biomass and had the potential to be an alternative green fertilizer to avoid relying solely on agrochemicals or natural fertilizers, which were the traditional agricultural practices among farmers. These results are consistent with Ardakani and Sharifi [61], who studied the effect of worm castings-based growth media with biochar and arbuscular mycorrhizal fungi for producing organic tomatoes (*Solanum lycopersicum* L.) in a greenhouse. Incorporating biochar with the worm cast fertilizer significantly increased the growth of tomatoes plants (shoot DW and stem diameter) compared to the untreated soil. Moreover, Sigh et al. [19] showed that planting paddy rice (*Oryza sativa*, Hindu University Rice-9-10 variety) in soil amended with 10 t/ha of RHB, commercial bio-formulation (CSR-BIO), and RHB+CSR-BIO gave the highest rice yield with RHB+CSR-BIO. In addition, RHB and CSR-BIO increased the panicle length, tiller number per plant, rice grain yield, and paddy straw yield compared with the unamended soil. Likewise, other studies have indicated that incorporating an appropriate amount of biochar into the soil enhanced the plant growth and biomass [eg. , 22,29,31], and enhanced plant yields. These results were obtained from plants grown in areas where the biochar was mixed with fertilizer prior to addition to the soil [e.g., 22,29,30].

Biochar acts as a soil amendment agent and together with the worm casting to improve the biophysical and chemical properties of the soils, making them more suitable for the plants, retaining nutrients, and allowing the plant roots to absorb the nutrients more efficiently [9,28,32]. Furthermore, the highly porous surface of biochar enables it to absorb and retain nutrients in the soil solution within the soil, due to ion exchange reactions at the surface [15,25,28], and so allows the plants to absorb the nutrients throughout the growth period continuously. The increased growth rate of the plants influences the increased biomass, which in turn directly affects the amount of carbon stored in the biomass. Thus, incorporating biochar with organic fertilizer as a soil amendment increases plant growth, yield, biomass, and productivity, and carbon storage [1,19,22,27,32,52].

3.7.2. Amount of carbon sequestered by growing pak choi on a roof-top BIA.

This study focused on the effects of incorporating RHB into soils for roof-top agriculture and carbon sequestration purposes. The experiment was designed to incorporate both RHB and worm casting within the soil. Both substances are organic carbon but with different carbon contents. Mixing both of them within the soil contributes to the amount of carbon in the soil (Figure 5 and Table 2). However, the soil carbon concentration and sequestration depend on several factors, such as the initial amount of carbon within the soil, its chemical characteristic, the amount of carbon within the biochar, and the quality and the stability of biochar [24,36,40].

Considering the characteristics of both types of carbon matter, the worm castings would decompose at a faster and higher rate than RHB, since the latter is in the form of amorphous carbon [9,11,14] bonded together with aromatic rings that makes it more difficult to break or dissolve [4-5,8]. However, the OM in the worm casting is readily decomposed by the microbial soil community, and the organic carbon in the manure has low stability. Moreover, the stability of soil OM also depends on the density of carbon, which limits its solubility or decomposition. The amount of carbon in worm casting and RHB were different in terms of the amount of carbon, type of carbon, and the stability and retention of the OM in the soil [37]. These characteristics impact on the amount of sequestered carbon within the soil. Moreover, these characteristics make biochar, applied alone or as a mixture with other organic compounds, suitable for soil amendment [22,28].

This study revealed that soil supplementation with both RHB and worm casting yielded a higher amount of sequestered carbon than soil alone or soil plus RHB without worm casting. In conclusion, the type and the amount of carbon incorporated within the soil affected the amount of soil carbon sequestration. Incorporating RHB, a highly stable organic carbon, together with worm casting within the soil contributed to a higher amount of soil carbon sequestration, and so incorporating RHB within soils in roof-top agricultural areas is a possible approach to battle climate change by reducing carbon-based GHG emissions through carbon sequestration [4,12,20,29]. At the same time, growing crops in an urban area also reduces the food-miles and increases urban green spaces.

3.7.3. Increasing food security and enhanced sustainable agriculture in urban areas using RHB.

Roof-top agriculture, as urban agriculture can improve various ecosystem services, enrich urban biodiversity, and reduce food insecurity. Food production provided by green roofs can help support and sustain food for urban communities, as well as provide a unique opportunity to effectively grow food in spaces that are typically unused [18,43,47-48].

Using biochar as a soil amendment in an urban agricultural area, both on the roof-top and unused land enhances its potential to become an important alternative agricultural source and makes urban agriculture a key contributor to an environmentally sustainable urban management. Moreover, biochar amended soil reduces the soil greenhouse gas emissions from agricultural areas [17-18,35] and helps mitigating climate change in terms of carbon sequestration, both within the soil and the plant biomass [12,29,36-37].

Adding RHB into the soil can improve soil properties and increase the soil nutrients. Biochar produced from bio-feedstocks that are safe for the ecosystem and human health offers agricultural green roofs the additional benefit of increasing the water holding capacity and permanent wilting point in green roof substrates [9,23-24]. The biochar reduced the cumulative leaching of nutrients from green roofs by reducing the nutrient concentration and leaching times in the runoff [34]. Biochar addition makes green roof substrates lighter and improves the plant water supply, potentially expanding plant selection in dry climates and improving their stormwater retention [27].

In addition, using biochar as a soil amendment in green urban agriculture contributes to the mitigation strategies for the urban heat island effect, provides a more aesthetically pleasing environment for work and life as well as environmental education [36,43]. The cultivation of food on buildings is a key component of multifunctional land use in the cities that contribute to sustainability and habitability [43,45].

4. Conclusions

The incorporation of RH biochar in the soil used for crop (pak choi) production enhanced carbon sequestration in an urban roof-top agricultural area. Soil mixed with worm casting can increase biomass and carbon storage in biomass more than planting by mixing only RHB in every ratio. Mixing an organic fertilizer (worm casting) with the RHB within the soil resulted in the highest amount of sequestered carbon, both in the form of plant biomass and within the soil. The comparison between the amount of carbon stored in the plant biomass and within the soil indicated that the latter retained a higher amount of carbon, especially in the treatments with RHB plus worm casting. The amount of sequestered carbon increased with the amount of RHB incorporated within the soil, especially in the treatments with worm casting. Therefore, incorporating RHB within roof-top agricultural soil is a viable means to enhance carbon sequestration and help reduce GHG emissions.

Funding

This research was supported by the **"**Building a Smart Community for Climate Change and Natural Disasters Adaptation. Sub-project: Using biochar in urban farming areas for food security and carbon sequestration on high-rise buildings**"**, 2016 Ratchadapisek Sompoch Endowment Fund for in-depth high potential research projects**.**

Acknowledgments

The Controlled Temperature Rice Husk Biochar Retort for Slow Pyrolysis (CTRHBRSP) was supported by Pa-Deng Biochar Research Center. The authors would like to thank Ms. Bupphachat Mattayom for formatting the references list.

Conflicts of Interest

The authors declare no conflict of interest.

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