**Title**

Effects of different feedstock type and carbonization temperature of biochar on oat growth and nitrogen uptake in coapplication with compost

**Author names and affiliations**

Shoki Ochiai 1, Kazunori Iwabuchi 2\*, Takanori Itoh 2, Toshihiro Watanabe 2, Mitsuru Osaki 2, Katsumori Taniguro 3

1 Graduate School of Agriculture, Hokkaido University, Kita-9, Nishi-9, Kita-ku, Sapporo, Hokkaido 060-8589, Japan

2 Research Faculty of Agriculture, Hokkaido University, Kita-9, Nishi-9, Kita-ku, Sapporo, Hokkaido 060-8589, Japan

3 Tanigurogumi Corporation, Shiobara 1100, Nasushiobara, Tochigi 329-2921, Japan

**Corresponding author**

Kazunori Iwabuchi, Research Faculty of Agriculture, Hokkaido University, Kita-9, Nishi-9, Kita-ku, Sapporo, Hokkaido 060-8589, Japan, +81-[0]11-706-4171, iwabuchi@bpe.agr.hokudai.ac.jp

**Declarations**

**Funding**

Araya Foundation from Hokkaido Branch of The Japanese Society of Agriculture and Food Engineering

**Conflicts of interest/Competing interests**

Not applicable

**Availability of data and material**

The datasets and analyses of the current study are available from the corresponding author on reasonable request

**Code availability**

Not applicable

**Footnote**

Shoki Ochiai’s present affiliation is Miyakonojo Research Station, Kyushu Okinawa Agricultural Research Center, National Agriculture and Food Research Organization (NARO), Miyakonojo, Miyazaki 885-0091, Japan

**Acknowledgments**

The authors acknowledge the support of the Araya Foundation from Hokkaido Branch of The Japanese Society of Agriculture and Food Engineering for this work. The analysis of specific surface area and average pore size of biomass feedstocks and biochar was carried out with Quantachrome Instruments Autosorb 6AG (Yuasa‐Ionics Co. Ltd., Osaka, Japan; Quantachrome Co., Boynton Beach, FL, USA) at the Institute for Catalysis, Hokkaido University. We express our gratitude to the Instrumental Analysis Division, Global Facility Center, Creative Research Institution, Hokkaido University for performing elemental analyses using a CE-440 elemental analyzer.

**Abstract**

*Purpose:* We aimed to verify whether (i) biochar-compost application improves plant growth when compared with compost application alone and (ii) a diversity of biochar caused by feedstock type and carbonization temperature affects the extent of plant growth.

*Methods:* We prepared six types of biochar from larch (*Larix kaempferi* Sarg.) and dairy manure at 300°C, 450°C, and 600°C for 1 h. Compost was applied as control, and each biochar was co-applied with compost to oat plants (*Avena sativa* L.). The total nitrogen input of all the seven treatments was adjusted to the same level to assess their effects on plant nitrogen uptake and nitrogen content.

*Results:* Compared with the control, biomass production increased from 13.1% to 34.0% with the wood-biochar application and from 39.7% to 64.2% with manure biochar application because of more mineralization of compost and nitrogen fixation through rhizobacteria and/or diazotrophic endophytes. The diversity of biochar caused a difference in the extent of oat growth, and feedstock type of biochar was a more dominant factor than carbonization temperature. Due to the favorable chemical properties of manure-biochar like high pH and more labile-C and -N content, the manure biochar application increased average biomass production by 26.0% compared with the wood biochar application. The carbonization temperature had no significant impact on oat growth, but the optimal temperature was indicated as approximately 450 °C.

*Conclusions:* Biochar diversity causes a difference in plant growth in biochar-compost application and the selection of appropriate biochar, such as manure biochar at 450 °C, would be a guideline for achieving a robust crop production system.

**Keywords**

biomass, feedstock type, wood biochar, dairy manure biochar, carbonization temperature

**1. Introduction**

The use of organic fertilizers, such as compost, is fundamental to achieving sustainable crop production systems. However, using compost over chemical fertilizer results in lower crop productivity and it is currently difficult to use compost alone to meet the food demands associated with rapid population growth. The low crop productivity is primarily due to the existing form of nitrogen in compost. Microbial mineralization of the organic nitrogen in compost is necessary for plant growth, and this process limits the rate at which nitrogen is supplied to crops (Berry et al. 2002; Seufert et al. 2012).

 To overcome the limitations of compost (low nitrogen availability), the current study considered biochar-compost application. Biochar is believed to improve the soil properties and create hotspots of microbial growth owing to its favorable physicochemical properties (Amelootet al. 2013; Cernansky 2015; Lehmann et al. 2011), thereby increasing crop productivity and nitrogen availability. Indeed, the application of biochar with N fertilizer increases the yields of radish by 266%, rice by 12%, and wheat by 17%, respectively, compared with no biochar application (Chan et al. 2007; Wang et al. 2012). These studies suggest that biochar-compost application is more beneficial for plant growth than the application of compost alone. However, there is no consensus on the effectiveness of the application of biochar-compost at present. For example, compost co-applied with plant-based biochar leads to higher plant nutrient uptake as a result of improvement in the soil physicochemical properties caused by biochar application, thereby leading to higher biomass or grain yield (Agegnehu et al. 2016; Hairani et al. 2016; Schulz et al. 2014). In contrast, some researchers reported that the biochar-compost application decreases or has no effect on crop yields compared with simple compost application (Schmidt et al. 2014; Schulzand Glaser 2012), suggesting the need for further research to clarify guidelines and avoid such situations.

 We assumed that the difference of consensus in the biochar-compost application is associated with a wide variety of biochar available. Biochar is produced from different types of biomass; hence, its physicochemical properties are influenced by the feedstock type. Indeed, biochar derived from woody biomass (the most common type of biochar) possesses a function of soil amendment rather than that of nutrients supplement. In contrast, biochar derived from organic waste, such as animal manure, contains more minerals than biochar from woody biomass (Shinogi et al. 2003). Additionally, the carbonization temperature used to produce biochar can change its properties, even when the same feedstock type is used. At higher carbonization temperatures, the specific surface area (SSA) of biochar tends to increase, and nitrogen content of biochar tends to decrease (Cao and Harris 2010; Zhaoet al. 2013).

 Although a significant amount of research has been done on the biochar-compost application in recent years, a wide variety of biochar has not been considered carefully, and little is known about the effects of biochar type on plant growth. We have established two hypotheses to clarify the above-mentioned issues. Hypothesis #1: biochar-compost application improves plant growth when compared with compost application alone. Hypothesis #2: in the biochar-compost application, a diversity of biochar (caused by feedstock type and carbonization temperature) affects the extent of plant growth. In order to verify these hypotheses, we prepared six types of biochar from two types of feedstock (fresh dairy manure and wood shavings) at three carbonization temperatures (300°C, 450°C, and 600°C) and grew oat plant (*Avena sativa* L.) as model biomass in the biochar-compost application as well as compost application alone.

**2. Material and Methods**

**2.1 Characteristics of soil and compost**

Red soil (Kanto loam soil) was used in this study. To model the degraded soil, red soil was dried at 50°C for 48 h and milled to pass through a 2-mm sieve. The red soil had a pH of 5.6, NO3-N of 0.047 g kg−1, NH4-N of 0.005 g kg−1; and clay, silt, and sand content of 15.7%, 5.7%, and 78.6%, respectively. Compost was collected from a farm in Kitahiroshima, Japan. This material was produced by composting dairy manure for several months using mechanical turning, with straw as a bulking agent. Compost had a wet-basis moisture of 70%; pH of 8.85; C/N ratio of 18.5; and total N, P, and K concentrations of 24.4, 3.9, and dry mass of 19.4 g kg−1, respectively.

**2.2 Biochar production**

Wood biochar (WDBC) and dairy manure biochar (DMBC) were produced from wood shavings of larch (*Larix kaempferi* Sarg.) (WD) and fresh dairy manure (DM). WD was collected at the Tomakomai experimental forest of the Field Science Center for Northern Biosphere, Hokkaido University, Tomakomai, Japan; DM was collected from an experimental farm of the Field Science Center for Northern Biosphere, Hokkaido University, Sapporo, Japan. DM was immediately dehydrated to a water content of 60% wet-basis, and then kept frozen until use. Before carbonization, feedstocks (WD and DM) were oven-dried at 105°C for 24 h and milled to pass through a 2-mm sieve. Homogenized feedstocks were placed in alumina crucibles covered with lids and underwent carbonization in the muffle furnace at temperatures of 300°C, 450°C, and 600°C for 1 h.

**2.3 Cultivation experiment**

Oat plants (*Avena sativa* L.) were grown in 2 L pots in a greenhouse with a mean temperature of 28°C. The experimental design is summarized in Table 1. This study prepared seven treatments with five replicates each: compost alone as a control (I), WDBC‑compost application (II–IV), and DMBC-compost application (V–VII). Comparison between control (I) and each biochar-compost application (II–VII) indicates how biochar-compost affects the plant growth. In addition, comparison among biochar-compost application (II–VII), which consists of a full factorial experimental design with the feedstock type and carbonization temperature as two factors, represents the effects of biochar type on plant growth. To assess the effects on plant nitrogen uptake, the application amount of compost and biochar for each treatment was adjusted to approximately 350 mg N per pot, corresponding to about 250 kg N per ha (Table 1). All treatments received enough chemical fertilizer: 72 mg P and K per pot, corresponding to about 50 kg P and K per ha. One liter of red soil and the calculated amount of compost and biochar were mixed in the pots (Table 1). The total volume of each pot was adjusted to 2 L volume by mixing perlite. Three seeds were planted in each pot and the two weakest seedlings were thinned out on the 7th day after germination. To maintain sufficient moisture, all pots were watered with deionized water every other day.

**2.4 Biochar and plant analysis**

**2.4.1 Biochar analysis**

The pH values were measured using a pH meter (HI9912N, HANNA, Chiba, Japan) with a 1 % w/v suspension in deionized water prepared by shaking at 150 rpm for 1 h. Ash content was measured by heating samples at 600°C for 3 h in a muffle furnace. Elemental compositions of feedstock and biochar were determined using an elemental analyzer (Exeter Analytical CE440, Exeter Analytical Inc., USA) for total carbon and nitrogen and by an ICP-MS (ELAN DRC-e; Perkin Elmer, Waltham, MA, USA) for total P, K, Ca, Mg, and Na. Before ICP-MS analyses, the samples were digested in 60% (w/v) HNO3 at approximately 110°C in the DigiPREP apparatus (SCP Science, Canada) for approximately 2 h. SSA and average pore size (APS) were determined by the multipoint Brunauer–Emmett–Teller method applied to the N2 adsorption isotherms measured at −196°C (Quantachrome Instruments Autosorb 6AG, Yuasa‐Ionics Co. Ltd., Osaka, Japan; Quantachrome Co., Boynton Beach, FL, USA, and Belsorp Mini II, MicrotracBEL Co. Ltd., Osaka, Japan). Prior to taking the measurements, homogenized samples were degassed at 150°C for 2 h (Belprep Vac II, MicrotracBEL Co. Ltd., Osaka, Japan). All analyses were repeated three times.

**2.4.2 Plant analysis**

After the completion of the cultivation experiment (42 days after germination), the above and below ground oat plant in each pot were harvested and washed with deionized water. Washed plants were oven-dried at 50°C for 48 h and the dry mass per plant was measured as biomass production (g plant−1). The above-ground parts of the plants were milled to fine particles, and the nitrogen content of the above-ground part of oat plant (%) was measured by an organic elemental analyzer (2400 Series II CHNS/O Elemental Analyzer System; PerkinElmer, Inc., Waltham, USA). Plant nitrogen uptake (mg plant−1) was calculated using multiplication of biomass production (g plant−1) and nitrogen content (%) of the above-ground part of the oat plant.

**2.4.3 Nitrogen isotope analysis**

Nitrogen isotope analysis was used to trace the nitrogen dynamics in biochar application. The stable isotope compositions of each sample (compost, biochar, cultivation soil, and above-ground plant part) were measured using an isotope ratio mass spectrometer (Delta V Advantage, Thermo Fisher Scientific Inc., Bremen, Germany). The nitrogen was separated from each sample through complete oxidation at 1000°C and reduction at 680°C (Flash EA 1112, Thermo Fisher Scientific Inc., Bremen, Germany), and it was then introduced into the mass spectrometer with a helium carrier gas. The stable isotope composition is expressed as δ15N value = ((15N/14Nsample)/(15N/14Nstandard) − 1) × 1000 [‰], where 15N/14Nsample and 15N/14Nstandard are the atom ratio of 15N to 14N in the sample and atmospheric N2, respectively.

**2.5 Statistical analysis**

A total of 35 assays, corresponding to 7 treatments (I–VII) with 5 replicates, were subjected to Dunnett’s test (α = 0.05) to compare each of the biochar-compost application (II–VII) with the control (I). Besides, to clarify the influence of biochar type in the biochar-compost application, a total of 30 assays, corresponding to 6 treatments (II–VII) with 5 replicates, were used to conduct a two-way analysis of variance (two-way ANOVA) with the feedstock type and carbonization temperature as two factors (α = 0.05). In both analyses, biomass production, plant nitrogen uptake, plant nitrogen content, and δ15N value of plant were considered as response variables. All analyses were performed using R statistical software (version 3.6.2 for Windows. R Core Team, 2019).

**3. Results**

**3.1 Properties of biomass feedstocks and biochar**

The physical and chemical properties of biomass feedstocks and biochar are summarized in Table 2. The carbon content of WD and WDBC was higher than that of DM and DMBC, increasing with higher carbonization temperature. Nitrogen content was higher in DM and DMBC than in WD and WDBC. DMBC showed higher nitrogen content than raw DM, due to larger organic matter volatilization than nitrogen volatilization during carbonization. On the other hand, the nitrogen content of DMBC decreased with the higher carbonization temperature, due to active nitrogen volatilization at high temperatures. Inorganic elemental content and ash content were both higher in DM and DMBC than in WD and WDBC. They became higher with increasing carbonization temperature due to the reduction of organic matter by volatilization. The pH values were higher in DM and DMBC than in WD and WDBC, and the values increased with high carbonization temperature due to high ash content. SSA of DMBC increased approximately 50-fold at the carbonization temperature of 600°C compared with that of DM, and SSA of WDBC increased approximately 120-fold at 600°C compared with that of WD. The similar trend of a sudden increase in SSA at higher carbonization temperatures was also reported in previous studies: the SSA of plant-based biochar tends to increase suddenly at approximately 500°C because of the active removal of volatile matter deposited in pores during carbonization (Xiao et al. 2018) and Zhang et al. (2018) observed that the SSA of manure-based biochar suddenly increased to more than 500°C due to the significant increase in volatile release. The APS tended to decrease with increasing temperature, and the APS of DMBC was larger than that of WDBC.

**3.2 Biomass production of oat plant**

The biomass production of the oat plant is shown in Fig. 1. Although all biochar-compost treatments (II–VII) increased biomass production by 13.1%–64.2% compared with the compost treatment alone (I), a significant difference was confirmed only in the DMBC450-compost and DMBC600-compost treatments, according to the Dunnett’s test (I vs VI: *p* = 0.021; I vs VII: *p* = 0.039) (Table 3).

To understand the influence of biochar type on biomass production in the biochar-compost treatments (II–VII), a two-way ANOVA was conducted (Table 4). The statistical analysis indicated that there were no significant differences in an interaction between feedstock type and carbonization temperature (*p* = 0.658) and carbonization temperature (*p* = 0.445). Meanwhile, the feedstock type showed a considerable association with biomass production (*p* = 0.016); DMBC treatments increased the average biomass production by 26.0% compared with WDBC treatments (Fig. 1 and Table 4).

**3.3 Nitrogen uptake and nitrogen content of oat plant**

Nitrogen uptake and nitrogen content of the oat plant are shown in Figs. 2 and 3, respectively. Similar to biomass production, the plant nitrogen uptake and nitrogen content increased by 49.7–76.0% and 14.0–45.2% for WDBC-compost treatments (II–IV) and by 113.6–186.8% and 36.7–70.6% for DMBC-compost treatments (V–VII) compared with the control (I), even in the equivalent nitrogen input. Dunnett’s test determined significant differences in nitrogen uptake and nitrogen content between each of all the DMBC-compost treatments and the control (Table 3). In contrast, the WDBC300-compost and WDBC450-compost treatments (II and III) had no significant differences in nitrogen uptake and nitrogen content compared with the control, whereas the WDBC600-compost treatment (IV) showed a significant difference in nitrogen content (Table 3). Overall, the biochar-compost application promoted the supply of nitrogen to the plant, resulting in higher nitrogen uptake and nitrogen content of the plant compared with the application of compost alone.

When comparisons were made between the biochar-compost treatments (II–VII) using a two-way ANOVA, no significant differences were found in the interaction between feedstock type and carbonization temperature to nitrogen uptake and nitrogen content (Table 4). With regard to feedstock type, the DMBC-compost treatments (V–VII) increased both plant nitrogen uptake by 42.6–62.9% (*p* < 0.001) and nitrogen content by 15.7–19.9% (*p* = 0.002) compared with the WDBC-compost treatments (II–IV) (Figs. 2 and 3, Table 4), despite the fact that only half the amount of compost was applied compared with the WDBC application (Table 1). As for carbonization temperature, higher temperatures increased plant nitrogen uptake to some extent but there was no significant difference (*p* = 0.098). Meanwhile, the impact of carbonization temperature was significant on nitrogen content (*p* < 0.001), and the maximum value was observed for DMBC600-compost and WDBC600-compost, respectively (Fig. 3).

**3.4 Nitrogen isotope analysis**

To trace the nitrogen source of the plant, nitrogen isotope analysis was conducted (Fig. 4). Generally, the plant δ15N value is reflected by the δ15N value of the cultivation soil (He et al. 2009; Yoneyama et al. 1986). Indeed, the δ15N value of oat plant in the control (I: 10.0‰) was similarly high to that in compost and red soil (8.15 and 7.97‰), representing that the nitrogen source of the oat plant was mainly from the red soil and the applied compost. In contrast, the plant δ15N values of all the biochar-compost treatments (II–VII: 4.71–6.58‰) were lower than not only those of control (*p* < 0.001, Table 3) but also those of the red soil, compost, and DMBC (7.86 to 8.15‰). Considering the δ15N value of plant approaches to that of the atmosphere (δ15N atm. = 0 [‰]) when absorbed nitrogen is derived from biological nitrogen fixation (Quilliam et al. 2013), the plants in all the biochar-compost treatments utilized nitrogen not only from the red soil and applied compost but also from the atmosphere, through nitrogen fixation in the rhizosphere.

Considering the comparisons among the biochar-compost treatments (II–VII), the DMBC-compost treatments (V–VII) showed lower δ15N values than those shown by the WDBC-compost treatments (II–IV) (*p* < 0.001, Table 4). Conversely, neither the interaction (*p* = 0.351) nor carbonization temperature (*p* = 0.388) had great influence on the δ15N values (Table 4).

**4. Discussion**

The results revealed that although all the biochar-compost applications tended to promote plant growth when compared with compost application alone, significant difference was observed only with DMBC450- and DMBC600-compost applications. It indicates that hypothesis #1 is conditionally supported. Moreover, the diversity of biochar caused a difference in the extent of plant growth, indicating that hypothesis #2 is proven.

Nitrogen analyses in this study supported the fact that the increase in biomass production at biochar-compost application is caused by more nitrogen supply to the plant. An explanation for this would be the enhanced nitrogen availability of compost by the biochar addition. Biochar can enhance microbial activity by providing suitable habitats for microorganisms such as porous structures and easily degradable carbon (Hamer et al. 2004; Jaafaret al. 2015; Mašeket al. 2013), resulting in promoting the mineralization of soil organic matter (Hameret al. 2004; Zimmermanet al. 2011). Furthermore, recent studies observed that biochar application increases nutrient contents in the soil due to improved soil porosity and water-holding capacity (Batista et al. 2018; Sun and Lu 2014). Therefore, the biochar-compost application is believed to accelerate the mineralization of organic matter in compost by enhancing microbial activity, resulting in increased nitrogen release from compost.

It is also noteworthy that the oat plants used nitrogen from the atmosphere, as demonstrated in the isotope analysis (Fig. 4). Considering rhizobacteria and diazotrophic endophytes are involved in nitrogen fixation in gramineous plants (Elbeltagy et al. 2001; Soares et al. 2006), it is strongly suggested that the addition of biochar could enhance their activities. Indeed, the combined application of biochar from grapevine twigs and plant growth-promoting rhizobacteria (PGPR) significantly increases the shoot and root length of maize (*Zea mays* L.) (Ahmad et al. 2015). Moreover, the application of biochar-compost with PGPR (*Pseudomonas fluorescens*) inoculation is capable of mitigating water stress and can enhance cucumber growth (Nadeem et al. 2017). Both this study and previous studies suggest that the application of biochar-compost enables plants to utilize nitrogen from the atmosphere because of the enhanced activity of rhizobacteria and/or diazotrophic endophytes, thereby increasing biomass production. It is interesting to understand whether biochar is beneficial to either endophytes, rhizobacteria, or both. Note that the effects of water stress mitigation by biochar addition on plant growth remains unclear because all treatments received sufficient water.

 We then explored the effects of biochar type (feedstock type and carbonization temperature) on plant growth. The interaction between feedstock type and carbonization temperature had no significant effect on the response variables (Table 4), which allows us to consider the effects of each factor independently.

 The present study revealed that the type of biochar feedstock had a substantial impact on biomass production: the DMBC-compost application significantly enhanced oat growth due to the higher nitrogen supply compared with the WDBC-compost application. The results strongly suggest that DMBC enhances microbial activity and promotes the mineralization of compost more than WDBC. A possible explanation for this finding is the more favorable physicochemical characteristics of DMBC for microbial activity. DMBC is rich in minerals, including P, K, Ca, Mg, and Na, which are essential for microbial and plant growth. Moreover, the abundance of minerals increases the pH of DMBC (8.89–10.61), and a higher pH tends to increase microbial abundance, whereas a lower pH tends to decrease it (Lehmann et al. 2011). In addition, carbon mineralization in biochar depends on feedstock types such as woods and grasses, and the carbon in manure-based biochar mineralizes faster than that in plant-based biochar (Singh et al. 2012; Zimmerman et al. 2011). Thus, the favorable chemical characteristics of DMBC for microbial activity, such as a high pH and a more decomposable portion (labile-C), enable a faster release of available nitrogen from compost. It should also be noted that the DMBC application promoted nitrogen fixation compared with the WDBC application possibly due to the favorable chemical characteristics of DMBC for PGPRs, although further research is required to support this claim. Another possible explanation could be that the oat plants absorbed nitrogen from DMBC itself. Because DMBC contains much more nitrogen than WDBC (Table 2), the nitrogen could also be utilized for plant growth. This suggestion could be supported by previous studies concluding that biochar made from animal manures can act as both soil amendment and an organic fertilizer supplying nitrogen (Chan et al. 2008; Subedi et al. 2016), although the availability of nitrogen contained in DMBC was not measured in the present study.

 In contrast to the feedstock type, carbonization temperature had no significant impact on biomass production, nitrogen uptake, and δ15N value (Table 4). In a pot experiment examining the effects of the application of biochar and chemical fertilizer on corn growth, differences in feedstock type caused eight times more variation in growth than carbonization temperature (Rajkovich et al. 2012). These results indicate that feedstock type is a more dominant factor than carbonization temperature in influencing plant growth. However, it should be noted that the highest nitrogen content was observed for WDBC600 and DMBC600 (Fig. 3). Because biochar produced at higher temperatures is favored over improvements to soil water-holding capacity (Gray et al. 2014; Kinney et al. 2012) and nitrogen retention (Zheng et al. 2013), these aspects may contribute to the highest nitrogen content. Although, the plant nitrogen content peaked at 600°C, oat growth was most enhanced at 450°C. Interestingly, it has also been observed that, on average, corn growth was the highest when various types of biochar produced at a temperature of 500°C were used rather than biochar produced at 300°C, 400°C, 500°C, and 600°C (Rajkovich et al. 2012), and sewage sludge biochar produced at 450°C was the most suitable for garlic cultivation among biochar produced at 400°C, 450°C, 500°C, and 550°C (Song et al. 2014). These results suggest that an optimal carbonization temperature for plant growth is approximately 450°C–500°C. This finding may be explained by the physical and chemical aspects of biochar. In terms of physical aspects, higher temperatures are preferable to improve physical properties, such as porosity, due to the developed porous structure of biochar. Meanwhile, in terms of chemical aspects, higher temperatures may have a negative impact on microbes because biochar becomes more recalcitrant to biological degradation (less labile-C and -N) and more toxic due to polycyclic aromatic hydrocarbons in its chemical structure (Buss et al. 2016). Accordingly, the conflicting effects may generate an optimal carbonization temperature.

 This study showed a possible solution to overcome the disadvantage of dairy manure compost, which is low capacity of nitrogen supply. However, further research is necessary to fully implement this technology in agricultural procedures. Additional cultivation experiments with different conditions of soil, compost, targeting nutrient, and time period are needed. For example, phosphorus availability in organic amendments and biochar application varied with soil and manure types, and the biochar’s ability to phosphorus sorption was highly influenced by soil acidity (Ara et al. 2018; Xu et al. 2014).Further, some recent studies have reported that the impact of biochar application on soil properties and plant growth in long-term cultivation sometimes differ from the impact observed after short-term use (Huang et al. 2018; Oladele 2019). These studies suggest that the proposed coapplication method may also be affected by such conditions, and further examinations would be necessary before applying the coapplication technology on site.

**5. Conclusions**

This study showed that biochar-compost application tends to promote plant growth when compared with compost application alone, and that manure-biochar at 450°C and 600°C increases plant growth significantly. The positive impact would be due to increased mineralization of compost and nitrogen fixation through rhizobacteria and/or diazotrophic endophytes. We also found that the extent of plant growth is affected by diversity of biochar, such as feedstock type and carbonization temperature, and feedstock type is a more dominant factor than carbonization temperature. Manure biochar is a more suitable biochar because it has favorable chemical properties that enhance microbial activity more than wood biochar and could serve as a nitrogen source. The study demonstrated that the difference consensus on the effectiveness of biochar-compost application on plant growth is due to a diversity of biochar, and the selection of appropriate biochar is critical to establish the proposed technology.

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Table 1. Experimental setup: treatment, application rate of compost, wood biochar (WDBC), and dairy manure biochar (DMBC), and total nitrogen input per application.

|  |  |  |  |
| --- | --- | --- | --- |
| Experimental treatment | Compost | Biochar (BC) | Nitrogen input |
| WD | DM |
| (g-wet pot−1) | (g-dry pot−1) | (mg-dry pot−1) |
| I. Compost | 48.7 |  |  | 356.2 |
| II. Compost + WDBC (300°C) | 48.7 | 7.2 |  | 356.2 |
| III. Compost + WDBC (450°C) | 48.7 | 7.2 |  | 356.2 |
| IV. Compost + WDBC (600°C) | 48.7 | 7.2 |  | 356.2 |
| V. Compost + DMBC (300°C) | 24.3 |  | 6.9 | 353.3 |
| VI. Compost + DMBC (450°C) | 24.3 |  | 7.7 | 351.0 |
| VII. Compost + DMBC (600°C) | 24.3 |  | 9.2 | 348.5 |

WD: Wood

WDBC: Wood biochar

DM: Dairy manure

DMBC: Dairy manure biochar

a: Carbonization temperature of biochar in parentheses

Table 2. Physical and chemical properties of biomass feedstocks and biochar

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Biomass feedstocks | Temperature | pH | Ash | Elemental composition | C/N | SSA | APS |
| C | N | P | K | Ca | Mg | Na |
| °C |  | % | g kg−1 dry-basis |  | m2 g−1 | nm |
| Wood | Raw | 4.46± 0.02 a | 0.02± 0.01 | 499.4± 2.5 | n.d. | 0.11± 0.03 | 0.22± 0.05 | 0.54± 0.03 | 0.07± 0.01 | 0.04± 0.06 | - | 4.5± 2.5 | 8.2± 3.7 |
| 300 | 4.77± 0.01 | 0.05± 0.04 | 584.4± 2.5 | n.d. | 0.10± 0.02 | 0.30± 0.09 | 0.60± 0.07 | 0.04± 0.03 | 0.05± 0.05 | - | 3.6± 0.9 | 9.8± 2.4 |
| 450 | 4.63± 0.03 | 0.23± 0.02 | 721.0± 5.5 | n.d. | 0.10± 0.02 | 0.41± 0.04 | 1.10± 0.18 | 0.11± 0.02 | 0.13± 0.04 | - | 139.8± 30.7 | 2.2± 0.0 |
| 600 | 5.34± 0.01 | 0.24± 0.03 | 806.9± 5.8 | n.d. | 0.11± 0.05 | 0.55± 0.03 | 1.33± 0.10 | 0.14± 0.04 | 0.17± 0.06 | - | 532.7± 2.6 | 2.0± 0.0 |
| Dairy manure | Raw | 8.30± 0.01 | 17.81± 0.17 | 414.3± 7.1 | 19.1± 1.3 | 8.51± 0.47 | 22.24± 1.41 | 10.22± 0.08 | 4.49± 0.07 | 8.02± 0.35 | 25.4± 2.3 | 3.5± 0.8 | 14.1± 3.2 |
| 300 | 8.89± 0.06 | 29.42± 0.12 | 481.8± 5.7 | 25.5± 0.1 | 13.07± 0.98 | 34.18± 2.41 | 16.12± 0.71 | 7.12± 0.38 | 12.37± 0.65 | 22.0± 0.3 | 3.4± 0.2 | 12.6± 1.2 |
| 450 | 10.10± 0.01 | 40.97± 1.05 | 492.6± 32.5 | 22.4± 0.2 | 16.33± 0.34 | 43.74± 3.44 | 20.92± 0.48 | 9.17± 0.17 | 15.73± 0.74 | 25.7± 2.0 | 5.7± 0.2 | 14.5± 0.8 |
| 600 | 10.61± 0.01 | 46.07± 0.25 | 506.6± 31.8 | 18.6± 0.3 | 18.00± 0.49 | 48.28± 2.64 | 23.34± 0.47 | 9.77± 0.22 | 17.83± 0.38 | 31.8± 1.5 | 171.5± 5.0 | 2.8± 0.1 |

n.d.: not detected

SSA: Specific surface area

APS: Average pore size

a The numerical values represent mean ± standard deviation (n = 3)

Table 3. Summary of Dunnett’s test on between each biochar-compost treatment and compost alone (control)

|  |  |
| --- | --- |
| Treatment | Response variables |
|  | *Biomass production* | *Nitrogen uptake* | *Nitrogen content* | *δ15N value of plant* |
| Compost + WDBC (300°C)a | *p* = 0.800 | *p* = 0.368 | *p* = 0.616 | ***p* < 0.001** |
| Compost + WDBC (450°C) | *p* = 0.392 | *p* = 0.143 | *p* = 0.425 | ***p* < 0.001** |
| Compost + WDBC (600°C) | *p* = 0.971 | *p* = 0.070 | ***p* = 0.001** | ***p* < 0.001** |
| Compost + DMBC (300°C) | *p* = 0.252 | ***p* = 0.003** | ***p* = 0.010** | ***p* < 0.001** |
| Compost + DMBC (450°C) | ***p* = 0.021** | ***p* *<* 0.001** | ***p* = 0.013** | ***p* < 0.001** |
| Compost + DMBC (600°C) | ***p* = 0.039** | ***p* <0.001** | ***p* <0.001** | ***p* < 0.001** |

WDBC: Wood biochar

DMBC: Dairy manure biochar

a: Carbonization temperature of biochar in parentheses

*p*-values in boldface are statistically significant

Table 4. Summary of the two-way analysis of variance test on biomass production, nitrogen uptake, nitrogen content, and δ15N of plant

|  |  |
| --- | --- |
| Factor | Response variables |
|  | *Biomass production* | *Nitrogen uptake* | *Nitrogen content* | *δ15N value of plant* |
| Feedstock type | ***p* = 0.016** | ***p* <0.001** | ***p* = 0.002** | ***p* <0.001** |
| Carbonization temperature | *p* = 0.445 | *p* = 0.098 | ***p* <0.001** | *p* = 0.388 |
| Feedstock type × Carbonization temperature | *p* = 0.658 | *p* = 0.574 | *p* = 0.906 | *p* = 0.351 |

*p*-values in boldface are statistically significant

**Figure captions**

**Fig.** **1** Biomass production of oat plants in WDBC- and DMBC-compost treatments. Control is compost application alone. Data express mean ± standard error (n = 5). WDBC and DMBC represent wood biochar and dairy manure biochar, respectively

**Fig. 2** Nitrogen uptake of the above-ground part of oat plants in WDBC- and DMBC-compost treatments. Control is compost application alone. Data express mean ± standard error (n = 5). WDBC and DMBC represent wood biochar and dairy manure biochar, respectively

**Fig. 3** Nitrogen content of above-ground part of oat plant in WDBC- and DMBC-compost treatments. Control is compost application alone. Data express mean ± standard error (n = 5). WDBC and DMBC represent wood biochar and dairy manure biochar, respectively

**Fig. 4** δ15N value of above-ground part of oat plant WDBC- and DMBC-compost treatments. Control is compost application alone. Data express mean ± standard error (n = 5). WDBC and DMBC represent wood biochar and dairy manure biochar, respectively. Gray area indicates the δ15N value of red soil, dairy manure biochar, and compost

Fig. 1



Fig. 2



Fig. 3



Fig. 4

