REVIEW
Biochar Amendment of Soils According to their Physicochemical Properties

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Abstract

In this work, we reviewed the following: 1) the influences of feedstocks and pyrolysis temperature on the physicochemical properties of biochar as a soil amendment material in Japan; and 2) the effects of biochar application on the physicochemical properties of two Japanese soils. We analyzed the physico-chemical properties of biochar produced from waste woodchips (Japanese cedar and Japanese cypress), waste moso bamboo chips, rice husk, sugarcane bagasse, poultry manure, and domestic wastewater sludge at pyrolysis temperatures of 400°C, 600°C, and 800°C. Biochar produced from both wood-based biomass and sugarcane bagasse are suitable as a soil amendment material for enhancing water retention in soil. Biochar produced from wood-based biomass at a low pyrolysis temperature (400°C) is suitable for enhancing the cation exchange capacity, whereas biochar produced from wood-based biomass at a high pyrolysis temperature (800°C) can enhance nitrate adsorption. Poultry manure-derived biochar can improve the soil pH and supply phosphate. Based on two case studies using sand dune soil and calcare-ous soil, we demonstrated that soils can be effectively improved by considering specific soil properties that require improvement/remediation, and by applying a suitable biochar to enhance these properties.

Introduction

Biochar is an organic carbon byproduct that is generated during the pyrolysis of waste biomass in the absence of oxygen. Because biochar is highly resistant to microbial decomposition in soils (Baldock and Smernik 2002), its storage in the soil is a promising approach to carbon sequestration (Glaser et al. 2009, Lehmann, 2007). In addition, biochar incorporation can enhance crop produc-tion by improving the physicochemical properties of soil (Sohi et al. 2010). Therefore, it is attracting great attention as a method for carbon sequestration and soil improvement to enhance crop production (Fig. 1).

It should be noted that biochar incorporation in agricultural soils does not always translate into higher crop yields (Spokas et al. 2012) because the physicochemical properties of biochar differ according to the feedstock type and pyrolysis conditions (Chia et al. 2015); thus, not all biochars are the same. The ameliorating effects of biochar also depend on its physicochemical properties. Moreover, the physicochemical properties that require remediation/im-provement differ in each soil. Therefore, the feedstock types and pyrolysis temperatures should be selected to obtain a biochar tailored to improve specific soil properties (Fig. 2).

Understanding how feedstock selection and pyrolysis conditions influence the physicochemical properties and elemental compositions of biochar is crucial for designing selective biochars to remediate/improve specific soil properties (Novak et al. 2014). However, the effects of feedstocks and pyrolysis temperature on the physicochemi-cal properties and elemental compositions of biochar have not been systematically reviewed in Japan.

We have therefore reviewed the following: 1) the influences of feedstocks and pyrolysis temperature on the physicochemical properties of biochar in Japan; and 2) the effects of biochar application on specific physicochemical properties of two Japanese soils.
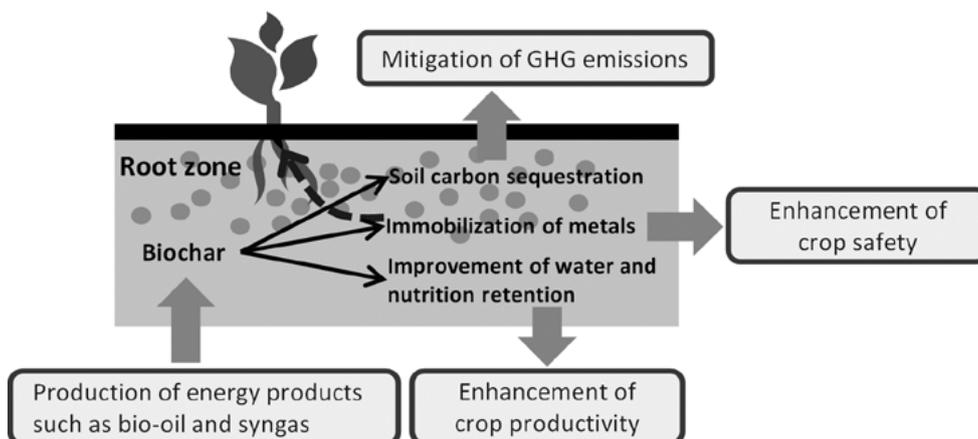
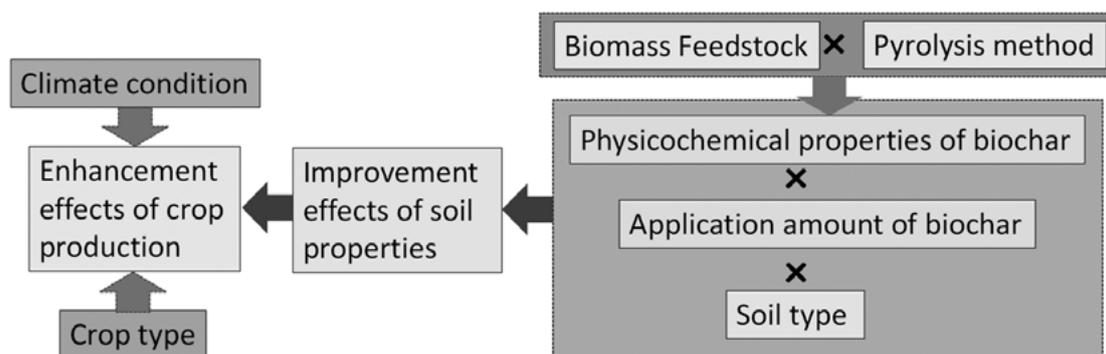Fig. 1. Effects of biochar as a soil amendment

Fig. 2. Conceptual diagram showing the effects of biochar application on soil properties and crop production

Biochar production and characterization

1. Biochar production

To analyze the physicochemical properties of biochar, samples were produced from seven different feedstocks at three different pyrolysis temperatures (400°C, 600°C, and 800°C). The range of pyrolysis temperatures is generally used for making commercial products of biochar derived from wood-based biomass and poultry manure in Japan. The feedstocks used were waste woodchips (Japanese cedar (CE) and Japanese cypress (CY)), waste moso bamboo chips (MB), rice husk (RH), sugarcane bagasse (SB), poultry manure (PM), and domestic wastewater sludge (WS). These feedstocks are commonly produced in rural areas of Japan. CE, CY, and MB were categorized as wood-based biomass. RH and SB were categorized as crop residues. PM was categorized as livestock manure. WS was categorized as wastewater sludge (NEDO, 2014). The biomass feedstocks were air-dried and heated in a batch-type carbonization furnace (MB-202020-AC, Koyo

Thermo Systems Co., Ltd., Japan) at pyrolysis temperatures of 400°C, 600°C and 800°C, with a hold time of 2 h.

2. Biochar yields and compositions

Figure 3 shows the biochar yields and compositions produced from seven different feedstocks at three different pyrolysis temperatures. The biochar yields were influenced by the feedstock and pyrolysis temperature. The RH-, PM-, and WS-derived biochar yields (39-59%, 47-68% and 43-54%, respectively) were higher than those (22-41%, 23-39%, 25-39% and 19-28%, respectively) from the CE-, CY-, MB-, and SB-derived biochars (Fig. 3 (a)), which may have been due to the higher ash content of RH, PM, and WS (Fig. 3 (c)) (Windeatt et al. 2014). Moreover, the biochar yields decreased sharply as the pyrolysis temperature increased from 400°C to 800°C for all feedstocks (Fig. 3 (a)).

The biochar compositions were also affected by the feedstock and pyrolysis temperature. As the pyrolysis temperature increased, the volatile matter content decreased and the ash content increased for all feedstocks (Fig. 3 (b)

(a) Biochar yield

(b) Volatile matter

(c) Ash content

(d) Carbon content

(e) Hydrogen content

(f) Nitrogen content
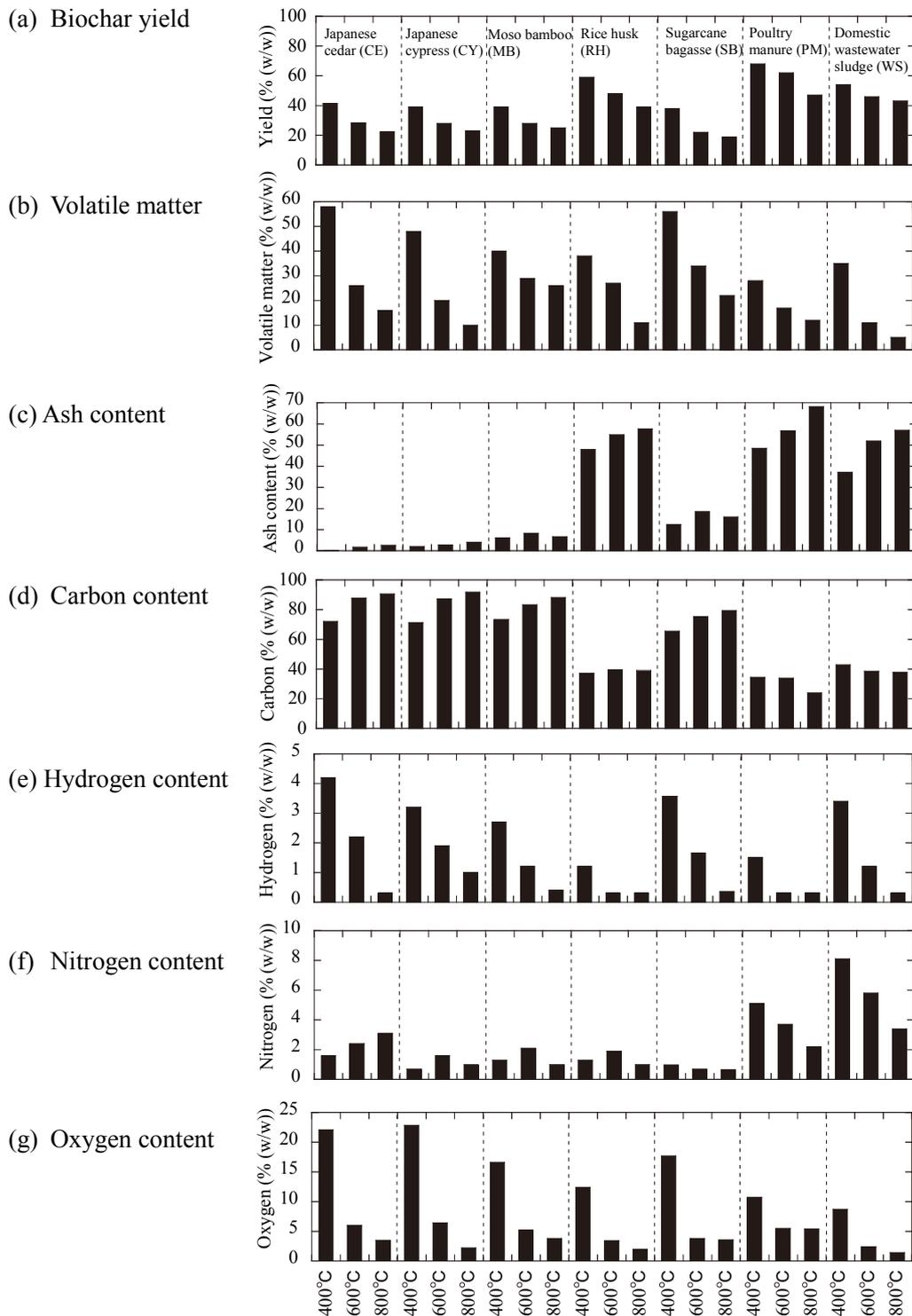
(g) Oxygen content

Fig. 3. Biochar yields and elemental compositions of biochars produced from seven different biomass feedstocks at three different pyrolysis temperatures

and (c)). The nitrogen content, hydrogen content, and oxygen content all decreased with higher pyrolysis temperature, whereas the carbon content increased (Fig. 3 (d), (e), (f), and (g)). These results are similar to those previously reported (Ahmed et al. 2016, Enders et al. 2012, Ronsse et al. 2013, Suliman et al. 2016). Among the feedstocks, the CE-, CY-, MB-, and SB-derived biochars contained higher concentrations of carbon, especially at higher temperatures

(Fig. 3 (d)). The carbon content of the RH-, PM-, and WS-derived biochars was lower than that of the CE-, CY-, MB-, and SB-derived biochars (Fig. 3 (d)), which may have been due to the high ash contents of these feedstocks (Fig. 3 (c)) (Enders et al. 2012, Windeatt et al. 2014).

3. Chemical properties of biochars

Figure 4 shows the chemical properties of biochars produced from seven different biomass feedstocks at three different pyrolysis temperatures. The pH and electrical conductivity (EC) of biochar were measured in 1 g:25 mL biochar:water suspensions. The pH in water of the biochars except for the CY-, RH- and SB-derived biochars formed at 400°C was alkaline (7.3-12.2) (Fig. 4 (a)). It increased with higher pyrolysis temperature. Similarly, EC, which is used to indicate the total water-soluble ions in biochar, also increased with higher pyrolysis temperature (Fig. 4 (b)), but varied very widely among the feedstocks. The increase in pH was due mainly to the release of some basic elements as the pyrolysis temperature increased (Rehrah et al. 2016). Therefore, the pH and EC of biochar are correlated for all feedstocks ($r = 0.7$) (Fig. 4 (a) and (b)). A biochar with high EC might affect the growth of crops (Matsumaru and Singyoji, 2005) as the recommended EC for animal manure is less than 5 mS cm^{-1} (Yukishigenka-suishinkaigi, 1997). Therefore, inhibited crop growth must be considered when utilizing a PM-derived biochar with high EC (Fig. 4 (b)).

The cation exchangeable capacity (CEC) is the total capacity of a biochar to adsorb and exchange positively charged species (Carrier et al. 2012). The CEC of biochar decreased sharply as the pyrolysis temperature increased from 400°C to 600°C (Fig. 4 (c)). The decreases in CEC were consistent with the results published by Mukherjee et al. (2011). These decreases could be partly explained by reductions in the contents of oxygenated functional groups on the biochar surface (Suliman et al. 2016). The higher oxygen content of biochar formed at 400°C might indicate the presence of more oxygenated functional groups (Fig. 3 (g)). The CEC of the CE-, CY-, MB-, and RH-derived biochars exceeded that of the SB-, PM-, and WS-derived biochars (Fig. 4 (c)).

4. Physical properties of biochar

Figure 5 shows the physical properties of biochars produced from seven different biomass feedstocks at three different pyrolysis temperatures. The particle density in each biochar was measured by the gas displacement method using helium. The pore volumes in the biochar were measured by mercury intrusion porosimetry. The particle density in each biochar increased with higher pyrolysis temperature (Fig. 5 (a)). In contrast to the particle density, the total pore volume did not have a linear relationship with the pyrolysis temperature (Fig. 5 (b)). Moreover, the total pore volumes in biochars derived from MB, RH, PM, and WS were relatively low.

Pore volumes corresponding to an equivalent pore diameter for the available water capacity (0.2-9 µm) can be an important index for improving the water retention
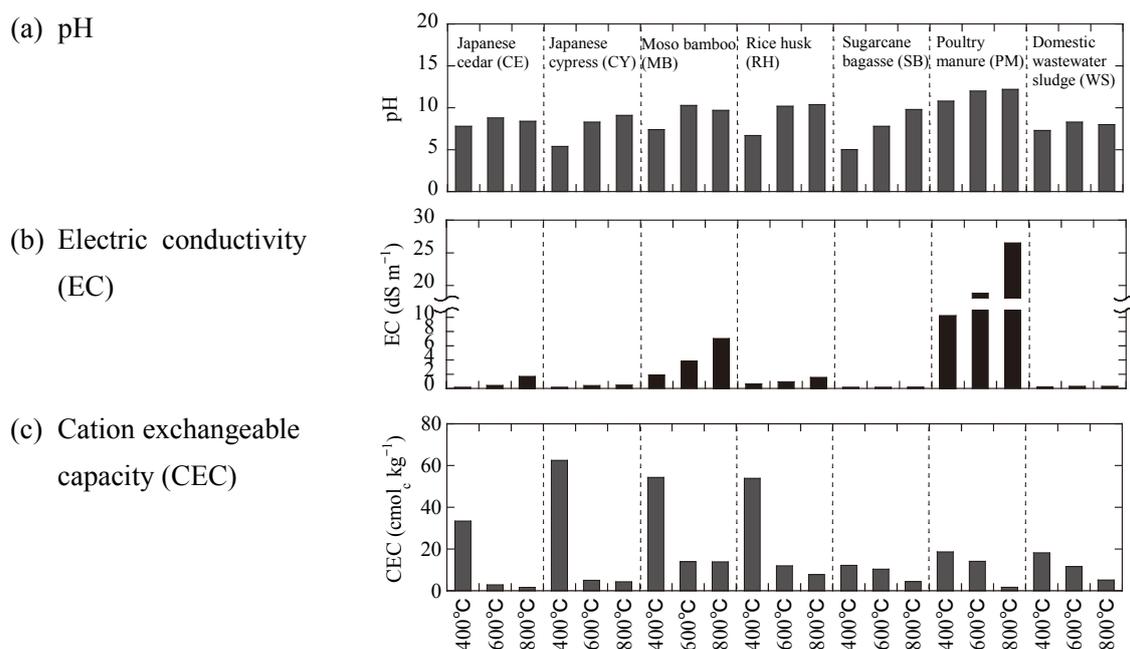

Fig. 4. Chemical properties of biochars produced from seven different biomass feedstocks at three different pyrolysis temperatures

properties of agricultural soils (Kameyama et al. 2016c). The pore volume corresponding to the available water capacity of the SB-derived biochar was the highest, whereas the pore volume of the WS-derived biochar was the lowest (Fig. 5 (c)). Thus, the SB-derived biochar may be suitable as a soil amendment material for enhancing the available water capacity. The pore volumes of biochars derived from wood-based biomass (CE, CY, and MB) at 400°C and 600°C were also similar (Fig. 5 (c)). However, the pore volumes of biochar produced from CE and CY at 800°C exceeded than that obtained from MB at 800°C (Fig. 5 (c)).

5. Fertilizer component of biochar

Figure 6 shows the fertilizer contents of biochars produced from various biomass feedstocks at three different pyrolysis temperatures. All of the biochars contained nitrogen, phosphorus, and potassium (Fig. 3 (f), Fig. 6 (a) and (b)). However, the nitrogen content of biochar is known to be generally unavailable to crops, whereas the phosphorus content and potassium content of biochar are available to crops (Maki et al. 2005, Maki et al. 2009, Tanikawa and Seitou 2014). And pyrolysis substantially reduces the nitrogen degradability of the biomass feedstocks in soils (Maki et al. 2009). Thus, the nitrogen content of biochar

does not comprise an effective fertilizer.

The phosphorus content and potassium content of biochar are also influenced by the feedstock and pyrolysis temperature (Fig. 6 (a) and (b)). The phosphorus content of biochars produced from PM and WS exceeded the levels obtained from the other feedstocks (Fig. 6 (a)). And the potassium content of biochars produced from MB and PM exceeded the levels obtained from the other feedstocks (Fig. 6 (b)). These levels were dependent on the contents of the feedstocks (Nagumo et al. 2014). Both the phosphorus content and potassium content of biochar increased with higher pyrolysis temperature (Fig. 6 (a) and (b)).

The availability of phosphorus in biochar is related to the feedstock employed. Thus, the available phosphorus content of the WS-derived biochar was lower than that of the PM-derived biochar (Fig. 6 (c)), although both biochars had a similar phosphorus content (Fig. 6 (a)). This demonstrates that most of the phosphorus found in the WS-derived biochar is not available to crops, as shown by Yauchi et al. (2014). In contrast, most of the phosphorus found in the PM-derived biochar would be available to crops. However, the available phosphorus content of the PM-derived biochar exhibited a slow-acting property rather than a fast-acting one (Tanikawa and Seitou 2014, Wang et al. 2015).
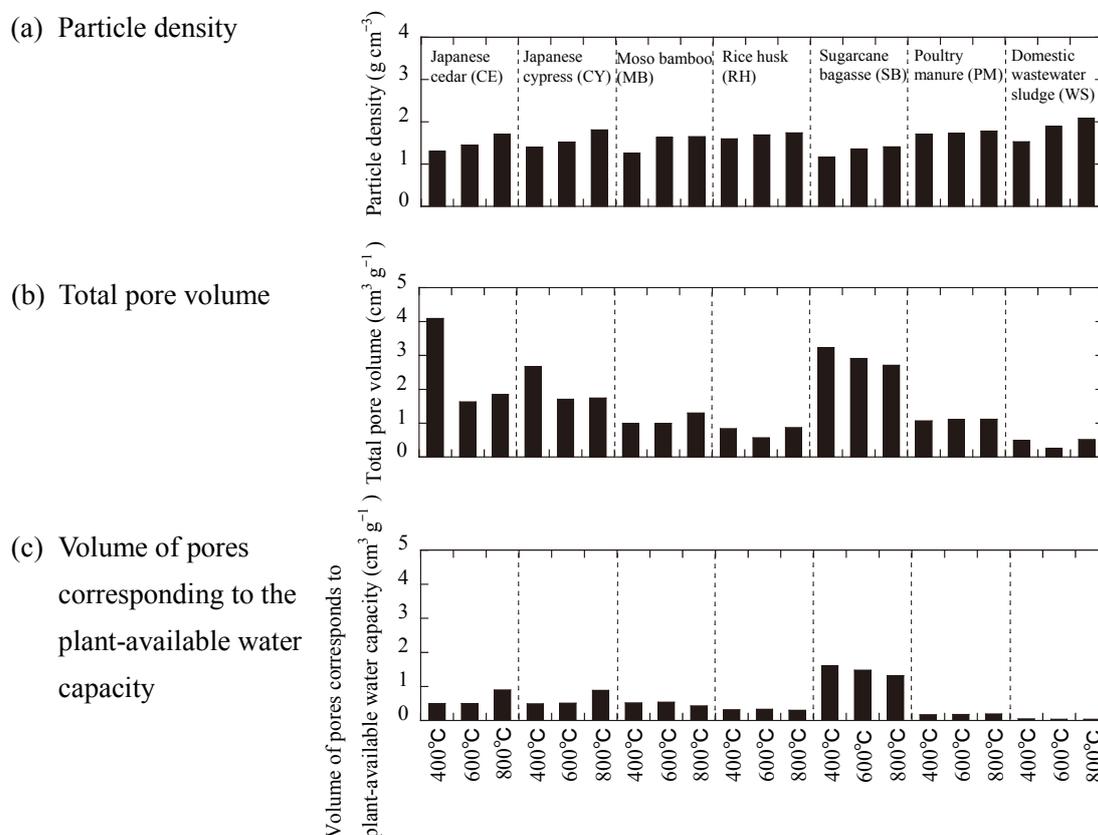

Fig. 5. Physical properties of biochars produced from seven different biomass feedstocks at three different pyrolysis temperatures

6. Heavy metal contents of biochar

Figure 7 shows the heavy metal contents of biochar produced from various biomass feedstocks at three different pyrolysis temperatures. The allowable upper limits for heavy metal contents in sludge fertilizers and animal manure fertilizers are regulated by the Fertilizers Regulation Act in Japan. The heavy metals present in the feedstock are mostly retained and concentrated in the biochar product as a non-volatile mineral ash component. Therefore, it is necessary to carefully select and analyze the feedstock to avoid contaminating the biochar with high levels of heavy metals.

The contents of most of the heavy metals (Hg, Ni, Cr, and Pb) in biochar increased with higher pyrolysis temperature (Fig. 7 (c), (d), (e), and (f)), which might be explained by the concentration of heavy metals with increasing pyrolysis temperature. The Cd content of the WS-derived biochar decreased sharply as the pyrolysis temperature increased from 600°C to 800°C (Fig. 7 (b)). The boiling points of As and Cd are 613°C and 766.8°C, respectively, and thus lower than those of other heavy metals. Therefore, the Cd content of the WS-derived biochar might have been volatilized at a high pyrolysis temperature (e.g., 800°C). However, a clear trend was not detected in the As content of biochar (Fig. 7 (a)).

7. Nitrate adsorption capacity of biochar

The nitrate adsorption capacity of biochar depends on the pyrolysis temperature (Fig. 8) (Kameyama et al. 2016a). Among the biochars produced from each feedstock, those produced at 800°C had the highest nitrate adsorption rates. The amount of nitrate adsorption by the biochar produced from wood-based biomass (CE, CY, and MB) at 800°C was significantly higher than that by the biochar produced from non-wood-based biomass (RH, SB, PM, and WS) at 800°C. Therefore, biochar made from wood-based biomass at higher temperatures can be employed as a soil amendment material to enhance nitrate adsorption.

8. Recommended biochar for improving specific soil properties

Understanding how the feedstock selection and pyrolysis conditions influence the physicochemical properties and elemental compositions of biochar is crucial for the design of selective biochars to remediate/improve specific soil qualities (Novak et al. 2014). Based on physicochemical properties of biochars made from seven different feedstocks and three different pyrolysis temperature, Table 1 indicates the suitability of these biochars for improving specific soil properties. For example, biochars produced from wood-based biomass (CE, CY, and MB) have a highly porous

(a) Phosphorus content

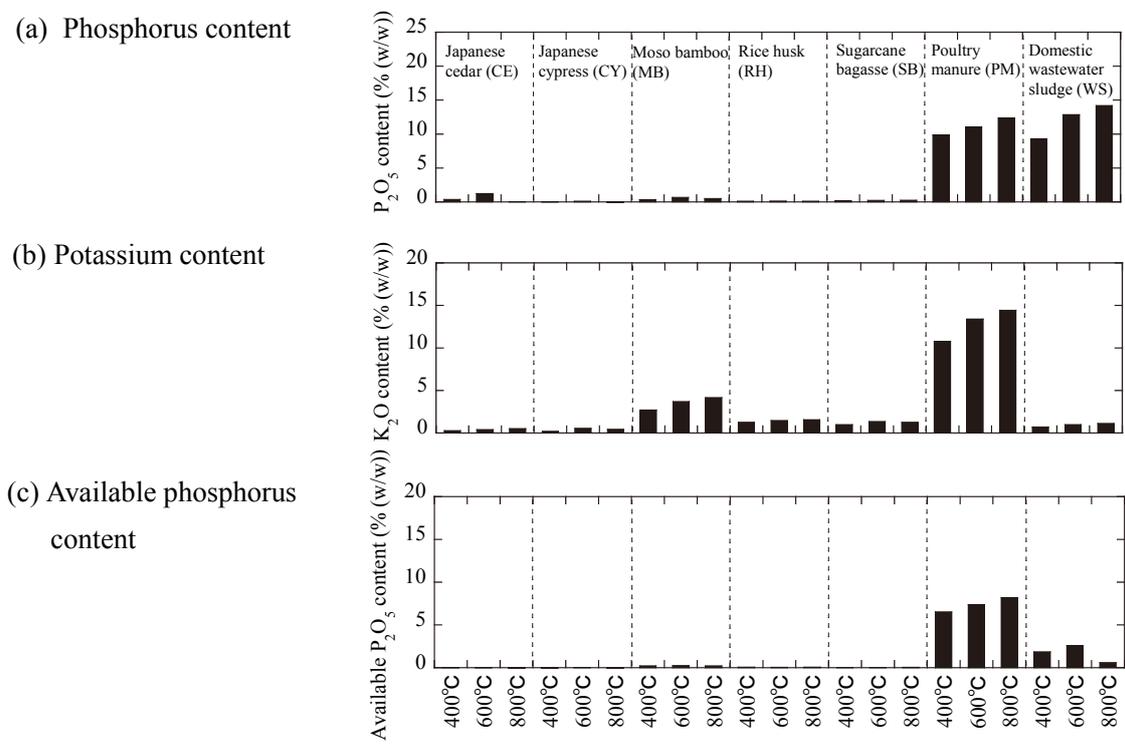(b) Potassium content

(c) Available phosphorus content

Fig. 6. Fertilizer contents of biochars produced from seven different biomass feedstocks at three different pyrolysis temperatures

structure and are suitable as soil amendment materials for enhancing water retention. The biochars produced from wood-based biomass at low temperatures (400°C) are suitable as a soil amendment material to enhance the CEC, whereas biochars produced from wood-based biomass at high temperatures (800°C) can be employed as a soil amendment material for enhancing nitrate adsorption.

The feedstock is another important parameter that influences the characteristics of a biochar. Thus, the biochar produced from RH at a low temperature (400°C) can be used as a soil amendment material to enhance

the soil CEC, whereas the biochar produced from RH at a high temperature (600-800°C) may be a suitable soil amendment material for improving the soil pH. The biochar produced from SB had a highly porous structure and could be employed as a soil amendment material for enhancing water retention. The biochar produced from PM may be an adequate soil amendment material for enhancing the soil pH and supplying phosphate. The biochar produced from WS at a low temperature (400-600°C) can be used as a soil amendment material to supply phosphate.
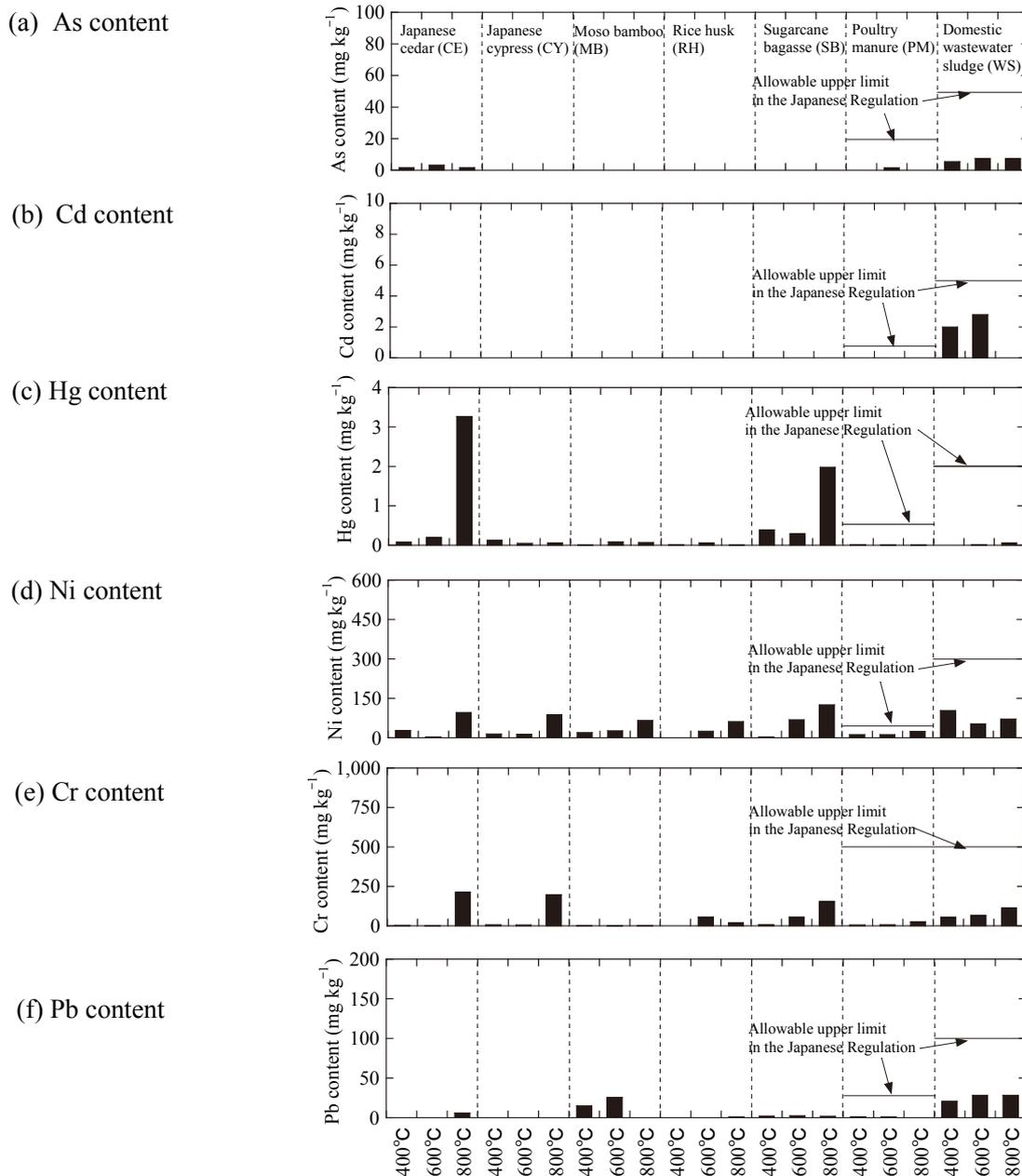

Fig. 7. Heavy metal contents of biochars produced from seven different biomass feedstocks at three different pyrolysis temperatures

Biochar application to Japanese agricultural soils

1. Application of wood-based biomass-derived biochar to sand dune soil

Sand dune soils generally have low water and nutrient retention capacities. Therefore, the leaching of fertilizer components from crop root zones by precipitation and ir-

rigation can be a serious problem in the Sanrihama area, Fukui Prefecture, Japan. To solve this problem, we analyzed regional biomass resources and found that the biochar produced from wood-based biomass at a lower pyrolysis temperature was suitable for application in sand dune soil to enhance its water and nutrient retention capacities (Iwata et al. 2014). The biochar had high water and nutrient retention

Table 1. Suitability of biochar produced from seven different feedstocks and three different pyrolysis temperatures for improving specific soil properties

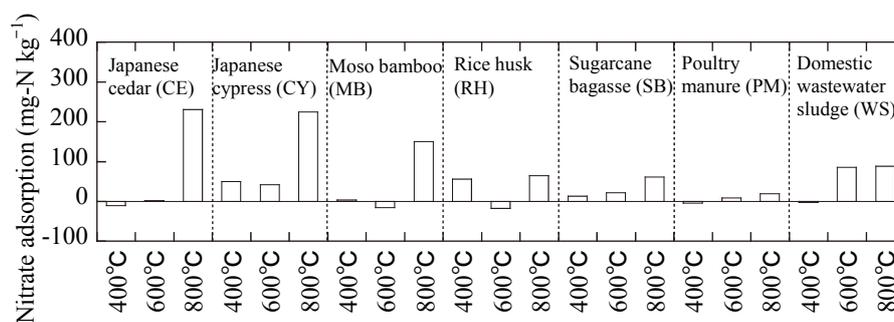| Feedstock	Pyrolysis temperature	Enhancing water retention capacity	Enhancing nutrient retention capacity (CEC)	Neutralization of soil acidity	Supply of phosphorus	Enhancing nitrate retention capacity
Woodchips (CE and CY)	400°C	Suitable	Suitable			
	600°C	Suitable				
	800°C	Suitable				Suitable
Moso bamboo chip (MB)	400°C	Suitable	Suitable			
	600°C	Suitable		Suitable		
	800°C	Suitable		Suitable		Suitable
Rice husk (RH)	400°C		Suitable			
	600°C			Suitable		
	800°C			Suitable		
Sugarcane bagasse (SB)	400°C	Suitable				
	600°C	Suitable				
	800°C	Suitable		Suitable		
Poultry manure (PM)	400°C			Suitable	Suitable	
	600°C			Suitable	Suitable	
	800°C			Suitable	Suitable	
Domestic wastewater sludge (WS)	400°C				Suitable	
	600°C				Suitable	
	800°C					

Fig. 8. Nitrate adsorption by biochars produced from seven different biomass feedstocks at three different pyrolysis temperatures (partially rearranged from Kameyama et al. 2016a)

capacities (Fig. 4 (c), Fig. 5 (c), Table 1). The biochar was applied to the soil at 0 (control), 20, and 40 t-DW ha^{-1} in a field experiment (Kameyama et al. 2016b).

Applying the biochar significantly enhanced the available water capacity of the soil. Compared with the control, the available water capacity increased by 20-30% with 20 t-DW ha^{-1} of biochar and by 50-60% with 40 t-DW ha^{-1} (Fig. 9 (a)). In addition, applying biochar significantly enhanced the CEC of the soil. Compared with the control, the CEC increased by 2-4% with 20 t-DW ha^{-1} and by 8-9% with 40 t-DW ha^{-1} (Fig. 9 (b)). Furthermore, the decrease in soil matric potential in the root zone of small turnips was suppressed by the application of biochar at 40 t-DW ha^{-1}. These results demonstrate the positive effects of applying biochar produced from wood-based biomass at a lower pyrolysis temperature on the water and nutrient retention properties of a sand dune soil.

2. Application of sugarcane bagasse-derived biochar to calcareous soil

Miyako Island is located in the subtropical zone of Japan, where the predominant geological feature is highly permeable coral limestone. In this region, sugarcane is cultivated on more than 80% of the agricultural land and SB is the main biomass resource. The land surface is covered with calcareous soil called "Shimajiri Maji," which is classified as Typic Hapludalfs according to the United States Department of Agriculture (USDA) Soil Taxonomy

(Soil Survey Staff 2010). The soil has a low water retention capacity and high permeability; therefore, fertilizer-derived nitrogen readily leaches from the root zone during rainfall. The leached nitrogen might contaminate the groundwater, which is the main water resource on this island. To address this problem, SB-derived biochar was applied to calcareous soil (calcaric dark red soil) to enhance its water retention capacities and to reduce nitrate leaching (Kameyama et al. 2010, Kameyama et al. 2012, Kameyama et al. 2013, Kameyama et al. 2016c). The biochar had a high water retention capacity (Fig. 5 (c), Table 1).

The application of biochar significantly improved the available water capacity (by over 60%) when applied at more than 3% w/w (about 60 t-DW ha^{-1}) (Kameyama et al. 2016c). In addition, the application of biochar produced from SB at a high pyrolysis temperature (800°C) decreased the nitrate concentration in leached water and reduced nitrate leaching from the soil because of nitrate adsorption by the biochar (Kameyama et al. 2012). Moreover, Chen et al. (2010) showed that the application of SB-derived biochar increased the yield and sugar content of sugarcane, while the nitrate concentration of the leached water decreased due to the high water retention capacity of the biochar according to a lysimeter-based study.

By analyzing the life cycle of CO_2 emissions when SB-derived biochar was applied to sugarcane fields, taking into account the CO_2 emissions due to pyrolysis, transportation and farmland application processes, as well as soil

(a) Water retention capacity
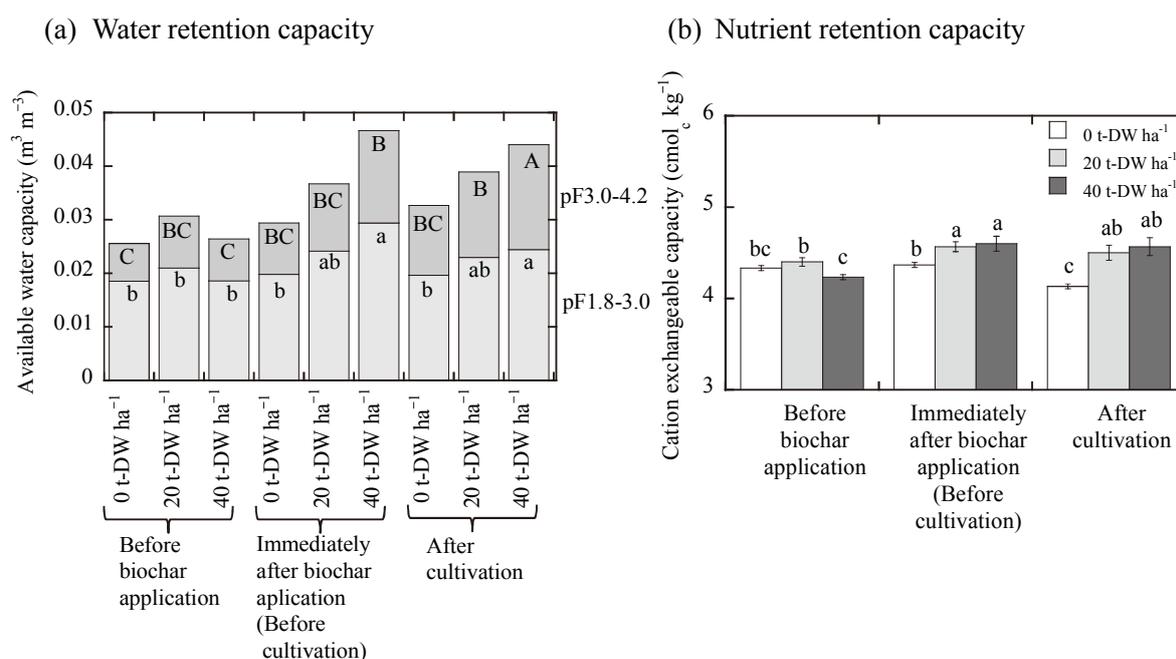
(b) Nutrient retention capacity

Fig. 9. Enhancing effects of (a) water retention capacity and (b) nutrient retention capacity of sand dune soil with application of biochar produced from wood-based biomass at a lower pyrolysis temperature (Mean values with different letters are significantly different at $P < 0.05$; partially rearranged from Kameyama et al. 2016b.)

carbon sequestration, the CO_2 mitigation potential with farmland application of SB-derived biochar was estimated as 0.2-0.3 t-CO_2 t-DW^{-1} feedstock (Kameyama et al. 2010). Thus, based on these studies we conclude that SB-derived biochar is suitable for agricultural use on Miyako Island.

Conclusion

The physicochemical properties of biochar mainly depend on both the feedstock used and the pyrolysis conditions. Because both can vary widely, biochars may have very different properties. Therefore, we should select suitable biochars for use as soil amendment materials by considering their physicochemical properties. In this work, we reviewed the following: 1) the influences of different feedstocks and pyrolysis temperatures on the physicochemical properties of biochars in Japan; and 2) the effects of biochar application on specific physicochemical properties of two Japanese soils. Biochars produced from wood-based biomass (CE, CY, and MB) are suitable as soil amendment materials for enhancing water retention. Similarly, SB-derived biochar can be employed as a soil amendment material for enhancing water retention. Biochar produced from wood-based biomass at a low pyrolysis temperature (400°C) can be used as a soil amendment material for improving the CEC, whereas biochar produced from wood-based biomass at a high pyrolysis temperature (800°C) can be employed as a soil amendment material for enhancing nitrate adsorption. PM-derived biochar is an adequate soil amendment material for enhancing the soil pH and supplying phosphate. Based on two case studies, we demonstrated that soils can be effectively improved by considering specific soil properties that require improvement/remediation, and by applying a suitable biochar to improve these properties.

Acknowledgments

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