# Effects of biochar on physico-chemical properties of soil, nutrient uptakes, water use efficiency, and crop production

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# Effects of biochar on physico-chemical properties of soil, nutrient uptakes, water use efficiency, and crop production

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*A thesis submitted for the degree of*

*Doctor of Philosophy (PhD.)*

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**Anand Mishra**

**2020**

## Declaration

I hereby declare that this submission is my own work in its entirety and that to the best of my knowledge, it contains no material previously published or written by another person nor material to a substantial extend has been accepted for the award of any other degree or diploma of the university of higher learning, except where due acknowledgement has been made in the text.

Anand Mishra Date

I certify that the declaration above by the candidate is true to the best of my knowledge and that this report is acceptable for evaluation for the degree of *Doctor of Philosophy*.

Prof. Yoshiyuki SHINOGI, PhD Date

Prof. Syuntaro HIRADATE, PhD Date

Associate Prof.
Takeo YAMAKAWA, PhD Date

## Abstract

On one hand, the world's population is expected to reach 9 billion by end of 2050. The population growth will require an increase in food supply by more than 50%. On the other hand, activities such as overgrazing, deforestation, industrialization, pollution may cause land degradation which will accelerate the loss of organic matter due to erosion and deterioration of physico-chemical properties of the soil. The climate change, water scarcity, and land degradation may negatively affect food production in future. There will be more extreme weather events, such as droughts and flooding. Therefore, we need to reduce greenhouse gas emissions and increase crop production through some adaptation and mitigation strategies.

Application of organic matter to soil can improve physico-chemical properties and crop production and is considered as one of the adaptation strategy. However, organic matter decomposes quickly into soil and we need to apply it again and again. Therefore, we need to find some stable soil amendment such as biochar which can be used in soil in combination with organic or inorganic fertilizer for sustainable crop production. The properties of biochar applied to soil changes over time due to aging of biochar. Therefore long term residual effects of biochar on crop production needs to be investigated.

Increasing water use efficiency (WUE), growing drought tolerance crop varieties, improving water holding capacity of soil, increasing irrigation efficiency are the possible ways to increase the crop production under drought condition. Biochar is porous in nature and usually have high surface area which helps to increase the water holding capacity of the soil and enhances the crop production.

There are limited studies on effects of rice husk (RH) and rice husk biochar (RHB) on physico-chemical properties of soil and rice production. In addition, the residual effects of application of RH and RHB on komatsuna production are also limited. Furthermore, the effects of biochar application on soybean production under different irrigation regimes have not been studied yet. Therefore, the objectives of this study were to investigate: 1) the comparative effects of RH and RHB application on physico-chemical properties of soil and rice

production 2) the comparative residual effects of RH and RHB application on dry matter yield (DMY), nutrient uptakes, agronomy efficiency (AE), and recovery efficiency (RE) of komatsuna after three years of application into soil, and 3) the effects bamboo biochar application on physico-chemical properties of soil, yield, nutrient uptakes, and WUE of soybean under different irrigation regimes.

We conducted laboratory and greenhouse experiments for achievement of first objective (Chapter 3). RH and RHB were applied at the rates of 2 and 4% (w:w), respectively. Unamended treatment served as control. Rice seedlings were transplanted in pots in the month of May and harvested in September 2014 under greenhouse condition. Soil samples were prepared and analysed for physico-chemical properties. The results indicated that RH and RHB application significantly increased porosity but decreased bulk density. The application of RHB also significantly increased pH of soil. The application of 2% RHB significantly increased the grain yield and DMY of rice by 38.7% and 27.3%, respectively. However, 2% RH did not significantly increase these values compared with control. Our results did not identify any reasons behind an increase in rice yield by the application of 2% RHB. Further studies are needed to clarify the reasons for an increase in rice yield with the application of 2% RHB.

We conducted laboratory and greenhouse experiments for achievement of second objective (Chapter 4). RH was applied at 2% (w:w), whereas RHB was applied at rates of 2 and 4% (w: w), and their effects on rice cultivation were examined in our previous study in 2014 (Chapter 3). In October 2017, three years after the rice cultivation, the soil media were used to see their residual effects on komatsuna cultivation in this study. Komatsuna seeds were sown in pots in a greenhouse and plants were harvested after thirty-five days. Results showed that 2% RHB application significantly increased the DMY by 27.2% and 19.3% compared with those of the control and 2% RH application, respectively. The 2% RHB significantly increased nutrient uptakes, AE, and RE than those of the control. Meanwhile, 2% RH did not significantly increase these values compared with control. We concluded that 2% RHB was more effective than 2% RH in terms of increase in DMY, nutrient uptakes, AE, and RE.

We conducted laboratory and greenhouse experiments for achievement of third objective (Chapter 5). Bamboo biochar (BB) was applied at the rate of 1 and

3% (w:w). Three irrigation treatments were applied to recover the water level to 100%, 80%, and 60% of field capacity (FC), on alternate days. Soybean seeds were sown in pots in a greenhouse and plants were harvested after eighty-seven days. Results showed that 3% BB significantly increased the plant available water content. Bulk density was significantly reduced by 91.4% by 3% BB application. I1B2 (100% FC with 3% BB) increased aboveground biomass yield (AGBY) by 114.0% compared to I1B0 (100% FC without biochar). Whereas, I3B2 (60% FC with 3% BB) increased AGBY only by 108.2% compared to I3B0 (60% FC without biochar). P and K uptakes of I1B2 were significantly increased compared to I1B0. The K uptake was increased by 132.0% at I1B2 compared to I1B0. We concluded that biochar application enhances the physico-chemical properties of soil and 3% BB application significantly increased the AGBY and WUE for AGBY.

From results of our experiments we concluded that the application of RH and RHB improves physico-chemical properties of soil. The 2% RHB application also significantly increased rice yield and DMY; however, 2% RH did not significantly increase these values compared with control. The residual effects of RH and RHB application shows that both 2% RHB and 4% RHB significantly increased the DMY, nutrient uptake, AE, and RE of komatsuna; meanwhile, we do not find any significant increase in above parameters by application of 2% RH. Lastly, the application of BB shows that only 3% of BB significantly increased the physico-chemical properties of soil and increased the AGBY and WUE for AGBY.

Experiments were conducted in the greenhouse condition for only one cropping season. Therefore, further studies are needed, to know the long-term effects of the application of biochar in both the greenhouse and field condition.

**Keywords**: biochar, irrigation regimes, komatsuna production, nutrient uptakes, rice production, soil physico-chemical properties, soybean production, water use efficiency

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Anand Mishra

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## List of Abbreviations and Acronyms

| | |
|---|---|
| ANOVA | Analysis of variance |
| C | Carbon |
| Ca | Calcium |
| CEC | Cation exchange capacity |
| C: N | Carbon nitrogen ratio |
| EC | Electrical conductivity |
| FAO | Food and Agriculture Organization |
| FC | Field capacity |
| FTIR | Fourier Transform Infrared Spectroscopy |
| g | Gram |
| H | Hydrogen |
| ha | Hectare |
| TK | Total potassium |
| TN | Total nitrogen |
| TP | Total phosphorous |
| SOM | Soil organic matter |
| RHB | Rice husk biochar |
| RH | Rice husk |
| BB | Bamboo biochar |
| s | Second |
| BET | Brunauer-Emmett-Teller |
| VWC | Volumetric water content |
| w: w | Weight per weight |
| Exc. K | Exchangeable potassium |
| Exc. Ca | Exchangeable calcium |
| Exc. Na | Exchangeable sodium |

| | |
|---|---|
| Exc. Mg | Exchangeable magnesium |
| Available P | Available phosphorous |
| ASTM | American Society for Testing and Materials |
| $\theta_s$ | Saturated water content |
| $\theta_{fc}$ | Field capacity water content |
| $\theta_{wp}$ | Permanent wilting water content |
| $\theta_a$ | Plant available water content |
| SDGs | Sustainable Development Goals |
| *F* | Porosity |
| *BD* | Bulk density |
| WUE | Water use efficiency |
| SY | Seed yield |
| AGBY | Aboveground biomass yield |
| AE | Agronomy efficiency |
| RE | Recovery efficiency |
| DMY | Dry matter yield |
| NARC | Nepal Agricultural Research Council |

# Chapter 1 Introduction

## 1.1. Research background

On one hand, the world's population is expected to reach 9 billion by end of 2050 (Godfray *et al*., 2010). The population growth will require an increase in food supply by more than 50% (Mueller *et al*., 2012). On the other hand, activities such as overgrazing, deforestation, industrialization, pollution may cause land degradation which will accelerate the loss of organic matter due to erosion and deterioration of physico-chemical properties of soil (Barman *et al*., 2013). The loss of organic matter in soil and deterioration of soil physico-chemical properties will reduce soil fertility (Barman *et al*., 2013). The climate change, water scarcity, and land degradation may negatively affect food production in future (FAO, 2013a; Mehmood *et al*., 2017). The emission of greenhouse gases (GHG) such as, $CO_2$, $CH_4$, $N_2O$ through agricultural activities may accelerate global warming (IPCC, 2013). The global warming will negatively affects agriculture (Gregory *et al*., 2005). In future, there will be more extreme weather events, such as droughts and flooding. Therefore, we need to reduce GHG emissions and increase crop production through some adaptation and mitigation strategies (FAO, 2013a; Gregory *et al*., 2005; Mehmood *et al*., 2017).

Application of organic matter to soil can improve physico-chemical properties of soil and crop production and is considered as one of the adaptation strategy (Lal, 2006; FAO, 2013a). However, the organic matter decomposes quickly into soil and we need to apply it again and again (Lal, 2006). Therefore, we need to find some stable soil amendment such as biochar which can be used in soil in combination with organic or inorganic fertilizer for sustainable crop production.

Biochars is produced through thermal degradation of biomass through the process of pyrolysis and is a promising alternative solution for utilization of residue return to croplands. The application of biochar into soil increases the crop production and mitigates climate change (Glaser *et al*., 2002; Crane-Droesch *et al*., 2013; Mehmood *et al*., 2017).

Downie *et al*. (2009) reported that the physical, chemical, and biological properties of biochar changes over time (due to aging of biochar) when it is applied into soil. Brodowski *et al*. (2007) reported that biochar is broken down into silt size or smaller particles through physical processes, whereas Kuzyakov *et al*. (2009) reported that biochars resist into soils for more than 1000 years. There are two types of aging of biochar: short-term and long-term aging. Short-term aging occurs when fresh biochar is exposed to water immediately after its production (IBI, 2014; Aller, 2017). Long-term aging occurs after biochar subsequent exposure to soil and environmental processes that will alter its properties (Mia *et al*., 2017; Aller, 2017). Although biochar properties changes over time due to aging; however, most of the studies have been done to investigate the effects of fresh biochars on agronomic and environmental systems (Aller, 2017). Few studies investigate the effects of biochar due to aging on crop production (Major *et al*., 2010; Borchard *et al*., 2014; Aller, 2017). Long term residual effects of biochar on crop production needs to be investigated in future.

In 2015, the United Nations (UN) adopted the Sustainable Development Goals (SDGs). The 17 goals were introduced for the sustainable use of our resources of planet and will help to reduce poverty, hunger, and gender inequality. It will also help for a proper education and good life for all (Griggs *et al*., 2013; Steffen *et al*., 2015; Schmidt *et al*., 2015). The use of biochar could help to achieve at least ten of these goals as shown in the Fig. 1.1. Biochar has important role in terms of ending poverty (1), as well as for achieving zero hunger (2), good health and well-being (3), and clean water and sanitation (6). In addition, the SDGs goals such as affordable and clean energy (7), industry, innovation and infrastructure (9), and sustainable cities and communities (11) can be achieved by use of biochar as soil amendment. Furthermore, the application of biochar in soil can also help to achieve SDGs goals such as climate action (13), life below water (14), and life on land (15).

About 70% of area of Earth's surface is covered by water (Siddique and Bramley, 2014; Chai *et al*., 2016); however, only 2.5% is freshwater (Gleick and Palaniappan, 2010). Schiermeier (2014) and Chai *et al*. (2016) reported that 800 million people lack access to safe drinking water and 2.5 billion have no proper sanitation. Abiotic stresses such as salinity and drought are common nowadays (Rizwan *et al*., 2016a; Akhtar *et al*., 2014). The climate change will increase the frequency of drought and intensity of water resource limitations in near future and will adversely affects crop production (Garcia Galiano *et al*., 2015). The intensity, frequency, and distribution of rainfall are expected to change because of climate change (IPCC, 2007). Due to rapid population growth, increasing environmental degradation, and climate change getting more crops per drop (FAO, 2003) is more important.

As the water is becoming limited therefore we need to improve water use efficiency (WUE) and plant available water content for the resilience of food production. The WUE is one of the important parameter which needs to be improved to tackle the problem of water scarcity for sustainable use of water resources. The increase in WUE and plant available water by the addition of biochar is more important than water retained in soil profile in order to increase the yield of crop (Verheijen *et al*., 2010; Aller, 2017). The WUE can be improved by implementing deficit irrigation (DI), which is irrigating the crop with less water than full irrigation (FI). The judicial uses of DI do not significantly reduce the yield and quality of crop (Chai *et al*., 2016).

In the recent years, integrated approaches for improving crop production to resist conditions of low nutrient soil, drought, salinization or other forms of degradation is practiced (Ismail and Iberahim, 2003; Zahir *et al*., 2012; Akhtar *et al*., 2014). Hence, the combination of biochar and DI may save irrigation water and improve WUE compared to their separate use (Akhtar *et al*., 2014).

There are limited studies on the effects of rice husk (RH) and rice husk biochar (RHB) application on physico-chemical properties of soil and rice production. Additionally, the residual effects of RH and RHB application on komatsuna production after three years of application into soil have not been studied. Furthermore, the effects of biochar application on soybean production under different irrigation regimes have not been studied yet.

## 1.2. Objective and scope of the study

The objectives of this study were to investigate:

1) the comparative effects of RH and RHB application on physico-chemical properties of soil and rice production.
2) the comparative residual effects of RH and RHB application on dry matter yield (DMY), nutrient uptakes, agronomy efficiency (AE), and recovery efficiency (RE) of komatsuna after three years of application into soil.

3) the effects of biochar application on physico-chemical properties of soil, yield, nutrient uptakes, and WUE of soybean under different irrigation regimes.

We used the RH and RHB as an amendment for conducting the experiment of Chapters 3 and 4 for the following reasons. In Japan, more than 1.8 million tons per year of RH are produced (Chauhan *et al*., 2017). The immense amount of annually produced RH needs to be effectively managed. It can be directly incorporated into the crop field or after conversion of RH into RHB. The application of biochars of RH residue is promising alternative solution for utilization of RH residue return to croplands (Zhao *et al*., 2014).

We also used bamboo biochar (BB) as amendment for conducting the experiment of Chapter 5 for the following reasons. BB is highly micro-porous in structure. The pyrolysis of bamboo can produce upto 50% of the carbon and the remaining 50% is used to produce energy and fuels (Lehmann, 2007). In addition, the porosity of BB is about five times greater and the absorption efficiency is about ten times higher than that of wood charcoal (Ahmed *et al*., 2016).

Rice and soybean is the main cropping pattern in Japan. After rice cultivation soybean is usually cultivated in rice field. In addition, rice and soybean is main food and staple part of Japanese diet. Therefore, we selected rice and soybean as test crops in this study. We also studied the residual effects of RH and RHB on komatsuna production in converted paddy soil which is one of the important green leafy vegetable in Japan. Komatsuna contains vitamins and important nutrients.

## 1.3. Organization of the dissertation

This thesis contains altogether six chapters as follows:

Chapter 1 presents the research background, objectives and scope of study, and structure of the thesis.

Chapter 2 discusses the review of the past and recent articles on application of biochar to soil. This chapter gives an idea about the effects of biochar on soil physico-chemical properties, nutrient uptakes, nutrient use efficiency, and crop production. Furthermore, it also gives a brief idea about the effects of biochar application under DI on crop production and WUE.

Chapter 3 presents the study on first objective. We conducted a series of laboratory and pot experiments in the greenhouse for the achievement of the objective one. In chapter 3, we studied the effects of application of RH and RHB on physico-chemical properties of soil and rice production.

Chapter 4 presents the study on second objective. We conducted a series of laboratory and pot experiments in the greenhouse for the achievement of the second objective. In chapter 4, we studied the residual effects of application of RH and RHB on DMY, nutrient uptakes, AE, and RE of komatsuna after three years of its application into soil.

Chapter 5 presents the study on third objective. We conducted a series of laboratory and pot experiments in the green house for the achievement of the third objective. In chapter 5, we studied the effects of bamboo biochar application on physico-chemical properties of soil, yield, nutrient uptakes, and WUE of soybean under different irrigation regimes.

In Chapter 6, we discussed general conclusions and future study recommendations.

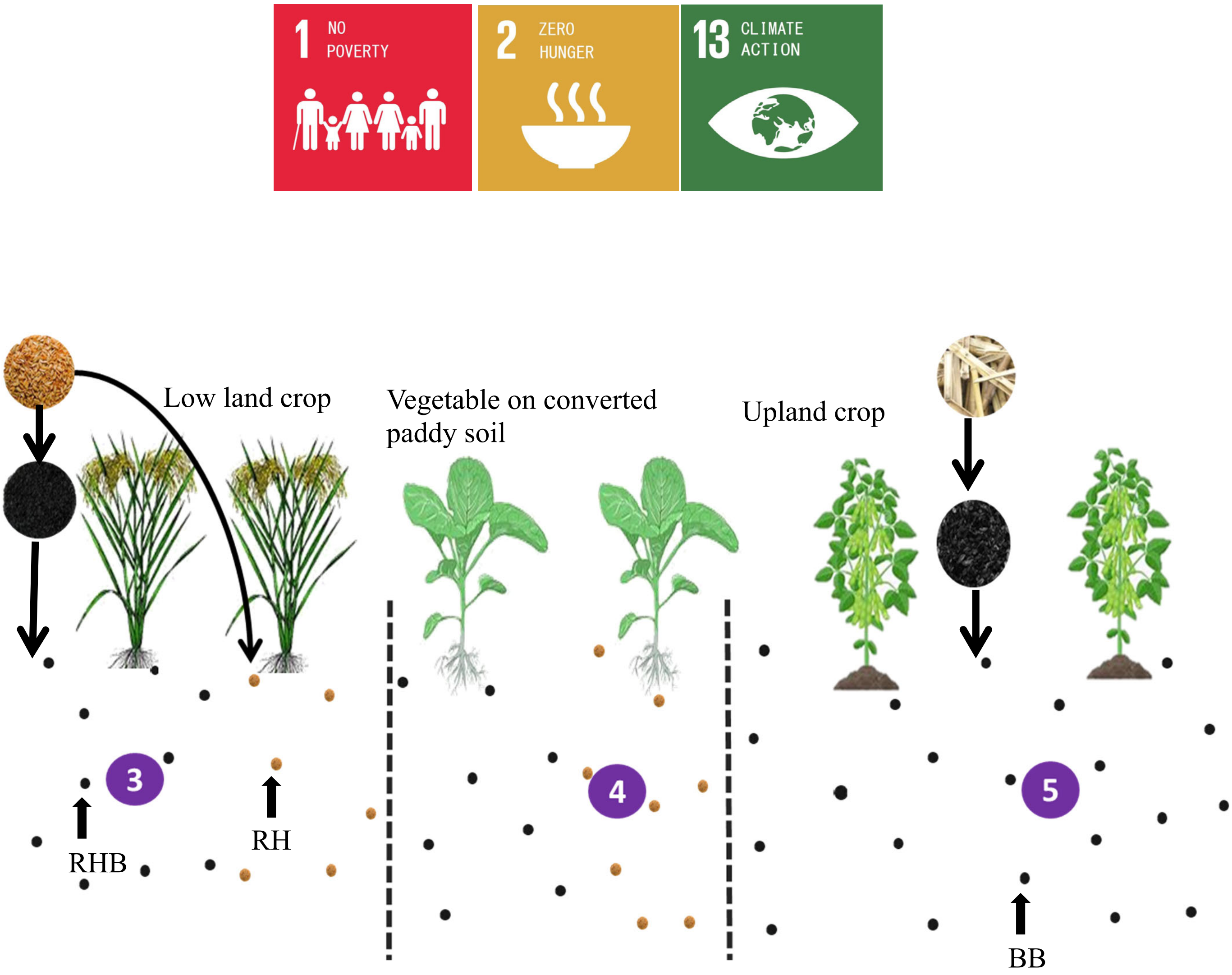



Fig. 1.1: Flow of research and organization of dissertation where RHB= rice husk biochar, RH= rice husk, BB= bamboo biochar, 3= Chapter 3, 4= Chapter 4 and 5= Chapter 5

# Chapter 2 Review of literature

## 2.1. Biochar and its production

Biochar is a carbon-rich product obtained by burning of biomass, such as wood, manure or plant leaves, in a closed container under a limited oxygen environment by the process of pyrolysis. In technical terms, biochar is produced by thermal decomposition of organic material under limited supply of oxygen, and at temperatures less than 400-500°C (IBI, 2014).

Mostly, biochar is produced by one of the following pyrolysis processes 1) Slow pyrolysis, 2) Fast pyrolysis, 3) Flash pyrolysis, 4) Vacuum pyrolysis, 5) Intermediate pyrolysis, and 6) Hydro pyrolysis.

In slow pyrolysis, the biomass is heated at relatively low temperature around 400°C over a longer period of time to maximize char formation. However, in fast pyrolysis, the biomass is heated to a temperature around 850-1,000°C, at heating rate of 10-20°C $s^{-1}$ for short interval of time. Flash pyrolysis is a modified form of fast pyrolysis where the heating order is of 1000°C for short period of time 0.1-1.0 s. Under vacuum pyrolysis, the biomass is heated at low pressure and in the absence of oxygen. The pressure ranges from 0.05-0.20 MPa and the temperature is kept between 450 to 600°C. In intermediate pyrolysis the formation of tars is reduced and dry char is final product of this method, which is suitable for agriculture use. Hydro pyrolysis is the new technique by which the biomass is converted into high-quality bio-oil (Ronsee *et al*., 2013).

Cellulose, hemi-cellulose, and lignin are the major constituents of biomass. At the temperature ranging from (150-350°C), cellulose is converted into condensable vapor (tar). The hemi-cellulose is converted into non-condensable vapor at the temperature range of (275-350°C). Lignin is converted slowly into char and liquid at the temperature range of (250-500°C) (Ronsee *et al*., 2013). Fig. 2.1 shows the production process of biochar. Fig. 2.1 shows the manufacturing process of biochar.

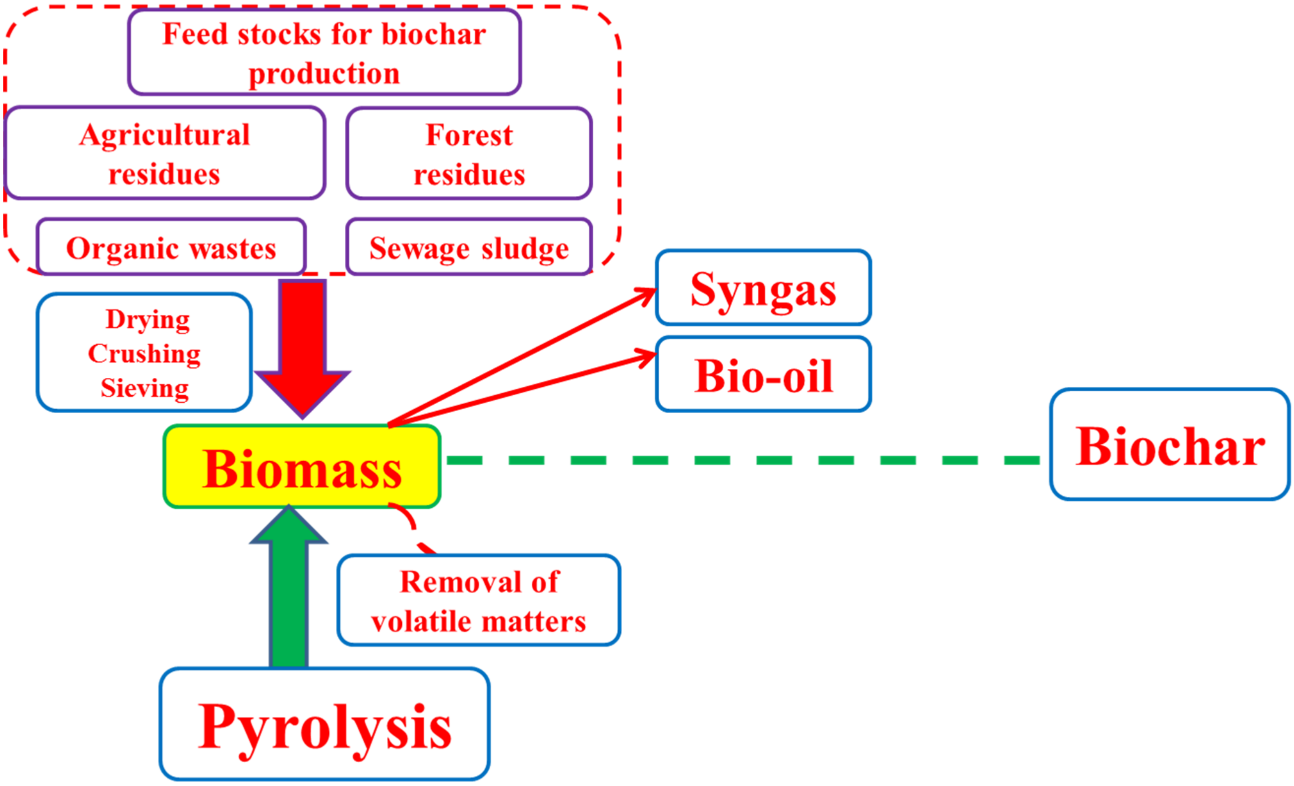



Fig. 2.1: Brief introduction of biochar manufacturing process

Fig 2.1 shows brief introduction of biochar manufacturing process and is adopted from Xiao *et al*. (2016)

## 2.2. Characteristics of biochar

Biochar can be produced from a wide range of feed stocks, which includes wood materials, agricultural residues and manures (Singh *et al.,* 2010b; Wang *et al.,* 2011). It contains high C, low N, high surface area, and cation exchange capacity compared to the feedstock from which it is produced (Singh *et al.,* 2010b).

Biochar yield varies with the type of feedstock used and pyrolysis temperature. The biochar yield for rice husk, poultry manure, and waste sludge varies from 39-59%, 47-68%, and 43-54%, respectively, whereas the yield of biochar produced from Japanese cedar, Japanese cypress, meso bamboo, and sugarcane bagasse ranges from 22-41%, 23-39%, 25-39%, and 19-28%, respectively (Kameyama *et al.,* 2017). The higher yield of rice husk, poultry manure, and waste sludge biochar is due to the presence of higher ash content in them (Windeatt *et al.,* 2014). The biochar yield decreases with the increase in pyrolysis temperature. With the increase of temperature, the volatile matter decreases, whereas the ash content increases (Kameyama *et al.,* 2017). With the increase of pyrolysis temperature, the nitrogen, hydrogen, and oxygen contents decreased, whereas the carbon content increases (Ahmed *et al.,* 2016).

Fourier Transformation Infrared Spectroscopy (FTIR) analysis showed that the aliphatic C-H stretching (2950-2850 $cm^{-1}$) was lost by increasing the pyrolysis temperature from 400 to 600°C, whereas the peaks of aromatic carbon appeared, i.e. C-H stretching (750-900 $cm^{-1}$ and 3050-300 $cm^{-1}$), C=C (1380-1450 $cm^{-1}$), C-C and C-O stretching (1580-1700 $cm^{-1}$) (Jindo *et al.,* 2014). At the higher temperature 700-800°C, the hydroxyl group (3200-3400 $cm^{-1}$) and aromatic groups (1580-1600 $cm^{-1}$ and 3050-3000 $cm^{-1}$) gradually disappears. In the biochar produced at the lower temperature (300 and 500°C) many functional groups were found (Yuan *et al.,* 2011).

The C:N ratio is the important parameter for the prediction of mineralization and N release in soils. C:N ratio of less than 30 is ideal for the N mineralization; however, C:N ratio greater than 30 will cause N immobilization. The C:N ratio of biochar varies with the feedstock ranging from 8 to 1500 (Enders *et al.,* 2012). Usually, the biochar produced from the soft wood has the highest C: N ratio (Mukome *et al.,* 2013). It is also influenced by the pyrolysis temperature, with the increase of pyrolysis temperature, the C:N ratio increases.

The pH is also one of the important characteristics for the measurement of acidity and alkalinity. Biochar is generally alkaline in nature. The pH of biochar increases with the pyrolysis temperature. The low-temperature biochar is acidic in nature. The pH of biochar is also dependent on the feedstock used for the production (Kameyama *et al.,* 2017).

Cation exchange capacity (CEC) is the measure of total capacity of soil to hold exchangeable cations and is one of the important parameters for the assessment of soil quality. Biochar surfaces are generally negatively charged, the cations are attracted on the surfaces of biochar by the electrostatic forces. The CEC decreases with the increase of pyrolysis temperature and is also dependent on feedstock types (Kameyama *et al.,* 2017). The decrease in CEC with the increase of temperature is due to decrease in oxygen functional group at higher temperature (Suliman *et al.,* 2016).

Electrical conductivity (EC) is the measure of major soluble and readily dissolved cations in aqueous solution, which relates to the ability of the material to conduct electrical current through it (Rhoades, 1996). The EC of biochar is more dependent on feedstock than the pyrolysis temperature. Usually, manure derived biochar has high EC values (Joseph *et al.,* 2010).

## 2.3. History of use of biochar as soil amendment

Biochar has been used as a soil amendment since long time ago. The textbook entitled 'Nogyo Zensho' (Encyclopedia of Agriculture) written by Yasusad Miyazaki in 1697 shows the oldest description of charcoal use in agriculture (Miyazaki, 1697). In Asia, rice husk charcoal has been used since the beginning of rice cultivation (Ogawa and Okimori, 2010).

In 1980, Kishimoto and Sugiura published a book entitled 'Introduction to Charcoal Making' to encourage uses of charcoal (Kishimoto and Sugiura, 1980). They contributed considerably towards the present prosperity of the charcoal business in Japan and Asia. In 1980, the studies on the charcoal utilization in agriculture and forestry were started in Japan (Ogawa and Okimori, 2010). The effects of bark charcoal on soybean cultivation were studied by Ogawa (Ogawa *et al*., 1983*a*; 1983*b*). At the beginning of 20$^{th}$ century, firewood and charcoal were major sources of energy for daily life (Ogawa and Okimori, 2010).

The use of biochar in the basin of Amazon in South America was started from the 20th Century (Lehmann *et al.,* 2003). Soils of the Amazon basin are defined as Oxisols and is generally acidic, red, and infertile. It is believed that, prior to colonization, the indigenous people of Amazonian basin incorporated burned house-hold and agricultural waste into the soil which makes the soil extremely fertile compared to the highly acidic, low fertility Oxisols and Ultisols which are common in that area (Neves *et al*., 2003). 'Amazonian Dark Earths' contained significantly greater amounts of charcoal-derived carbon (C), soil organic carbon (SOC), and nutrients. Moreover, soil containing biochar in Amazon basin are alkaline in nature and are rich in nutrients such as nitrogen (N), calcium (Ca), and phosphorus (P), and retain more water than unamended Oxisols. In addition, these Terra Preta soils have greater level of soil microbial activity and less nutrient leaching than unamended soils (Lehmann *et al.,* 2003). Extensive research has been conducted on the way in which biochar modifies soil properties of Terra Preta soil (Lehmann *et al.,* 2007; Glaser *et al.,* 2001). At present, charcoal is used mainly in agriculture, greening, tree rehabilitation, humidity control in house construction, water purification, and sewage treatment.

## 2.4. Effects of biochar application on physico-chemical properties of soil

Application of biochar into soil, changes the chemical properties of soil which may enhances the growth and yield of crops (Palansooriya *et al*., 2019). Soil pH is one of important parameter relating to soil fertility. Several studies reported that application of biochar into soil can alter its pH. The effects of biochar application in acidic soil is more beneficial compared to its application in alkaline soil (Lehmann and Joseph, 2015; Lehmann and Rondon, 2006). Gul and Whalen (2016) reported that the application of biochar increases the soil pH. Similarly, Major *et al*. (2010) reported that the application of biochar increased the soil pH in savanna Oxisol soil and increased Ca and Mg availability in soil. Wang *et al*. (2014) reported that application of rice husk biochar in tea garden soil increased the pH from 3.33 to 3.63. Lehmann and Rondon (2006) reported that the higher pH value of biochars is an important factor for enhancing the crop productivity in acidic and highly weathered soils.

Electrical conductivity (EC) is one of the important characteristic which effects the growth and quality of crops. Application of biochar from various feed stocks increased the soil EC in the range of 2-85% (Palansooriya *et al*., 2019). The application of pine sawdust biochar shows the highest increase in soil EC at the application rate of 45 t $ha^{-1}$. Kelly *et al*. (2015) reported that the biochar application at the rate of 100 t $ha^{-1}$ significantly increased the soil pH and EC in a wheat cultivated soil. The factors affecting the soil EC by the application of biochar are feedstock used, pyrolysis condition, production method, and application rate of biochar into soil.

Cation exchange capacity (CEC) is the measurement of the capacity of soils to retain nutrients. Application of biochar to soil increases the CEC of soil (Igalavithana *et al*., 2016; Lehmann and Joseph, 2015; Verheijen *et al*., 2010). Laird *et al*. (2010) reported that application of biochar significantly increased CEC by 4 to 30% compared to control. Similarly, the application of (*Leucaena leucocephala*) derived biochar in highly weathered soil increased the CEC from 7.41 to 10.8 c mol $kg^{-1}$ (Jien and Wang, 2013). The increase in the amount of exchangeable cations by the addition of biochar helps to improve the soil fertility and nutrient retention in soil. This may be due to the high specific surface area and number of carboxylic groups of the biochar (Cheng *et al*., 2006). Wang *et al*. (2014) reported the application of biochar increased the extractable K, Ca, Na, and Mg approximately ranging from 60 to 670%. The application of biochar increased the K content of soil from 42 to 324 mg $kg^{-1}$ (Wang *et al*., 2014).

The application of biochar into soil increased total C from 2.27 to 2.78%, total N from 0.24 to 0.25%, and available P from 15.7 to 15.8 mg $kg^{-1}$ (Jones *et al*., 2012).

Biochar has large surface area and low bulk density (Downie *et al*., 2009). Addition of biochar into soil increases the soil surface area (Chan and Xu, 2009) which helps to increase the aeration and soil water content in soil (Downie *et al*., 2009). Water is one of the most essential factors for the survival of plant. The application of biochar can increase the soil water retention such as field capacity, permanent wilting point, and plant available water (Cely *et al*., 2014). Liu *et al*. (2016) reported that the application of straw derived biochar increased the plant water holding capacity in Entisol due to the high surface area and porosity of the biochar. The bulk density of biochar is low, when it is applied to soil, it increases the porosity and decreases the bulk density of the amended soil (Liu *et al*., 2016). Similarly, Brewer *et al*. (2014) reported that the application of biochar changes tensile strength of amended soil and improves the plant growth. Laird *et al.* (2010) reported that the bulk density was reduced after 500 days of laboratory incubation experiment by the application of wood biochar at the application rate of 0.5 to 2.0% (w:w).

Blanco-Canqui (2017) reported in his recent review that biochar increased water holding capacity in 17 out of 19 soils, which suggested that the biochar is effective in increasing the water retention of the soil. Even at the low application rates of biochar application, the water retention was increased. However, Paneque *et al.* (2016) concluded that the application rate of biochar must be greater than 15 t $ha^{-1}$ for the increment of water retention in soil. The increase water retention in soil is more for the sandy soil compared to that of the clayey soil by the addition of biochar.

Hydraulic conductivity is defined as the rate of water movement per unit time. It is one of the important hydrological processes. Biochar application to the soil effects water movement into the soil. Busscher *et al.* (2010) reported that the application of pecan shell biochar in loamy sand at the application rate of 0.5, 1.0, and 2.0% (w:w) increased the hydraulic conductivity from 1.1 mm $min^{-1}$ to 2.7, 1.7, and 2.0 mm $min^{-1}$, respectively. Biochar application to soil also increases saturated hydraulic conductivity from 16.7 to 33.1 cm $h^{-1}$, decrease soil erosion rate from 1458 to 532 g $m^{-2}$ $h^{-1}$ (Jien and Wang, 2013). Uzoma *et al.* (2011) reported that the application of wood biochar reduced unsaturated hydraulic conductivity and suggested that 20 t $ha^{-1}$ is better than 10 t $ha^{-1}$ in sandy soil. Igalavithana *et al*. (2017) reported that the application of biochar produced at 500°C decreased the saturated hydraulic conductivity in sandy loam soil. The maximum decrease in saturated hydraulic conductivity was observed in 5% (w:w) application rate, no further decrease in hydraulic conductivity was observed even by increasing the application rate of biochar.

In some cases, there were no changes in soil physical and chemical properties by the application of biochar. For example, Jones *et al*. (2012) found that soil EC changes from 46 to 43 μS $cm^{-1}$ and bulk density changes from 1.04 to 1.08 g $cm^{-3}$ after 3 years of biochar addition. Nelissen *et al*. (2015) reported that the application of biochar increases the porosity and decreases the bulk density in first year of application of biochar but no change in hydraulic conductivity and plant available water was found after second year of application.

Application of biochar also increases soil organic carbon (SOC) due to its high C content. Zhang *et al*. (2015) reported that SOC was increased at different soil depths under wheat straw-biochar treatment in a 2-year experiment of wheat and maize cropping system in an alkaline soil. Fig. 2.2 shows the benefits of use of biochar in crop production.

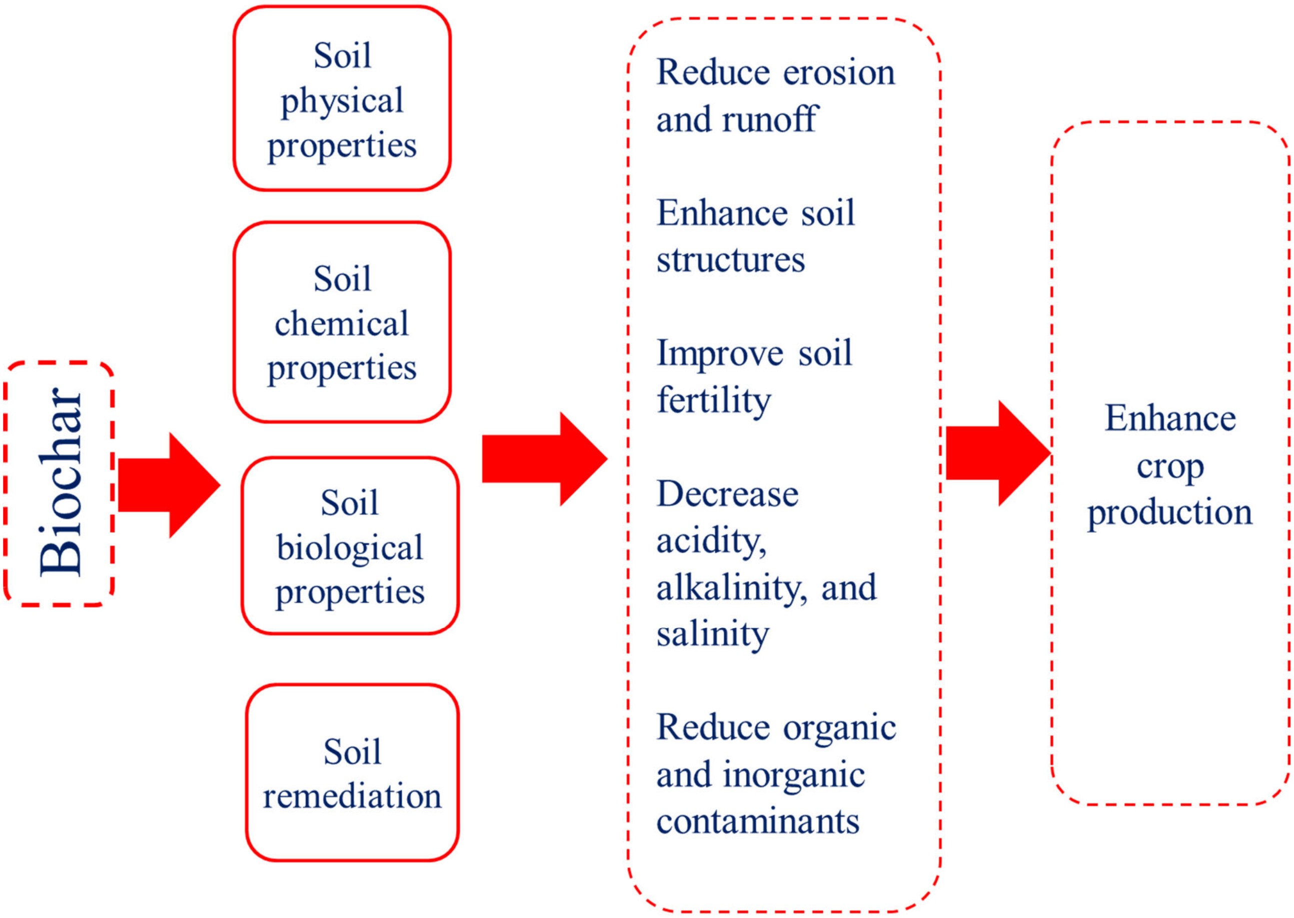



Fig 2.2: Benefits of use of biochar in crop production

Fig 2.2 shows the benefits of use of biochar in crop production and is adopted from Palansooriya *et al*., (2019).

## 2.5. Effects of biochar application on nutrient availability and plant uptake

Biochar application into soil increases the availability of essential plant nutrients which ultimately enhance the plant growth (Lehmann, 2007; Al-Wabel *et al*., 2018). Nutrient availability and uptake by plant depends on the type of biochar, soil, and plant traits.

The effects of biochar application on N uptake is associated with soil CEC, pH, and texture (Steiner *et al*., 2008). N uptake of biochar amended plots was increased by 127% compared to control plots and was positively correlated with rice grain yield (Partey *et al*., 2016). In another study conducted by Prendergast *et al*. (2014), N uptake by the roots of wheat was increased by application of wood biochar at the rate of 20 and 60 Mg $ha^{-1}$ compared to control due to the development of extensive root systems. Abbasi and Anwar (2015) reported that the biochar produced from white clover residues and poultry manure applied alone or in combination (50:50) increased the N uptake of maize compared to control; however, there was no significant increase in N uptake in wheat cultivation compared to control. Sigua *et al*. (2014) also reported that the N uptake was increased by the application of sorghum derived biochar with and without application of P based fertilizer in aboveground parts of winter wheat. In some cases, addition of biochar do not have any influence on nutrient uptake by plants; Walter and Rao (2015), for example, reported that application of grass and rice husk biochars had no effect on N and P uptakes by sweet potato. They explained the possible reason for no increase in N and P uptakes of sweet potato may be due to high C:N ratio of biochar which might have increased soil N immobilization and inhibited nutrient uptake. Chan and Xu (2012) reported that application of biochar to soil at the rates of 20 and 50 t $ha^{-1}$ can add 64 and 160 t $ha^{-1}$ of total N, respectively, but only (0.1 kg N $ha^{-1}$) amount of N is made available to crops for 50 t $ha^{-1}$ application into soil. Major *et al*. (2012) suggested that N should be applied through chemical fertilizers and organic amendments such as animal manures and compost to get maximum benefits of biochar application, in order to maximize N uptake and crop production. Nutrient uptake also changes with the aging of biochar into soil. For example, Zhao *et al*. (2014) did not find any effect on increase in nutrient uptakes (N, P, Ca, or Mg) by rice in the first growing season, but nutrient uptake was higher after three growing seasons and two complete rice-wheat rotations. Sigua *et al*. (2015) found that biochar prepared by mixing poultry litter and pine chips (50:50) significantly increase nutrients (P, K, Ca, Mg, Na, Al, Fe, Cu, and Zn) uptakes in aboveground and belowground parts of winter wheat; however, nutrient uptake by winter wheat was decreased compared to control by the application of poultry litter biochar which might be due to the high salt content present in poultry litter biochar. Nutrient-uptake by plant also depends on soil type. Smider and Singh (2014), for example, reported that application of biochar to an acidic Ferrosol increased the uptake of most nutrients (N, K, P, S, Cu, Fe, Mn, and Zn) by corn, but uptake of most nutrient were reduced (except K, S, and Mn) in a neutral Tenosol soil.

## 2.6. Effects of biochar application on the nutrient use efficiency of organic and inorganic fertilizers

Application of biochar into soil in combination of organic or inorganic fertilizers, can improve the nutrient use efficiency of nutrients and crop production. Several studies have shown that the nutrient use efficiency of inorganic fertilizer was increased by the co-application of biochar and chemical fertilizers (Alburquerque *et al*., 2013; Liu *et al*., 2012; Steiner *et al*., 2008; Al-Wabel *et al*., 2018). Maru *et al*. (2015) reported that application of poultry litter biochar with 75% recommended dose of N, increased the nutrient use efficiency in rice grown in field and pot conditions. Likewise, application of biochar in combination of chemical fertilizer increased the N use efficiency of maize in calcareous soil compared to control (Liu *et al*., 2012). Zhang *et al*. (2010) demonstrated that N use efficiency and rice yield were increased in acidic and organic C rich paddy soil by the application of biochar at the rate of 10 and 40 t $ha^{-1}$ and N fertilizer. Likewise, Partey *et al*. (2014) reported that the application of biochar with NPK fertilizer to maize increased the N use efficiency which led to an increase in grain yield by 27% compared to NPK fertilizer alone. Farrel *et al*. (2014) reported that application of biochar in combination of P-based fertilizer in field experiment significantly increased wheat yield by effective P utilization. Blackwell *et al*. (2015) conducted both field and pot experiment and found that application of biochar in combination of inorganic fertilizer increases nutrient uptake and P use efficiency in nutrient-deficient sandy soil due to mycorrhizal associations and greater access to available P for roots which increased the crop yield. Application of biochar in combination with kcl fertilizer increased the K, Ca, N, and P in soil and subsequently maize yield by increasing the agronomy and nutrient use efficiency compared to kcl fertilizer alone (Widowati and Asnah, 2014).

Application of biochar into soil in combination of organic fertilizers, can also improves the nutrient use efficiency of nutrients and crop production (Sohi *et al*., 2010; Al-Wabel *et al*., 2018). The application of biochar in combination with compost enhanced the soil characteristics, maize growth, and yield by two fold in two consecutive crop seasons (Nur *et al*., 2014). Agegnehu *et al*. (2015) reported that application of biochar and compost increased the maize yield and nutrient use efficiency by enhancing the physico-chemical properties of soil. Steiner *et al*. (2008) demonstrated that the application of biochar in combination with compost increases N recovery by 17.4% in grains compared to inorganic fertilizer treatments. Application of biochar and compost in Ferralsols soil increases the P use efficiency of plants due to reduction in P leaching and increase in P availability (Agegnehu *et al*., 2015). Partey *et al*. (2014) reported that application of green manure and biochar improves the nutrient of soil, N use efficiency, and maize yield.

## 2.7. Effects of biochar application on crop production

The effects of biochar addition to soil on crop production are not uniform due to variation in the composition of feedstock from which biochar is manufactured, properties of soil, plant traits, and experimental conditions (Al-Wabel *et al*., 2018).

Raboin *et al*. (2016) reported that the application of cattle manure biochar at the rate of 50 t $ha^{-1}$ to acidic soil increases the maize grain yields by 46-58% for three different seasons in 2010, 2012, and 2014. Major *et al*. (2010) reported that application of wood biochar at a rate of 20 t $ha^{-1}$ increased the maize yield in infertile and acidic tropical soil. Though the maize productivity does not significantly increased in the first year, the yield improved by about 29%, 31%, and 143% compared to the control for the next three consecutive seasons, respectively (Major *et al*., 2010). The liming effect due to addition of biochar may be the reason for increase in yield and enhancement in nutrient availability. The application of willow wood biochar significantly increased the peanut yield (Agegnehu *et al*., 2015). Agegnehu *et al*. (2016a) documented that application of biochar in combination of compost increased the seed and pod yield by 22 and 24%, respectively, compared to control, whereas for maize experiment, the maize grain yield was increased by 29% for the treatment (biochar only) and for the treatment (combined application of biochar and compost) can only increase the maize yield by 13% compared to control (Agegnehu *et al*., 2016a). According to authors the possible reason for increase in yield might be due to improvement in soil water retention, reduction of P, and N leaching from soil.

Biochar application into soil also increases the growth and yield of root crops. For example, Liu *et al*. (2014) reported that the application of wheat straw biochar at the rate of (5, 10, 20, 30, and 40 t $ha^{-1}$) increases the sweet potato yield by (10%, 74%, 89%, 107%, and 121%), respectively. Akhtar *et al*. (2014) found that addition of biochar manufactured from the mixture of rice husk and shell of cotton seed significantly increased the tomato fruit fresh weight in sandy loam soil. The increase in tomato yield might be due to increase in water retention in soil by addition of biochar (Akhtar *et al*., 2014). However, Güereña *et al*. (2013) reported that incorporation of maize stove biochar produced at 600 °C applied at different application rates upto 30 t $ha^{-1}$ into fertile soil does not increase the maize yield significantly. Niu *et al*. (2017) and Major *et al*. (2010) reported that there was no significant increase in maize yield for the first year of cultivation by the application of biochar. Niu *et al*., (2017) reported that this might be due to presence of phytotoxic compound in biochar which might have reduced the growth and development of plant.

Application of biochar at the rate of 40 t $ha^{-1}$ in upland red soil increased the yield of sweet potato by 53.8% and rapeseed by 36.0% (Liu *et al*., 2014). Blackwell *et al*. (2010) reported that application of biochar at the rate of 1.0 t $ha^{-1}$ in combination with a P fertilizer (50 kg $ha^{-1}$) significantly increased wheat yield compared to control. The application of biochar in alkaline soil also has positive effect on growth and yield of crop; however, it depends on the type and production temperature of biochar (Spokas, 2010).

Application of biochar into soil increased the yield, biological N fixation (BNF), and nodulation of several legume crops. For example, Mete *et al*. (2015) reported that application of biochar alone increased the total soybean biomass and seed yield by 67% and 54%; however, application of biochar in combination of NPK inorganic fertilizer increased the total biomass and seed yield by 367% and 391%. In another study, Rondon *et al*. (2007) reported that the application of biochar at the rate of 78 t $ha^{-1}$ increased the BNF of common bean. Mia *et al*. (2014) reported that biochar application at a rate of 10 t $ha^{-1}$ enhanced BNF, nodule number, and the total biomass of red clover.

A meta-analysis on biochar application and its impact on crop production shows that the application of biochar in soil significantly increased the crop yield (Jeffery *et al.*, 2011). They pointed out the possible reasons for increase in yield may be due to improvement in water holding capacity of soil and liming effect due to the application of biochar. They also reported that the poultry litter biochar was superior compared to other biochar in increasing the crop yield, whereas bio-solids derived biochars reduced the crop yield.

Gonzaga *et al*. (2017) reported that maize growth and yield was not affected by the application of biochar derived from bio-solids which was manufactured in muffle furnace. The plant growth was decreased but plant N and P concentrations was significantly increased by the application of the bio-solids biochar applied at the rate of 60 t $ha^{-1}$ which was produced by a traditional retort kiln (Gonzaga *et al*., 2017).

## 2.8. Effects of deficit irrigation on crop production

The application of water below the evapotranspiration (ET) requirements of crop is known as deficit irrigation (DI). Deficit irrigation is classified into two types: a regulated deficit irrigation and a partial root zone drying irrigation. In regulated deficit irrigation, the crop is irrigated with less amount of water than the actual water needed during a specific period of their growth (Jovanovic and Stikic, 2018). In partial root zone drying irrigation, only one side of the root zone is irrigated for a certain period of time while another side remains dry (Wang *et al*., 2009). To avoid long term drying of root zone on another side, the irrigation cycle is changed from one side to another after a certain period of time. There are two types of partial root zone drying irrigation: an alternate partial root zone drying and a fixed partial root zone drying.

DI may reduce the yield of the crop if it is practiced at the critical growth stage of the crop. Grain filling stage is the critical growth stage for inducing DI. Mostly, the effect of DI is less during the vegetative growth stage of plants. The sensitivity of crop to water deficit is affected by many factors such as, climate, plant species, and management practices (Chai *et al.,* 2016).

Garcia del Moral *et al.* (2011) reported that the most sensitive growth stage for DI in wheat is stem elongation and booting followed by anthesis and grain filling.

Water stress in soybean reduced the yield by 9 to 13% during the early flowering to full bloom stage, by 46% during early pod development and by 45% during later pod formation stage (Chai *et al.,* 2016).

## 2.9. Effects of biochar application under deficit irrigation condition

Several studies reported the beneficial effects of biochar application to the soil under water deficit conditions (Akhtar *et al*., 2014; Paneque *et al*., 2016; Rogovska *et al*., 2014; Al-Wabel *et al*., 2018; Tayyab *et al*., 2018; Ali *et al*., 2017). Paneque *et al*. (2016) reported that the application of biochar increases the vegetative growth and seed production of sunflower grown under non-irrigated field condition. Agbna *et al*. (2017) also reported that application of biochar enhanced the growth, yield, and quality of tomato under DI condition. Addition of biochar at the rate of (30% (v: v)) protected the tomato seedling from wilting due to enhancement of soil moisture content in sandy soils (Mulcahy *et al*., 2013).

Application of biochar improves hydrological characteristics, soil physical properties, increased soil water content, yields, and water use efficiency (WUE) (Xiao *et al*., 2016). Akhtar *et al*. (2014) reported that biochar application to sandy loam soil significantly improved the relative water contents (RWC), stomatal conductance (Gs), chlorophyll contents, WUE, photosynthetic rate (Pn), and stomatal density of leaves of tomato under drought condition. Similarly, Haider *et al*. (2015) reported that addition of biochar to sandy soil improves soil water content, plant growth, and photosynthesis under both deficit and excess water. In addition, biochar application in sandy soil increased the WUE of maize in sandy soil (Uzoma *et al*., 2011). Similarly, biochar produced at 450$^{\circ}$C addition to soil increased the Pn, the WUE, and Gs of okra (*Abelmoschus esculentus* L. Moench) under DI condition compared to the control (Batool *et al*., 2015).

Keshavarz Afshar *et al*. (2016) reported that biochar application at a rate of 1.0 and 2.0% in sandy soil did not affect the chlorophyll contents and gas exchange traits in milk thistle (*Silybum marianum* L.) seedlings grown under DI conditions. There was no significant change in the leaf, plant and stem weight, leaf area, and plant height of milk thistle under moderate (60% of control) and severe (40% of control) DI compared to the control (50% of field capacity) (Keshavarz Afshar *et al*., 2016). Therefore, effects of biochar under deficit irrigation condition depend on soil, biochar types, and plant species (Keshavarz Afshar *et al*., 2016).

# Chapter 3 Comparative study on effects of rice husk and rice husk biochar on physico-chemical properties of soil and rice production

## 3.1. Abstract

This study was conducted to evaluate the comparative study on effects of rice husk (RH) and rice husk biochar (RHB) application on physico-chemical properties of soil and on rice production. The RH and RHB were applied at the rates of 2% and 4% (w:w), respectively. Unamended treatment served as control. Rice seedlings were transplanted in pots in the month of May and harvested in September 2014 under greenhouse condition. Soil samples were prepared and analysed for physico-chemical properties. The results indicated that RH and RHB application significantly increased porosity but decreased soil bulk density. The application of RHB significantly increased pH of soil. The application of 2% RHB significantly increased the grain and dry matter yield of rice by 38.7% and 27.3%, respectively compared to control. We did not find any significant increase in grain and dry matter yield of rice by application of 2% RH compared to control. Our results did not identify any reasons behind an increase in rice yield by the application of 2% RHB. Further studies are needed to clarify the reasons for an increase in rice yield with the application of 2% RHB.

Keywords: rice husk, rice husk biochar, rice growth, rice yield, soil physico-chemical properties

## 3.2. Introduction

More than half of the world's population depends of rice (*Oryza sativa L.*) as staple food (Muthayya *et al*., 2014). To feed the growing population, the global rice production must be increased by about 1% annually (Normile, 2008). The average yield of rice is constant and lower than the production potential due to imbalanced use of chemical fertilizers (CFs) (Moe *et al*., 2019). Singh *et al*. (2001) reported that imbalanced use of CFs reduces the rice yield by 38% and also decreases soil fertility. The use of CFs enhances the rice yield however the yield is not sustainable over the longer period of time (Moe *et al*., 2019). Therefore, it is important to minimize the use CFs in crop production to reduce adverse environmental impacts, such as greenhouse gas emissions (Chen *et al*., 2014), soil acidification (Guo *et al*., 2010), and surface water eutrophication (Le *et al*., 2010).

The depletion of soil organic matter (SOM) affects the soil quality and fertility and has become one of the major threats to agricultural productivity (Lal, 2009). To increase rice yield with less CFs, the enhancement in soil quality is important (Huang *et al*., 2017). The soil quality can be improved by recycling of organic fertilizers including crop residues such as rice husk (RH), rice husk biochar (RHB), and compost to soil (Fan *et al*., 2011; Huang *et al*., 2018).

The RH is rice seed shell which is derived from the de-husking process of rice milling (Kadoglidou *et al*., 2019). They represent about 20-22% of the milling process (Foo *et al*., 2009) and composed of 28% cellulose, 28.6% hemicelluloses, 24.4% lignin, and 18.4% extractive matter (Lim *et al*., 2012). The global production of RH is about 20 million tons annually (Vadivel and Brindha, 2015). Therefore, the immense amount of annually produced RH needs to be effectively managed. One way to accomplish this is by directly incorporating RH into the paddy field and thereby increasing the SOM. However, RH can easily decompose after a few years of application in soil. Therefore, another possible way to manage RH is to convert it into RHB and apply them to the field. The conversion of RH into RHB and its application in agriculture is an ecologically sound option for improving soil fertility and crop yield (Gupta *et al*., 2019). Liu *et al*. (2016) reported that the effect of biochar on crop production depends on many factors such as physico-chemical properties of biochar, climate, soil type, fertilization status, and crop type. On one hand, Smith *et al*. (2010) reported that the biochar application into soil increases microbial activity which causes the loss of soil organic matter; while on the other hand, the addition of biochar into soil reduces the greenhouse gases emissions from soils (Taghizadeh-Toosi *et al*., 2011). Application of biochar into soil increases the N retention (Agyarko-Mintah *et al*., 2017), reduces N leaching losses and increases fertilizer N utilization efficiency (Knowles *et al*., 2011; Cao *et al*., 2013).

At present, there is limited knowledge on the effects of RH and RHB on physico-chemical properties of soil and rice production. Therefore, this study was conducted with the following two objectives: to qualify the comparative study on effects of RH and RHB on a) physico-chemical properties of soil and b) rice production.

## 3.3. Materials and Methods

### 3.3.1. Experimental design and treatments

Soil was collected from a depth of 0 to 20 cm from a paddy field of Kyushu University's Kasuya-Machi farm, Fukuoka, Japan (33° 37' 00" N, 130° 28' 00" E). Commercial RH and RHB purchased from local market were used. Both RH and RHB were applied at a rates of 2% or 4% (w:w). Unamended soil was used as a control. Plastic pot of 70 x 40 x 25cm (L x W x D) was filled with soil medium, and we prepared five treatments as follows: soil and chemical fertilizer with no amendment (control); soil with 2% RHB and chemical fertilizer (2% RHB); soil with 4% RHB and chemical fertilizer (4% RHB); soil with 2% RH plus chemical fertilizer (2% RH); soil with 4% RH plus chemical fertilizer (4% RH). Compound fertilizer N:P:K (8:16:8) was used to ensure the sufficient supply of nutrient. The fertilizer was applied in three split doses. Forty grams of fertilizer was applied one week before rice transplanting, another 20 g was applied at the tillering stage, and final dose of fertilizer (20 g) was applied at the panicle initiation stage. All treatments received an equal amount of water and there was no water stress in this experiment. Yuki Hikari variety of rice was used as the test crop. It was released in 1981 in Hokkaido, Japan and was derived from the progeny of crossed between Hokkaido landraces (Kinoshita *et al*., 2017). In each pot, eight hills with one seedling in each hill were transplanted with twenty-one days seedlings.

### 3.3.2. Characterization of soil, rice husk biochar (RHB), and rice husk (RH)

Elemental C and N (ultimate analysis) of soil, RHB, and RH were analyzed using an MT-5 CN Corder elemental analyzer (Yanaco New Science Inc., Kyoto, Japan). The pH ($H_2O$) was measured using a LAQUA twin B-712 pH meter (HORIBA Ltd., Kyoto, Japan) (1:5, biochar: $H_2O$, w:v). Cation exchange capacity (CEC) was determined using the ammonium acetate extraction method (Muramoto, 1992), and exchangeable cations were then measured by using a Z-5300 atomic absorption spectrophotometer (Hitachi, Tokyo, Japan). We used exchangeable cation, CEC values for RH from † Essoka *et al*. (2014) and total potassium (TK) value for RH from ※ Koyama *et al*. (2016) (Table 3.2). The specific surface area was determined from adsorption isotherms, using the Brunauer-Emmett-Teller (BET) method. The fixed carbon, volatile matter, moisture content, and ash content (proximate analysis) of RH and RHB were determined using the methods of the American Society for Testing and Materials (ASTM) D1762-84 (2007). Volatile matter was ascertained by measuring the weight loss of RH and RHB after heating at 950°C for 6 min in a covered crucible. The ash content was determined by measuring the weight loss after combustion in air at 750°C for 6 h.

### 3.3.3. Determination of physico-chemical properties of soil, rice husk biochar (RHB), and rice husk (RH)

Amended and non-amended soils were also analyzed for physico-chemical properties. Soil pH ($H_2O$) was measured as described in section 3.3.2. For N, P, and K determination, soil, RHB, and RH samples were digested using the salicylic acid-$H_2SO_4$-$H_2O_2$ (Ohyama, 1991). Total N (TN) was determined using the indophenol method (Cataldo *et al*., 1974) and total phosphorus (TP) was analyzed using the ascorbic acid method (Murphy and Riley, 1962). Total potassium (TK) was measured by atomic absorption spectrophotometry using a Z-5300 spectrophotometry. Soil samples corresponding to control, 2% RHB, 4% RHB, 2% RH, and 4% RH were prepared by first mixing and manually packing them in soil core rings of 100 $cm^3$ diameter. For water retention experiment, samples were prepared by mixing amendments and soil. The prepared samples were packed in soil core rings of 100 $cm^3$ manually. Samples were submerged in deionized water overnight before start of the water retention experiment. Field capacity water content

($\theta_{fc}$; -33 kPa) and permanent wilting point water content ($\theta_{wp}$; -1500 kPa) were determined by the centrifuge method of Richards *et al.* (1938). Plant available water content ($\theta_a$) was calculated as the difference between $\theta_{fc}$ and $\theta_{wp}$.

$$\theta_a = (\theta_{fc} - \theta_{wp}) \quad \text{(Equation 3.1)}$$

Bulk density was determined as the ratio of oven dry weight at 105°C for 24 hours to the total volume of the sample. Particle size distribution was determined using the pipette method (Gee and Bauder, 1986). The textural class was identified from the Marshal triangle (Konert and Vandenberghe, 1997). Porosity was determined as: (Danielson and Sutherland, 1986).

$$F = ((1-BD) / PD) \times 100 \quad \text{(Equation 3.2)}$$

where: $F$ (%), $BD$ (g cm$^{-3}$), and $PD$ (g cm$^{-3}$) are the total porosity, bulk density, and particle density of soil, respectively. Particle density of soil was assumed to be 2.65 g cm$^{-3}$. The particle size distribution of soil was determined using the pipette method (Gee and Bauder, 1986). The textural class of soil was then identified from the Marshal triangle (Konert and Vandenberghe, 1997). The saturated hydraulic conductivity ($K_s$) is the rate of movement of water within the soil and it was measured by the falling head method. The Darcy's equation was used to determine the saturated hydraulic conductivity (Richards, 1931).

$$Q/A = (-K_s * (\Delta H/L)) \quad \text{(Equation 3.3)}$$

In Darcy's equation, it is assumed that $\Delta H = H_2 - H_1$, where $H_2$ above $H_1$ for vertical flow and $H_2$ is to the right of $H_1$ for horizontal flow. The term on the left side ($Q/A$) has units of length per unit time or velocity. Since the gradient term $\Delta H/L$ is unit less, $K_s$ has the same units as of velocity. The surface functional group on RH and RHB was analyzed by Fourier Transformation Infrared Spectroscopy (FTIR-620, JASCO).

### 3.3.4 Effects of rice husk and rice husk biochar application on rice growth and yield

Rice growth and yield parameters were measured from middle four hills of each pot. Observations on plant height, panicle length, number of grains per panicle, number of filled grains of panicles were recorded for each treatment at harvest. The harvested samples were sun dried. Thousand-grain weight was determined by selecting 1000 grains randomly and weighing it on a digital balance in gram. Plants were oven dried at 70°C for 72 h, and dry matter yield (DMY) was measured in grams on a digital balance. Rice yield was determined by adjusting the seeds moisture content to 14%. The grain yield was determined in tons per hectare. Harvest index (HI) was calculated as the ratio of economic yield (seed weight) to biological yield (total DM weight) (Yoshida, 1981).

### 3.3.5. Statistical analysis

The experiment was conducted in a completely randomized design with three replications. The data were analyzed using one-way ANOVA followed by Tukey's HSD test ($p < 0.05$). All analyses were done with STATISTIX 8 (Analytical Software, Tallahassee, FL, US).

## 3.4. Results

### 3.4.1. Characterization of rice husk (RH) and rice husk biochar (RHB)

Results of proximate and ultimate analysis of soil, RHB, and RH are presented in Table 3.1. The volatile matter of RH was approximately four times higher than that of RHB. The ash content and fixed carbon of RHB were higher than those of RH. Ultimate analysis of RH and RHB revealed that C and N of RHB were higher than those of RH, whereas H of RH was higher than that of RHB. C:N ratio of RHB was lower than that of RH. Soil texture was classified as clayey soil by the pipette method. Percentages of clay, silt, and sand were 47.4, 23.5, and 29.1%, respectively.

Table 3.1: Proximate and ultimate analysis of soil, rice husk biochar (RHB), and rice husk (RH)

| Properties | Soil | RHB | RH |
|---|---|---|---|
| Proximate analysis (%) | | | |
| Moisture content | - | 4.25 | 3.51 |
| Volatile matter | - | 15.64 | 67.64 |
| Ash | - | 44.87 | 17.11 |
| Fixed carbon | - | 35.24 | 11.74 |
| Ultimate analysis (%) | | | |
| C | 2.00 | 40.10 | 38.30 |
| H | 0.80 | 1.70 | 5.60 |
| N | 0.20 | 0.50 | 0.30 |
| C:N ratio | 10.00 | 80.20 | 127.70 |

### 3.4.2. Effects of rice husk (RH) and rice husk biochar (RHB) application on soil physico-chemical properties

Physico-chemical properties of soil, RHB, and RH are presented in Table 3.2. RHB was alkaline, whereas soil was slightly acidic. The CEC of RHB was higher than that of soil. Additionally, higher Exc. K was found in RHB compared with that in soil. In contrast, Exc. Ca was higher in soil than that in RHB.

The BET surface area of RHB was higher than those of RH and soil. TP and TK were higher for RHB than for RH. The available P of RHB was higher than that of soil. RH had the lowest BD.

Table 3.2: Physico-chemical properties of soil, rice husk biochar (RHB), and rice husk (RH)

| Properties | Soil | RHB | RH |
|---|---|---|---|
| pH | 5.87 | 10.50 | 6.80 |
| CEC (cmol (+) $kg^{-1}$) | 26.70 | 37.4 | 31.54† |
| Exc Ca (cmol (+) Ca $kg^{-1}$) | 7.72 | 3.58 | 20.0† |
| Exc Mg (cmol (+) Mg $kg^{-1}$) | 1.04 | 1.31 | 8.80† |
| Exc K (cmol (+) K $kg^{-1}$) | 0.34 | 19.96 | 0.64† |
| Exc Na (cmol (+) Na $kg^{-1}$) | 0.13 | 0.35 | 0.27† |
| (BET) surface area ($m^2$ $g^{-1}$) | 11.20 | 97.20 | 2.60 |
| TP (g $kg^{-1}$) | 1.96 | 2.01 | 0.49 |
| Available P (mg 100 $g^{-1}$) | 12.58 | 60.36 | - |
| TK (g $kg^{-1}$) | 2.80 | 13.70 | 4.52※ |
| Bulk density (g $cm^{-3}$) | 1.19 | 0.17 | 0.10 |

BET: Brunauer-Emmett-Teller ; CEC: Cation Exchange Capacity; Exc: exchangeable; TP: total phosphorus; TK: total potassium; †: Essoka *et al*. (2014); ※:Koyama *et al*. (2016).

Table 3.3 shows the effects of RH and RHB application on pH, bulk density and porosity of soil. The pH of soil was significantly ($p < 0.05$) higher in the 2% and 4% RHB than that in the control, but no significant differences ($p < 0.05$) were observed between 2% and 4% RH application and the control.

In this study, *BD* significantly ($p < 0.05$) decreased with increasing application rates of RH and RHB. The application of RH and RHB significantly ($p < 0.05$) decreased the *BD* in the 2% and 4% RHB as well as 2% and 4% RH than that in the control.

The application of RH and RHB significantly increase the porosity of soil. Porosity of soil was significantly ($p < 0.05$) higher in the 2% and 4% of RHB and RH than that in the control.

Table 3.3: Effects of RH and RHB application on pH, bulk density (*BD*), and porosity (*F*) of soil.

| Treatments | pH | *BD* (g cc$^{-3}$) | *F* (%) |
|---|---|---|---|
| Control | 5.87 $^{c}$ | 1.19 $^{a}$ | 55.00 $^{d}$ |
| 2% RHB | 6.02 $^{b}$ | 1.11 $^{b}$ | 58.00 $^{c}$ |
| 4% RHB | 6.14 $^{a}$ | 1.04 $^{c}$ | 61.00 $^{b}$ |
| 2% RH | 5.89 $^{c}$ | 1.07 $^{c}$ | 59.67 $^{b}$ |
| 4% RH | 5.90 $^{c}$ | 0.98 $^{d}$ | 63.00 $^{a}$ |

Same letters are not significantly different at ($p < 0.05$) by Tukey's HSD test.

Table 3.4 shows the effects of RH and RHB application in soil on saturated water content, field capacity water content, permanent wilting point water content, and plant available water content. No significant differences were found among the treatments on above parameters compared to that of control.

Table 3.4: Effects of RH and RHB application on saturated water content ($\theta_s$), field capacity water content ($\theta_{fc}$), permanent wilting point water content ($\theta_{wp}$), and plant available water content ($\theta_a$).

| Treatment | $\theta_s$ cm$^3$ cm$^{-3}$ | $\theta_{fc}$ cm$^3$ cm$^{-3}$ | $\theta_{wp}$ cm$^3$ cm$^{-3}$ | $\theta_a$ cm$^3$ cm$^{-3}$ |
|---|---|---|---|---|
| Control | 0.447 $^{a}$ | 0.372 $^{a}$ | 0.112 $^{a}$ | 0.260 $^{a}$ |
| 2% RHB | 0.481 $^{a}$ | 0.395 $^{a}$ | 0.114 $^{a}$ | 0.281 $^{a}$ |
| 4% RHB | 0.492 $^{a}$ | 0.427 $^{a}$ | 0.132 $^{a}$ | 0.295 $^{a}$ |
| 2% RH | 0.486 $^{a}$ | 0.380 $^{a}$ | 0.115 $^{a}$ | 0.265 $^{a}$ |
| 4% RH | 0.507 $^{a}$ | 0.429 $^{a}$ | 0.137 $^{a}$ | 0.292 $^{a}$ |

Same letters are not significantly different ($p < 0.05$) by Tukey's HSD test.

The effects of RH and RHB application on saturated hydraulic conductivity of soil is shown in Fig 3.1. Saturated hydraulic conductivity was significantly ($p < 0.05$) higher in the 4% RH than that in the control, but no significant difference ($p < 0.05$) were observed between 2% or 4% RHB application and the control.

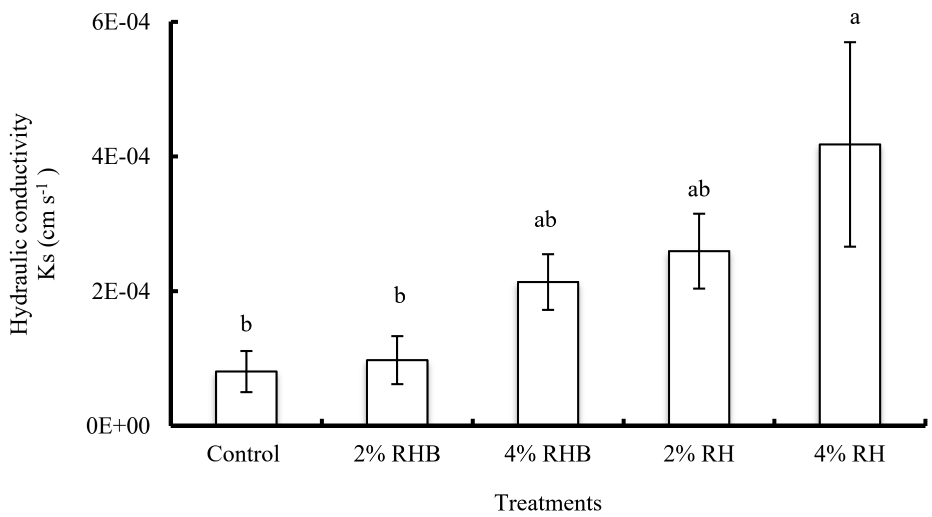



Fig. 3.1: Effects of RH and RHB application on saturated hydraulic conductivity of soil. Error bars indicate the standard deviations of means (S.D.) (n=3).

FTIR analysis of RH and RHB samples are presented in Fig. 3.2a for RH and Fig. 3.2b for RHB, respectively. The RH showed 5 major peaks; the peak at 3,306 $cm^{-1}$ corresponded to O-H stretching carboxylic group, the peak at 2,363 $cm^{-1}$ corresponded to -C≡C- stretching of alkynes, a peak at 1,603 $cm^{-1}$ corresponded with the C=C phenyl ring, peak at 1,033 $cm^{-1}$ indicative of secondary alcohol C-C or Si-O-Si stretch, and the peak at 781 $cm^{-1}$ corresponding with aromatic C-H bending. The RHB showed 4 major peaks; the peak at 2,359 $cm^{-1}$ corresponded to -C≡C- stretching of alkynes, a peak at 1,559 $cm^{-1}$ correlated with C=C phenyl ring, peak at 1,051 $cm^{-1}$ indicative of secondary alcohol C-C or Si-O-Si stretch, and the peak at 791 $cm^{-1}$ correlated with aromatic C-H bending.

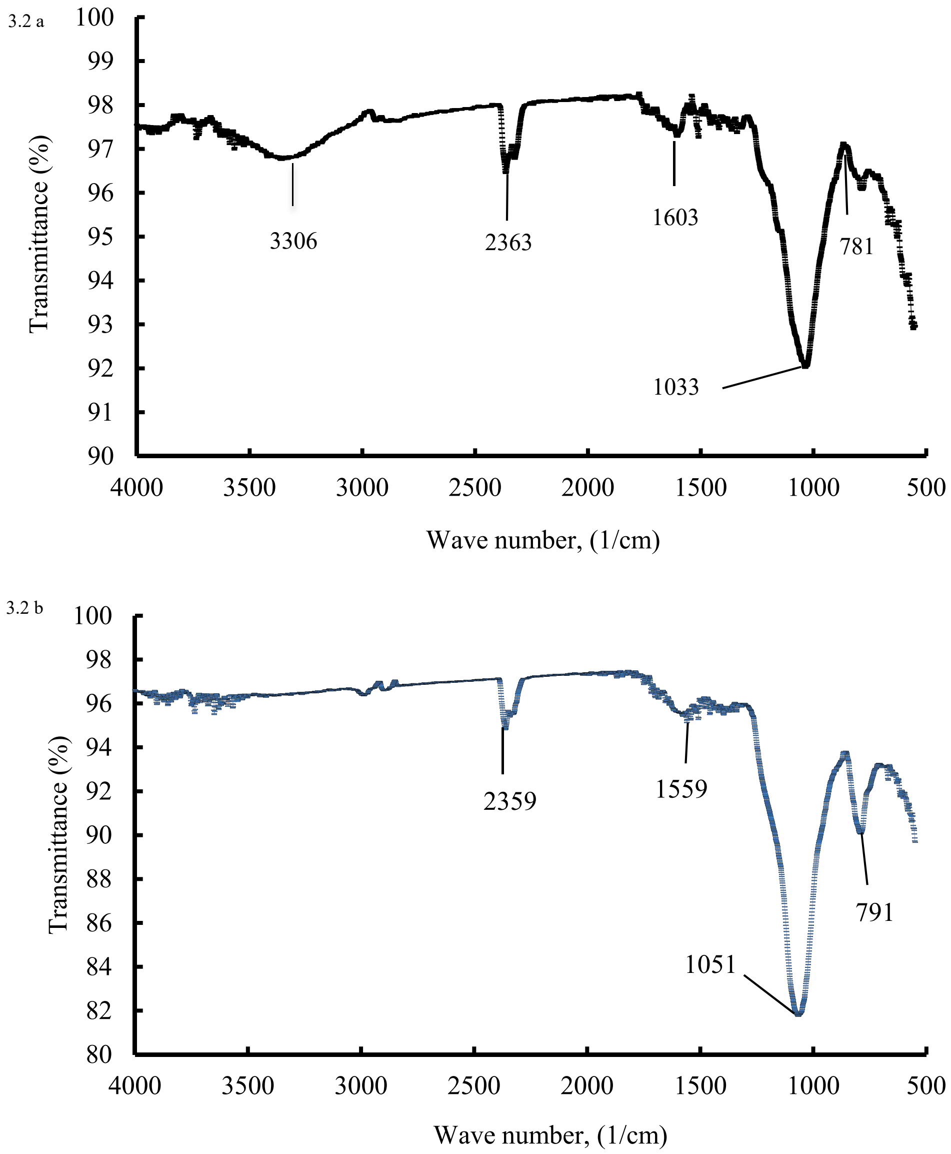



Fig. 3.2: Fourier transform infrared spectroscopy (FTIR) analysis of a) RH and b) RHB

### 3.4.3. Effects of RH and RHB application on rice growth and yield components

Table 3.5 shows the effects of RH and RHB application on panicle length, panicle weight, plant height, and number of tiller of rice. No significant differences ($p$ <0.05) were found among the treatments for the panicle length. The plant height was significantly ($p$ < 0.05) higher in the 4% RH than that in the control, but no significant differences ($p$ < 0.05) were observed between 2% and 4% RH. No significant differences were observed among the treatments for number of tillers.

Table 3.5: Effects of rice husk and rice husk biochar application on growth components of rice

| Treatment | Panicle length (cm) | Panicle weight (g) | Height (cm) | Tiller number |
|---|---|---|---|---|
| Control | 13.5 ± 0.5 $^{a}$ | 3.4 ± 0.4 $^{a}$ | 81.7 ± 1.7 $^{b}$ | 26.5 ± 1.4 $^{a}$ |
| 2% RHB | 14.2 ± 0.8 $^{a}$ | 4.0 ± 0.3 $^{a}$ | 83.8 ± 2.0 $^{ab}$ | 28.8 ± 3.9 $^{a}$ |
| 4% RHB | 13.9 ± 0.2 $^{a}$ | 3.7 ± 0.4 $^{a}$ | 83.1 ± 0.7 $^{ab}$ | 24.9 ±1.9 $^{a}$ |
| 2% RH | 13.8 ± 0.1 $^{a}$ | 3.4 ± 0.2 $^{a}$ | 83.2 ± 0.5 $^{ab}$ | 25.8 ± 4.0 $^{a}$ |
| 4% RH | 13.2 ± 0.2 $^{a}$ | 3.7 ± 0.2 $^{a}$ | 85.8 ± 1.3 $^{a}$ | 24.8 ± 2.4 $^{a}$ |

Same letters are not significantly different ($p < 0.05$) by Tukey's HSD test.

Table 3.6 shows the effects of RH and RHB application on grains per panicle, filled grains, panicle number, 1000 grain-weight, and yield of rice. No significant differences ($p$ <0.05) were observed for number of grains per panicle, filled grains, panicle number, and 1000 grain weight compared to that of control. Grain yield was significantly higher in the 2% RHB amended soils than that in the control. The 2% RHB significantly increased the grain yield by 38.7% compared to that of the control. No significant differences were observed between 2% RH, 4% RH, 4% RHB, and control.

Table 3.6: Effects of rice husk and rice husk biochar application on yield components of rice

| Treatment | No. of grains per panicle | Filled grain (%) | Panicle number (per hill) | 1000 grain-weight（g） | Yield (t ha$^{-1}$) |
|---|---|---|---|---|---|
| Control | 71 ± 8.7 $^{a}$ | 86.1 ± 2.5 $^{a}$ | 22.2 ± 1.6 $^{a}$ | 21.0 ± 0.3 $^{a}$ | 3.18 ± 0.04 $^{b}$ |
| 2% RHB | 75 ± 7.2 $^{a}$ | 88.0 ± 0.5 $^{a}$ | 25.8 ± 2.9 $^{a}$ | 22.4 ± 0.5 $^{a}$ | 4.41± 0.17 $^{a}$ |
| 4% RHB | 76 ± 8.1 $^{a}$ | 86.8 ± 6.5 $^{a}$ | 20.7 ± 1.1 $^{a}$ | 22.0 ± 0.8 $^{a}$ | 4.08 ± 0.81 $^{ab}$ |
| 2% RH | 70 ± 2.7 $^{a}$ | 85.4 ± 4.0 $^{a}$ | 24.8 ± 1.6 $^{a}$ | 21.4 ± 0.6 $^{a}$ | 3.75 ± 0.16 $^{ab}$ |
| 4% RH | 79 ± 2.5 $^{a}$ | 88.5 ± 1.9 $^{a}$ | 21.3 ± 3.7 $^{a}$ | 22.2 ± 0.2 $^{a}$ | 3.88 ± 0.17 $^{ab}$ |

Same letters are not significantly different ($p < 0.05$) by Tukey's HSD test.

The effect of RH and RHB application on dry matter yield of rice is shown in Fig 3.3. The 2% RHB significantly increased the DMY by 27.3% compared to that of control. No significant differences were observed between 2% RH, 4% RH, 4% RHB, and control.

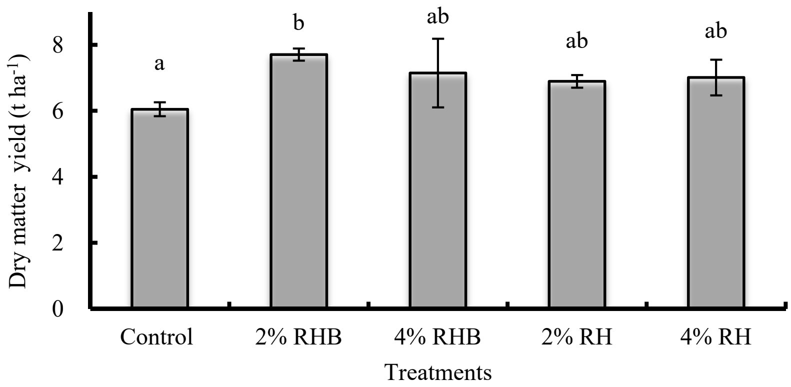



Fig. 3.3: Effects of RH and RHB application on dry matter yield (DMY) of rice. Error bars indicate the standard deviations of means (S.D.) (n=3).

The effect of RH and RHB application on harvest index of rice is shown in Fig 3.4. No significant differences were observed among the treatments for harvest index of rice.

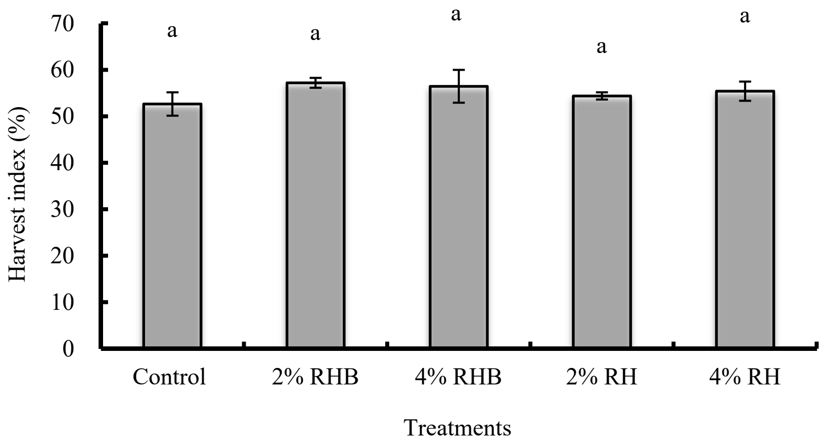



Fig. 3.4: Effects of RH and RHB application on harvest index (HI) of rice. Error bars indicate the standard deviations of means (S.D.) (n=3).

## 3.5. Discussion

### 3.5.1. Characterization of rice husk (RH) and rice husk biochar (RHB)

The proximate analysis of RH and RHB indicates RH has more volatile matter and less fixed carbon compared to that of RHB (Table 3.1). Our results are consistent with Paethanom *et al*. (2012). They found that higher pyrolysis temperature resulted in higher fixed carbon content. At a higher pyrolysis temperature, volatiles matters are removed, which resulted the higher fixed carbon of the biochar particle. Paethanom *et al*. (2012) reported that the RHB produced at 600°C, 800°C and 1,000°C pyrolysis temperatures had 26.37%, 34.33%, and 38.88% fixed carbon; 51.7%, 53.9%, and 56.1% ash content and 21.9%, 11.7%, and 5.0% volatile matter, respectively. The volatile matter and fixed carbon for RHB in our study were 15.64% and 35.24%, respectively (Table 3.1). Therefore, we assumed that the RHB used in this experiment was produced at temperature of 600-800°C. We also found the pH of RHB was higher (10.5) which confirms that RHB used in our experiment was produced at higher temperature. Similar to our findings, Masulili *et al*. (2010) reported high pH (>8.0) of RHB produced at 600°C pyrolysis temperature.

Jindo *et al*. (2014) performed FTIR analysis of biochar produced at different temperatures. They reported that loss of aliphatic compounds occurs when the charing temperature increased from 400 to 600°C; at the same time the formation of aromatic carbon appeared more clearly. The biochar produced at pyrolysis temperature of 600°C had a higher recalcitrant character due to increase in the number of aromatic compounds and is a suitable method for carbon sequestration (Jindo *et al*., 2014). The FTIR analysis of RHB revealed that there was an absence of the hydroxyl group (Kizito *et al*., 2015; Jindo *et al*., 2014) (Fig 3.2b).

### 3.5.2. Effects of rice husk (RH) and rice husk biochar (RHB) application on soil physico-chemical properties

The application of RHB significantly increased the soil pH (Table 3.3). The increase in pH by the application of 2% and 4% RHB may be due to the high pH of RHB (Table 3.2). In addition, RHB used in this experiment had high ash content (Table 3.2), which might have increased the pH of RHB amended soil. Similar increase in soil pH was reported by Gamage *et al*. (2016) due to the addition of RHB into soil. Dai *et al*. (2014) reported that the RHB has high ash content which contains alkaline carbonates, alkali earth metals and organic anions into soil and might increase pH of soil.

The application of RH and RHB decreased the bulk density of soil (Table 3.3). The possible reason for decrease in bulk density by the application of RH and RHB might be due to lower BD of RH and RHB compared to control (Verheijen *et al*., 2009; Persaud *et al*., 2018). The application of biochar increases the volume of soil which might be due to the rearrangement of soil and biochar particles (Gamage *et al*., 2016). Tejada and Gonzalez

(2007) reported that the application of organic amendment to soil reduces the BD due the rearrangement of particles from release of applied pressure by soil-organic particles. The application of RH and RHB increased the porosity of soil. This may be due to bulk density is negatively correlated with the porosity.

The application of RH and RHB do not have significant effect on water holding capacity of soil (Table 3.4). Similar to our findings, Tryon (1948) did not find any significant increase in plant available water in loamy soil. However, Uzoma *et al*. (2011) reported significant increase in plant available water in sandy soil. Abrishamkesh *et al*. (2015) reported that the effect of biochar application on plant available water content depends on soil and biochar types.

The application of 4% RH significantly increased the saturated hydraulic conductivity (Fig 3.1). This might be due to improved macro-porosity due to enhanced macro-aggregation (Messing and Jarvis, 1993; Igalavithana *et al*., 2017).

### 3.5.3. Effects of rice husk (RH) and rice husk biochar (RHB) application on rice yield

The application 2% RHB significantly increased the grain and dry matter yield of rice (Table 3.6; Fig. 3.3). Similar to our findings, Koyama *et al*. (2016) and Munda *et al*. (2016) reported that the application of biochar increased the rice yield due to increase in Si and N, P, and K uptakes. However, de Melo Carvalho *et al*. (2013) did not find any increase in rice yield where there was no water or fertilizer stress. The addition of biochar to the soil has dual benefits. Biochar can supply nutrient directly (due to some native nutrient available in biochar particle) to the plant as well as it can absorb the nutrient cations from the soil and supply to the plant (Thammasom *et al*., 2016; Munda *et al*., 2016; Major *et al*., 2010; Peng *et al*., 2011). The negative charges on biochar surface might have increased the number of adsorption sites of nutrient onto the biochar (Thammasom *et al*., 2016). The increase in rice yield may be also due to fact that biochar has some ash-derived nutrients, such as K, Ca, and Mg (Thammasom *et al*., 2016). The RHB used in our study has high CEC and exchangeable cations such as Ca, K, and Mg compared to that of control soil which might have increased the rice yield in our experiment. The RHB used in this experiment was found to be rich in C (Table 3.1) and other major plant nutrients in the soil which may have increased in rice yield (Alburquerque *et al*., 2014).

## 3.6 Conclusions

The application of RH and RHB significantly decreased the bulk density while porosity of soil was significantly increased. The application of 2% and 4% RHB significantly increased the pH of soil. However RH did not have any significant impact on pH of soil. No significant increase in water holding capacity of soil was observed by application of RH and RHB. We concluded that application of RH and RHB to soil improves soil physico-chemical properties. The application of 2% RHB significantly increased the dry matter and rice yield by 27.3% and 38.7%, respectively. We did not find any significant increase in dry matter and rice yield by application of 2% RH compared to control. Our results did not identify any reasons behind an increase in rice yield by the application of 2% RHB. Further studies are needed to clarify the reasons for an increase in rice yield with the application of 2% RHB.

# Chapter 4 Comparative study on residual effects of rice husk and rice husk biochar on dry matter yield, nutrient uptakes, and agronomy efficiencies of komatsuna (*Brassica rapa* L.)

## 4.1. Abstract

Comparative study on residual effects of rice husk (RH) and rice husk biochar (RHB) on dry matter yield (DMY), nutrient uptakes, and agronomy efficiencies (AE) of komatsuna (*Brassica rapa* L.) were examined in this study. RH was applied at 2% (w: w), whereas RHB was applied at rates of 2% and 4% (w:w), and their effects on rice cultivation were examined in our previous study in 2014. In October 2017, three years after the rice cultivation, the soil media were used to see their residual effects on komatsuna cultivation in this study. Komatsuna seeds were sown in pots in a greenhouse and plants were harvested after thirty-five days. Results showed that 2% RHB application significantly increased the DMY by 27.2% and 19.3% compared with those of the control and 2% RH application, respectively. The 2% RHB significantly increased nutrient uptakes, AE, and recovery efficiency (RE) than those of the control. Meanwhile, 2% RH did not significantly increase these values compared with control.

Keywords: Agronomy efficiencies, komatsuna, nutrient uptakes, Rice husk, rice husk biochar

## 4.2. Introduction

World population is expected to increase to 9 billion by 2050, leading to greater demand for food, freshwater, and energy (Haider *et al*., 2017). To meet the increased demand for food, the crop yield per unit area has to be increased through intensive farming. However, long-term intensive farming usually leads to lower soil fertility, which causes plant nutrient deficiencies (Sanchez, 2002) and crop yield reduction (Gunarathne *et al*., 2017). Although farmers can use inorganic fertilizers to improve crop yields, they are costly inputs (Baligar *et al*., 2001) with low overall efficiency (Baligar and Bennet, 1986; Fageria *et al*., 2012)). Leaching, run-off, gaseous emissions, and fixation in soil are known as the main causes of the reduced efficiency of inorganic fertilizers (Baligar *et al*., 2001).

Agronomic efficiency (AE) is yield increase per unit of nutrient applied and recovery efficiency (RE) is defined as the increase in crop uptake of a nutrient in the aboveground parts of the plant in response to application of that nutrient (Liu *et al*., 2011). Both AE and RE are measured when a study on nutrient omission plot has been implemented (Liu *et al*., 2011). These indicators are commonly used in agronomic research to assess the efficiency of fertilizer application.

Currently, UNEP (2009) reported that approximately 140 billion Mg of agricultural wastes are globally generated annually. Future increases in food production will generate a further larger quantity of agriculture waste (Walsh *et al*., 2000). About three billion people depend on rice as a staple food worldwide (Nguyen 2005), and in Japan, 7.9 million Mg of rice are produced annually (Chauhan *et al*., 2017). High demand and production of rice results in a large supply of rice husk (RH) which is a by-product of hulling rice. Williams *et al.* (1972) reported that incorporation of RH into soil can significantly improve soil properties, by decreasing bulk density (BD), increasing soil organic matter (SOM), available nutrients, and ultimately increase crop yield. Furthermore, conversion of RH into rice husk biochar (RHB) is gaining interest as a sustainable way to reuse RH. Application of RH or RHB to crop fields, therefore not only improves the physico-chemical properties of soil but also resolves waste disposal problems.

Biochar is a carbon rich compound produced by pyrolysis of biomass in a limited oxygen environment. Currently, biochar is receiving interest because of its potential for carbon sequestration and its ability to increase soil fertility and crop production (Sohi *et al.,* 2010). Hardie *et al.* (2014) reported that the porous structure of biochar helps to improve soil properties such as hydraulic conductivity, water holding capacity, and BD. The effect of biochar on crop yields might be due to an increase in soil pH, enhancement in cation exchange capacity (CEC), and increase in soil water retention (Sohi *et al.,* 2010). Biochar has a large surface area and a high CEC, which helps to increase the nutrient retention capacity of soil and AE of fertilizers, which ultimately increase crop yields. Application of biochar into the soil also increases nutrient uptake of plants either by its inherent nutrient content, or by improving nutrient absorption (Lehmann *et al.,* 2003). Furthermore, fertilizer retention in soil by biochar application reduces leaching of nutrients and enhances fertilizer use efficiency (Lehmann *et al.,* 2003). Accordingly, combined application of both chemical fertilizers and biochar can improve AE, by increasing nutrient retention and delaying release of nutrients into soil (Al-Wabel *et al.,* 2017). However, Muñoz *et al*. (2009) reported that the effects of biochar on crop production can be changeable depending on the application method and rates, soil types, soil fertility, temperature for biochar in production, and residence time.

In our previous experiment, we found that 2% RHB application significantly increased yield of rice compared with that in the control, but 4% RHB application had lower yield than in 2% RHB application (Mishra *et al.,* 2017).

The effects of biochar application on physico-chemical properties of soil and crop production may change over time due to physico-chemical interactions of biochar with soil (Kookana *et al.,* 2011). In this study, the residual effects of RH and RHB application at three years after the rice cultivation were studied on a) dry matter yield (DMY), b) N, P, and K uptakes, c) AE for nitrogen (AEN), phosphorous (AEP), and potassium (AEK), and d) RE for nitrogen (NRE), phosphorous (PRE), and potassium (KRE) by using komatsuna (*Brassica rapa* L.) as the test crop. Komatsuna, known as Japanese mustard spinach, is a popular leafy vegetable grown in Japan belonging to the family Brassicaceae. It has high nutritional value and requires application of high levels of N fertilizer within a short growth period (Moh *et al.,* 2018).

## 4.3. Materials and Methods

### 4.3.1. Experimental design and treatments

We used soil media that were previously used for a rice cultivation experiment (Mishra *et al*., 2017). In brief, soil was collected from a depth of 0 to 20 cm from a paddy field of Kyushu University's Kasuya-Machi farm, Fukuoka, Japan (33$^{\circ}$ 37' 00" N, 130$^{\circ}$ 28' 00" E), and the soil was manually mixed with RH or RHB that were sieved with a 2 mm mesh screen. RH was applied at a rate of 2% (w:w), whereas RHB was applied at rates of 2% or 4% (w:w) in 2014. Unamended soil was used as a control. Rice was cultivated from May to September 2014 in pots in a greenhouse. In September 2014, rice was harvested and the soil media were left fallow in the same pots for three years until September 2017 in the greenhouse.

In October 2017, soil media from the previous experiment were removed from pots, air-dried, and passed through a 2 mm mesh screen. No additional RH or RHB were added for this experiment. Plastic pot was filled with each of 3.5 kg soil medium, and we prepared five treatments as follows: soil with no amendment (T1, the negative control); soil with chemical fertilizer (T2, the control); soil with 2% RH plus chemical fertilizer (T3); soil with 2% RHB plus chemical fertilizer (T4); soil with 4% RHB plus chemical fertilizer (T5). For the chemical fertilizer application, each pot received 0.5 g of N from $(NH_4)_2SO_4$, 0.5 g of $P_2O_5$, and 0.5 g of $K_2O$ from $KH_2PO_4$ + $K_2HPO_4$. Komatsuna seeds, purchased from Tohoku Seed Co. Ltd., were sowed in pots containing the soil media, and the plants were cultivated in a greenhouse at Hakozaki, Kyushu University, Fukuoka, Japan (33° 37' 36" N, 130° 25' 30" E) from October to November 2017. All treatments received equal application of irrigation water during the cultivation.

### 4.3.2. Residual effects of rice husk (RH) and rice husk biochar (RHB) application on physico-chemical properties of soil

To determine the residual effects of RH and RHB application on physico-chemical properties, the samples were first sieved with a 2-mm mesh screen. Soil pH ($H_2O$) (1:5, soil: $H_2O$, w:v) was measured using LAQUA twin B-712 pH meter. For N, P, and K determination, soil samples were digested using the salicylic acid-$H_2SO_4$-$H_2O_2$ (Ohyama, 1991). Total N (TN) was determined using the indophenol method (Cataldo *et al.*, 1974) and total phosphorus (TP) was analyzed using the ascorbic acid method (Murphy and Riley, 1962). TK was measured by atomic absorption spectrophotometry using a Z-5300 spectrophotometry.

Amended and non-amended soils were also analyzed for physico-chemical properties. Soil samples corresponding to control, 2% RH, 2% and 4% RHB were prepared by first mixing and manually packing them in soil core rings of 100 $cm^3$ diameter. Bulk density (*BD*) was determined as the ratio of oven dry weight at 105°C for 24 h to the total volume of the sample. Soil organic matter (SOM) was determined by the ignition method (Storer, 1984).

Total porosity of soils was calculated using the *BD* and particle density (2.65 g $cm^{-3}$) values in the relationship developed by Danielson and Sutherland, (1986). This method assumes that soil porosity (*F*) is the fraction of total volume not occupied by soil assuming a particle density of 2.65 g $cm^{-3}$ (Danielson and Sutherland, 1986).

$$F = ((1 - BD) / PD) * 100 \qquad \text{(Equation 4.1)}$$

where: *F* (%) is the porosity, *BD* = bulk density (g $cm^{-3}$), *PD* = particle density (g $cm^{-3}$) of soil (assumed to be 2.65 g $cm^{-3}$).

The particle size distribution of soil was determined using the pipette method (Gee and Bauder, 1986). The textural class of soil was then identified from the Marshal triangle (Konert and Vandenberghe, 1997).

**4.3.3. Determination of dry matter yield (DMY) of komatsuna**

Thirty-five days after sowing, komatsuna plants were harvested by cutting at the cotyledon node. Plants were oven dried at 70°C for 72 h, and DMY was measured in grams on a digital balance.

### 4.3.4. Determination of N, P, and K uptakes by komatsuna

Oven-dried komatsuna shoot samples were ground into fine powder by using a Cyclotec 1093 sample mill 100-120 mesh, Tecator AB (Hoedanaes, Sweden). Samples were digested and TN, TP, and TK were measured by the same procedure as described in section 4.3.2. Uptakes of N, P, and K by komatsuna were calculated by multiplying N, P, and K content of komatsuna by the DMY.

### 4.3.5. Computation of agronomy efficiencies and recovery efficiencies

Agronomy efficiencies for nitrogen (AEN), phosphorous (AEP), and potassium (AEK) were calculated as follows: (Peng *et al.*, 1996):

$$\text{AEN (g g}^{-1}\text{N)} = (DMY_F - DMY_0) \text{ / N fertilizer applied} \quad \text{(Equation 4.2)}$$

$$\text{AEP (g g}^{-1}\text{P)} = (DMY_F - DMY_0) \text{ / P fertilizer applied} \quad \text{(Equation 4.3)}$$

$$\text{AEK (g g}^{-1}\text{K)} = (DMY_F - DMY_0) \text{ / K fertilizer applied} \quad \text{(Equation 4.4)}$$

where: $DMY_F$ and $DMY_0$ are DMY (g) of plant from fertilized pots and unfertilized pots, respectively.

Recovery efficiencies for nitrogen (NRE), phosphorous (PRE), and potassium (KRE) were calculated as follows (Dobermann, 2005):

$$NRE(\%) = ((NUF – NUU) / \text{N fertilizer applied}) * 100 \qquad \text{(Equation 4.5)}$$

$$PRE(\%) = ((PUF – PUU) / \text{P fertilizer applied}) * 100 \qquad \text{(Equation 4.6)}$$

$$KRE(\%) = ((KUF – KUU) / \text{K fertilizer applied}) * 100 \qquad \text{(Equation 4.7)}$$

where: *NUF*, *PUF*, and *KUF* are N, P, and K uptakes of fertilized pots, respectively; *NUU*, *PUU*, and *KUU* are N, P, and K uptakes of unfertilized pots, respectively.

**4.3.6. Statistical analysis**

The experiment was conducted in a completely randomized design with three replications. The data were analyzed using one-way ANOVA followed by Tukey's HSD test ($p < 0.05$). All analyses were done with STATISTIX 8 (Analytical Software, Tallahassee, FL, US).

## 4.4. Results

### 4.4.1. Proximate and ultimate analysis of soil, rice husk biochar (RHB), and rice husk (RH)

Results of proximate and ultimate analysis of soil, RHB, and RH are presented in Table 3.1 (Chapter 3). In brief, the proximate and ultimate analysis of soil, RHB, and RH were as follows. The volatile matter of RH was approximately four times higher than that of RHB. The ash content and fixed carbon of RHB were higher than those of RH. Ultimate analysis of RH and RHB revealed that C and N of RHB were higher than those of RH, whereas H of RH was higher than that of RHB. C:N ratio of RHB was lower than that of RH.

Soil texture was classified as clayey soil by the pipette method. Percentages of clay, silt, and sand were 47.4, 23.5, and 29.1%, respectively.

### 4.4.2. Residual effects of rice husk (RH) and rice husk biochar (RHB on physico-chemical properties of soil

Physico-chemical properties of soil, RHB, and RH are presented in Table 3.2 (Chapter 3). In brief, the physico-chemical properties of soil, RHB, and RH were as follows. RHB was alkaline, whereas soil was slightly acidic. The CEC of RHB was higher than that of soil. Additionally, higher Exc. K was found in RHB compared with that in soil.

In contrast, Exc. Ca was higher in soil than that in RHB. The BET surface area of RHB was higher than those of RH and soil. TP and TK were higher for RHB than for RH. The available P of RHB was higher than that of soil. RH had the lowest bulk density.

Table 4.1 shows SOM, BD, porosity, and saturated water content ($\theta_s$) of soil media before komatsuna cultivation. SOM was significantly higher in the RH treatment and increased with increased application of RHB. BD was significantly lower in the RH treatment and decreased with increased application of RHB. We found that soil water content (SWC) increased with applications of RH and RHB, though the differences among the treatments were not statistically significant.

Table 4.1: Residual effects of rice husk (RH) and rice husk biochar (RHB) application on soil organic matter (SOM), bulk density (*BD*), porosity, and saturated water content ($\theta_s$) before komatsuna cultivation

| Treatment | SOM (%) | BD ($g\ cm^{-3}$) | F (%) | $\theta_s$ ($cm^3\ cm^{-3}$) |
|---|---|---|---|---|
| Control | 6.79 $^{c}$ | 1.18 $^{a}$ | 55.28 $^{c}$ | 0.44 $^{a}$ |
| 2% RH | 7.88 $^{b}$ | 1.05 $^{bc}$ | 60.19 $^{ab}$ | 0.49 $^{a}$ |
| 2% RHB | 7.64 $^{b}$ | 1.11 $^{b}$ | 57.92 $^{b}$ | 0.48 $^{a}$ |
| 4% RHB | 8.51 $^{a}$ | 1.02 $^{c}$ | 61.32 $^{a}$ | 0.50 $^{a}$ |

Same letters are not significantly different ($p < 0.05$) by Tukey's HSD test.

Table 4.2 shows the residual effects of RH and RHB application on TN, TP, TK, and pH of soil media before komatsuna cultivation. There was less effects of the rice cultivation on the differences in the soil chemical properties among the treatments by the application of RH and RHB as no significant increase in TN and TP was found after rice cultivation. The non-significant differences in TN and TP may be due to the cultivation of rice. However, TK was significantly higher in the 2% and 4% RHB amended soils than for that in the control. In addition, soil pH before komatsuna cultivation was significantly ($p < 0.05$) higher in the 2% and 4% RHB than that in the control, but no significant differences ($p < 0.05$) were observed between 2% RH application and the control.

Table 4.2: Residual effects of RH and RHB application on total nitrogen (TN), total phosphorous (TP), total potassium (TK), and pH before komatsuna cultivation

| Treatment | TN (%) | TP (%) | TK (%) | pH |
|---|---|---|---|---|
| Control | 0.141 $^{a}$ | 0.220 $^{a}$ | 0.373 $^{c}$ | 5.95 $^{c}$ |
| 2% RH | 0.137 $^{a}$ | 0.223 $^{a}$ | 0.412 $^{bc}$ | 6.04 $^{bc}$ |
| 2% RHB | 0.142 $^{a}$ | 0.234 $^{a}$ | 0.467 $^{ab}$ | 6.14 $^{b}$ |
| 4% RHB | 0.144 $^{a}$ | 0.247 $^{a}$ | 0.495 $^{a}$ | 6.35 $^{a}$ |

Same letters are not significantly different ($p < 0.05$) by Tukey's HSD test.

### 4.4.3. Residual effects of rice husk (RH) and rice husk biochar (RHB) application on dry matter yield (DMY) of komatsuna

The residual effects of RH and RHB application on DMY of komatsuna are shown in Fig 4.1. The 2% RHB and 4% RHB had significantly higher DMY than in control and 2% RH. DMY was increased by 27.2% and 19.3% in 2% RHB compared with those in control and 2% RH, respectively. DMY was reduced by 4.6% in 4% RHB compared with that in 2% RHB, but no significant differences were observed between 2% RHB and 4% RHB.

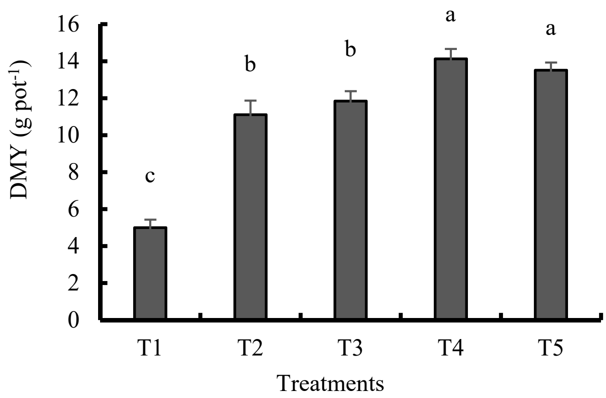



Fig. 4.1: Residual effects of RH and RHB on DMY of komatsuna. Error bars indicate the standard deviations of means (S.D.) (n=3). Where T1= no fertilizer, T2= control, T3= 2% RH, T4= 2% RHB, T5= 4% RHB

### 4.4.4. Residual effects of rice husk (RH) and rice husk biochar (RHB) application on N, P, and K uptakes of komatsuna

The residual effects of RH and RHB on N, P, and K uptakes of komatsuna are shown in Fig. 4.2. N uptake was significantly higher in 2% RHB than in control and 2% RH (Fig. 4.2a). P uptake was significantly higher in 2% RHB and 4% RHB than in control (Fig. 4.2b). K uptake was significantly higher in 2% RHB and 4% RHB than in control and 2% RH (Fig. 4.2c). No significant differences were found between control and 2% RH for N, P, and K uptakes of komatsuna.

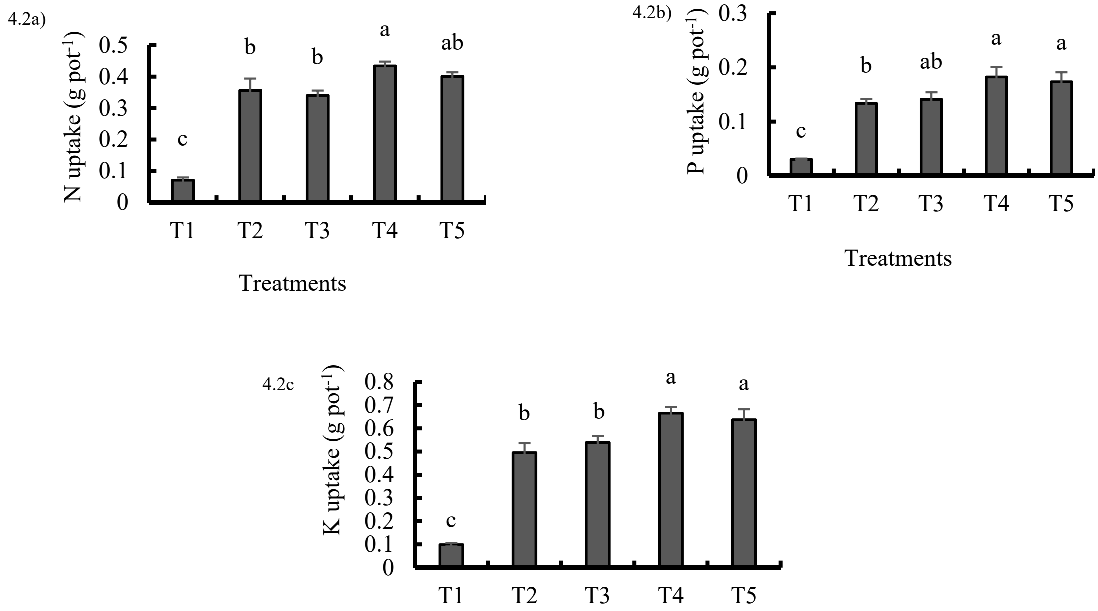



Fig. 4.2: Residual effects of RH and RHB application on 4.2a) N uptake, 4.2b) P uptake 4.2c), and K uptake of komatsuna. Error bars indicate the standard deviations of means (S.D.) (n=3). Where T1= no fertilizer, T2= control, T3= 2% RH, T4= 2% RHB, T5= 4% RHB

### 4.4.5. Residual effects of rice husk (RH) and rice husk biochar (RHB) on agronomy efficiencies and recovery efficiencies of komatsuna

The residual effects of RH and RHB on AEN, AEP, and AEK of komatsuna are shown in Table 4.3. AEN was significantly higher in 2% RHB and 4% RHB than in control and 2% RH. AEN of 2% RHB was greater than that of control by 6.04 g $g^{-1}$ N. Similarly, AEP and AEK were significantly higher in 2% RHB and 4% RHB than in control and 2% RH. No significant differences were found between control and 2% RH in AEN, AEP, and AEK.

Table 4.3: Residual effects of RH and RHB application on AE for nitrogen (AEN), AE for phosphorous (AEP), and AE for potassium (AEK) of komatsuna

| Treatments | AEN ($g\ g^{-1}$ N) | AEP ($g\ g^{-1}$ P) | AEK ($g\ g^{-1}$ K) |
|---|---|---|---|
| T2 | 12.23 $^{b}$ | 28.01 $^{b}$ | 14.73 $^{b}$ |
| T3 | 13.69 $^{b}$ | 31.37 $^{b}$ | 16.50 $^{b}$ |
| T4 | 18.27 $^{a}$ | 41.87 $^{a}$ | 22.01 $^{a}$ |
| T5 | 17.03 $^{a}$ | 39.03 $^{a}$ | 20.52 $^{a}$ |

Same letters are not significantly different at ($p < 0.05$) by Tukey's HSD test. Where T1= no fertilizer, T2= control, T3= 2% RH, T4= 2% RHB, T5= 4% RHB

The residual effects of RH and RHB application on recovery efficiencies (NRE, PRE, and KRE) of komatsuna are shown in Fig. 4.3. NRE was significantly higher in 2% RHB than in control and 2% RH (Fig. 4.3a). However, no significant differences were observed between control, 2% RH, and 4% RHB. PRE was significantly higher in 2% RHB than in control (Fig. 4.3b), but no significant differences were observed between control, 2% RH, and 4% RHB. KRE was significantly higher in 2% RHB and 4% RHB than in control (Fig. 4.3c), but no significant differences were observed between control and 2% RH.

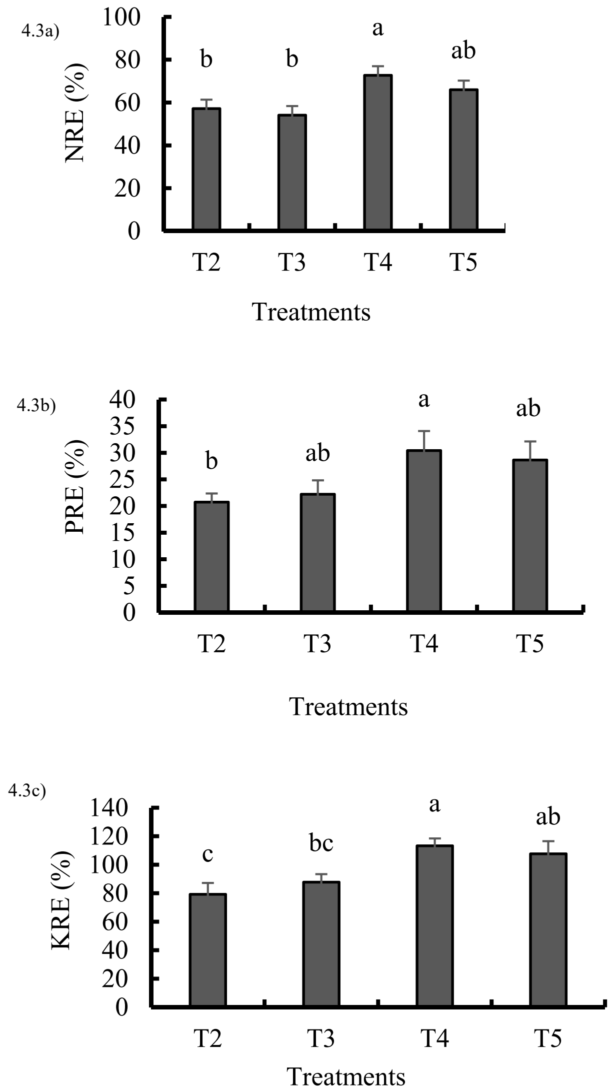



Fig. 4.3: Residual effects of RH and RHB application on 4.3a) NRE (%), 4.3b) PRE (%), and 4.3c) KRE (%) of komatsuna. Error bars indicate the standard deviations of means (S.D.) (n=3). Where T1= no fertilizer, T2= control, T3= 2% RH, T4= 2% RHB, T5= 4% RHB

## 4.5. Discussion

### 4.5.1. Residual effects of rice husk (RH) and rice husk biochar (RHB) application on dry matter yield (DMY) of komatsuna

In this experiment, we investigated the residual effects of RH and RHB on komatsuna production three years after rice cultivation. We found that the application of RHB (2% RHB and 4% RHB) significantly increased DMY compared with that in control (Fig. 4.1). Similarly, Hien *et al*. (2017) reported that 2% RHB application significantly increased spinach fresh yield compared with that in the control, whereas 5% RHB application decreased yield compared with that in 2% RHB application. The significant increase in DMY in our experiment for 2% RHB and 4% RHB might have been due to the following reasons. Biochar amendment has two functions. First, biochar increases crop yields mainly due to its direct supply of nutrients (Peng *et al*., 2011; Xu *et al*., 2013). Biochar is a soil fertilizer and provides some nutrients, particularly N, P, K, and Mg because of its inherent nutrient and higher cation content than those of soil (Xu *et al*., 2013). We found that residual effects of 2% and 4% RHB application increases soil K (Table 4.2), compared to that in the control, although not all the nutrients will be available for plants due to recalcitrance nature of biochar (Xu *et al*., 2013). The increase in the soil K (Table 4.2) in our experiment might have been due to ash and higher K contents of biochar (Table 3.1, Chapter 3). Jeffery *et al*. (2011) reported that greater availability of nutrients in the soil, particularly K, is one of the main positive effects of biochar on crop productivity. In agreement with Jeffery *et al*. (2011), higher soil K in 2% RHB and 4% RHB might have increased DMY in 2% RHB and 4% RHB. The second function of biochar is as a conditioner which improves soil physico-chemical properties, enhance nutrient adsorption, improve nutrient accessibility, and influence the crop yield (Peng *et al*., 2011; Xu *et al*., 2013; Oladele *et al*., 2019). Biochar as a conditioner might also have increased DMY in 2% RHB and 4% RHB. The increase in DMY was also associated with an increase in AEs (Table 4.3). Partey *et al.* (2014) reported that application of biochar with N, P, and K fertilizer increased the AEs, which led to 27% increase in maize yield compared with the yield with the application of N, P, and K fertilizer alone.

### 4.5.2 Residual effects of rice husk (RH) and rice husk biochar (RHB) application on N, P, and K uptakes of komatsuna

We found a significant increase in N, P, and K uptakes in 2% RHB compared with that in control (Fig. 4.2). These results are in agreement with previous studies (Mishra *et al.,* 2018; Ippolito *et al.,* 2012). The RHB used in this experiment had 44.87% ash content, which might have contributed to increase soil K (Table 4.2) and may have been responsible for the higher K uptake of komatsuna in 2% RHB and 4% RHB than in control (Fig. 4.2c). Lehmann *et al*. (2003) and Rondon *et al*. (2007) also observed that application of biochar increased plant K uptake due to higher K content of biochar.

### 4.5.3. Residual effects of rice husk (RH) and rice husk biochar (RHB) application on agronomy efficiencies and recovery efficiencies of komatsuna

We found that AEN, AEP, and AEK were significantly higher in 2% RHB and 4% RHB (Table 4.3) than in control and 2% RH. The increase in AEs might have been due to increased nutrients availability or soil organic matter (SOM) from biochar application (Baligar *et al*., 2001; Yamato *et al*., 2006). We observed an increase in SOM in the RHB treatments (Table 4.1). Baligar *et al*. (2001) reported that SOM helps to maintain good soil aggregation, saturated water content ($\theta_s$), and exchangeable K and Mg. Best management practices such as the application of crop residues, compost, or biochar can improve the SOM and contribute to sustainable crop production through higher recovery efficiencies (Baligar *et al*., 2001). Martinsen *et al*. (2014) reported that NRE, PRE, and KRE increased from 10–15%, 6–9%, and 21–31% to 30–45%, 18–27%, and 60–90%, respectively, with application of biochar. In agreement with Martinsen *et al*. (2014), we also found that N, P, and K recovery efficiencies were significantly higher in 2% RHB than in control (Fig. 4.3). There was no significant impact of RH application on NRE in 2% RH (Fig 4.3a), which might be due to the decomposition of RH without N immobilization after three years of rice cultivation. No significant increase in TN, TP, TK, and pH by application of RH may represents that there was decomposition of RH without N immobilization (Table 4.2). KREs in 2% RHB and 4% RHB were significantly higher than that in control (Fig. 4.3c) and were higher than 100%. The residual effects of 2% and 4% RHB application might have significantly increased the total K in 2% RHB and 4% RHB compared to those of control (Table 4.2), which possibly increased KREs in 2% RHB and 4% RHB compared to that in control.

## 4.6. Conclusions

This study revealed that the residual effects of RHB application led to higher levels of DMY, nutrient uptakes (N, P, and K), AE (AEN, AEP, and AEK), and RE (NRE, PRE, and KRE) of komatsuna in 2% RHB than those of control. The 2% RHB significantly increased the DMY by 27.2% and 19.3% than those for control and 2% RH, respectively**.** No significant increase in DMY, nutrient uptakes, AEs, and REs in 2% RH than those in control was found. We concluded that 2% RHB was more effective than 2% RH in terms of increase in DMY, nutrient uptakes, AE, and RE.

Because this study was conducted for only one season, further studies are needed to verify the residual effects of RH and RHB on DMY, nutrient uptakes (N, P, and K), AE, and RE.

# Chapter 5 Effects of biochar on physico-chemical properties of soil, yield, and water use efficiency of soybean under different irrigation regimes

## 5.1. Abstract

To investigate the effects of biochar on soil physico-chemical properties, seed yield (SY), above ground biomass yield (AGBY), and water use efficiency (WUE) of soybean under different irrigation regimes, a pot experiment was conducted. Bamboo biochar (BB) was applied at the rate of 1 and 3% (w:w). Three irrigation treatments were applied to recover the water level to 100%, 80%, and 60% of field capacity (FC), on alternate days. Results showed that 3% BB application rate significantly increased the plant available water content. Bulk density was significantly reduced by 91.4% by 3% BB application. I1B2 (100% FC with 3% BB) increased AGBY by 114.0% compared to I1B0 (100% FC without biochar). Whereas, I3B2 (60% FC with 3% BB) increased AGBY only by 108.2% compared to I3B0 (60% FC without biochar). P and K uptake of I1B2 were significantly increased compared to I1B0. The K uptake was increased by 132.0% at I1B2 compared to I1B0. We concluded that biochar application enhances the physico-chemical properties of soil and 3% BB application significantly increased the AGBY and WUE for AGBY.

Keywords: biochar, irrigation, soil properties, soybean, water use efficiency

## 5.2. Introduction

About 70% of globally available freshwater is used for agriculture (WRI, 2005). Due to climate change and increases in population, the competition for freshwater resources is increasing. However, to feed 8 billion people, it has been recommended that the globally irrigated area should be increased by more than 20% and crop yield should be increased by 40% by 2025 (Lascano *et al*., 2007). Increases in temperature and the variability in rainfall are becoming common due to climate change, which will make drought more common in the future (Pachauri *et al*., 2014).Therefore, it is necessary to use irrigation water efficiently. Nowadays, full irrigation (FI) is considered as an imprudent method of use of water and is not suitable for the water-scarce areas. Deficit irrigation (DI) and partial root-zone drying irrigation are water-saving techniques that can be used to increase water use efficiency (WUE) (Liu *et al*., 2006). In areas of water scarcity, DI and soil amendment with organic material which increases the water-holding capacity of the soil, are two ways to mitigate water stress.

Biochar is a C-rich product, produced from plant or animal residues through pyrolysis in an anoxic or low oxygen environment. The properties of biochar depend on the production temperature and feedstock. It is used for improving soil physico-chemical properties, plant growth, and to mitigate climate change by C sequestration (Basso *et al*., 2013). It is also used for increasing the water-holding capacity of soil (Basso *et al*., 2013). Sohi *et al.* (2009; 2010) reported that the application of biochar increases both water holding capacity and crop yield and decreases the amount of irrigation required to grow the crop. Lehman *et al.* (2006) reported that the crop productivity was increased by 20-120% with the application of biochar. Application of 35 t $ha^{-1}$ in Terra Preta soils increased the field capacity (FC) by 18% compared to control (Lehman *et al.,* 2006). Kameyama *et al.* (2012) reported that application of bagasse biochar at rates of 1, 3, 5, and 10% (w:w) increased the plant available water content ($\theta_a$) proportionally for sandy soil from 0.02 to 0.06 (v:v) and for clay soil from 0.04 to 0.15 (v:v).

Soybean (*Glycine max* L. Merr.) is a grain legume crop that represents 50% of legume acreage and 68% of legume production globally (Herridge *et al*., 2008). Moderate DI in the vegetative growth stage for a short period does not reduces soybean yield. However, long-term DI can reduce yield. The reproductive stage is most sensitive to DI and may significantly reduce yield (Lich *et al*., 2013).

N, P and K uptake by crop depend on the types of biochar, crop and soil characteristics. Biochar application to soil increases the N uptake (Chan *et al*., 2008), whereas grass and rice husk biochar have no effect on N and P uptake in sweet potato due to the high C: N ratio of the biochar that leads to N immobilization (Walter and Rao, 2015).

To overcome drought conditions, it is important to increase yield by increasing WUE. Since biochar is porous in nature, it can increase the water-holding capacity of soil. The addition of biochar in water-deficit conditions may enhance the physico-chemical properties of soil, soybean yield (SY), above ground biomass yield (AGBY), and WUE. Research on the effects of biochar on soybean SY, AGBY, and N, P, and K uptake under DI is lacking.

Hence, this study was conducted with an objective to investigate the effects of biochar on (a) physico-chemical properties of soil, and (b) SY, AGBY, WUE, and N, P, and K uptake ability of soybean under different irrigation regimes.

## 5.3. Materials and methods

### 5.3.1. Experimental design and treatments

A greenhouse experiment was conducted at Kaizuka, Fukuoka, Japan (33° 37' 36" N, 130° 25' 30" E) from May to August 2017. Soil (at a depth of 0 to 15 cm) was collected from the upland field at Fukuoka Agriculture and Forestry Research Center (33° 43' 5" N, 130° 58' 33" E). It was air-dried and passed through a 4-mm mesh to remove stones and rubble. Ten kg of soil was filled in each Wagner pot (1/2000a).

The commercial bamboo biochar (BB) was purchased from Tachibana-Bamboo Co. Ltd., Fukuoka, Japan. The biochar was made from the *Phyllostachys* genus growing in the Yame city, Fukuoka, Japan. It was manufactured at 800-1000°C for 40 min.

BB was ground and sieved with a 2-mm mesh before manual mixing with soil. The BB was applied at the rate of 1 and 3% (w:w) (20 and 60 t $ha^{-1}$ on a volumetric basis). Untreated soil served as a control.

Irrigation treatments were applied, to recover the water level to 100%, 80%, and 60% of FC. The nine treatments of this experiment are shown in Table 5.1. Vegetable soybean purchased from Tohoku Seed Co. Ltd. was used as the test crop. Two weeks after sowing, one healthy seedling was retained; other seedlings were removed from the pot. Six grams of a compound fertilizer containing N: P: K in a 3:8:8 ratios were applied to supply of nutrients to soybean.

Table 5.1: Details about treatments

| Irrigation / Biochar (B) | 100% FC (I1) | 80% FC (I2) | 60%FC (I3) |
|---|---|---|---|
| 0% BB (B0) | I1B0 | I2B0 | I3B0 |
| 1% BB (B1) | I1B1 | I2B1 | I3B1 |
| 3% BB (B2) | I1B2 | I2B2 | I3B2 |

### 5.3.2. Characterization of biochar

Elemental C and N were analyzed by an elemental analyzer MT-5 CN Corder elemental analyzer (Yanaco New Science Inc., Kyoto, Japan). The pH ($H_20$) was measured by using a LAQUA twin B-712 pH meter (HORIBA Ltd., Kyoto, Japan) (1:5, biochar: $H_2O$, w:v). Cation exchange capacity (CEC) and exchangeable cations (Exc.) were determined using the ammonium acetate shaking extraction method (Muramoto, 1992). Exchangeable cations were measured by using a Z-5300 atomic absorption spectrophotometer (Hitachi, Tokyo, Japan). The specific surface area was obtained from adsorption isotherms, using the Brunauer-Emmett-Teller (BET) method. The fixed C, volatile matter and ash content were determined by the methods of the American Society for Testing and Materials (ASTM) D1762-84 (2007). The volatile matter was ascertained by measuring the weight loss of the BB while heating in a covered crucible at 950$^{\circ}$C for 6 min. The ash content was determined by measuring the weight loss after combustion in air at 750$^{\circ}$C for 6 h.

### 5.3.3. Determination of physico-chemical properties of soil

To determine physico-chemical characteristics, soil was ground with a mortar and pestle. It was sieved with a 2-mm mesh. Soil pH ($H_20$) (1:5 soil: $H_2O$) was measured by using a LAQUA twin B-712 pH meter (HORIBA Ltd., Kyoto, Japan) (1:5, biochar: $H_2O$, w:v). For N, P, and K determination, the soil and biochar samples were digested using the salicylic acid-$H_2SO_4$–$H_2O_2$ digestion method (Ohyama, 1991). Total N (TN) was determined using the indophenol method (Cataldo *et al*., 1974) and total phosphorus P (TP) was analyzed using ascorbic acid method (Murphy and Riley, 1962). Total K (TK) was measured by using a Z-5300 atomic absorption spectrophotometer (Hitachi, Tokyo, Japan).

For water retention experiment, samples were prepared by mixing biochar and soil. The prepared samples were packed in soil core rings of 100 $cm^3$ manually. Samples were submerged in deionized water overnight before start of the water retention experiment. Field capacity water content ($\theta_{fc}$; -33 kPa) and permanent wilting point water content ($\theta_{wp}$; -1500 kPa) were determined by the centrifuge method of Richards *et al*. (1938). Plant available water content ($\theta_a$) was calculated as the difference between $\theta_{fc}$ and $\theta_{wp}$. Bulk density was determined as the ratio of oven dry weight at 105°C for 24 hours to the total volume of the sample. Soil organic matter was determined by the ignition method (Storer, 1984). Particle size distribution was determined using the pipette method (Gee and Bauder, 1986). The textural class was identified from the Marshal triangle (Konert and Vandenberghe, 1997). Porosity ($F$) was determined as: (Danielson and Sutherland, 1986)

$$F = ((1 - BD) / PD) \times 100 \qquad \text{(Equation 5.1)}$$

where: $F$ (%), $BD$ (g $cm^{-3}$), and $PD$ (g $cm^{-3}$) are the total porosity, bulk density, and particle density of soil, respectively. Particle density of soil was assumed to be 2.65 g $cm^{-3}$.

### 5.3.4. Irrigation treatments

After three weeks of sowing, irrigation treatments, at 100%, 80% and 60% of FC were started. The irrigation volumes ($W_i$) were calculated at each irrigation time based on average of 5 EC moisture sensors (Decagon, USA) reading installed at the depth of 5 and 15 cm using the following formula:

$$W_i\,(\mathrm{L}) = V_s\,(\mathrm{L}) \times (\theta_{fc} - \theta_{aw}) \qquad \text{(Equation 5.2)}$$

where: $V_s$ is the soil volume of pot, $\theta_{fc}$ is the volumetric water content (%) at field capacity (FC) , and $\theta_{aw}$ is the actual volumetric water content (%).

Irrigation amount applied was recovered to 100%, 80% and 60% of FC on alternate days. The irrigation treatment lasted for 35 days. Water in volumes of 23.6, 18.9 and 14.2 liter (L) of was applied for 100%, 80% and 60% of FC, respectively. The same volume of water was applied to biochar and control treatments.

### 5.3.5. Determination of seed yield (SY) and aboveground biomass yield (AGBY)

SY and AGBY were observed after final harvest. The SY was measured in grams per plant. Above ground biomass was oven dried at 70°C for 72 hours and measured by digital balance in grams per plant to find AGBY.

### 5.3.6. Determination of water use efficiency for seed yield (WUEY) and water use efficiency for aboveground biomass yield (WUEB)

Water use efficiency (g $L^{-1}$) for seed yield (WUEY) and aboveground biomass yield (WUEB) were calculated using the following equations (Viet, 1962):

$$WUEY = \frac{SY}{WUSY} \qquad \text{(Equation 5.3)}$$

$$WUEB = \frac{AGBY}{WUAGBY} \qquad \text{(Equation 5.4)}$$

where: $WUEY$ (g $L^{-1}$) is the water use efficiency for seed yield, $WUEB$ (g $L^{-1}$) is the water use efficiency for aboveground biomass yield (g $L^{-1}$) , $SY$ (g) is the seed yield, $AGBY$ (g) is the aboveground biomass yield, $WUSY$ (L) is the water used to produce $SY$, and $WUAGBY$ (L) is the water used to produce $AGBY$.

### 5.3.7. Determination of N, P, and K uptake by soybean

The shoots and leaves were separated from the other plant parts, were dried and ground into a powder by using a mill 100–120 mesh, Tecator AB (Hoedanaes, Sweden). Samples were digested by using the salicylic acid-$H_2SO_4$–$H_2O_2$ digestion method (Ohyama, 1991). TN, TP, and TK were measured by same procedure as described in 2.3. N, P, and K uptake was calculated by multiplying the N, P, and K content by AGBY.

### 5.3.8. Statistical analysis

The experiment was conducted in a fully randomized design. The combined effects of irrigation and biochar were analyzed using a two-way ANOVA. The Tukey's HSD test at $p < 0.05$ was applied as post-ANOVA test. All analyses were done with Statistix 8 software.

## 5.4. Results

### 5.4.1. Effects of biochar on physico-chemical properties of soil

Soil texture was identified as sandy loam by pipette method. Percentages of silt, sand and clay were 25.0%, 60.0% and 15.0%, respectively. BET surface area of soil and BB were 11.20 and 501.20 $m^2 g^{-1}$, respectively. The pH of BB and soil were 10.45 and 5.95, respectively. BB was alkaline, whereas the soil was slightly acidic.

Table 5.2 indicates the proximate analysis and bulk density of BB. Volatile matter and ash content of BB were low. The bulk density of BB was lower compared to control.

Table 5.2: Proximate analysis and bulk density of biochar

| | Volatile matter (%) | Ash content (%) | Moisture content (%) | Fixed carbon (%) | Bulk density ($g cm^{-3}$) |
|---|---|---|---|---|---|
| BB | 12.0 | 6.5 | 7.2 | 74.3 | 0.39 |

Table 5.3 shows TN, TP, TK, total carbon (TC), total hydrogen (TH), and C:N ratio of BB and soil. TC, TN and C:N ratios of BB were higher compared to control.

Table 5.3: Total nitrogen (TN), total phosphorous (TP), total potassium (TK), total carbon (TC), total hydrogen (TH), and C:N ratios of bamboo biochar and soil

| Samples | TN (%) | TP (%) | TK (%) | TC (%) | TH (%) | C:N ratio |
|---|---|---|---|---|---|---|
| Soil | 0.14 | 0.21 | 0.28 | 1.55 | 0.92 | 14.09 |
| BB | 0.92 | 1.30 | 4.64 | 83.76 | 0.87 | 90.30 |

Table 5.4 shows the effects of biochar application on TN, TP, and TK of soil. The addition of biochar to soil had almost no impact on TN of soil, whereas TP was slightly increased by the 3% BB application rate. The 3% BB rate increased TK compared to control.

Table 5.4: Effects of biochar application on total nitrogen (TN), total phosphorous (TP) and total potassium (TK) of soil

| Treatments | TN (%) | TP (%) | TK (%) |
|---|---|---|---|
| 1% BB | 0.15 | 0.24 | 0.30 |
| 3% BB | 0.16 | 0.28 | 0.39 |

Table 5.5 indicates CEC and exchangeable cations (Ca, Mg, Na, and K) of soil and BB. The CEC of BB was higher compared to soil. Similarly, BB has higher Exc (K) and Exc. (Mg) than those of soil. In contrast, soil has higher Exc. (Ca) than that of BB.

Table 5.5: Chemical properties of soil and biochar

| Samples | Exc. (Ca) (c mol Ca $kg^{-1}$) | Exc. (Mg) (c mol Mg $kg^{-1}$) | Exc. (Na) (c mol Na $kg^{-1}$) | Exc. (K) (c mol K $kg^{-1}$) | CEC (c mol $kg^{-1}$) |
|---|---|---|---|---|---|
| Soil | 7.72 | 1.04 | 0.13 | 0.34 | 20.15 |
| BB | 2.99 | 5.20 | 0.22 | 63.15 | 27.40 |

Table 5.6 shows the effects of application of biochar on porosity, bulk density, and SOM. Porosity was significantly increased by 107.5% by application of 3% BB compared to control. In contrast, the bulk density was significantly ($p < 0.05$) decreased by 91.4% by application of 3% BB compared to control. The SOM was significantly increased for both 1% BB and 3% BB treatments compared to control. However, 0% BB and 1% BB treatments were not significantly different from each other in terms of porosity and bulk density.

Table 5.6: Effects of biochar application on soil porosity, bulk density, and soil organic matter (SOM)

| Treatments | Porosity (%) | Bulk density (g $cc^{-1}$) | SOM (%) |
|---|---|---|---|
| 0% BB | 55.70 $^{b}$ | 1.16 $^{a}$ | 6.13 $^{a}$ |
| 1% BB | 56.90 $^{b}$ | 1.14 $^{ab}$ | 7.55 $^{b}$ |
| 3% BB | 59.90 $^{a}$ | 1.06 $^{c}$ | 9.32 $^{c}$ |

Same letter are not significantly different at $p < 0.05$by Tukey's HSD test.

Table 5.7 shows the effects of biochar application on saturated water content ($\theta_s$), field capacity water content (($\theta_{fc}$), permanent wilting point water content (($\theta_{wp}$), and plant available water content (($\theta_a$). The 3% BB application rate significantly increased the saturated water content ($\theta_s$) by 110.3%. The 1% BB and 3% BB application rate significantly increased the $\theta_{fc}$ by 106.0% and111.7%, respectively, compared to control. The 3% BB application rate significantly increased the $\theta_a$ by 115.0% compared to control. However, 0% BB and 1% BB treatments were not significantly different from each other in terms of $\theta_s$, $\theta_{fc}$, and $\theta_a$.

Table 5.7: Effects of biochar application on saturated water content ($\theta_s$), field capacity water content ($\theta_{fc}$), permanent wilting point water content ($\theta_{wp}$), and plant available water content ($\theta_a$).

| Treatments | Water retention characteristics | | | |
|---|---|---|---|---|
| | $\theta_s$ (%) | $\theta_{fc}$ (%) | $\theta_{wp}$ (%) | $\theta_a$ (%) |
| 0% BB | 52.49 $^{b}$ | 34.80 $^{c}$ | 15.08 $^{a}$ | 19.72 $^{b}$ |
| 1% BB | 54.94 $^{ab}$ | 36.90 $^{b}$ | 15.76 $^{a}$ | 21.15 $^{ab}$ |
| 3% BB | 57.88 $^{a}$ | 38.89 $^{a}$ | 16.14 $^{a}$ | 22.70 $^{a}$ |

Same letter are not significantly different at $p < 0.05$by Tukey's HSD test.

### 5.4.2. Effects of biochar application on seed yield (SY), aboveground biomass yield (AGBY), water use efficiency for seed yield (WUEY), and water use efficiency for aboveground biomass yield (WUEB) of soybean under different irrigation regimes

Fig. 5.1 shows the effects of biochar application on (a) SY and (b) AGBY under different irrigation regimes. The effects of biochar application rates on SY were statistically non-significant. However, SY was significantly ($p<0.001$) increased by increases in irrigation amount, but interactions between the two types of treatments were not significant. The highest SY was observed at I1B2 and the lowest was at I3B0. AGBY was significantly ($p<0.001$) increased by increases in either irrigation amounts or biochar rates, but interactions between two types of treatments were not significant. The highest AGBY was observed at I1B2 followed by I1B1 and I1B0, respectively and the lowest at I3B0. SY and AGBY at I1B0 were increased by 160.0% and 152.0%, respectively, compared to those at I3B0.

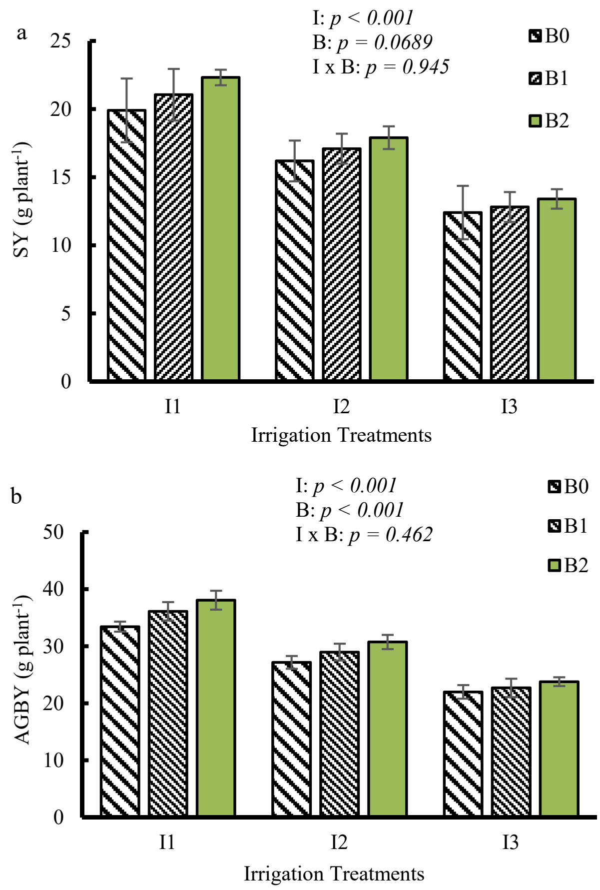
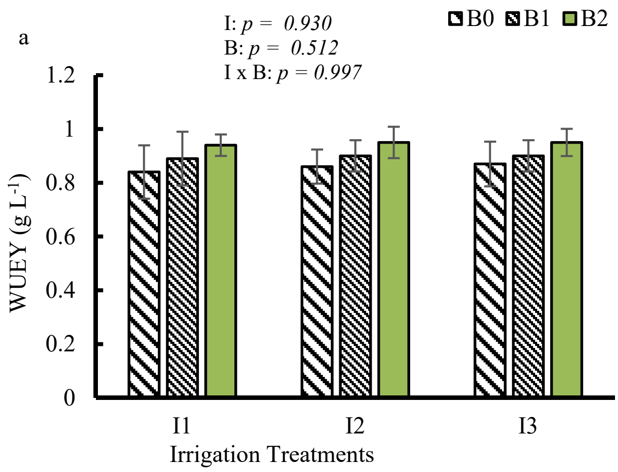



Fig. 5.1: Effects biochar application on (a) seed yield (SY) and (b) aboveground biomass yield (AGBY) under different irrigation regimes. B0, B1, and B2 indicate biochar application at the rate of 0, 1, and 3% (w: w), respectively. I1, I2, and I3 indicate irrigation levels, 100%, 80%, 60% of FC, respectively. While, I and B indicate biochar and irrigation treatments. Error bars indicate standard deviations of the mean (S.D.) (n=3).

Fig. 5.2 shows the effects of biochar application on (a) WUEY and (b) WUEB under different irrigation regimes. We did not find any significant increase in WUEY in either irrigation regimes or biochar treatments. The WUEB was non-significantly affected by irrigation treatments. However, biochar application significantly ($p < 0.05$) increased WUEB at I3B2. This indicates that higher application rate of biochar increases the WUEB. No interaction effect between biochar application rates and irrigation regimes were observed for either WUEY or WUEB.



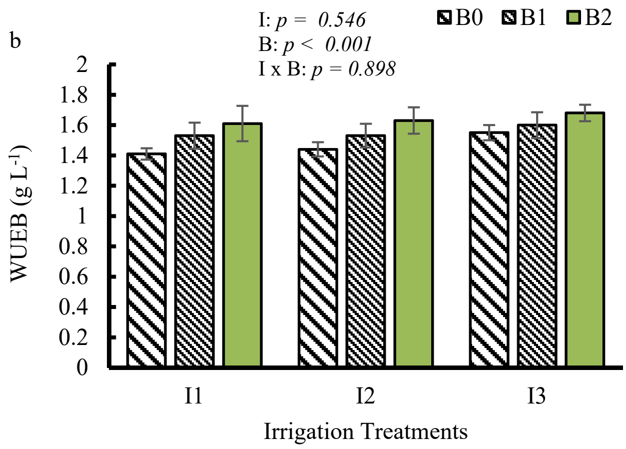




Fig. 5.2: Effects biochar application on (a) water use efficiency for seed yield (WUEY) and (b) water use efficiency for aboveground biomass yield (WUEB) under different irrigation regimes. B0, B1, and B2 indicate biochar application at the rate of 0, 1, and 3% (w: w), respectively. I1, I2, and I3 indicate irrigation levels, 100%, 80%, 60% of FC, respectively. While, I and B indicate biochar and irrigation treatments. Error bars indicate standard deviations of the mean (S.D.) (n=3).

### 5.4.3. Effects of biochar application on N, P and K uptake ability of soybean under different irrigation regimes

Fig. 5.3 shows the effects of biochar application on (a) N uptake, (b) P uptake, and (c) K uptake ability of soybean under different irrigation regimes. N uptake by soybean was increased significantly with the increase in the amount of water applied ($p < 0.001$). The highest and lowest N uptake were observed at I1B2 and I3B0, respectively. The biochar application rates non-significantly affected N uptake by soybean. Interaction effect between both irrigation regimes and biochar application rates treatments were non-significant for N uptake. I1B0 treatment increased N uptake by about twice compared to I3B0.

In addition, both biochar application rates and irrigation regimes had significantly effects on P uptake by soybean ($p < 0.001$). The mean P uptake values were larger for I1 and I2 than under I3 (Fig 5.3 (b)). Increases in biochar application rates increased P uptake by soybean. Similarly, interaction effect between the biochar application rates and irrigation regimes were observed only at ($p < 0.05$). B1 and B2 application rates of biochar significantly increased P uptake at I1. Furthermore, significant increase of P uptake was only observed for B2 at I2. At I3, the differences were not significant under B0, B1, and B2 application rates of biochar. I1B0 treatment increased the P uptake by 154.0% compared to I3B0.

Biochar application had a significant and positive impact on K uptake by soybean ($p < 0.001$). Similarly, increasing irrigation amount significantly increased the K uptake. Furthermore, interaction effect between biochar application rates and irrigation regimes were also observed for K uptake ($p < 0.001$). Biochar application rates B1 and B2 significantly increased K uptake at I1. However, only B2 application rate of biochar significantly increased K uptake at I2. At I3, the differences were not significant under B0, B1, and B2 application rates of biochar. K uptake for I1B0 was increased by 132.0% compared to I3B0. Also, I1B1 and I1B2 increased K uptake by 117.7% and 150.6% compared I1B0, respectively.

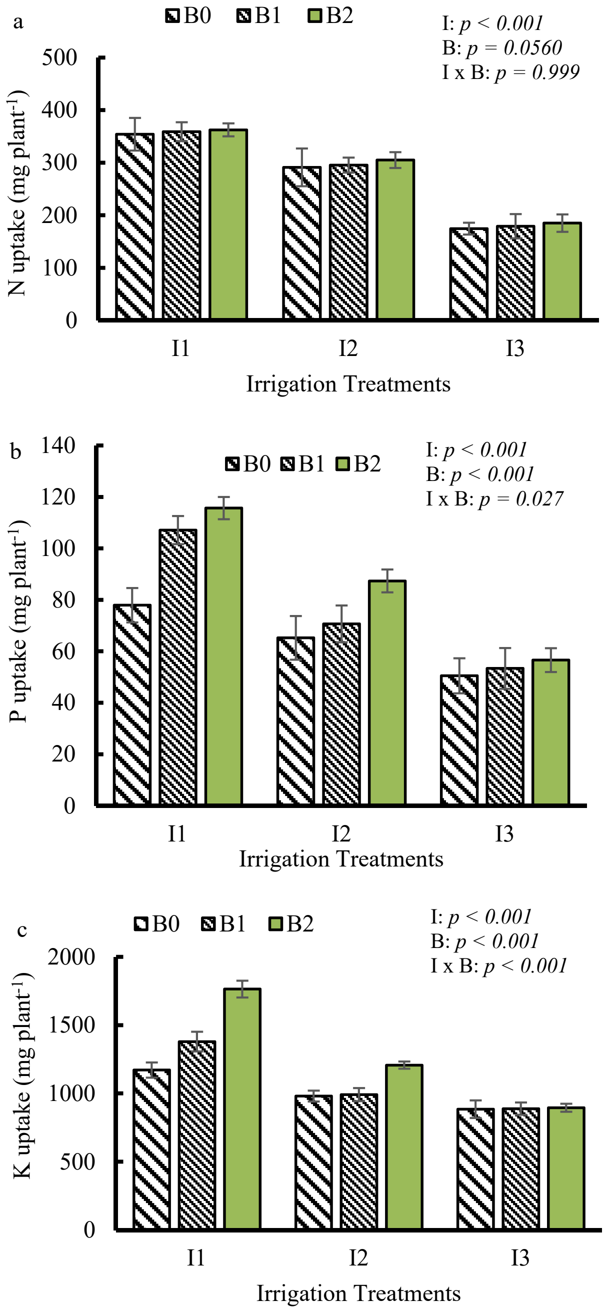



Fig. 5.3: Effects of biochar application on (a) N uptake (b) P uptake, and (c) K uptake under different irrigation regimes. B0, B1, and B2 indicate biochar application at the rate of 0, 1, and 3% (w: w), respectively. I1, I2, and I3 indicate irrigation levels, 100%, 80%, 60% of FC, respectively. While, I and B indicate biochar and irrigation treatments. Error bars indicate standard deviations of the mean (S.D.) (n=3).

## 5.5. Discussion

### 5.5.1. Effects of biochar application on physico-chemical properties of soil

The results of this study revealed that application of biochar in sandy loam soil increased volumetric water content probably due to increase in porosity of the soil which enables it to hold more or the high surface area of biochar compared to soil (Mishra *et al*., 2017; Akhtar *et al*., 2014).

Bulk density was decreased by the application of biochar to the soil. The decrease in bulk density by the application of biochar decreases the degree of compaction, increases porosity and increases the moisture retention capacity of soil (Rogovska *et al*., 2014). A similar reduction in bulk density was observed in the Midwestern Mollisols (Chan *et al*., 2008; Rogovska *et al*., 2014). The application rates 1% BB and 3% BB increased soil organic matter (SOM) which was directly related to the amount of biochar added to soil (Rogovska *et al*., 2014; Agbna *et al*., 2017) (Table 5.6). Biochar significantly increased soil organic matter (SOM) and organic carbon (OC) compared to control soil. Increase in OC depends on the C content of biochar applied (Abbasi and Anwar, 2015). Application of biochar at 5, 10 and 20 g $kg^{-1}$ significantly increased soil total carbon (TC) by 17.6, 37.6, and 68.8%, respectively, compared to control (Laird *et al*., 2010).

### 5.5.2. Effects of biochar application on seed yield (SY), aboveground biomass yield (AGBY), water use efficiency for seed yield (WUEY), and water use efficiency for aboveground biomass yield (WUEB) of soybean under different irrigation regimes

We did not find any significant increase in SY or WUEY of soybean by the application of biochar; thus, we reject our hypothesis that application of biochar would increase the SY or WUEY. However, 100% FC significantly increased the SY and AGBY of the soybean compared to DI treatments. There are a number of possible reasons for biochar not to increasing the SY or WUEY of soybean.

Biochar application is more effective in soil with lower levels of organic matter and higher bulk density (Keshavarz Afshar *et al*., 2016). However, the soil used in this experiment had comparatively higher organic matter and lower bulk density (Table 5.6).

The application rates 1% BB and 3% BB were not enough to significantly increase the SY and WUEY of soybean under DI condition. In contrast, Akhtar *et al.* (2014) reported that the yield and WUE of tomato were increased by the application of 5% of biochar. The increase in yield and WUE might be due to the higher application rate of biochar than that used in this experiment. In addition, the positive impact of biochar on water-holding capacity can be expected due to the aging of biochar after the first year of application (Keshavarz Afshar *et al*., 2016).

We observed that application of biochar increases the AGBY and WUEB (Fig.5.1 (b) and Fig. 5.2 (b)). The reason for this may be due to the negative surface charge of biochar that increases the CEC and favors retention of cations such as Ca, Mg and K. Our results indicated that biochar has higher CEC as well as exchangeable cations compared to control soil, which might have increase the CEC of biochar amended soil (Table 5.5). The higher CEC of biochar is due to the high surface area and oxygen content of biochar, which increases the ability of the soil to retain nutrients (Verheijen *et al*., 2010). Schimmelpfenning *et al.* (2012) reported that biochar with a surface area greater than 100 $m^2$ $g^{-1}$ has the ability to improve both water and nutrient retention in the soil which is beneficial for both microbes and plants. Our result highlighted that the surface area of BB was 501.20 $m^2$ $g^{-1}$. This may be another possible reason for the increase in AGBY and WUEB.

The sixty percentage of FC significantly decreased SY and AGBY of soybean compared to 100% FC (Fig. 5.1 (a) and (b)). In line with our results, Brevedan and Egli (2003) also reported that the SY was reduced by 39% in a water-stressed condition compared to full irrigation (FI). Decreases in soybean SY under water-deficit conditions have also been reported by earlier researchers (Eck *et al*. 1987; De Costa and Shanmugathasan 2002; Rosadi *et al*. 2005). The reason for the decrease in SY of soybean by deficit irrigation (DI) might be due to stomatal sensitivity to water-stress; they tend to close when plants are water-stressed. The closure of stomata in water-stressed conditions results in lowering of stomatal conductance of soybean and causes a decline in the photosynthesis rate (Mahajan and Tuteja, 2005). Teran and Singh (2002) also found that the net photosynthesis, leaf area index, and pod filling were decreased by an increase in DI that ultimately reduced growth and SY.

### 5.5.3. Effects of biochar application on N, P, K uptake ability of soybean under different irrigation regimes

We did not find any significant increase in N uptake by the application of biochar; however, P and K uptakes were increased significantly by the application of biochar. Thus we reject our hypothesis that application of biochar would increase N uptake by soybean. The 100% FC significantly increased the N, P and, K uptake by soybean compared to DI treatments (Fig. 5.3 (a), (b) and (c)). Our results are in line with those reported in previous studies of (Jeffery *et al*., 2011; Ippolito et al., 2012; Novak *et al*., 2014).

The addition of biochar increased P and K of soil, while N was almost unchanged in the soil. We found N uptake by soybean was non-significantly affected by the application of biochar. In contrast, Van Zwieten *et al*. (2010) found that the application of biochar significantly increased N uptake. The possible reason for the non-significant impact of biochar application on N uptake may be the slow release of nutrient by biochar. According to Chan and Xu (2012), only a small amount of N (0.12 kg N $ha^{-1}$) is available to crops when 60 t $ha^{-1}$ of biochar is added to soil. This small increase in the amount of available N was not enough to increase the N uptake by soybean in our study. In line with our results, Zhao *et al.* (2014) also reported no significant effect of biochar application on N uptake by rice in the first growing season, but N uptake increased considerably after three growing seasons. We found that P and K uptakes were significantly increased by application of biochar. This might be due to higher P and K contents in bamboo biochar (Table 5.4). Furthermore, the application of biochar to the soil increased the CEC of soil, which increases the ability of soil to hold K and store them for the plant uptake. In addition, bamboo biochar (BB) had higher exchangeable K, which might have increased the K uptake by soybean (Table 5.5). Ippolito *et al*. (2012) also found that K content in plant biomass was increased due to the application of biochar. Biochar produced from plant biomass increased K uptake and enhanced K content in common bean (Rondon *et al*., 2007). The application of fresh biochar has more available K which can be easily taken up by plants (Karer *et al*., 2013). Biochar used in this experiment was also derived from plant biomass and the soybean cultivation was done for the first year, which might be another possible reason the increase in K uptake by soybean.

We found that 100% FC significantly increased N, P and K uptakes of soybean compared to 60% FC (Fig. 5.3). In line with our results, Smika *et al.* (1965) also found that the application of N fertilizer increases the crop yield when available water conditions are sufficient and vice versa. Under DI condition, soil-N mineralization is reduced and thus lowered N availability (Bloem *et al*., 1992), which may have decreased the N uptake in water-deficit conditions in this study. Similarly, P uptake by soybean is also reduced under water-stressed conditions (Pinkerton and Simpson, 1986). The translocation of P to the shoots is severely affected even under relatively mild drought stress condition (Resnik, 1970). We also found similar reduction in P uptake by soybean with the increase in DI. K availability to the crop decreases with increase in water-stress due to the decrease of mobility in K under water-stress conditions. Kuchenbuch *et al*. (1986) reported that low levels of soil moisture reduced root growth and K uptake by onion. We also found a similar decrease in K uptake at 60% FC for soybean. Therefore, we concluded that the irrigation regimes had a profound effect on nutrient uptake ability of soybean.

## 5.6. Conclusions

We concluded that the application of 3% BB increased the AGBY and WUE for AGBY. I1B2 (100% FC with 3% BB) increased AGBY by 114.0% compared to I1B0 (100% FC without biochar). Whereas, I3B2 (60% FC with 3% BB) increased AGBY only by 108.2% compared to I3B0 (60% FC without biochar). P and K uptakes of I1B2 were significantly increased compared to I1B0. The uptake of K was increased by 132.0% at I1B2 compared to that of I1B0. The increase in porosity, water holding capacity, and decrease in bulk density by application of 3% BB (B2) might have enhanced the AGBY, WUEB, P, and K uptake ability of soybean of I1B2 compared to I1B0.

Further investigations are required to monitor changes in soil-crop systems to gain insights into the effects of biochar and different irrigation regimes over longer time periods on soybean production. In addition, the effects of biochar on other soil types, such as soils with less SOM may be tested in the future to determine the effects of biochar on soybean SY and AGBY under different irrigation regimes.

# Chapter 6 General Conclusions and Future Recommendations

## 6.1. General Conclusions

This study was conducted to investigate the effects of rice husk (RH) and rice husk biochar (RHB) on soil physico-chemical properties of soil and rice production (Chapter 3). We also clarify the residual effects of RH and RHB on dry matter yield (DMY), nutrient uptakes, agronomy use efficiency (AE), and recovery efficiency (RE) of komatsuna (Chapter 4). We further studied the effects of bamboo biochar (BB) application on physico-chemical properties of soil, yield, nutrient uptakes, and water use efficiency (WUE) of soybean under different irrigation regimes (Chapter 5).

We conducted the series of laboratory and greenhouse pot experiments for the fulfillment of the first objective (Chapter 3). Rice husk (RH) and rice husk biochar (RHB) were applied at the rates of 2% and 4% (w:w), respectively. Unamended treatment served as control. Rice seedlings were transplanted in pots in the month of May and harvested in September 2014 under greenhouse condition. Soil samples were prepared and analysed for physico-chemical properties. The results indicated that RH and RHB application significantly increased porosity but decreased soil bulk density. The application of RHB significantly increased pH of soil. The application of 2% RHB significantly increased the grain and dry matter yield of rice by 38.7% and 27.3%, respectively. However, 2% RH did not significantly increase these values compared with control. Our results did not identify any reasons behind an increase in rice yield by the application of 2% RHB. Further studies are needed to clarify the reasons for an increase in rice yield with the application of 2% RHB.

We conducted the series of laboratory and greenhouse pot experiments for the fulfillment of the second objective (Chapter 4). RH was applied at 2% (w:w), whereas RHB was applied at rates of 2% and 4% (w:w), and their effects on rice cultivation were examined in our previous study in 2014. In October 2017, three years after the rice cultivation, the soil media were used to see their residual effects on komatsuna cultivation in this study. Komatsuna seeds were sown in pots in a greenhouse and plants were harvested after thirty-five days. Results showed that 2% RHB application significantly increased DMY by 27.2% and 19.3% compared with those of the control and 2% RH application, respectively. The 2% RHB significantly increased nutrient uptakes, AE, and RE than those of the control. Meanwhile, 2% RH did not significantly increase these values compared with control. We concluded that 2% RHB application was more effective than 2% RH in terms of increase in DMY, nutrient uptakes, AE, and RE.

We conducted the laboratory and greenhouse pot experiments for the fulfillment of third objective (Chapter 5). In this experiment, BB was applied at the rate of 1 and 3% (w:w). Three irrigation treatments were applied to recover the water level to 100%, 80%, and 60% of field capacity (FC), on alternate days. Results showed that 3% BB application rate significantly increased in plant available water content. Bulk density was significantly reduced by 91.4% by 3% BB application. I1B2 (100% FC with 3% BB) increased aboveground biomass yield (AGBY) by 114.0% compared to I1B0 (100% FC without biochar). Whereas, I3B2 (60% FC with 3% BB) increased AGBY only by 108.2% compared to I3B0 (60% FC without biochar). P and K uptake of I1B2 were significantly increased compared to I1B0. The K uptake was increased by 132.0% at I1B2 compared to I1B0. We concluded that biochar application enhances the physico-chemical properties of soil and 3% BB application significantly increased the AGBY and WUE for AGBY.

Overall, the application of RH and RHB improves physico-chemical properties of soil. The 2% RHB application increased the pH, porosity, dry matter and grain yield of rice; however, 2% RH did not significantly increase these values compared with control. The residual effects of RH and RHB application shows that both 2% RHB and 4% RHB significantly increased the DMY, nutrient uptake, AE, and RE of komatsuna; however, we do not find any significant increase in above parameters by application of 2% RH. Similarly, the application of BB shows that only 3% BB of significantly increased the physico-chemical properties of soil and also increased the AGBY and WUE for AGBY.

Experiments were conducted in the greenhouse condition for only one season. Therefore, further studies are needed to know the effects of biochar on crop production under field condition. In addition, long-term effects of the application of biochar and its impact on water holding capacity of soil under deficit irrigation condition and its impact on WUE are needed to be investigated in both greenhouse and field condition.

### 6.2. Future Recommendations

In this experiment we found the application of rice husk (RH) and rice husk biochar (RHB) improves physico-chemical properties of soil (Chapter 3). The residual effects of RHB application into soil increased dry matter yield, nutrient uptakes, agronomy use efficiencies, and recovery efficiency of komatsuna (Chapter 4). We also found that application of bamboo biochar into soil improves the soil physico-chemical properties, nutrient uptakes, soybean production, and also increased water use efficiency for aboveground biomass yield (Chapter 5). However, several questions and underlying mechanism remained unanswered. The following are recommendations for future research.

The optimum rate of application of biochar under specific soil type is still not well defined. Cost-benefit analysis studies of biochar application are necessary to know the optimum rate of application. It is necessary to conduct the experiments with different rates of biochar in various soil textures to know the optimum rate of application for particular soil type under farmer's field condition in future.

The application of biochar increases the water holding capacity of soil. However, the effects of biochar application on water holding capacity and its influences after long-term application of biochar are still unknown. Therefore, it is necessary to conduct farmer's field trails to know the long-term impacts of biochar on water holding capacity and its performances under deficit irrigation conditions in terms of water use efficiency.

Biochar generally has low nutrient but its combination with organic and inorganic fertilizers can improve soil physico-chemical properties, crop yield, and nutrient use efficiency. The application rate of organic or inorganic fertilizers and biochar is needed to be investigated in the coming future for the optimization of the crop yield under different soil texture.

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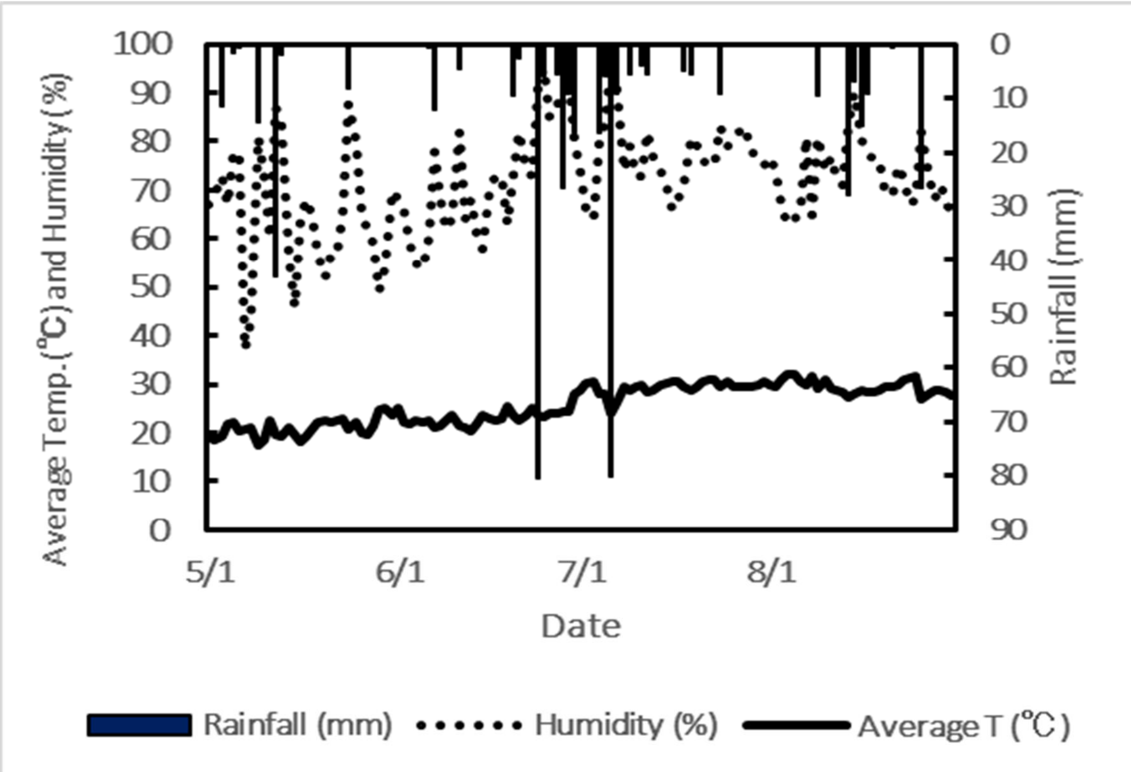
# APPENDIX

Appendix 1: Climate condition of experiment site of 2014

| | Rainfall | | Sunshine hours | | Solar radiations | |
|---|---|---|---|---|---|---|
| Month | 2014 (mm) | Avg* (mm | 2014 | Avg* | 2014 (MJ m-2) | Avg* (MJ m-2) |
| May | 94 | 142.5 | 280.7 | 194.6 | 21.2 | 17.9 |
| Jun | 101 | 254.8 | 107.9 | 149.4 | 13.6 | 16.2 |
| Jul | 373 | 277.9 | 148 | 173.5 | 14.7 | 16.9 |
| Aug | 462.5 | 172 | 79.7 | 202.1 | 10.7 | 17.6 |
| Sept | 107 | 178.4 | 159.5 | 162.8 | 14.2 | 14.4 |

Note: Avg* is the average values in last 30 years (1981 to 2010)




Climate condition from May to August, 2017


Commercial RH, RHB, and BB used in this experiment

Soil collection

Addition of amendment and pot experiment preparation

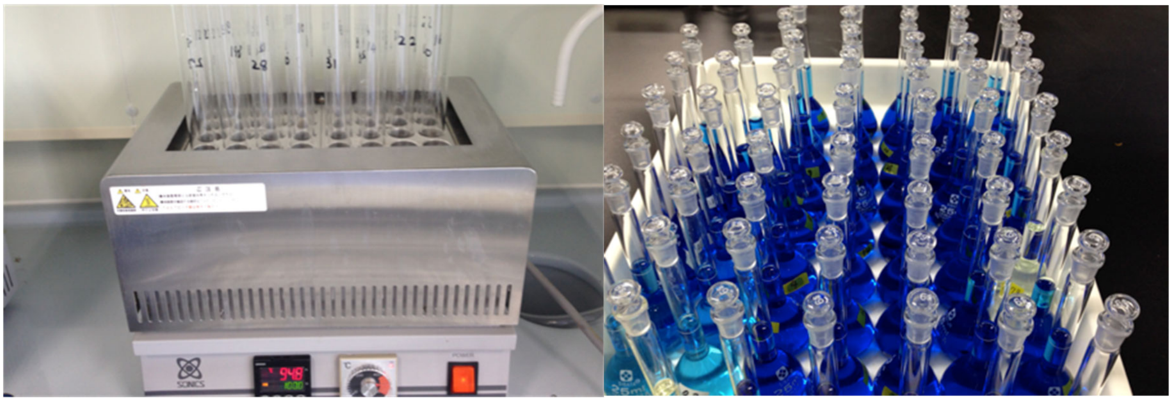
Rice seedling and rice plant after transplanting

Rice plant at 15days and 40 days after transplanting

Rice plant at harvest

Pot experiments


Analysis of saturated hydraulic conductivity, EC, and pH



Analysis of TN, TP, and TK

Gilford 300 spectrophotometer and polarized atomic absorption spectrophotometer for nutrient analysis