The response of sweet corn to biochar and chemical fertilizer applications for a sandy soil

Nattaporn Prakongkep1* • Robert John Gilkes2 • Worachart Wisawapipat3 • Parapond Leksungnoen3 • Wiwat Suaysom1 • Claude Hammecker1,4

1Land Development Department 2003/61 Ladyao, Chatuchak, Bangkok, 10900 Thailand.
2The University of Western Australia, 35 Stirling, Highway, Crawley, WA, 6009 Australia.
3Department of Soil Science, Faculty of Agriculture, Bangkhen Campus, 50 Kasetsart University, Bangkok, 10900 Thailand.
4Institut de Recherché pour le Développement (IRD), UMR 210, place Viala, Montpellier France.

*Corresponding author, E-mail: asoil@hotmail.com; nattaporn@ldd.go.th.

Accepted 23rd October, 2020.

Abstract. Sandy soils have limited agricultural production. Farmers try to overcome sandy soil constraints by using various soil amendments. This study aims to evaluate the combined effects of biochar and chemical fertilizer on plant growth and nutrient uptake for sweet corn grown on a sandy soil in a greenhouse experiment. The pot experiment was conducted in a greenhouse at the Land Development Department, Bangkok using a super agro sweet corn variety (Market’s variety) (Zea mays L.) on an Ustic Quartzipsamment at field capacity. The Complete Block Design with 2 replications and 16 treatments included 2 controls, 14 different biochar treatments (eucalyptus wood and rice husk biochars) with and without chemical (N, P and K) fertilizers applied at 1 and 2 times the fertilizer recommendation. The results showed that treatment 16 (rice husk biochar 40 ton ha⁻¹ with chemical fertilizer at 2 times fertilizer recommendation: R40F2) was the best treatment which significantly (p<0.05) increased sweet corn growth and nutrient uptake. Clearly, biochar can increase nutrient uptake and plant yield to the benefit of farmers however biochar does not have sufficient plant nutrient contents to support maximum plant growth. Applying biochar together with chemical fertilizers is the best solution for sandy soils.

Key words: Sweet corn, rice husk biochar, eucalyptus wood biochar, chemical fertilizer, sandy soil.

INTRODUCTION

The limiting factors for agricultural use of sandy soils include nutrient deficiencies, acidity, low organic matter content and low water holding capacity. To overcome these constraints, farmers need to add diverse inputs. When soil cannot supply all essential plant nutrients to support plant growth, farmers usually apply high quantities of chemical fertilizers. Chemical fertilizer application is one of the most effective inputs to increase nutrient uptake by crop plants and enhance yields (Sultana et al., 2015). Fertilizer prices represent a large portion of a producer’s capital. It is very important to maximize fertilizer use efficiency; therefore, chemical fertilizer application is based on soil testing and “tailor-made fertilizers” or precise application rates. Rice is the most important economic crop and it is the primary staple crop in the country. Over 50% of the Thai farmland is devoted to rice with about 20 million tons of rice produced annually.
Eucalyptus has been extensively planted in Thailand. The total area of eucalyptus growth is approximately 400,000 ha. The annual planting rate of Eucalyptus has increased gradually over the last decade in response to the high demand for wood, especially chips and poles, for both domestic consumption and export. Eucalyptus plantation practices include pruning some branches which creates abundant wastes. Thai farmers in northeastern part of Thailand have paddy fields or maize with eucalyptus plantings on ridges. Based on these types of land use, rice husk and eucalyptus branches are predominant agricultural wastes in the region. Biochar production can utilize these waste materials (Lehmann and Joseph, 2015).

Biochar is a carbon-rich material produced by heating biomass in the absence of oxygen. Biochar can persist in soils for years and can enhance carbon sequestration for a long period (Downie et al., 2011). Biochar added to soil can enhance crop growth, increase water and nutrient retention as well as increase soil carbon sequestration (Ahmed et al., 2016). The properties of biochars depend on feedstock and pyrolysis temperature (Zhao et al., 2013; Tag et al., 2016). Biochar obtained from rice wastes have unique chemical properties because of the incorporation of silica into its structure (Prakongkep et al., 2013) whereas, biochar produced from woody materials contains little Si and has a higher carbon content. All biochars contain plant nutrient elements (Jindo et al., 2014; Prakongkep et al., 2015).

The use of biochar as a soil amendment is not an innovative concept. The effect of biochar addition on crop yield is more pronounced for infertile soils compared to fertile soils (El-Naggar et al., 2019). Moreover, the effect of biochar on crop yield and plant nutrition is variable, and it is not always effective with supplementation with mineral fertilizers sometimes being necessary to promote crop growth (Chan et al., 2008; Alburquerque et al., 2013). Positive effects on crops due to the addition of biochar combined with chemical fertilization have been reported (Blackwell et al., 2015; Inal et al., 2015) however biochar application alone may improve soil quality and increase maize yields (Manolikaki and Diamadopoulos, 2019).

This study was conducted to assess the combined effect of biochar and chemical fertilizer on acidic sandy soils for sweet corn growth. Sweet corn was selected as the crop as it is one of the most popular crops in the tropics and it exhibits a marked response to fertilizer treatment (Kaizzi et al., 2012).

### MATERIALS AND METHODS

#### Properties of soils

A sandy soil was taken from 0-15 cm depth from an agricultural field near the Land Development Regional Office 5, Khon Kaen province, Northeastern, Thailand (Longitude 102.8458E and Latitude 16.4697N). The loamy sand was classified as Ustic Quartzipsamment (Soil Survey Staff, 2014a). The soil was air-dried, sieved to pass through 2 mm mesh, thoroughly mixed and stored in polythene bags at room temperature. It was used for standard chemical and physical analysis (Soil Survey Staff, 2014b) and the pot experiment. Core samples taken in the field were used for bulk density measurement. Soil properties are presented in Tables 1 and 2.

#### Biochar production and characterization

Biochars were obtained by carbonization at 300-350°C of eucalyptus wood and rice husks. Biochars were crushed to a uniform particle size then passed through 2 mm sieve prior to experimental use. Biochar morphology was observed by scanning electron microscopy (SEM, JEOL6400) of the biochar fracture surfaces. The pH and EC of the biochar were measured in a 1:10 (biochar: distilled water) extract. For ash content, biochars were burned in a furnace at 600°C for 6 hrs. For total element determination, biochar ashes were digested with aqua regia [1:3 hydrochloric acid (HCl); nitric acid (HNO3)] and for water soluble elements, biochars were extracted with distilled water [0.5 g: 100 mL] shaking overnight. Both

| Latitude   | Longitude | Sand | Silt | Clay | Texture          | Water retention (% by weight) | Bulk density (g cm⁻³) |
|------------|-----------|------|------|------|------------------|------------------------------|-----------------------|
| 16.4697N   | 102.8458E | 83   | 12   | 5    | Loamy sand       | FC 1/3 atm                   | PWP 15 atm            | 1.3                     |

Table 1. Latitude and longitude and physical properties of top soil (Ap horizon, 0-15 cm depth) from Khonkhen province, Northeastern Thailand.
Table 2. Chemical properties of top soil (Ap horizon, 0-15 cm depth) from Khonkhen province, Northeastern Thailand.

| pH 1:1 | EC1:5 (dS cm⁻¹) | OM (%) | Total N (%) | CEC (cmol kg⁻¹) | Exchangeable cations (cmol kg⁻¹) | Avail. P (mgP kg⁻¹) |
|--------|----------------|--------|-------------|-----------------|---------------------------------|-------------------|
| 5.9    | 0.08           | 0.17   | 0.10        | 1.2             | 0.24                           | 0.24              | 0.07   | 0.47   | 90 |

Table 3. Detailed treatment combination used for pot experiment.

| Treatment | Soil amendment                  | Chemical fertilizer* | Abbreviation |
|-----------|---------------------------------|----------------------|--------------|
| 1         | Control                         | -                    | C01          |
| 2         | Control                         | -                    | C02          |
| 3         | -                               | recommendation rate  | F1           |
| 4         | -                               | 2 times recommendation rate | F2 |
| 5         | Eucalyptus wood biochar 10 t ha⁻¹ | -                    | E10          |
| 6         | Eucalyptus wood biochar 40 t ha⁻¹ | -                    | E40          |
| 7         | Rice husk biochar 10 t ha⁻¹     | -                    | R10          |
| 8         | Rice husk biochar 40 t ha⁻¹     | -                    | R40          |
| 9         | Eucalyptus wood biochar 10 t ha⁻¹ | recommendation rate | E10F1        |
| 10        | Eucalyptus wood biochar 10 t ha⁻¹ | 2 times recommendation rate | E10F2 |
| 11        | Eucalyptus wood biochar 40 t ha⁻¹ | recommendation rate  | E40F1        |
| 12        | Eucalyptus wood biochar 40 t ha⁻¹ | 2 times recommendation rate | E40F2 |
| 13        | Rice husk biochar 10 t ha⁻¹     | recommendation rate  | R10F1        |
| 14        | Rice husk biochar 10 t ha⁻¹     | 2 times recommendation rate | R10F2 |
| 15        | Rice husk biochar 40 t ha⁻¹     | recommendation rate  | R40F1        |
| 16        | Rice husk biochar 40 t ha⁻¹     | 2 times recommendation rate | R40F2 |

* Chemical fertilizer application rate was based on soil testing; Urea (46-0-0), triple superphosphate (TSP) (P₂O₅; 0-46-0), potassium chloride (muriate of potash) (KCl; 0-0-60) were used at the rate of 188-30-30 kg ha⁻¹ (83-14-14 mg pot⁻¹) (recommendation rate of chemical fertilizer) and 376-60-60 kg ha⁻¹ (166-28-28 mg pot⁻¹) (2 times the recommendation rate of chemical fertilizer), respectively (Department of Agriculture 2010).

Table 4. Ash, pH and EC of biochars.

| Biochar         | Ash (%) | pH1:5 | EC1:5 (dS m⁻¹) |
|-----------------|---------|-------|----------------|
| Eucalyptus wood | 36      | 7.6   | 0.10           |
| Rice husk       | 38      | 7.7   | 0.70           |
Table 5. Total elements, water soluble and proportion of water soluble of biochar (mg kg⁻¹)

| Biochar              | Si   | Al  | Ca    | Cu  | Fe  | K    | Mn  | Mg  | Na  | Ni  | P   | Pb  | Zn  |
|----------------------|------|-----|-------|-----|-----|------|-----|-----|-----|-----|-----|-----|-----|
| Eucalyptus wood      |      |     |       |     |     |      |     |     |     |     |     |     |     |
| Total element        | 2,500| 420 | 3,239 | 10  | 731 | 386  | 68  | 292 | 661 | 6   | 106 | 5   | 6   |
| Water soluble        | nd   | 4.6 | 336   | 0.2 | 0.5 | 90   | 0.6 | 35  | 318 | nd  | nd  | 0.5 | nd  |
| Proportion           | nd   | 0.01| 0.10  | 0.02| 0.001| 0.20 | 0.009| 0.12| 0.48| nd  | nd  | 0.10| nd  |
| Rice husk            |      |     |       |     |     |      |     |     |     |     |     |     |     |
| Total element        | 194,000| 199 | 1,771 | 7.0 | 496 | 7,761| 282 | 810 | 250 | 3   | 835 | 3.0 | 28  |
| Water soluble        | nd   | 8.3 | 287   | 1.1 | 7.6 | 4,848| 24.9| 183 | 154 | 0.1 | 434 | 0.1 | 0.5 |
| Proportion           | nd   | 0.04| 0.16  | 0.16| 0.02| 0.60 | 0.09| 0.23| 0.62| 0.03| 0.50| 0.03| 0.02|

nd = non detectable

Table extracts were analyzed by ICP-OES.

Experimental site
The experiment was conducted in a glasshouse at the Office of Science for Land Development, Bangkok, Thailand (Elevation 20 m.s.l, Longitude 100.57094E and Latitude 13.83768N), during the period from September to October 2018. The average temperature was 29.0°C.

Plant material
Super Agro sweet corn (open pollinated variety) (Zea mays L.) was used for this pot experiment.

Experimental design and treatments
The experimental design used was a completely randomized design (CRD) with two replications. Biochar and/or chemical fertilizers were mixed with 2 kg soil to prepare the substrates for sweet corn growth. The test treatments were shown in Table 3.

Cultural practices
Four sweet corn seeds were placed at 1 cm depth into 8 inch diameter plastic pots, containing about 2 kg of loamy sandy soil (sand 83%, silt 12% and clay 5%). Five days after seedling emergence the seedlings were thinned to two per pot. The moisture content in all pots was maintained at field capacity and irrigated with DI water. All pots were randomized every morning to avoid differences in sunlight. Fungicide (Captan 2 g: 1000 mL water) solution was applied every seven days. The experiment was terminated 30 days after seeding. A harvest of the above ground (stalks and leaves) biomass took place at the end of the experiment. The plant material was dried at 60°C until a constant weight was reached and then ground. The soil in each pot was thoroughly mixed. Soil samples were collected from each pot.
Table 6. Duncan’s Multiple Range Test (DMRT) (α = 0.05) of mean pH, EC, available K and available P of soil at 30 days after sweet corn planting (Pot experiment).

| Treatment | pH1:1H₂O (µs cm⁻¹) | EC1:5H₂O | Avail K (mg kg⁻¹) | Avail P (mg kg⁻¹) |
|-----------|----------------------|-----------|-------------------|-------------------|
| 1 C1      | 5.27f                | 29.1c-f   | 21.6e             | 0.99cde           |
| 2 C2      | 5.32def              | 23.2ef    | 22.6de            | 0.56e             |
| 3 F1      | 5.28ef               | 47.3b-e   | 26.3de            | 0.75de            |
| 4 F2      | 5.31def              | 84.6a     | 34.1cde           | 1.41bc            |
| 5 E10     | 5.32def              | 22.4f     | 23.7de            | 0.44e             |
| 6 E40     | 5.44a-d              | 28.3def   | 27.4de            | 0.53e             |
| 7 R10     | 5.12g                | 26.1ef    | 35.1cd            | 0.69de            |
| 8 R40     | 5.49ab               | 37.6b-f   | 88.5a             | 1.93ab            |
| 9 E10F1   | 5.23fg               | 40.7b-f   | 29.3cde           | 0.57e             |
| 10 E10F2  | 5.31def              | 55.6b     | 25.7de            | 1.28cd            |
| 11 E40F1  | 5.55a                | 39.8b-f   | 32.1cde           | 0.72de            |
| 12 E40F2  | 5.47abc              | 57.4b     | 28.0de            | 1.02cde           |
| 13 R10F1  | 5.35c-f              | 47.3b-e   | 41.0c             | 0.91cde           |
| 14 R10F2  | 5.41b-e              | 51.4bcd   | 34.5cde           | 1.25cd            |
| 15 R40F1  | 5.52ab               | 46.2b-f   | 63.3b             | 1.45bc            |
| 16 R40F2  | 5.52ab               | 53.0bc    | 66.7b             | 2.37a             |
| CV%       | 2                    | 40        | 51                | 54                |

Means in each column followed by different letter (s) are significantly different at the 0.05 probability level

at the end of the experiment for chemical analysis.

Plant analysis

A combination of nitric-perchloric acids HNO₃–HClO₄ in a ratio 2:1 was used for plant digestion. Uptake of nutrients by plants was calculated by multiplying nutrient concentration with the dry matter weight.

Statistical analysis

One-way ANOVA was performed with the Excel Microsoft Office professional Plus 2010 to compare the means of nutrients concentration, plant height and dry weight of aboveground (stalks and leaves) and soil properties. The treatments comparison was made with the Duncan (Post-hoc) test at p<0.05 level of significant using Statistica software (version 8.0) (Statsoft Inc., 2007).

RESULTS AND DISCUSSION

The soil reaction was rated as moderately acid (pH 5.9) (Table 2). Analysis of the experimental soil before planting revealed that it was very low in organic matter, low in total N, and medium in K content and high in available P (Table 2). These results were used to calculate chemical fertilizer recommendations for the pot experiment. Eucalyptus wood and rice husk biochars are slightly alkaline (pH 7.6 to 7.7) with a high ash content (36 to 38%) and low EC (0.1 to 0.7 µs cm⁻¹) (Table 4). Total element, water soluble element and the proportion of water soluble elements in the biochars used in our experiment are shown in Table 5. Effects of biochar on soil properties are shown in Table 6, application of rice husk and eucalyptus biochars (40 ton ha⁻¹) with/without
Table 7. Duncan's Multiple Range Test (DMRT) ($\alpha = 0.05$) of mean height, dry weight and element uptake of aboveground (stalks and leaves) at 30 days after sweet corn planting (Pot experiment).

| Treatment | Height (cm) | Dry weight (g) | Si | N | P | K | Ca | Mg | S | Fe | Mn | Zn | Cu |
|-----------|-------------|----------------|----|---|---|---|----|----|---|----|----|----|----|
|           |             |                | g |    |   |   |    |    |   |    |    |    |    |
|           |             |                |   |    |   |   |    |    |   |    |    |    |    |
| 1.C1      | 24.9abc     | 1.29ef         | 0.22j | 1.94e | 0.18g | 3.10gh | 0.49de | 0.43fg | 0.095c | 92e-h | 167gh | 42e | 4.86d-g |
| 2.C2      | 25.1abc     | 1.19ef         | 0.30ij | 1.38e | 0.14g | 2.39h | 0.42de | 0.35g | 0.085c | 81fg | 227fg | 55de | 3.58g |
| 3.F1      | 18.3c       | 1.38ef         | 2.00d-g | 5.19d | 0.27fg | 3.59gh | 0.81b-e | 0.63de | 0.103c | 151def | 461c-g | 82cde | 4.83d-g |
| 4.F2      | 22.3bc      | 1.86de         | 3.62bc | 8.39c | 0.48ce | 5.48-g | 1.07abc | 0.79cde | 0.065c | 162de | 565cde | 155ab | 8.38cd |
| 5.E10     | 24.5abc     | 1.03f          | 0.51hij | 1.35e | 0.17g | 2.46h | 0.26e | 0.30g | 0.070c | 65gh | 157h | 52de | 3.57fg |
| 6.E40     | 25.3abc     | 0.86f          | 0.56g-j | 1.25e | 0.15g | 2.28h | 0.30e | 0.30g | 0.026c | 54h | 162h | 36e | 2.91g |
| 7.R10     | 29.3ab      | 1.40ef         | 0.71f-j | 1.33e | 0.19g | 4.60e-h | 0.39de | 0.32g | 0.055c | 84fg | 320e-h | 55de | 4.20efg |
| 8.R40     | 29.5ab      | 2.22d          | 2.04d-f | 2.20e | 0.61cd | 9.24bc | 0.41de | 0.25g | 0.132c | 136d-g | 287e-h | 72de | 4.43efg |
| 9.E10F1   | 18.0c       | 1.93de         | 1.93d-h | 6.40d | 0.39ef | 4.09gh | 0.93a-d | 0.91bc | 0.134c | 167d | 650bcd | 108b-e | 7.70cde |
| 10.E10F2  | 23.3bc      | 3.42c          | 3.22bcd | 10.81ab | 0.65bd | 6.71de | 1.44a | 1.06b | 0.182bc | 275bc | 716abc | 154ab | 12.03ab |
| 11.E40F1  | 23.8abc     | 1.80de         | 1.71e-h | 5.32d | 0.35ef | 3.26gh | 0.75cde | 0.64de | 0.033c | 135d-g | 337e-h | 114bcd | 7.18cf |
| 12.E40F2  | 23.5bc      | 2.34d          | 2.30cde | 9.47bc | 0.61d | 7.21cd | 1.38a | 0.97bc | 0.094c | 182d | 397d-h | 210a | 10.54abc |
| 13.R10F1  | 26.1ab      | 2.29d          | 1.49e-i | 6.01d | 0.47e | 6.53def | 0.62cde | 0.60ef | 0.091c | 174d | 472c-f | 150abc | 8.06cd |
| 14.R10F2  | 27.0ab      | 3.74bc         | 5.42a | 9.77abc | 0.76b | 9.75b | 1.31ab | 1.25a | 0.149c | 251c | 946a | 197a | 13.13a |
| 15.R40F1  | 25.3abc     | 4.35b          | 4.48ab | 8.96bc | 0.76b | 16.65a | 1.07abc | 0.80cd | 0.392a | 330b | 684a-d | 149abc | 8.69bc |
| 16.R40F2  | 31.0a       | 5.29a          | 4.60ab | 11.58a | 1.17a | 16.42a | 1.47a | 0.97bc | 0.310ab | 405a | 879ab | 166ab | 12.83a |
| CV %      | 17          | 56             | 76   | 66  | 63  | 70  | 55  | 48  | 85  | 58  | 57  | 54  | 49  |

Means in each column followed by different letter(s) are significantly different at the 0.05 probability level.
Chemical fertilizer (E40, R40, E40F1, E40F2, R40F1 and R40F2) significantly increased soil pH. The higher recommendation rate (F2) of fertilizer raised EC moderately. Rice husk biochar (40 ton ha⁻¹) with/without chemical fertilizer (R40, R40F1 and R40F2) increased available K and P in soil.

The effect of biochar on plant growth and nutrient uptake is shown in Table 7. The results show that the growth of sweet corn was affected by biochar additions at high rate of application (40 ton ha⁻¹). Maximum height of sweet corn plants (average height 31 cm) was with the application of R40F2. Plant dry weight was significantly affected by experimental treatments (Table 7). The dry weight of sweet corn plants obtained after 30 days of growth indicated that R40F2 was the most efficient treatment. Significant (P<0.05) differences in nutrient uptake by plants were observed due to the use of different amendments (Table 7). Silicon uptake for R10F2, R40F1 and R40F2 were higher than for other and control treatments. Sweet corn fertilized with rice husk biochar at twice the recommended rate of chemical fertilizer (R40F2) produced the highest N, P, K Ca, S, Fe, Mn, Zn and Cu uptakes.

Generally, biochar has a limiting effect on acidic soil pH (Dume et al., 2015) as observed here. Some studies have found biochar to be most effective when it is applied with mineral fertilizers (Chan et al., 2008; Atkinson et al., 2010; Van Zwieten et al., 2010; Alburquerque et al., 2013; Li and Shangguan, 2018) as is indicated by this study. Sweet corn height, dry weight and nutrient uptake were markedly affected by experimental treatments (Table 7). Biochar applications at higher levels affected sweet corn growth and nutrient uptake. The highest aboveground (stalks and leaves) nutrient uptake was for plants treated with rice husk biochar for two times the recommended rate of chemical fertilizer (R40F2). Control plants, chemical fertilizer only, biochar application without chemical fertilizer did not show significantly differences in plant properties however, the positive effects on crop growth due to the addition of biochar combined with chemical fertilization are evident.

Comparing eucalyptus wood biochar and rice husk biochar, improvements in sweet corn growth and nutrient uptake due to rice husk biochar were better than for eucalyptus wood biochar because total and available forms of plant nutrient elements such as K and P in rice husk biochar are higher than for eucalyptus wood biochar. Moreover, rice husk biochar has a high silica content (Figure 1) which is present as amorphous forms of silica resembling cristobalite and tridymite (Prakongkep et al., 2013). Amorphous and crystalline forms of silica in rice husk biochar partly dissolve in soil solution and probably play an important role for sweet corn growth. Silicon reduces biotic stresses and abiotic stresses including climate stress, water deficiency stress, and mineral stresses (Guntzer et al., 2012). Silicon enhanced uptake of major essential elements and water and maintained physiological processes such as photosynthesis by plants exposed to a water deficit (Gao et al., 2005; Eneji et al., 2008; Gong et al., 2008). The present data support this interpretation.

**CONCLUSION**

Biochars were produced from eucalyptus wood and rice husk by carbonization at 300 to 350°C. Sweet corn was grown for 30 days after seedling emergence in a
glasshouse pot trial in a sandy soil (loamy sand: Ustic Quartzipsamment) amended with biochars at 10 and 40 ton ha\(^{-1}\) with/without chemical fertilizer. The addition of R4OF2 resulted in the highest increase of aboveground dry weight (5.29 g pot\(^{-1}\)) compared to the control (1.19-1.29 g pot\(^{-1}\)). Biochar alone is not sufficient to maximize crop production; therefore, additional mineral fertilizers must be applied. Rice husk biochar increased sweet corn growth more than eucalyptus wood biochar because rice husk biochar has a high content of silicon and potassium.

AKNOWLEDGEMENTS

This study was funded by Land Development Department through “Towards Improvement of Soil Quality in the Context of Land Use and Climate Changes in Thailand Phase II” project. We would like to acknowledge to Mr. Channarong Ketdan and Ms. Pratanna Ploddee for soil sample collection and Plant, Fertilizer and Soil Amendment Division, Office of Science for Land Development for plant analysis. The authors would like to thank Soil Mineralogy and Micromorphology staff for their assistance during the glasshouse experiment.

REFERENCES

Ahmed F, Arthur E, Plauborg F, Andersen MN (2016). Biochar effects on maize physiology and water capacity of sandy subsoil. Mechanization Agric. Conserv. Resour. 62:8-13.

Alburquerque JA, Salazar P, Barrón V, Torrent J, del Campillo MDC, Gallardo A, Villar R (2013). Enhanced wheat yield by biochar addition under different mineral fertilization levels. Agron. Sustain. Dev. 33:475-484.

Atkinson CJ, Fitzgerald JD, Hipps NA (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. Plant Soil 337:1-18.

Blackwell P, Joseph S, Munroe P, Anawar HM, Storer P, Gilkes RJ, Smernik RJ, Morris S, Munroe PR, Chan KY, Van Zwieten L, Meszaros I, Downie A, Joseph S (2008). Agronomic values of green waste biochar as a soil amendment. Soil Res. 45:629-634.

Department of Agriculture (2010). Chemical fertilizer recommendation of economic crops; Department of Agriculture, Ministry of Agriculture and Cooperatives, Bangkok, Thailand.

Downie AE, Van Zwieten L, Smernik RJ, Morris S, Munroe PR (2011). Terra Preta Australis: Reassessing the carbon storage capacity of temperate soils. Agric. Ecosyst. Environ. 140:137-147.

Dume B, Berecha G, Tulu S (2015). Characterization of biochar produced at different temperatures and its effect on acidic nitosol of Jimma, Southwest Ethiopia. Int. J. Soil Sci. 10:63-73.

El-Naggar A, Lee SS, Rinklebe J, Farooq M, Song H, Sarmah AK, Zimmerman AR, Ahmad M, Shaheen SM, Ok YS (2019). Biochar application to low fertility soils: A review of current status, and future prospects. Geoderma 337:536-554.

Enesi AE, Inanaga S, Munakata S, Li J, Hattori T, An P, Tsuji W (2008). Growth and nutrient use in four grasses under drought stress as mediated by silicon fertilizers. J. Plant Nutr. 31:355-365.

Gao X, Zou C, Wang L, Zhang F (2005). Silicon improves water use efficiency in maize plants. J. Plant Nutr. 27:1457-1470.

Gong H, Chen K, Zhao Z, Chen G, Zhou W (2008). Effect of silicon on defense of wheat against oxidative stress under drought at different developmental stages. Biologia. Plantarum. 52:592-596.

Guntzer F, Keller C, Meunier JD (2012). Benefits of plant silicon for crops: A review. Agron. Sustain. Dev. 32:201-213.

Inak A, Gunes A, Sahin O, Taskin M, Kaya E (2015). Impacts of biochar and processed poultry manure, applied to a calcareous soil, on the growth of bean and maize. Soil Use Manage. 31:106-113.

Jindo K, Mizumoto H, Sawada Y, Sanchez-Monedero M, Sonoki T (2014). Physical and chemical characterizations of biochars derived from different agricultural residues. Biogeoosci. 11:6613-6621.

Kaizzi KC, Byalebeka J, Semalulu O, Alou I, Zimwanguyizza W, Nanamba A, Musinguzi P, Ebanyat P, Huuya T, Wortmann CS (2012). Maize response to fertilizer and nitrogen use efficiency in Uganda. Agron. J. 104:73-82.

Lehmann J, Joseph S (2015). Biochar for environmental management: An introduction. In: Biochar for Environmental Management, Routledge. pp. 33-46.

Li S, Shangguan Z (2016). Positive effects of apple branch biochar on wheat yield only appear at a low application rate, regardless of nitrogen and water conditions. J. Soils Sediments 18:3235-3243.

Manolikaki I, Diamadopoulos E (2019). Positive effects of biochar and biochar-compost on maize growth and nutrient availability in two agricultural soils. Commun. Soil Sci. Plan. 50:512-526.

Prakongkep N, Gilkes RJ, Wiriyaktimateekul W (2015). Forms and solubility of plant nutrient elements in tropical plant waste biochars. J. Plant Nutr. Soil Sci. 178:732-740.

Prakongkep N, Gilkes RJ, Wiriyaktimateekul W, Duangchan A, Darunsontaya T (2013). The effects of pyrolysis conditions on the chemical and physical properties of rice husk biochar. J. Met. Mater. Miner. 3:97-103.

Soil Survey Staff (2014a). Keys to Soil Taxonomy, Twelfth Edition; United States Department of Agriculture Natural Resources Conservation Service.

Soil Survey Staff (2014b). Soil Survey Field and Laboratory Methods Manual. Soil Survey Investigations, Report No. 51, Version 2.0. United States Department of Agriculture, Natural Resources Conservation Service.

Statsoft Inc. (2007). Statistica (data analysis software system). Version 8.0. www.statsoft.com.

Sultana J, Siddique MNA, Abdullah MR (2015). Fertilizer recommendation for agriculture: Practice, practicalities and adaptation in Bangladesh and Netherlands. Int. J. Bus. Manag. Soc. Res. 1:21-40.

Tag AT, Duman G, Ucar S, Yanik J (2016). Effects of feedstock type and pyrolysis temperature on potential applications of biochar. J. Anal. Appl. Pyrolysis 120:200-206.

Van Zwieten L, Kimber S, Morris S, Chan K, Downie A, Rust J, Joseph S, Cowie A (2010). Effects of biochar from slow pyrolysis of paper mill waste on agronomic performance and soil fertility. Plant Soil 327:235-246.

Zhao L, Cao X, Mašek O, Zimmerman A (2013). Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. J. Hazard Mater. 256:1-9.

http://www.sciencewebpublishing.net/jacr