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Wheat Straw Biochar Application to Loam-Sand Soil: Impact on Yield Components of Summer Maize and Some Soil Properties

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ABSTRACT

Applying biochar to soils is a method to improve crop yield and soil fertility. The aim of this study was to investigate the effect of biochar on crop yield and some soil properties. Biochar was derived from wheat straw at different temperatures (200-600°C), and according to the amount of the stable organic matter yield index (10.06 %), the temperature of 3°C was chosen as the optimum temperature. Moreover, 12 lysimeters (0.8 m×1.2 m) were set up, and filled with loam-sand soil. Then, biochar treatments were added into lysimeters with different dosages (0, 10, 25, 50 t ha^{-1} (B0, B1, B2 and B3)) in August, 2017. The crop yield of maize were collected in November, 2017. Soil properties were analyzed after the harvesting. The results indicated that the application of biochar decreased the soil bulk density, and increased the soil organic carbon (SOC), total N, total porosity and the cation exchange capacity (CEC). The diverse dosages of biochar of B_1, B_2 and B_3 could enhance the grain yield by 12.86%, 35.83% and 54.29%; respectively. Furthermore, biochar with dosage of 50 t ha^{-1} showed the most effect on CEC, pH, EC, N and OC of soil. Overall, the current study's results confirmed that the added biochar could augment the maize production, and improve the soil characteristics.

Keywords: *Biochar, Maize Yield, Soil Properties, Lysimeter.*

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1. INTRODUCTION

Biomass has plenty of roles to determine the strategies for sustainable agriculture that is essential to apply an incredibly practical management in this part. Currently, researchers have been examining to discover the environmental conversion processes and applications for biomass. This has arisen in a variety of issues to describe the solid product from dry or wet pyrolysis. Biochar is a pyrolysis product that can be used for environmental applications. Biochar technology is identified as a production to improve soil fertility and cause carbon sequestration, as well as an alternative adsorbent to remove different kinds of contaminants. Recent researches have shown that biochar amendment could enhance water retention capacity of soil as well as nutrient-holding ability due to its considerably porous structure, high specific surface area, and CEC. Moreover, the effectiveness of biochar on the properties of soil and crop productivity is the subject to feedstock types, pyrolysis conditions, and dosage of biochar application. Biochar has been characterized as a stable structure, resistant to decomposition which can remain in the soil in the range of hundreds to thousands years (*Lehmann* et al., 2015). Considering the point that most of the oxygen and hydrogen existed in organic matters were lost when converted to biochar, consequently, biochar had dramatically more stable carbon contents than the original organic matter (*Keiluweit* et al., 2010). These have been some proofs that why scholars have gained different results in some field experiments. For instance, positive results suggested that biochar amendment improved crop yield by improving the soil fertility, and decreasing the N fertilizer which induced N_2O emissions from agricultural lands (*Jeffery* et al., 2011; *Liu* et al., 2014; *Cayuela* et al., 2013). *Ullah* et al (2018), proved that biochar of both types i.e. wheat straw biochar and sugarcane bagasse biochar when applied to soils in rain fed areas of Potohar region increased the maize grain yield and biomass. Additionally, comparing different rates of biochar showed that grain yield and maize crop would be greater by applying greater rates of biochar. *Yang* et al (2015) found that the yields of corn, peanut, and sweet potato during one crop season were increased by using both rice straw and corn stalk-derived biochar. Their experiments showed that biochar addition could increase soil water content, especially at a high rate (10%) of application. Therefore, it was considered that biochar application might increase crop yield by holding much water in the soil. The affirmative effects of biochar on crop production have been mostly proved in experiments in tropical areas and on soils with low nutrients and acidic soils (*Liu* et al., 2013) that such effects have been basically attributed to the liming effect of the alkaline biochar and the increase of soil water holding capacity (*Jeffery* et al., 2011). In contrast, biochar application has often shown a temporary influence on the crop productivity in moderate climate and on alkaline soils (*Borchard* et al., 2014; *Tammeorg* et al., 2014; *Jones* et al., 2012). Moreover, the benefits of biochar on crop productions seemed to be restricted by high fertility of soil condition (*Lusiba* et al., 2017; *Liu* et al., 2013). Biochar has the potential to improve soil properties by direct influence on the soil structure, distribution of soil pore size and density under the biochar application that affects water holding capacity, aeration, nutrient retention, permeability of soil alongside plant uptake of nutrients. It has also been confirmed that soil improvement is induced due to increase in the soil surface area after the application of biochar (*Chan* et al., 2008; *Novak* et al., 2009; *Lehmann* and *Joseph*, 2015). With regard to the eventual effects of biochar, the aims of this study were determining the optimum temperature for wheat straw biochar that is obtained by slow pyrolysis and its characteristics, and investigating the possibility of biochar application on maize yield, yield components, and some properties of a loam-sand soil.

2. MATERIAL AND METHODS

2.1. Experiment site and lysimeter set up

Twelve undisturbed soil lysimeters with Loam Sand texture were collected, in the Shahid Chamran University (31̊ 30' N, 48̊ 65' E) of Ahvaz City, Khouzestan Province, Iran. Each lysimeter was 0.8 m in diameter and 1.2 m deep. The lysimeters were made by polyethylene with free drainage that was installed at the Research Farm, Shahid Chamran University.

2.2. Preparation of optimum biochar for soil amendment

Wheat straw was air dried and converted to the small size with electric mills. The air dried material was heated in a carbonization kiln at five different pyrolysis temperatures (200–600˚C), with a fixed residence time of 4 hours. The biochar yield was calculated as the proportion of the weight of pyrolysis product to the dry wheat straw. The oxidisable organic carbon content (OC) was determined by the method of potassium dichromate oxidation. Loss on ignition (LOI) of the resultant biochar was obtained by heating the produced biochar in a kiln at 750˚C for 6 hours (ASTM method, D-1762-84) (*Masto* et al., 2013). Stable organic matter (SOM) was determined as follows (*Masto* et al., 2013):

$$SOM = LOI - (OC \times 1.724) \qquad (1)$$

Where, 1.724 is the factor to convert organic carbon to organic matter. The stable organic matter yield index (SOMYI) was determined as per the following equation:

$$SOMY = (Biochar\ yield/100) \times SOM \qquad (2)$$

The process parameter for biochar preparation was optimized to get maximum SOMYI used as biochar amendment.

2.3. Properties of biochar

The concentration of different elements (C, H, N, S, and O) in optimum biochar was measured by the CHNSO analyzer (vario ELIII-elementar- made in Germany). The morphology of optimum biochar was investigated using a scanning electron microscopy (SEM, Leo 1455 VP model, made in Germany). Surface area was obtained using methylene blue method (*Chintala* et al., 2013). The method mentioned by (*Chintala* et al., 2013) was used to measure cation exchange capacity (CEC). And a Fourier Transform Infrared Spectroscopy (FTIR, Spectrum GX, and Perkin-Elmer) was used to analyze the functional groups in optimum .

2.4. Field experiment design

The field trial was established in June, 2017. The soil was first treated with biochar (B) amended at four application rates of 0, 10, 25, 50 t ha^{-1} (B_0, B_1, B_2 and B_3); respectively. All treatments were arranged in a complete random block design with three replications. Before maize sowing in august 2017, biochar was spread on the soil surface, and was incorporated into the soil by plowing with a spade, and then thoroughly mixing the soil with a rake by hand to a depth about 0.15 m. For doing fertilization, N fertilizer (urea) was applied at 100 kg N ha^{-1} that must be added in three stages of plant growth. Additionally, P (triple phosphate) at 80 kg P_2O_5 ha^{-1} and K (potassium sulfate) at 60 kg K_2O ha^{-1} were just added before sowing. Maize was sown on the 6th of August, and harvested on the 20th of November, in 2017.

2.5. Climate conditions and irrigation

The amount of irrigation was calculated by using evaporation transpiration's data of grass and maize's crop coefficient in each growth stage. The maize's crop coefficient was determined by utilizing FAO 56. The sum of evaporation transpiration of grass during the trial period was equivalent to 920 mm over four months. Overall, the water use in the summer cultivation was estimated to be 853 mm.

2.6. Yield measurement, soil sampling and analysis

Grain yield was estimated by manually harvesting all the plants in each lysimeter. Firstly, the total yield of maize ears for each treatment was weighed. Secondly, each sample was dried in oven at 75˚C for 48 h. Then, all of the samples were weighed again, and the grain yield along with the other parameters was calculated. Biological yield was determined by weighing all the plant organs except the plant root. Topsoil (0–0.15 m) samples were collected after the maize harvest. Randomly, three samples of chosen soil cores were taken with a sampler in each lysimeter. A re-sealed plastic bag was used to ship the samples to the laboratory in order to do more analysis. After the samples were air-dried, and the plant residues and gravels were removed, they were passed through a 2 mm sieve. From each soil sample, a part was ground more to pass through a 0.15 mm sieve for the analysis of soil organic C and total N. Soil pH was measured in soil to water ratio of 1:1. The Walkley and Black procedure was used to determine soil organic carbon (*Walkley* and *Black*, 1934). Total nitrogen (N) was determined using the Kjedahl digestion and distillation procedure (*Kjeldahl*, 1883). The cation exchange capacity (CEC) at pH 7 was determined by the NH4OAc method (*Chintala* et al., 2013). Available phosphorus was determined using Bray No. I extraction solution (*Olsen* and *Sommers,* 1982). Some physical and chemical characteristics of basic soil were mentioned in Tab. 2.

2.7. Assessment of Water Use Efficiency (WUE)

The WUE was calculated as described in Uzoma et al. (2011);

$$WUE = \frac{Maize\ Yield}{ET_a} \qquad (3)$$

Where, ET_a is the actual evaporation transpiration of plant.

Statistically, purposed items were analyzed with a one-way ANOVA followed by Duncan's multiple range test (at $p \leq 0.05$) to compare the differences amongst the treatments on SPSS software.

3. RESULTS

3.1. Characterization of wheat straw biochar

Properties of biochars produced under different temperatures in this study have been shown in Tab. 1. It can be identified that biochar yields decreased with increasing the temperature. Some other authors have found the same results where the increased pyrolysis temperature decreased the biochar yield (*Kumar* et al., 2013; *Zhao* et al., 2017). It can be explained due to the fact that below 250 °C, the samples lost weight mainly due to moisture and hydration water loss; while above 250 °C, the feedstock began to decompose and transform into vapor containing complex organic compounds mixed with gases (including water vapor, CO_2, CO, H_2, CH_4, and heavier hydrocarbons). Hence, when the temperature increased, more organic matter decomposed which led to the decrease in biochar yields at higher temperature (*Sun* et al., 2014). According to the results of other studies, biochar was exposed to biological, chemical, and physical processes which were used in soil. Therefore, biochar carbon sustainability was more considerable than carbon content (*Masek* et al., 2013; *Kumar* et al., 2013). In accordance to the calculated value of stable organic matter yield index at various temperatures in this study, the most thermal constancy was obtained by 10.06 for wheat straw biochar at the temperature of 300°C. As it was shown in Tab. 1, although the amount of stable organic matters (SOM) at diverse temperatures enhanced with the increase in pyrolysis temperature up to 300°C, thereafter, it decreased which might be due to the increase in the ash content (*Divband Hafshejani* et al., 2016). Consequently, the temperature of 300 was determined as the optimum temperature of sustainable carbon biochar production, and was used to continue the experiments of this study (Elemental analysis of the biochar at optimum temperature showed that this material was carbon rich with carbon contents around 59.65% (Tab. 3). Moreover, the oxygen and hydrogen contents were obtained by 27.02% and 3.09%; respectively (Tab. 3). N, P, K, Ca, Mg, Na and S showed low levels (Tab. 3). These results were consistent with the findings reported in the literature (*sun* et al., 2014; *kloss* et al., 2012).

3.2. Soil properties

Based on table 2 and soil texture triangle, the soil had a sandy loam texture. Statistical analysis showed the noticeable effect of biochar treatments ($p \leq 0.05$) on soil's physical and chemical properties (Tab. 4). The results of soil's physical and chemical properties after maize harvest under the diverse biochar treatments have been presented in Tab. 5. Biochar amendments reduced soil bulk density, and increased total porosity, soil organic carbon, total N, cation exchange capacity, and pH of soil. According to the Tab. 5, bulk density of the B_1, B_2 and B_3 showed respectively 7.59%, 10.34% and 13.10% decrease compared to B_0 treatment. Consequently, all treatments caused a significant increase in total porosity compared with B_0 treatment. Physical soil parameters such as bulk density, pore volume and pore distribution have been the key factors to soil fertility and plant growth, and can be altered significantly by biochar amendment (*Mukherjee* and *Lal*, 2014). Biochar is highly porous and is characterized by a low bulk density. Depending on the feedstock of biochar and production conditions, bulk density ranged from 0.08 g cm^{-3} (*Gundale* and *Deluca*, 2006) to 1.7 g cm^{-3} (*Oberlin*, 2002). Regarding the fact that common bulk densities of mineral soil ranged from 1.16 to 2.00 g $cm^{-3,}$ a decrease was anticipated by adding biochar (*Atkinson* et al., 2010; *Major* et al., 2009; *Zwieten* et al., 2010). Additionally, adding biochar had no effect on pH of soil. Whereas, SOC was increased by 12.77%, 31.91% and 55.32% under B_1, B_2 and B_3 amendments; respectively. Total soil N content of the B_1, B_2 and B_3 was enhanced by 8.57%, 20% and 31.42% in comparison to B_0 treatment. Biochar increased the concentration of SOC and TN by 25–54% and 4–12%; respectively, whereas it had no effect on soil pH (*Zhang* et al., 2015). As shown in Tab. 5. CEC was found to increase by 13.41%, 30.61% and 46.50% under B_1, B_2 and B_3 amendments; respectively. The amendment of the soil with biochar and compost significantly improved the CEC of the soil, indicating that the retention of non-acidic cations by the soils increased. CEC has been realized as a considerable factor in maintaining inorganic nutrients such as K^+ and NH^{4+} in soil (*Lei* et al., 2013), and biochar has been brought about the intensification in CEC of some biochar-amended soils (*Glaser* et al., 2015; *Van Zwieten* et al., 2010), thereby increasing the availability and retention of plant nutrients in soil, and potentially increasing nutrient use efficiency. Biochar usually features a high CEC, thus when applied to soil it will add negative charges. Once biochar is incorporated into soil, CEC varies depending on soil pH, age and weathering conditions of biochar (*Major* et al., 2010). *Lee* et al. (2010) confirmed that CEC is dependent on pH by observing that, at pH values below 7, acidification leads to the release of bound cations. Biochar's CEC plays an important role in regard of nutrient retention and plant availability especially for infertile sandy soils common in smallholder farming systems in sub-Saharan Africa (*Gwenzi* et al., 2015). As it was shown, there has been a trend of improvement in investigated properties with increasing biochar rate. In their study, *Chan* et al. (2008) recognized a statistical difference only for extremely high biochar rates, namely rates as high as 50 and 100 t ha^{-1}, but not for a rate of 10 t ha^{-1}.

3.3. Crop yield and yield components

The analyses of variance for maize plant indicated significant effects ($P \leq 0.05$) of biochar doses on the grain yield, biological yield, harvest index, 1000 grain weight, ear length and water use efficiency (WUE); respectively (Tab. 6). Crop yields in the field experiment were collected, and have been presented in Tab. 7. The data showed that biochar addition could enhance the crop yields in all the treatments. Maize grain yield was significantly increased under different adding of biochar (B_1, B_2 and B_3) by 12.86%, 35.83 and 54.29% as compared to the under control treatment (B_0). The biological yield of maize ranged from 8.876 to 10.023 t -ha^{-1}; the distinguished low value belonged to the control treatment, and the high value referred to B_3 treatment. Likewise, the plants grown under different biochar treatments showed greater WUE than the control treatment. The application of biochar at diverse rates (B1, B2 and B3) significantly enhanced the WUE of plant by 15.69%, 33.33% and 49.02% more than the control treatment. Furthermore, biochar application significantly affected the harvest index, the ear length and the weight of 1000 grains. Considering the production harvest, it was obvious that the higher dosage of biochar had a more positive effect on crop yields and water use efficiency. As it was previously shown, biochar amendments have improved physical and chemical properties of the cultivated soil. Thereby, the main reason of maize yield and WUE enhancement could be ascribed to the increased nutrient availability by adding biochar (*Zhang* et al, 2015). Soil moisture amelioration might be another factor to increase maize yield on water stressed conditions. It has been indicated that biochar amendment can improve soil water holding capacity (*Akhtar* et al., 2014; *Rogovska* et al., 2014). Cation exchange capacity (CEC), as an essential index to improve soil fertility, was significantly increased. Therefore, it could promote nutrient retention or higher nutrient use efficiency and result in an increased maize yield and WUE. Furthermore, the high levels of soil organic carbon accumulation due to biochar amendments could enhance N efficiency and crop production with respect to biochar's surface area and porosity, bulk density, nutrient content, stability, cation exchange capacity (CEC) and carbon content, and it has been expected to improve water retention, nutrient retention and plant uptake of nutrients. Biochar amendment on different soils has led to the increased availability and uptake of nutrients by plants (*Hass* et al., 2012; *Uzoma* et al., 2011). In their study, *Alburquerque* et al. (2014) observed that biochar with higher ash content induced relatively higher increase in sunflower growth due to the increased plant availability of nutrients. Moreover, when the addition of biochar directly reduced a certain soil constraint, crop productivity would likely be increased. For instance, the use of biochar with high mineral content has been advisable to apply for soils that are dependent on high nutrient inputs or with low physical fertility (*Slavich* et al., 2013). The positive effects of biochar application on plant growth - for example due to the retention of nutrients – were the strongest when combined with organic or inorganic fertilizers, especially on tropical soils (*Alburquerque* et al., 2014; *Glaser* et al., 2015; *Schulz* and *Glaser*, 2012; *Van Zwieten* et al., 2010). *Peng* et al. (2011) found an increase in maize biomass by 64% (without NPK fertilizer) and an increase of maize biomass by 146% (with NPK fertilizer) for an Ultisol following biochar application (2.4 t ha^{-1}). In Tab. 7, it is visible that the higher dosage of biochar had a more positive effect on the crop yield and yield components. Whereas, the minimum grain yield, biological yield, harvest index, 1000 grain weight, ear length and WUE were observed in the control treatment.

4. CONCLUSIONS

Based on the results of this study, the application of biochar exhibited some promising positive impacts on soil properties, crop yield and yield components of maize. The application of biochar decreased soil bulk density along with pH, and enhanced SOM, total N, cation exchange capacity (CEC), and total porosity of soil. In addition, the application of all doses of biochar at 10, 25 and 50 t ha^{-1} significantly increased the grain yield, biological yield, harvest index, ear length and weight of 1000 grains. A lower dosage of biochar (10 t ha^{-1} or 25 t ha^{-1}) could enhance the grain yield by 18%–25% , and biochar of 50 $ton.ha^{-1}$ could increase the yield about 31%. Regarding the obtained results of the present investigation, further investigation will concentrate on the biochar effects on the physical and chemical characteristics of the soil and the mechanism of crop yield variation.

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Table 1: Properties of wheat straw biochar samples.

Temperature	Yield	OC	LOI	SOM	SOMYI
(°C)	(%)				
200	60.20	42.90	90	16	9.63
300	40.50	32	80	24.83	10.06
400	28.1	19	66.67	33.9	9.53
500	26.97	17.90	65	34	9.17
600	23.68	14.30	60	35.34	8.37

Table 2: physical and chemical properties of the soil.

Parameters	Amount	Parameters	Amount
Soil texture	Sandy loam	OC (%)	0.47
pH	7.82	TN (%)	0.03
CEC (cmol kg^{-1})	6.92	ρb (gr cm^{-3})	1.45
EC (dS m^{-1})	1.81	Porosity (%)	43.50

Table 3: Elemental analysis of wheat straw biochar sample at optimum temperature.

sample	Ca	Mg	Na	K	N	S	C	H	O	H/C	O/C
	(%)										
Wheat straw biochar	0.2	0.13	0.11	0.16	1.15	0.49	59.65	3.09	27.02	0.05	0.45

Table 4: A one-way ANOVA for the effects of biochar on soil organic carbon (SOC), total N, pH, cation exchange capacity (CEC), bulk density and total porosity of topsoil (0-15 cm)

factor	Sum of square						
	DF	SOC (g kg^{-1})	Total N (g kg^{-1})	pH	CEC (Cmol kg^{-1})	Bulk density (g cm^{-3})	Total porosity (%)
Biochar	3	0.082*	0.000052*	0.0052*	6.75*	0.021*	17.963*
Replication	2	0.001^{ns}	0.0000025^{ns}	0.00^{ns}	0.072^{ns}	0.00^{ns}	0.00^{ns}
Error	6	0.002	0.00000165	0.00	0.092	0.00	0.00

Table 5: The determination of soil organic carbon (SOC), total N, pH, cation exchange capacity (CEC), bulk density and total porosity of topsoil (0-15 cm)

Biochar dosage	SOC (g kg^{-1})	Total N (g kg^{-1})	pH	CEC (Cmol kg^{-1})	Bulk density (g cm^{-3})	Total porosity (%)
B_0	0.47 d	0.035 c	7.74 a	6.86 d	1.45 d	43.50 d
B_1	0.53 c	0.038 c	7.71 a	7.78 c	1.34 c	46.32 c
B_2	0.62 b	0.042 b	7.66 b	8.96 b	1.30 b	47.74 b
B_3	0.73 a	0.046 a	7.63 b	10.05 a	1.26 a	49.25 a
Columns with the non-same letters have significance difference at the five percent probability level.						

Table 6: A one-way ANOVA for the effect of biochar on maize yield and yield components.

factor	DF	Grain yield (t ha^{-1})	Biological yield (t ha^{-1})	Harvest index (%)	1000 grain Weight (gr)	Ear length (cm)	WUE (kg m^{-3})
Biochar	3	0.365*	1.410*	10.610*	670.256*	5.662*	0.076*
Replication	2	0.003^{ns}	0.012^{ns}	0.782^{ns}	30.725^{ns}	0.003^{ns}	0.00011^{ns}
Error	6	0.0012	0.0012	2.523	126.863	0.0012	0.00025

Table 7: The determination of crop yield and yield components of maize under biochar amended soil.

Biochar dosage	Grain yield (t ha^{-1})	Biological yield (t ha^{-1})	Harvest index (%)	1000 grain Weight (gr)	Ear length (cm)	WUE (kg m^{-3})
B_0	d 4.66	d 8.88	c 52.48	c 132.8	c 16.3	d 0.51
B_1	c 5.26	c 9.35	b 56.26	b 152.3	b 17	c 0.59
B_2	b 6.33	b 9.63	a 65.73	a 170.2	a 18.2	b 0.68
B_3	a 7.19	a 10.02	a 71.76	a 178.5	a 18.5	a 0.76
Columns with the non-same letters have significance difference at the five percent probability level.						