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EFFECTS OF SOLID AND LIQUID PYROLYSIS PRODUCTS ON SOIL PROPERTIES AND PLANT GROWTH

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Abstract

One of the reasons for the decrease in soil fertility is the decrease in organic matter content with agricultural activities. The addition of organic C such as pyrolysis process products has a significant effect on the development of soil physical, chemical and biological properties. In this study, the effects of biochar and liquid organic fertilizer obtained from urban wastes on soil properties and plant nutrient content were compared with NPK fertilizer application. Two different studies were carried out incubation and greenhouse studies. Changes in soil properties and plant growth were determined. According to the results obtained; significant increases were determined in soil pH and EC (electrical conductivity) values, NH_4-N, NO_3-N, available K, Ca and Na content with increasing levels. However, extractable P and DTPA (diethylenetriaminepentaacetic acid) extractable microelement contents decreased depending on the time. The changes in soil heavy metal content were not found to be statistically significant. Increasing application biochar and organic fertilizer levels significantly affected plant dry weight and nutrient content. The results obtained in some of the parameters evaluated were in the same group as the NPK applications. It is necessary to determine the appropriate application levels together with the application of biochar with NPK.

Key words: biochar, fertilizer, plant nutrient, plant growth, soil

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1. Introduction

The sustainability of agricultural systems is an important global issue. Sustainable agriculture aims to develop and implement different agricultural management strategies to reduce the harmful effects of intensive land use (Karim et al., 2021). Long-term cultivation of soils could result in degradation, containing soil acidification, soil organic matter depletion, and severe soil erosion (De Meyer et al., 2011). Excessive use of agricultural chemicals adversely affects the physical, chemical and biological properties of the soil, such as structure, water retention, nutrient balance, cation exchange capacity, and the risks of deterioration of the ecological environment. Intensive studies are carried out to improve the deteriorated properties of agricultural soils. Therefore, it is very important to remediate degraded soils with economical and sustainable methods (Yakout et al.,2015).

For this purpose, biochar applications in low fertile and degraded soils have been widespread recently. Biochar is the term given to the material resulting from the thermal degradation (pyrolysis) of organic matter with little or no oxygen present. Biochar amendment is often considered as an important solution to global warming and, thus, it is one of the most important practices in sustainable agriculture. Biochar has positive effects on carbon sequestration, greenhouse gas emission, soil fertility, and agricultural productivity (Lehmann et al., 2011).

The characteristics of biochar are influenced mainly by the preparation temperature and biomass. Higher pyrolysis temperature often results in the

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increased surface area and carbonized fraction of biochar leading to high sorption capability for pollutants. Solid biochars derived from various source materials show different properties of surface area, porosity and the number of functional groups which are essential concerning the effect of biochar (Tang et al., 2013). The liquid produced by pyrolysis is a dark-colored condensate similar to petroleum naphtha. It usually consists of organic acids, aldehydes, alcohols, phenols, carbohydrates, lignin-derived oligomers and phenolic compounds (Zellagui et al., 2016). Bio-oil (liquid) and biochar (solid) are obtained as the final product at the end of the pyrolysis process (Rezaee et al., 2021).

Studies have shown that bio-oil obtained from rapid pyrolysis can be used as a soil conditioner. This is related to the fact that bio-oil easily reacts with ammonia, urea and similar compounds to form organic nitrogen (Rezaee et al., 2021). These compounds polymerize and solidify on heating to produce stable products. These products are also called "slow-release fertilizers". These high-quality organic fertilizers, which are produced as a result of rapid pyrolysis from waste biomass, are obtained as economic products.

The overuse of chemical fertilizers causes a decrease in fertilizer efficiency and serious environmental problems. The soluble chemical fertilizers are easily leached, run off, and washed away from the soil. Nitrogen fertilizers are exposed to ammonia (NH_3) volatilization, nitrate (NO_3) leaching, and nitrous oxide (N_2O) release, which causes serious pollution of surface water, groundwater, and the atmosphere (Wen et al., 2017). Phosphorus is highly immobile due to soil interactions such as adsorption and precipitation, as well as the conversion to the organic form. In addition, excessive phosphorus fertilization significantly increases the risk of phosphorus loss through leaching, runoff, and erosion (Li et al., 2020). The phosphorus loss to surface water is the most important cause of eutrophication, and eutrophication seriously damages aquatic ecosystems (Chen et al., 2018).The estimated fertilizer loss in the environment includes 40-70% N, 80-90% P, and 50-70% K of fertilizers (Duhan et al., 2017). In addition, excessive application of chemical fertilizers severely undermines the quality of agricultural areas via soil salinization and depleting organic substances (Khan et al., 2021). To avoid these adverse effects, conventional fertilizers, slow-release fertilizers are purpose-designed and are gaining increasing global attention. Slow-release fertilizers are only slightly soluble and require additional time for mineralization, thereby giving them slow-release. Compared to conventional fertilizers, slow-release fertilizers have a low rate of releasing nutrients, prolonging nutrient availability for plant uptake, and diminishing nutrient loss into the environment (Wang et al., 2022).

Biochar and liquid product have multifunctional values that include their use of it for the following purposes: soil amendment to improve soil health, nutrient and microbial carrier, immobilizing agent for remediation of toxic metals and organic contaminants removal from soil and water, a catalyst for industrial applications, porous material for mitigating greenhouse gas emissions and odorous compounds, and feed supplement to improve animal health and nutrient intake efficiency and thus, productivity (Fellet et al., 2022; Wang et al., 2021a; Wang et al., 2021b).

Cultivated plants need a sufficient amount of nutrients. Organic fertilizer applications in production are important both in terms of nutritional needs and reducing production costs for the producer. solid and liquid pyrolysis products are promising products for fertilizer use. For a correct scientific understanding and progress, it is necessary to carry out studies on the value of biochar fertilizer (Karim et al., 2021).

The present study was to assess the effect of solid biochar and liquid pyrolysis product (liquid organic fertilizer) applications on soil properties and plant growth were compared with NPK application.

2. Material and methods

2.1. Soil and organic products used in the study

The soil was collected from the Bursa Uludag University, Center of Agricultural Research application area at a depth of 0-30 cm. The soil texture is clay. The some physical and chemical soil characteristics are shown in Table 1.

Table 1. Some physical and chemical properties of the soil used in the study

Properties	***Soil***
% Clay	53.4
% Loam	20.2
% Sand	26.4
pH	7.92
EC, µS cm^{-1}	298.0
Lime, %	4.96
Organic matter, %	1.00
Total N,%	0.09
NH_4-N, mg kg^{-1}	8.28
NO_3-N, mg kg^{-1}	10.4
Available P, mg kg^{-1}	15.0
Exc. K, mg kg^{-1}	145.1
Exc. Ca, mg kg^{-1}	5321.0
Exc. Na, mg kg^{-1}	111.7
DTPA-Fe, mg kg^{-1}	34.7
DTPA-Cu, mg kg^{-1}	4.61
DTPA-Zn, mg kg^{-1}	4.11
DTPA-Mn, mg kg^{-1}	22.8
DTPA-Pb, mg kg^{-1}	3.03
DTPA-Cd, mg kg^{-1}	trace
DTPA-Cr, mg kg^{-1}	0.017
DTPA-Ni, mg kg^{-1}	1.16

The materials used in the study were obtained from SYNPET Technologies. Synpet Technologies works on renewable crude oil, renewable natural gas, liquid fertilizer and biochar.

Used urban wastes were treated in high temperature and high pressure which is called hydrolysis stage. In hydrolysis stage, with the help high pressure "Water–gas shift reaction" occures and impurities in carbon-carbon bonds like sulfur and nitrogen are removed. These sulfur and nitrogen like materials were collected in liquid fertilizer part. Carbon-carbon bonds without/containing very little sulfur and nitrogen cracked in thermal conversion process without in the presence of oxygen developed by SYNPET Technologies. The liquid product was rich in nitrogen and defined as fertilizers containing organic elements including sulfur and trace metal elements used in agricultural applications. Biochar and liquid products were applied according to their nitrogen content.

Physico-chemical characteristics of biochar used in the experiment were as follows: pH: 9.61, EC (electrical conductivity) value: 1008 μS cm^{-1}; organic matter: 31.7%, Total N: 1.53%, NH_4-N: 0.45%, NO_3-N: 0.51%, total P: 2.27%, available P: 0.087%, total K: 0.12%, available K: 0.025% and total humic substances: 2.4%. Liquid organic fertilizer properties were as follows: pH: 2.3, EC value 24 mS cm^{-1}, organic matter: 32.4%, Total N: 4.2%, NH_4-N: 2.5%, NO_3-N: 0.7%, total P: 0.48%, available P: 0.43%, available K: 0.41%, total humic substances: 4.5%.

2.2. Incubation study

The study consisted of both incubation and greenhouse studies. A pot experiment was conducted in greenhouse conditions at Bursa Uludag University Faculty of Agriculture, Center of Agricultural Research. An incubation study was conducted in a temperature and humidity-controlled incubation room. The incubation study was carried out in plastic containers with a soil capacity of 250 g. Treatment levels were applied to pots only once with S1: 200, S2: 400, S3: 600, S4: 800 and S5: 1000 kg N ha^{-1}. The same applications are provided in the liquid organic fertilizer (L1-L5) according to the N content. NPK application consists of 250 kg N, 400 kg P and 250 kg K ha^{-1}. The study also included a control application In the 70-day study, soil samples were taken at the end of the first day, 35th day and 70th day. The moisture content of each sample was adjusted to 60-70 % of the field capacity and readjusted by adding deionized water every 2 days.

2.3. Greenhouse study

The pot trial was conducted in plastic pots 20 cm in height and 20 cm in diameter with a soil capacity of 4 kg. The same applications were used in the incubation study. Corn was used as a test plant in the study. After an incubation period of one month, the seeds were sown. The pots were watered with pure water during the study. At the end of the 60 days growth period, the plants were harvested with a cut-off from ground level. Plant wet weights were determined. The pot study was then arranged in a complete randomized block design. The pots were randomly rotated every 3 days to a different position within the greenhouse during to trial.

2.4. Analysis methods of soil and plant samples

Soils were dried and sieved through a 2 mm diameter sieve. Soil pH and EC were measured using a ratio of 1:1 w/v. The texture was determined using the hydrometer method. Organic matter content was determined using the modified Walkley-Black method. Total N was determined according to the Kjeldahl method. Ammonium-N and nitrate-N were determined using the indophenol blue method and the salicylic acid method. Available P was determined according to the molybdenum blue method. Exchangeable cations were extracted with ammonium acetate at pH 7.0 and available Fe, Cu, Zn, Mn, Cd, Cr, Ni and Pb were extracted with diethylene triamine pentaacetic acid (DTPA) (0.005 M DTPA+0.01 M $CaCl_2$+0.1 M TEA (triethanolamine) pH 7.3) and measured with a Perkin Elmer 2100DV ICP OES (Inductively Coupled Plasma Optical Emission Spectroscopy).

The plant samples were dried in a forced-air oven at 65 ºC for constant weight. Dry weights were determined. The total N content of plant samples (nitrogen) was determined with a Buchi K-437/K-350 digestion/distillation unit according to the Kjeldahl method. Total elements of the plant were digested at 180 degrees with 4 ml HNO_3 and 3 ml H_2O_2 (Berghof MWS 2 DAP 60 K microwave oven). The total macronutrients (P, K, Ca, Na), micronutrients (Fe, Cu, Mn, Zn) and heavy metals (Cd, Cr, Ni, Pb) were analyzed from extracts using the ICP OES (Perkin Elmer OPTIMA 2100 DV).

2.5. Statistical methods

Data were analyzed for variance using IBM SPSS statistical programs for Windows. The least significant difference (LSD) is multiple range test was used to group the means of treatment and their interactions.

3. Result and discussion

3.1. Effects of biochar and liquid organic fertilizer on soil properties

The effect of increasing levels of biochar applications on soil properties was found to be statistically significant. Soil pH values after 70^{th} days of incubation are shown in Table 2.

The pH value increased due to the increasing amount of solid biochar and liquid organic fertilizer application. The highest pH value was determined as 8.00 and 7.92 at the end of the incubation period (Table 2). An increase in soil pH was determined depending on the incubation time. Increases in soil pH with the application of biochar are frequently reported depending on soil properties (Ding et al., 2016). The

reason for the pH increase in biochar treated soils is the negatively charged phenolic, carboxyl and hydroxyl groups on the biochar surfaces that bind H^+ ions from the soil solution (Gul et al., 2015).

Another possible mechanism is the decarboxylation of organic anions initiated by biochar addition, owing to an increasing attack of organic anions by microbes, which may consume surplus H^+ from the soil solution, and thus increase soil pH (Wang et al., 2014). Zhang et al. (2019) reported that the soils with a higher background pH value than biochar either had no effect or decreased the pH. Soil EC values were significantly increased by both solid biochar and liquid organic fertilizer applications. These increases were also determined depending on the incubation times (Table 2). The highest EC values were determined at the end of the incubation period in S5 and L5 applications as 1704 and 1664 µS cm^{-1}. The application of biochar may increase or decrease soil pH, depending mainly on the salt contents of the biochar used (Shah et al., 2017).

The increase in EC can be attributed to the high amount of ash in the biochars (Abrishamkesh et al., 2015). These results suggested that the effect of biochar on soil EC was significant during all incubation periods and the effect increased with increasing levels of biochar application. Prakongkep et al.(2020) also reported that biochar increases the soil EC value.

Biochar and liquid organic fertilizer applications statistically effected total N, NH_4-N, NO_3-N and $NaHCO_3$-P content of soil (Table 3). The amount of NH_4-N and NO_3-N increased with increasing application doses of both biochar and liquid organic fertilizer. The highest NH_4-N and NO_3-N contents were obtained from S5 and L5 applications on 1th as 28.1 and 54.7 mg kg^{-1}. A decrease in the amount of NH_4-N in biochar and liquid organic fertilizer treatment was determined depending on the incubation period. In biochar application, the amount of NO_3-N amount decreased depending on the incubation time. In liquid organic fertilizer application, an increase was determined depending on the incubation time.

The increase in NO_3-N content with biochar and liquid organic fertilizer treatment may be associated with nitrification (Shen et al., 2014; Van Zwieten et al., 2013). At the same time, the decrease in NH_4-N and NO_3-N content of soil could be attributed to electrostatic attraction, cation exchange, and H-bonding. Biochar may absorb NO_3 from an aqueous solution, which may be one of the reasons for the reduced NO_3-N content in the soil. Mainly due to biochar could retain NH_4-N in soil through acid functional groups (e.g. carboxyl and hydroxyl) on its surface via cation exchange, it have a negative charge and adsorb NH_4-N by electrostatic attraction (Glaser et al., 2002; Kameyama et al., 2012; Zhao et al., 2017).

Adding biochar to the soil changes the C:N ratio of the soil. Different results were obtained in the studies. The addition of biochar to soils has been shown to result in slower mineralization of the biochar materials than the uncharred biomass (Knoblauch et al., 2012), decrease net N mineralization (Castaldi et al., 2012; Dempster et al., 2012a), cause increased net N mineralization (Castaldi et al., 2012), have no effect on mineralization (Schomberg et al., 2012), and to have little effect on dissolved organic-N (Dempster et al., 2012b). Furthermore, biochar addition has been shown to have no effect on soil-N immobilization (Cheng et al., 2012) or promote immobilization (Bruun et al., 2012).

The effects of biochar and liquid organic fertilizer on the available P content are given in Table 3. The highest P amount was determined in chemical (NPK) fertilizer application. L4 and L5 treatments followed NPK. The effect of biochar application levels was not found statistically significant.

Table 2. Effects of applications on soil pH, EC value depending on the incubation

		Incubation Time							
		1.day	***35. day***	***70.day***	***Mean***	***1.day***	***35. day***	***70.day***	***Mean***
		pH				***EC, µS cm^{-1}***			
Treatments	Control	7.97	8.02	8.04	8.01a*	552	777	912	747d**
	NPK	7.83	7.87	7.88	7.86d*	904	1122	1301	1109b**
	S1	7.97	7.98	8.03	7.99ab*	846	822	952	873c**
	S2	7.98	7.99	8.02	7.99ab*	1042	972	1229	1081b**
	S3	7.93	7.98	8.01	7.97ab*	1065	1123	1311	1167b**
	S4	7.87	7.93	7.94	7.91c*	1223	1270	1704	1399a**
	S5	7.93	7.94	7.98	7.95bc*	1022	978	1365	1122b***
	Means	7.94b**	7.96ab**	8.00a**		1040b**	1033b**	1312a**	
	L1	7.89	7.90	7.92	7.95bc*	787	1027	1115	977d*
	L2	7.88	7.88	7.91	7.89cd*	999	1155	1109	1088c*
	L3	7.88	7.89	7.90	7.89cd*	1273	1214	1521	1336b*
	L4	7.90	7.91	7.93	7.91bc*	1276	1280	1545	1367b*
	L5	7.93	7.95	7.93	7.94bc*	1449	1411	1664	1508a*
	Means	7.90b	7.91ab	7.92a		1157b*	1217b***	1391a**	
	*. $p<0,05$, **. $p<0,01$								

Table 3. Effects of applications on soil NH_4-N, NO_3-N, Total N, $NaHCO_3$-P value depending on the incubation

		NH_4-N, mg kg^{-1}				***NO_3-N, mg kg^{-1}***			
		1.day	35. day	70.day	Mean	1.day	35. day	70.day	Mean
Treatments	Control	9.4hıj	8.0ıjk	6.9jk	8.1f**	14.4lm	15.6l	39.4d	23.2d**
	NPK	12.0fg	11.3gh	7.9ıjk	10.4e**	51.3b	52.4b	67.4a	57.0a**
	S1	10.2ghı	6.5jkl	4.2l	7.0fd**	21.2ıj	14.2lm	12.1m	15.8e**
	S2	14.4ef	15.6de	7.1jk	12.3d**	28.8gh	30.2fg	16.6kl	25.2c**
	S3	18.3c	14.4ef	11.5gh	14.7c**	34.6e	27.0h	16.8kl	26.1c**
	S4	24.3b	17.5cd	15.2de	19.0b**	32.6ef	43.1c	19.1jk	31.6b**
	S5	28.1a	19.8c	15.0de	21.0a**	39.8d	34.0e	22.1ı	32.0b**
	Means	16.6a**	13.3b**	11.0c**		31.8a**	30.9a**	27.9b**	
	L1	15.8f	6.6ı	7.8hı	10.1e**	16.6f	17.0f	27.5cd	20.4d**
	L2	21.2e	10.2h	7.0ı	12.8d**	16.3f	18.8ef	29.9c	21.7d**
	L3	32.7c	14.8f	9.9gh	19.1c**	16.5f	20.2e	43.8a	26.8c**
	L4	49.8b	29.7d	13.3fg	30.9b**	20.6e	25.2d	43.9a	29.9b**
	L5	54.7a	23.1e	23.9e	33.9a**	25.0d	35.2b	43.7a	34.6a**
	Means	34.9a**	16.9b**	12.4c**		19.0c**	23.3b**	37.8a**	
	Total N, mg kg^{-1}					***$NaHCO_3$-P, mg kg^{-1}***			
Treatments	Control	0.154	0.156	0.153	0.154	25.2def	25.2def	24.6def	25.0b*
	NPK	0.156	0.161	0.168	0.159	57.3a	47.4b	35.7c	46.8a*
	S1	0.150	0.150	0.161	0.154	25.6d	23.3def	23.9def	24.3b*
	S2	0.152	0.158	0.164	0.157	26.5d	24.6f	23.3def	24.8b*
	S3	0.153	0.156	0.158	0.155	23.9def	24.7ef	22.6def	23.7b*
	S4	0.157	0.164	0.154	0.159	23.9def	25.5de	22.7def	24.0b*
	S5	0.152	0.160	0.164	0.159	21.9def	25.9d	23.2def	23.7b*
	Means	0.153	0.158	0.160		29.2a**	25.7ab**	25.1b**	
	L1	0.158	0.157	0.152	0.156	29.0	28.3	26.1	27.8c**
	L2	0.159	0.156	0.160	0.158	30.1	31.4	27.2	29.6bc**
	L3	0.164	0.158	0.154	0.159	32.2	32.9	23.8	29.6bc**
	L4	0.166	0.160	0.158	0.161	32.2	32.4	26.9	30.5b**
	L5	0.165	0.158	0.152	0.158	35.0	33.8	31.4	33.4a**
	Means	0.162	0.157	0.155		19.0c*	23.3b*	37.8a*	
	**. p<0.05 **. p<0.01*								

The change in liquid organic fertilizer applications was significant. This may be related to the solubility of phosphorus in the liquid organic fertilizer. A decrease in soil P content was determined in all treatments depending on the incubation period. A decrease of available P can be generated by P fixation by soil. Kahura et al. (2018) reported that the amount of fixed P increased with the contact time between soil and phosphorus during to incubation time. Various factors are effective on soil P content of biochar applications such as biochar feedstock, biochar application amounts, pyrolysis temperature, pH and duration of the experiment (Glaser and Lehr, 2019). The effects of biochar and liquid fertilizer applications on soil changeable K, Ca and Na content are given in Table 4.

Table 4. Effects of applications on soil NH_4OAC-K, Ca and Na value depending on the incubation

		K, mg kg^{-1}				***Ca, mg kg^{-1}***				***Na, mg kg^{-1}***			
		1.day	***35. day***	***70.day***	***Mean***	***1.day***	***35. day***	***70.day***	***Mean***	***1.day***	***35. day***	***70.day***	***Mean***
Treatments	Control	160.0	161.0	160.0	160.3c**	5.62	5.73	5.94	5.76	126.3	127.7	135.7	129.9
	NPK	225.0	221.7	219.7	222.1a**	5.61	5.61	6.12	5.78	128.3	128.0	140.0	132.1
	S1	172.7	173.5	166.0	170.7bc**	5.85	5.86	6.48	5.41	133.7	135.5	136.0	135.1
	S2	172.0	173.7	163.0	169.6b**	5.57	5.99	6.28	5.95	133.7	139.0	138.3	137.0
	S3	156.7	165.5	145.7	155.9c**	5.85	6.15	6.66	5.54	128.0	137.0	146.7	137.2
	S4	162.7	167.7	154.0	161.4bc**	5.81	6.08	6.64	6.18	131.0	133.7	141.7	135.4
	S5	152.7	161.7	145.3	153.2bc**	5.86	6.05	6.17	6.03	131.0	132.7	139.7	134.4
	Means	171.7	158.8	164.8		5.74ab*	5.35b*	6.33a*		131.5a*	120.4b*	140.0a*	
	L1	173.3	171.0	168.7	171.0a*	5.46	6.25	6.22	5.98	133.7	137.7	147.7	139.7c**
	L2	168.3	174.7	163.3	168.8ab*	5.64	5.97	6.63	6.08	141.0	144.3	156.0	147.1bc**
	L3	166.0	166.0	160.3	164.1bc*	5.54	6.05	6.49	6.03	148.3	152.3	161.3	154.0ab**
	L4	162.7	164.3	165.3	164.1c*	5.76	5.97	6.41	6.05	150.3	159.7	163.3	157.8a**
	L5	166.7	175.3	166.0	169.3ab**	5.74	6.16	6.14	6.01	158.3	161.3	163.3	161.0a**
	Means	167.4ab*	170.3a*	164.7b*		5.63c**	6.08b**	6.38a**		146.3ab*	151.1b*	158.3a*	
	**. p<0.05, **. p<0.01*												

The highest changeable K content of the soil was determined in the application of the chemical NPK fertilizer. The K content of the soil was determined to be lower at the end of the incubation period. The direct beneficial effects of biochar addition on the availability of nutrients are largely due to the higher content of potassium, phosphorus, and zinc availability and, to a lesser extent, calcium and copper (Lehmann et al., 2003). The insignificance of the change in soil changeable potassium and calcium content can be explained by the high K and Ca content of the soil. The increase in the amount of soil exchangeable Ca and Na after the addition of biochar was found to be similar with the studies of Cornelissen et al. (2018). The change in soil DTPA extractable heavy metal content of biochar and liquid organic fertilizer applications are given in Table 5.

Biochar application increased the soil DTPA-Fe amount depending on the increasing application doses. Liquid organic fertilizer application increased the amount of DTPA Fe, Mn, Ni and Cr depending on the increasing application doses also. The heavy metal concentration extracted with DTPA decreased depending on the incubation period.

Beesley et al. (2011) reported that biochars could form compounds with metal ions on their surfaces and therefore their bioavailability would decrease in soil. Xiao et al. (2019) stated that biochars are effective in reducing the extractable metal content with DTPA and in metal immobilization. He et al. (2019) demonstrated that the biochar soil oxidation reaction would significantly affect the performance of biochar on metal mobility and speciation in soils. Namgay et al. (2010) documented a decrease in the accessibility of heavy metals after the contaminated soil was amended with biochar, due to which plant absorption of the heavy metals is reduced. Unlike many other biological amendments, biochar having the ability to increase soil pH might have improved the sorption of these metals, consequently decreasing their bioavailability for plant uptake (Cheng et al., 2018; Fidel et al., 2017). Biochars can also immobilize the phytotoxicity of heavy metals in soil-forming less bioavailable organic bound fractions (Park et al., 2011).

3.2. Effects of plant growth

The effects of increasing levels of biochar and liquid organic fertilizer on dry weight (g pot^{-1}) and plant nutrient content of the plant were given in Table 6. The results were found to be statistically significant (Table 6).

The highest dry weight was determined in the NPK application as 24.5 g and the lowest dry weight was determined in the control application as 17.4 g. Chemical fertilizer application (NPK) and L3 applications were equally effective as a 24.5 g. Biochar and liquid organic fertilizer applications increased the dry weight of the plant between also 19.1 and 21.5 g pot^{-1}. Previous researchers have reported that biochar modifications increase plant growth when applied to soil (Agbna et al., 2017).

Sun et al. (2022) reported that biochar amendment enhanced soil fertility and crop production, particularly in soils with low nutrients. However, in soils with high fertility, no noticeable increase in production was noticed, and some studies even reported inhibition of plant growth (Carter et al., 2013). It has been shown that the application of biochar in the soil has a positive or negative impact on crop production. Hence, the mechanisms for the action of biochar in the soil must be understood before its application.

The nitrogen content of the plant was affected by the applications (Table 6). Plant nitrogen content varied between 1.23% and 2.31%. S3, S4 and S5 treatment of biochar applications and all of the liquid organic fertilizers were found higher than the control. L3, L4 and L5 treatment of liquid organic applications gave higher results than NPK application. These results are related to the nitrogen content and N availability of the applied biochar and liquid organic fertilizer.

Plant phosphorus (P) content varied between 0.431% and 0.617%. The effect of liquid organic fertilizer applications was more pronounced compared to control and NPK treatment. The effect of biochar applications varied between 0.412% and 0.508%. The value of S1 and S2 treatments of biochar was determined higher than the control. Both biochar and liquid organic fertilizer applications increased the plant K content depending on the doses. The highest potassium content of the plant was determined in the NPK application as 7.52 % and in the L5, S4 and S5 applications as 7.42, 7.29 and 7.24% respectively. Ca, Mg and Na contents of the plant were determined higher than the control application. The plant Ca content ranged from 1.40% to 2.15%, Mg content from 0.46% to 0.94%, Na content from 0.23% to 0.33% respectively.

The nutrient contents determined in the plant were compared with the limit values such as P, K, Ca, Mg and Na. It was evaluated to be in the "sufficient" or "excess" sufficiency class. The plant nitrogen content was rated in the "low" qualification class. Plant microelement and heavy metal contents were determined higher than control and NPK applications in high biochar and organic fertilizer applications, especially. Microelements and heavy metal contents were listed as Fe, Zn, Mn, Cu, Cr, Ni, Pb and Cd in terms of content. The highest amounts were obtained from the L5 application of liquid organic fertilizer. Plant micronutrient contents (Fe, Zn, Mn and Cu) were in the "sufficient" or "excess" qualification class depending on the applications.

Table 5. Effects of applications on soil Fe, Cu, Mn, Zn, Pb, Cd, Cr and Ni value depending on the incubation

		Incubation Time							
		1.day	***35. day***	***70.day***	***Mean***	***1.day***	***35. day***	***70.day***	***Mean***
		Fe, mg kg^{-1}				Mn, mg kg^{-1}			
Treatments	Control	52.7	44.9	42.1	46.6	65.6a	47.0e	47.6d	53.4
	NPK	53.0	48.4	41.8	47.7	69.0a	49.2cd	45.2d	54.5
	S1	46.3	49.4	45.7	47.1	51.5cd	49.4cd	49.9bcd	50.3
	S2	50.2	48.0	41.9	46.7	52.6ab	50.8cd	49.8cd	51.1
	S3	51.5	41.7	39.4	44.2	60.6cd	45.0d	46.4d	50.6
	S4	55.2	45.5	42.9	47.9	63.0abc	52.4bcd	48.7d	54.7
	S5	59.5	48.7	41.6	50.0	64.9a	51.7bcd	45.0d	53.9
	Means	52.6a**	46.7b**	42.3b**		58.5a**	49.9b**	48.0b**	
	L1	58.3	51.6	42.9	50.9	70.3	53.7	47.0	57.0
	L2	59.0	50.5	42.1	50.6	72.2	57.4	47.7	59.1
	L3	58.1	49.1	41.0	49.4	83.0	65.1	48.2	65.4
	L4	56.2	51.8	39.5	49.2	87.0	67.6	46.2	66.9
	L5	55.7	50.4	39.1	48.4	89.3	64.1	45.4	66.3
	Means	57.5a**	50.7b**	40.9c**		80.3a**	61.6b**	46.9c**	
		Zn, mg kg^{-1}				Cu, mg kg^{-1}			
	Control	11.6	10.5	11.0	11.0	12.2	12.1	11.3	11.8
	NPK	11.8	11.2	10.9	11.3	12.5	11.7	11.8	12.0
Treatments	S1	10.3	11.4	10.8	10.8	10.7	11.8	11.6	11.4
	S2	11.9	11.3	10.6	11.2	11.6	11.9	11.9	11.8
	S3	9.9	9.8	10.1	9.9	11.4	11.4	11.7	11.5
	S4	10.2	10.1	11.9	10.7	11.9	12.0	12.5	12.1
	S5	10.8	10.5	12.0	11.1	12.0	12.4	12.5	12.3
	Means	10.6	10.6	11.1		11.5	11.9	12.0	
	L1	12.2	12.1	10.7	11.6ab*	12.3	11.5	11.3	11.7
	L2	12.3	12.5	10.5	11.8a*	12.4	11.5	11.4	11.8
	L3	12.0	11.6	10.3	11.3bc*	12.7	11.1	11.5	11.8
	L4	11.6	11.0	10.0	10.8c*	12.9	11.8	11.3	12.0
	L5	12.0	11.3	10.5	11.3bc*	12.6	11.3	11.2	11.7
	Means	12,0a**	11,7a**	10,4b**		12,6a**	11,4b**	11,4b**	
		Ni, mg kg^{-1}				Cr, mg kg^{-1}			
Treatments	Control	2.19	1.86	1.64	1.89	0.038	0.035	0.035	0.036
	NPK	2.44	1.97	1.71	2.04	0.041	0.037	0.035	0.038
	S1	1.90	1.92	1.78	1.87	0.039	0.034	0.033	0.035
	S2	2.18	1.95	1.63	1.92	0.049	0.033	0.031	0.038
	S3	2.06	1.78	1.54	1.80	0.041	0.031	0.031	0.034
	S4	2.16	2.00	1.66	1.94	0.039	0.036	0.034	0.036
	S5	2.36	1.95	1.51	1.94	0.041	0.038	0.031	0.037
	Means	2.13a	1.92b	1.62c		0.042a**	0.034b**	0.032b**	
	L1	2.25cd	2.09d	1.64e	1.99c*	0.043cde	0.040cde	0.041cde	0.041c*
	L2	2.43c	2.23cd	1.72e	2.13b*	0.050bc	0.046cde	0.037e	0.044bc*
	L3	2.65b	2.26cd	1.70e	2.20ab*	0.058ab	0.049bcd	0.039cde	0.049b*
	L4	2.89a	2.24cd	1.67e	2.27a*	0.067a	0.062a	0.039cde	0.056a*
	L5	2.82ab	2.20d	1.57e	2.20ab*	0.066a	0.049bcd	0.037de	0.051ab*
	Means	2.61a**	2.20b**	1.66c**		0.057a**	0.049b**	0.039c**	
		Pb, mg kg^{-1}				Cd, mg kg^{-1}			
Treatments	Control	4.20a	4.00b-e	3.76hıj	3.99a**	0.010	0.010	0.010	0.010
	NPK	4.11ab	3.80g-j	3.75hıj	3.89bc**	0.010	0.010	0.010	0.010
	S1	3.93c-g	4.02bcd	3.73ıjk	3.89b**	0.009	0.010	0.010	0.010
	S2	3.93b-de	3.89d-h	3.58kl	3.80c**	0.010	0.010	0.011	0.010
	S3	3.68jk	3.67jk	3.43kl	3.59d**	0.010	0.010	0.011	0.010
	S4	3.86e-ı	3.84ghı	4.19a	3.96ab**	0.010	0.010	0.012	0.011
	S5	3.94c-g	3.97b-f	4.07abc	3.99a**	0.010	0.010	0.012	0.011
	Means	3.87a**	3.88b**	3.80c**		0.010b	0.010b	0.011a	
	L1	4.33	4.18	3.76	4.09a*	0.010	0.010	0.010	0.010
	L2	4.29	4.12	3.58	4.00ab*	0.010	0.010	0.010	0.010
	L3	4.23	3.89	3.60	3.91bc*	0.010	0.010	0.010	0.010
	L4	4.07	3.78	3.49	3.78d*	0.010	0.010	0.010	0.010
	L5	4.07	3.83	3.54	3.81cd*	0.010	0.010	0.010	0.010
	Means	4.20a**	3.96b**	3.59c**		0.010	0.010	0.010	
	**. p<0.05, **. p<0.01*								

Table 6. Effect of applications on dry weight and plant nutrient content

	Control	*NPK*	*S1*	*S2*	*S3*	*S4*	*S5*	*L1*	*L2*	*L3*	*L4*	*L5*
DW	17.37 d**	24.53 a	19.06 c	20.30 bc	21.58 bc	19.35 c	19.26 c	20.70 bc	22.54 b	24.53 a	21.19 bc	19.92 c
N,%	1.23 de**	1.94 bc	1.82 de	1.85 de	1.47 de	1.55 cd	1.86 bc	1.53 cde	1.84 bc	1.98 ab	2.07 ab	2.31 a
P,%	0.453 efg*	0.508 bcd	0.508 bcd	0.500 bcde	0.431 fg	0.476 cdef	0.412 g	0.464 def	0.512 bc	0.524 b	0.530 b	0.617 a
Mg,%	0.429 de**	0.552 de	0.464 e	0.579 cd	0.588 cd	0.634 c	0.671 c	0.529 de	0.823 b	0.942 a	0.893 ab	0.848 ab
Na, %	0.227 e**	0.263 bcd	0.290 d	0.300 abc	0.281 cd	0.302 abc	0.307 abc	0.290 bcd	0.318 ab	0.312 abc	0.283 cd	0.329 a
K,%	0.635 c*	0.752 a	0.638 c	0.676 abc	0.689 abc	0.724 ab	0.728 a	0.622 c	0.636 c	0.642 bc	0.702 abc	0.742 a
Ca,%	0.156 bcd**	0.195 ab	0.140 d	0.147 cd	0.145 cd	0.191 ab	0.199 ab	0.165 bcd	0.187 abc	0.212 a	0.215 a	0.185 abc
Cu,mg kg^{-1}	6.92 e**	12.00 bc	6.67 e	6.75 e	10.33 cd	8.83 de	8.67 de	7.50 de	13.67 ab	12.17 bc	15.58 a	15.67 a
Zn,mg kg^{-1}	69.50 b*	66.92 bc	64.67 bc	68.83 b	74.58 b	72.92 b	92.17 a	55.33 c	88.83 a	87.92 a	89.50 a	93.17 a
Fe,mg kg^{-1}	154.4 cd**	205.5 bcd	160.1 cd	176.2 bcd	186.9 bcd	211.7 bc	246.7 b	127.8 d	166.9 bcd	2213.4 bc	231.7 bc	360.0 a
Mn,mg kg^{-1}	51.67 f*	68.25 de	53.25 f	69.75 cde	69.67 cde	66.17 e	76.83 bcd	52.58 f	78.92 bc	89.58 a	84.33 ab	76.75 bcd
Ni,mg kg^{-1}	2.58	2.75	2.83	3.00	3.50	3.33	3.42	2.92	2.92	3.08	3.25	2.66
Pb,mg kg^{-1}	0.50	0.50	0.42	0.50	0.75	0.83	0.83	0.58	0.50	0.58	0.58	0.67
Cr,mg kg^{-1}	3.42	3.75	3.50	3.67	3.83	3.67	4.08	3.50	3.67	3.50	3.67	3.58
Cd,mg kg^{-1}	0.25bc*	0.18 c	0.33 b	0.33 b	0.33 b	0.50 a	0.33 a	0.25 bc	0.33 b	0.50 a	0.50 a	0.50 a
*DW, dry weight per pot *. p<0.05, **. p<0.01*												

Biochar has been reported to increase plant growth through several mechanisms. Mechanisms responsible for stimulation of plant yield by biochar is still under investigation, but in summary, the majority of studies stated either a slow release effect or increased nitrogen use efficiency, which they partly attributed to:(1) pH-change effects on microbial communities (Nielsen et al., 2014), (2) increased root growth and N uptake (Liu et al., 2021; Shi et al., 2020; Xiang et al., 2017), (3) increased mycorrhizal root colonization (Blackwell et al., 2015), (4) increased physical retention of dissolved nutrients and reduced leaching (El Sharkawi et al., 2018; Schmidt et al., 2015; Schmidt et al., 2017; Shi et al., 2020; Wen et al., 2017), (5) increased nitrification and reduced denitrification (Liao et al., 2020), (6) improved redox conditions and changes in abundance of growth promoting micro-organisms (Chew et al., 2020), (7) increased P and K availability (Farrar et al., 2019), and (8) slower diffusion of NH_4 and NO_3 to soil solution (Liao et al., 2020)

4. Conclusions

The addition of biochar in the soil can be extremely beneficial for plant growth as well as improving soil properties. Positive results were obtained depending on the application levels. Organic applications increased the pH value of the soil depending on the doses and incubation time. An increase in EC value was determined in all applications. The amount of NH_4-N and NO_3-N increased, while the amount of NH_4-N decreased due to fixation and nitrification depending on time.

The amount of available P increased depending on the application level, but decreased with time in biochar applications. While K decreased with time, the amount of Ca and Na increased. The DTPA extractable heavy metal contents of the soils decreased depending on the incubation time. Organic applications increased plant growth and nutrient content depending on the application levels. In particular, these effects were more pronounced in the N, K, Ca, Fe, Zn content in the biochar application, and in the N, P, K, Fe, Cu and Zn content in the liquid application.

It is necessary to work on the level of chemical fertilizer and the economic application of biochar by applying with biochar and chemical fertilizers.

References

Abrishamkesh S., Gorji M., Asadi H., Bagheri-Marandi G.H., Pourbabaee A.A., (2015), Effects of rice husk biochar application on the properties of alkaline soil and lentil growth, *Plant Soil Environment,* **61,** 475-482.

Agbna G.H.D., Dongli S., Zhipeng L., Elshaikh N.A., Guangcheng S., Timm L.C., (2017), Effects of deficit irrigation and biochar addition on the growth, yield, and quality of tomato, *Scientia Horticulture*, **222**, 90-101.

Beesley L., Moreno-Jiménez E., Jose L.G.E., Eva H., Robinson B., Sizmur T., (2011), A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils, *Environmental Pollution*, **159**, 3269-3282.

Blackwell P., Joseph S., Munroe P., Anawar H.M., Storer P., Gilkes R.J., Solaiman Z.M., (2015), Infuences of biochar and biochar-mineral complex on mycorrhizal colonisation and nutrition of wheat and sorghum, *Pedosphere*, **25**, 686-695.

Bruun E.S., Ambus P., Egsgaard H., Huggaard-Nielsen H., (2012), Effects of slow and fast pyrolysis biochar on soil c and n dynamics, *Soil Biology and Biochemistry*, **46**, 73-79.

Carter S., Shackley S., Sohi S., Suy T.B., Haefele S., (2013), The ımpact of biochar application on soil properties and plant growth of pot grown lettuce (*Lactuca sativa*) and cabbage (*Brassica chinensis*), *Agronomy,* **3**, 404-418.

Castaldi S., Riondino M., Baronti S., Esposito F.R., Marzaioli R., Rutigliano F.A., (2012), Impact of biochar application to a Mediterranean wheat crop on soil microbial activity and greenhouse gas fluxes, *Chemosphere*, **85**, 1464-1471.

Chen Q., Qin J., Sun P., Cheng Z., Shen G., (2018), Cow dung-derived engineered biochar for reclaiming phosphate from aqueous solution and its validation as slow-release fertilizer in soil-crop system, *Journal of Cleaner Production*, **172**, 2009-2018.

Cheng Y., Cai Z.C., Chang S.X., Wang J., Zhang J.B., (2012), Wheat straw and its biochar have contrasting

effects on inorganic N retention and N_2O production in a cultivated black chernozem, *Biology and Fertility of Soils*, **48**, 941-946.

Cheng H., Jones D.L., Hill P., Bastami M.S., Tu C.L., (2018), Influence of biochar produced from different pyrolysis temperature on nutrient retention and leaching, *Archives of Agronomy and Soil Science*, **64**, 850-859.

Chew J., Zhu L., Nielsen S., Graber E., Mitchell D.R.G., Horvat J., Mohammed M., Liu M., van Zwieten L., Donne S., Munroe P., Taherymoosavi S., Pace B., Rawal A., Hook J., Marjo C., Thomas D.S., Pan G., Li L., Bian R., McBeath A., Bird M., Thomas T., Husson O., Solaiman Z., Joseph S., Fan X., (2020), Biochar-based fertilizer: Supercharging root membrane potential and biomass yield of rice, *Science of the Total Environment*, **713,** 136431, http://doi.org/10.1016/j.scitotenv.2019.136431

Cornelissen G., Jubaedah N.L., Hale S.E., Martinsen V., Silvani L., Mulder J., (2018), Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian ultisol, *Science of the Total Environment*, **634**, 561-568.

De Meyer A., Poesen J., Isabirye M., Deckers J., Rates D., (2011), Soil erosion rate in tropical villages: a case study from Lake Victoria Basin, Uganda, *Catena*, **84**, 89-98.

Dempster D.N., Jones, D.L., Murphy D.M., (2012a), Clay and biochar amendments decreased inorganic but not dissolved organic nitrogen leaching in soil, *Soil Research*, **50**, 216-221.

Dempster D.N., Gleeson D.B., Solaiman Z.M., Jones D.L., Murphy D.V., (2012b), Decreased soil microbial biomass and nitrogen mineralisation with eucalyptus biochar addition to a coarse textured soil, *Plant and Soil*, **354**, 311-324.

Ding Y., Liu Y., Liu S., Li Z., Tan X, Huang X., Zen G., Zhou L., Zheng B., (2016), Biochar to improve soil fertility, *Agronomy for Sustainable Development*, **36,** 36, https://doi.org/10.1007/s13593-016-0372-z

Duhan J.S., Kumar R., Kumar N., Kaur P., Nehra K., Duhan S., (2017), Nanotechnology: the new perspective in precision agriculture, *Biotechnology Reports*, **15**, 11-23.

El Sharkawi H.M., Tojo S., Chosa T., Malhat F.M., Youssef A.M., (2018), Biochar-ammonium phosphate as an uncoated-slow release fertilizer in sandy soil, *Biomass Bioenergy*, **117**,154-160.

Farrar M.B., Wallace H.M., Xu C.Y., Nguyen T.T.N., Tavakkoli E., Joseph S., Bai S.H., (2019), Short-term effects of organo-mineral enriched biochar fertiliser on ginger yield and nutrient cycling, *Journal of Soils and Sediments*, **19**, 668-682.

Fellet G., Conte P., Bortolotti V., Zama F., Landi G., Chillura Martino D.F., Ferro V., Marchiol L., Lo Meo P., (2022), Changes in physicochemical properties of biochar after addition to soil, *Agriculture,* **12**, 320, https://doi.org/10.3390/agriculture12030320.

Fidel R.B., Laird D.A., Thompson M.L., Lawrinenko M., (2017), Characterization and quantification of biochar alkalinity, *Chemosphere*, **167**, 367-373.

Glaser B., Lehmann J., Wolfgang Z., (2002), Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal- a review, *Biology and Fertility of Soils*, **35**, 219-230.

Glaser B., Lehr V.I., (2019), Biochar effects on phosphorus availability in agricultural soils: A meta-analysis, *Scientific Reports*, **9**, 9338, https://doi.org/10.1038/s41598-019-45693-z

Gul S., Whalen J.K., Thomas B.W., Sachdeva V., Deng H., (2015), Physicochemical properties and microbial responses in biochar-amended soils: mechanisms and future directions, *Agriculture, Ecosysttems Environment*, **206**, 46-59.

He E., Yang Y., Xu Z., Qiu H., Yang F., Peijnenburg W., Zhang W., Qiu R., Wang S.Z., (2019), Two years of aging influences the distribution and lability of metal (loid)s in a contaminated soil amended with different biochars, *Science of the Total Environment*, **673,** 245-253.

Kameyama K., Miyamoto T., Shiono T., Shinogi Y., (2012), Influence of sugarcane bagasse-derived biochar application on nitrate leaching in calcaric dark red soil, *Journal of Environmental Quality*, **41**, 1131-1137.

Kahura M.W., Min H., Kim M.S., Kim J.G., (2018), Assessing phosphorus availability in a high pH, biochar amended soil under ınorganic and organic fertilization, *Ecology and Resilient Infrastructure*, **5,** 11-18.

Karim A.A, Kumar M., Singh E., Kumar A., Kumar S., Ray A., Dhal N.K., (2021), Enrichment of primary macronutrients in biochar for sustainable agriculture, *Critical Reviews in Environmental Science and Technology*, **52**, 1449-1490.

Khan H.A., Naqvi S.R., Mehran M.T., Khoja A.H., Niazi M.B.K., Juchelkova D., Atabani A., (2021), A performance evaluation study of nano-biochar as a potential slow-release nano-fertilizer from wheat straw residue for sustainable agriculture, *Chemosphere*, **285**, 131382, https://doi.org/10.1016/j.chemosphere.2021.131382

Knoblauch C., Maarifat A.A., Pfeiffer E.M., Haefele S.M., (2012), Degradability of black carbon and its impact on trace gas fluxes and carbon turnover in paddy soils, *Soil Biology and Biochemistry*, **43**, 1768-1778.

Lehmann J., Da Silva J.P. Jr Steiner C., Nehls T., Zech W., Glaser B., (2003), Nutrient availability and leaching in an archaeological anthrosol and a ferrasol of the Central Amazon basin: Fertilizer, manure, and charcoal amendments, *Plant and Soil*, **249**, 343-357.

Lehmann J., Rillig M.C., Thies J.E., Masiello C., Hockaday W.C., Crowley D., (2011), Biochar effects on soil biota- A review, *Soil Biology and Biochemistry*, **43**, 1812-1836.

Li H., Li Y., Xu Y., Lu X., (2020), Biochar phosphorus fertilizer effects on soil phosphorus availability, *Chemosphere*, **244**, 125471, https://doi.org/10.1038/s41598-019-45693-z

Liao J., Liu X., Hu A., Song H., Chen X., Zhang Z., (2020), Efects of biochar-based controlled release nitrogen fertilizer on nitrogen-use efficiency of oilseed rape (*Brassica napus* L.), *Scientific Reports*, **10**, 11063, https://doi.org/10.1038/s41598-020-67528-y

Liu X., Wang H., Liu C., Sun B., Zheng J., Bian R., Drosos M., Zhang X., Li L., Pan G., (2021), Biochar increases maize yield by promoting root growth in the rainfed region, *Archives of Agronomy and Soil Science*, **67**, 1411-1424.

Namgay T., Singh B., Singh B.P., (2010), Influence of biochar application to soil on the availability of As, Cd, Cu, Pb, and Zn to maize (*Zea mays* L.), *Australian Journal of Soil Research*, **48**, 638-647.

Nielsen S., Minchin T., Kimber S., Van Zwieten L., Gilbert J., Munroe P., Joseph S., Thomas T., (2014), Comparative analysis of the microbial communities in agricultural soil amended with enhanced biochars or traditional fertilisers, *Agriculture, Ecosystems and Environment*, **191**, 73-82.

Park J.H., Choppala G.K., Bolan N.S., Chung J.W., Chuasavathi T., (2011), Biochar reduces the bioavailability and phytotoxicity of heavy metals, *Plant and Soil*, **348**, 439-451.

Prakongkep N., Gilkes R., Wisawapipat W., Leksungnoen P., Kerdchana C., Inboonchuay T., Delbos, E., Strachan L.J., Ariyasakul P., Ketdan C., Hammecker C., (2020), Effects of biochar on properties of tropical sandy soils under organic agriculture, *Journal of Agricultural Science*, **13**, 1-17.

Rezaee M., Gitipour S., Sarrafzadeh M.H., (2021), Evaluation of phosphate and ammonium adsorption-desorption of slow pyrolyzed wood biochar, *Environmental Engineering and Management Journal*, **20**, 217-227.

Schmidt H.P., Pandit B.H., Cornelissen G., Kammann C., (2017), Biochar-based fertilization with liquid nutrient enrichment: 21 feld trials covering 13 crop species in Nepal, *Land Degradation and Development*, **28**, 2324-2342.

Schmidt H.P., Pandit B.H., Martinsen V., Cornelissen G., Conte P., Kammann C.I., (2015), Fourfold increase in pumpkin yield in response to low-dosage root zone application of urine-enhanced biochar to a fertile tropical soil, *Agriculture*, **5**, 723-741.

Schomberg H.H., Gaskin J.W., Harris K., Das K.C., Noval J.M., Busscher W.J., Watts D.W., Woodroof R.H., Lima I.M., Ahmedna M., Rehrah D., Xing B., (2012), Influence of biochar on nitrogen fractions in a coastal plain soil, *Journal of Environmental Quality*, **41**, 1087-1095.

Shah T., Khan S., Shah Z., (2017), Soil respiration, pH and EC as influenced by biochar, *Soil and Environment*, **36**, 77-83.

Shen J., Tang H., Liu J., Wang C., Li Y., Ge T., Jones D.L., Wu J., (2014), Contrasting effects of straw and straw-derived biochar amendments on greenhouse gas emissions within double rice cropping systems, *Agriculture, Ecosystems and Environment*, **188**, 264-274.

Shi W., Ju Y., Bian R., Li L., Joseph S., Mitchell D.R.G., Munroe P., Taherymoosavi S., Pan G., (2020), Biochar bound urea boosts plant growth and reduces nitrogen leaching, *Science of the Total Environment*, **701**, 134424, https://doi.org/10.1016/j.scitotenv.2019.134424

Sun Z., Hu Y., Shi L., Li G., Pang Z., Liu S., Chen Y., Jia B., (2022), Effects of biochar on soil chemical properties: A globalmeta-analysis of agricultural soil, *Plant, Soil and Environment*, **68**, 272-289.

Tang J., Zhu W., Kookana R., Katayama A., (2013), Characteristics of biochar and its application in remediation of contaminated soil, *Journal of Bioscience and Bioengineering*, **116**, 653-659.

Wang L., Butterly C.R., Wang Y., Herath H.M.S.K., Xi Y.G., Xiao X.J., (2014), Effect of crop residue biocharnon soil acidity amelioration in strongly acidic tea garden soils, *Soil Use Management*, **30**, 119-128.

Wang, C., Sun R., Huang R., (2021a), Highly dispersed iron-doped biochar derived from sawdust for Fenton-like degradation of toxic dyes, *Journal of Cleaner Production*, **297**, 126681, https://doi.org/10.1016/j.jclepro.2021.126681

Wang C., Huang R., Sun R., Yang J., Sillanp M., (2021b), A review on persulfates activation by functional biochar for organic contaminants removal: Synthesis, characterizations, radical determination, and mechanism, *Journal of Environmental Chemical Engineering*, **9**, 106267, https://doi.org/10.1016/j.jece.2021.106267

Wang C., Luo D., Zhang X., Huang R., Cao Y., Liu G., Zhang Y., Wang H., (2022), Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review, *Environmental Science and Ecotechnology*, **10**, 100167, https://doi.org/10.1016/j.ese.2022.100167

Wen P., Wu Z., Han Y., Cravotto G., Wang J., Ye B.C., (2017), Microwave-assisted synthesis of a novel biochar-based slow-release nitrogen fertilizer with enhanced water-retention capacity, *ACS Sustainable Chemistry and Engineering*, **5**, 7374-7382.

Xiang Y., Deng Q., Duan H., Guo Y., (2017), Efects of biochar application on root traits: a meta-analysis, *Global Change Biology Bioenergy*, **9**,1563-1572.

Xiao R., Wang P., Mi S., Ali A., Liu X., Li Y., Guan W., Li R., Zhang Z., (2019), Effects of crop straw and its derived biochar on the mobility and bioavailability in Cd and Zn in two smelter-contaminated alkaline soils, *Ecotoxicology and Environmental Safety*, **181**, 155-163.

Van Zwieten L., Kimber S.W.L., Morris S.G., Singh B.P., Grace P.R., Scheer C., Rust J., Downie A.E., Cowie A.L., (2013), Pyrolysing poultry litter reduces N_2O and CO_2 fluxes, *Science of the Total Environment*, **465**, 279-287.

Yakout S.M., Daifullah A.E.M., El-Reefy S.A., (2015), Pore structure characterization of chemically modified biochar derived from rice straw, *Environmental Engineering and Management Journal*, **14**, 473-480.

Zhang M., Riaz M., Zhang L., El-desouki Z., Jiang C., (2019), Biochar induces changes to basic soil properties and bacterial communities of different soils to varying degrees at 25 mm rainfall: More effective on acidic soils, *Frontiers in Microbiology*, **10**, 1321, https://doi.org/10.3389/fmicb.2019.01321

Zellagui S., Schönnenbeck C., Zouaoui-Mahzoul N., Leyssens G., Authier O., Thunin E., Brilhac, J.F., (2016), Pyrolysis of coal and woody biomass under N_2 and CO_2 atmospheres using a drop tube furnace-experimental study and kinetic modeling, *Fuel Processing Technology*, **148**, 99-109.

Zhao H., Zheng S., Li T., Yao X., Li Z., Wang P., (2017), Effects of environmental conditions on the adsorption of NH_4-N by rice-straw biochar, 904-914, *DEStech Transactions on Engıneerıng and Technology Research*, http://doi.org/10.12783/dtetr/apetc2017/11438