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A study on the effects of sugarcane bagasse hydrochar as an environmentally friendly fertilizer on bean plant and sandy loam soil characteristics

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Abstract

The present study investigated the effects of engineered sugarcane bagasse hydrochar on the soil properties of sandy loam and the growth parameters of bean plants. After preparing the optimal hydrochar, its physicochemical properties were determined through various analyses. The effects of different rates of hydrochar (0%, 1%, 2%, and 5% w/w) were then investigated on the bulk density, porosity, pH, organic carbon, nitrogen, and phosphorus content of the soil, as well as on plant height, lateral branch number, leaf number, and dry weight of aerial parts and roots. The results show that the addition of engineered sugarcane bagasse hydrochar at all levels improved the soil properties of sandy loam. However, an inverse effect was observed for the electrical conductivity (EC) parameter. The 5% hydrochar treatment resulted in a significant increase of 78.4% in organic carbon, while a minimal decrease of 0.4% was observed in pH. Regarding the growth parameters of bean plants, only the 1% engineered hydrochar treatment showed a positive effect on growth parameters.

Introduction

The increase in global population has led to an increase in agricultural production, which has had detrimental effects on water, air, and soil quality (De Jager et al., 2020). In recent years, the gradual decline in organic matter and the subsequent deterioration of soil quality have become significant global challenges (Parlavecchia et al., 2020). While ensuring food production safety, it is essential to maintain a healthy environment for plant growth. Declining soil fertility has compelled farmers to rely more on mineral fertilizers such as nitrogen and phosphorus to achieve higher yields (Chen et al., 2021). However, this practice results in the excessive accumulation of phosphorus and nitrogen in water sources, leading to water pollution. Water pollution disrupts the balance of aquatic ecosystems and imposes substantial costs for pollutant removal from water sources (Azimzadeh et al., 2021).

In addition, the mineral resources of fertilizers of nitrogen and phosphorus are limited and non-renewable. Therefore, finding sustainable solutions to address these challenges is crucial. One potential solution is the utilization of environmentally friendly materials that can effectively remove phosphorus and nitrate from aqueous solutions. These materials can then be further explored as slow-release fertilizers

(Azimzadeh et al., 2021). Indeed, the increase in greenhouse gas emissions resulting from agricultural activities has significant implications for climate change. It is imperative to adopt sustainable agricultural practices that not only ensure stable agricultural systems but also minimize the environmental impact and reduce production costs. In recent years, the production of biochar from agricultural residues has significantly contributed to their recycling. As a result, global concerns regarding the increase in greenhouse gases from the composting of agricultural residues have been partially addressed.

Biochar is a porous, cost-effective, and carbon-rich material that possesses various beneficial properties. It has the capacity to effectively remove contaminants from water, enhance soil fertility by increasing carbon reserves, stabilize soil nutrients, promote aggregate formation and stability, improve soil porosity, and enhance plant growth. However, challenges associated with the utilization of dry agricultural residues and the generation of hazardous gases, such as carbon monoxide (CO), and methane (CH_4) in during biochar production have prompted researchers to explore alternative approaches (Fang et al., 2015). One of the alternative methods is the production of hydrochar. Hydrochar is a specific type of biochar that is generated through the hydrothermal carbonization process. This process involves subjecting the biomass to high temperature and pressure conditions within a stainless steel autoclave, typically in the range of 180 to 260 °C (Liu et al., 2018). The hydrothermal process and the resulting hydrochar are known for their environmentally friendly mechanisms. However, the outcomes of hydrochar application on soil and plant systems are influenced by various factors, including the characteristics of the raw materials used, the temperature and duration of the hydrothermal process, the texture of the soil, the quantity of hydrochar applied, and the specific plant species involved. These factors collectively determine the effectiveness and impact of hydrochar application. It is crucial to consider and optimize these variables to achieve desired outcomes when using hydrochar in soil and plant management practices (Bento et al., 2019; Islam et al., 2021). Studies on the effect of hydrochar on soil and plants showed that the presence of oxygen-containing functional groups and the porous structure of hydrochar can be a factor in the success of nutrient stabilization (Xia et al., 2020; Yu et al., 2020). The researchers also expressed that hydrochar prevents soil degradation, increases soil porosity, enhances soil water holding capacity, and improves the stability of soil aggregates (Abel et al., 2013; De Jager et al., 2020; Islam et al., 2021). Schimmelpfennig et al. (2014) stated that plant growth decreased with the application of hydrochar, particularly in the first year of the experiment. Fang et al. (2015) stated that seed germination significantly increased with the addition of hydrochar. Puccini et al. (2018) observed the germination of lettuce decreased after using hydrochar. Baronti et al. (2017) observed a significant increase in biomass production of poplar trees after 2 years.

Hydrochar's behavior in the soil and its effect on different plant systems is still unclear due to the above. To avoid negative effects on soil and plants, their use should be carefully tested before large-scale use (George et al., 2012). The aim of this study was to examine the utilization of engineered hydrochar derived from sugarcane bagasse, following the adsorption of nitrate and phosphate, as an organic fertilizer for soil and its impact on bean characteristics. Sugarcane bagasse, which is a by-product of the sugar industry obtained after extracting water from sugarcane, is typically disposed of by burning, resulting in environmental pollution. However, due to the presence of cellulose, hemicellulose, and lignin in sugarcane bagasse, it possesses a porous surface, high mechanical strength, and the potential to serve as a biosorbent. By utilizing engineered hydrochar derived from sugarcane bagasse and enhancing its adsorption capacity for nitrate and phosphate, it can be repurposed as an organic fertilizer, thereby reducing waste and environmental pollution while providing beneficial effects for soil and bean growth (Feng et al., 2020). Therefore, the use of sugarcane bagasse is not only environmentally valuable but also is a suitable option for producing valuable and new products on a large scale.

Material and methods

Synthesis of sugarcane bagasse hydrochar

The present research was conducted at the Faculty of Water and Environmental Engineering, Shahid Chamran University of Ahvaz (2020-2021). To prepare the hydrochar, sugarcane bagasse obtained from the Amir Kabir agriculture and industry was used. It was then washed multiple times with distilled water to remove dust and impurities and dried at a temperature of 80 °C. 10 g of sugarcane bagasse, were mixed with 60 ml of deionized water and added to a stainless steel autoclave with a capacity of 100 ml. The autoclave was then placed at a temperature of at 220 ° C for 4 h. After the specified time, the autoclave was cooled to room temperature, and its contents were washed with deionized water to stabilize their pH. Subsequently, they were dried at a temperature of 50 °C for 24 hours, and the resulting solid products were introduced as sugarcane bagasse hydrochar (HCSB). To achieve particle homogeneity of the obtained sugarcane bagasse hydrochar, the product was passed through sieve number 10.

To increase the efficiency, the prepared hydrochars were placed on a stirrer at room temperature with a 1:1 weight ratio of magnesium chloride solution. After 24 hours, the solid phase was separated from the liquid and washed with deionized water to remove residual chemicals. The activated hydrochars were dried at a temperature of 100 °C for 24 hours. Finally, the obtained product was introduced as engineered sugarcane bagasse hydrochar.

Characterization of engineered hydrochar of sugarcane bagasse

The surface structure of engineered sugarcane bagasse hydrochar was examined using a scanning electron microscopy (SEM, Leo 1455 VP model, made in Germany). Fourier transform infrared spectroscopy (FTIR, Spectrum GX, and Perkin- Elmer) was used to identify different functional groups in engineered sugarcane bagasse hydrochar. The percentage carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) was determined using the elemental analyzer (CHNOS, Vario ELIII, Elementary, made in Germany). The X-ray fluorescence (XRF) was used to determine the percentage and type of metal oxides of the prepared engineered sugarcane bagasse hydrochar. The pH of the point of zero charge ($pH_{(pzc)}$) of engineered sugarcane bagasse hydrochar was determined with sodium chloride solution method (Hafshejani et al., 2016).

Soil

The soil samples used in this study were collected from a depth of 0-30 cm in the research field of the Faculty of Agriculture at Shahid Chamran University of Ahvaz, Iran. The soil samples were air dried until reaching a constant weight. After drying, the soils were crushed and passed through a 2 mm sieve to ensure uniformity. The soil properties such as bulk density by cylinder method, soil texture by hydrometer method were analyzed (Gee & Or, 2002), organic carbon by Walkley and Black method (Nelson & Sommers, 1996), total nitrogen was measured by Kjeldahl method, total phosphorus was measured by Olsen method (Kuo, 1996), cation and anion exchange capacity was measured by sodium nitrate replacement by hydrochloric acid and potassium chloride, and pH and EC in soil saturated extracts were measured. The physical and chemical properties of the soil are presented in Table (1).

Table 1- The physical and chemical properties of soil used in present study

Soil			
Property	Value	Property	Value
pH	7.48	Bulk density (g. cm^{-3})	1.56
EC (ds. m^{-1})	2.93	Porosity (%)	42.5
Soil texture	Sandy loam	Phosphorus (mg. Kg^{-1})	7.23
Nitrogen (%)	0.03	Organic carbon (%)	0.51

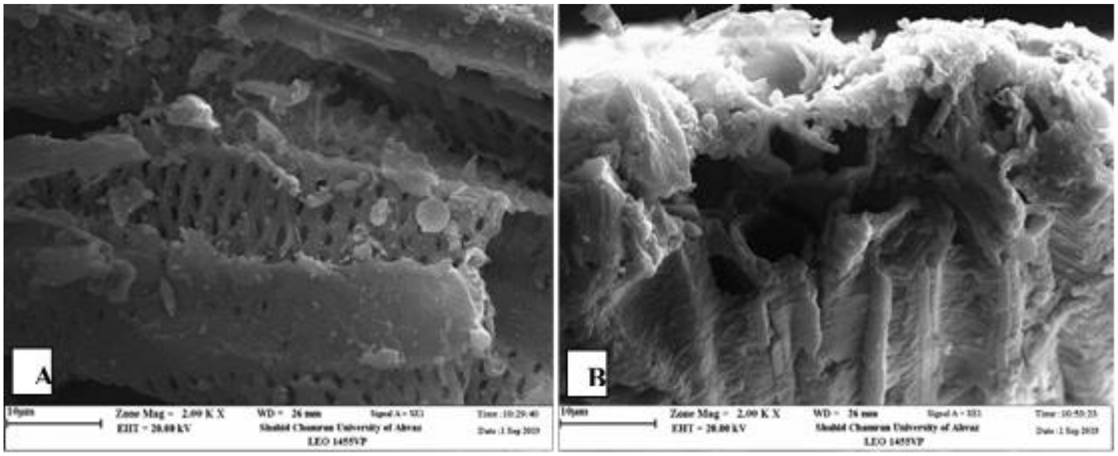

Fig 1- SEM image of sugarcane bagasse hydrochar (A), engineered sugarcane bagasse hydrochar (B)

Preparation of test pots

This study was conducted in a randomized complete block design with three replications and four engineered sugarcane bagasse hydrochar treatments (0% (control), 1%, 2% and 5% w/w). Air-dried soil was passed through a 2 mm sieve. Considering the bulk density of farm soil (1.56 g. cm^{-3}) and the volume of the pots (1020 cm^3), 1591 g of soil was needed to fill each pot. The amount of sugarcane bagasse hydrochar required for each treatment level was calculated. For example, a treatment of 1% (10 grams of hydrochar per kilogram of soil) required 15.91 grams of hydrochar. The soil and hydrochar mixed were transferred to the pots. After adding half of the soil into each pot, 3 bean seeds were placed, and the remaining soil and hydrochar mixed were added to the pot again. Then the pots were placed in water to be saturated from below. It should be noted that bean seeds were sterilized in 3% sodium hypochlorite for 3 minutes before planting and then washed several times with deionized water to remove the effect of sodium hypochlorite. Water with an average EC of 0.91 dS / m and an average pH of about 7.13 was used to irrigate pots during the growth period (35 days).The determination of field capacity moisture time was by placing the probes of the TDR device at a depth of 8 cm from the top of the soil columns. Finally, plants were harvested and plant height, number of leaves, number of lateral branches, fresh weight of roots, and shoots were measured. Then, to measure the dry weight of shoots and roots, these parts were dried in an oven at 70 ° C for 72 hours. After harvesting the plants, as investigating the effect of hydrochar on different soil properties (organic carbon, total nitrogen, absorbable phosphorus, acidity, electrical conductivity, bulk density, true bulk density, and total porosity) were measured for each pot. Then, the study data were analyzed at a significance level of 0.05 using SPSS software version 23. Duncan's multi-range test was used to investigate the effects of applying different levels of hydrochar on soil and plant properties. In addition, a one-way ANOVA was used to determine the difference between treatments. Charts were also drawn with Excel software.

Results and discussion

Characteristics of soil and engineered sugarcane bagasse hydrochar

The SEM analysis results of the hydrochars are shown in Fig (1 (A-B)). The presence of longitudinal pores on the sugarcane bagasse hydrochar indicates pyrolysis at low temperatures. (Fig (1- A)). By modifying the hydrochar with magnesium chloride (engineered sugarcane bagasse hydrochar), the surface impurities that had blocked the pores were removed, revealing the porous structure of the engineered hydrochar honeycomb (Fig (1-B)). Li et al. (2020) reported that the activation of hydrochar with magnesium ions resulted in an increased degree of carbonization. Furthermore, the surface of the activated hydrochar appeared more spongy and exhibited a higher number of pores compared to its original state (Li et al., 2020). As a result, this hydrochar has a greater capacity for retaining nutrients in the soil. Similar findings to those obtained in the current study have been reported by other researchers (Li et al., 2020; Qiao et al., 2019). The results of the functional groups on hydrochar are shown in Fig (2). According to the Fig. 2, the existence of groups O-H, C-H, C-O and C = C was confirmed within the wave range 3400, 2900, 1050-1180 and 1600cm^{-1}, respectively. The presence of these functional groups on the hydrochar confirms the presence of carbon in the structure of the synthesized hydrochar. These functional groups, characterized by their positive and negative charges, are predicted to have a high potential for retaining nutrients in the soil.

The results of determining the elements in the hydrochar sample before (sugarcane bagasse hydrochar) and after activation (engineered sugarcane bagasse hydrochar) are shown in Table (2).

According to Table (2), magnesium oxide (MgO) in sugarcane bagasse hydrochar was 0.43% while in engineered sugarcane bagasse hydrochar increased to 1.28. This change in sugarcane bagasse hydrochar, due to the positive charge of magnesium, can increase the retention of negatively charged nutrients in the soil. Also, by converting sugarcane bagasse to hydrochar and activated hydrochar, the amount of carbon (C) increased from 44.4% to 49.54 and 47.48%, respectively. On the other hand, the amounts of hydrogen, oxygen, oxygen to carbon ratio and hydrogen to carbon in the hydrochar are lower than raw sugarcane bagasse. This can be due to the processes of dehydration, decarboxylation and dehydrogenation and indicates carbonization in during the hydrothermal process (ZHANG et al., 2014).The point of zero charge ($pH_{(pzc)}$) engineered sugarcane bagasse hydrochar was obtained at 5.59 which indicates that this material in soils with pH lower than 5.59, has a greater ability to retain nutrients with a Negative charge. Also engineered hydrochar of sugarcane bagasse at pH above 5.59, has a greater ability to retain positively charged nutrients.

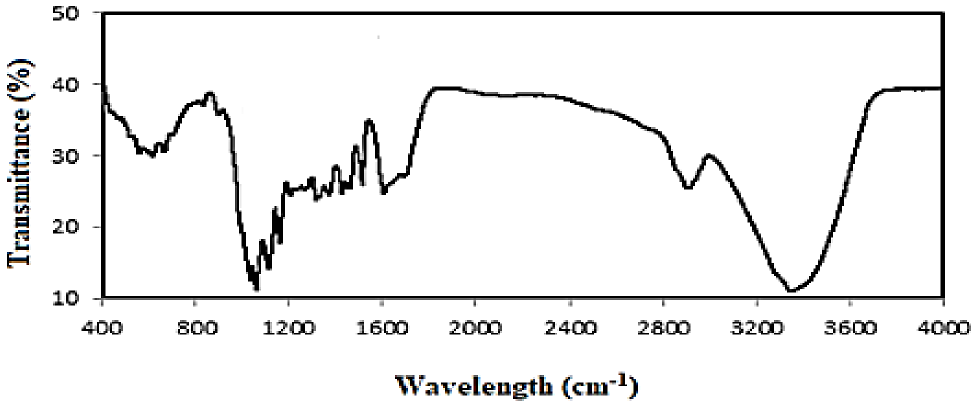

Fig 2- FTIR spectrums of engineered sugarcane bagasse hydrochar

Table 2- The elements and metal oxides of sugarcane bagasse, hydrochar sugarcane bagasse and engineered hydrochar sugarcane bagass

Product	Sugarcane bagasse	Sugarcane bagasse hydrochar	Engineered sugarcane bagasse hydrochar
C/H	1.61	1.39	1.45
C/O	0.75	0.59	0.6
S	0.24	0.47	0.19
O	44.44	38.88	39.05
H	5.98	5.78	5.99
C	44.4	49.54	49.25
N	0.95	1.13	0.92
MgO	0.42	0.43	1.28

The effect of engineered sugarcane bagasse hydrochar on physical and chemical properties of sandy loam soil

At the end of the growth season, the results of applying various levels of sugarcane bagasse hydrochar (0% (control), 1%, 2%, and 5% w/w) on the physical and chemical properties of the soil were evaluated, and the findings are presented in Table (3) ($p < 0.05$). The application of treatments 1%, 2% and 5%, resulted in an increase in soil organic carbon to 12.16%, 48.65%, and 78.38% respectively. Hydrochar contains stable carbon and nutrients that enhance soil quality and facilitate carbon storage within the soil (Bento et al., 2019). The results of research conducted Song et al (2018), demonstrated that the addition of hydrochar to the soil leads to an increase in soil organic carbon content. However, some researchers have suggested that hydrochar may have a lower capacity for long-term carbon storage compared to biochar, as biochar contains higher levels of polyaromatic carbon, which is more stable (Busch & Glaser, 2015). Hydrochar, being a porous material with a high carbon content, has the potential to enhance soil organic carbon levels (Bahcivanji et al., 2020; Taskin et al., 2019).

The use of fertilizers with high levels of organic matter clearly enhances the internal and external bonds of soil aggregates, leading to improved soil structure. In the present study, the application of engineered sugarcane bagasse hydrochar at 1%, 2%, and 5% concentrations resulted in significant increases in total nitrogen content compared to the control: 8.99%, 15.73%, and 43.82%, respectively. The presence of carbon compounds in hydrochar stimulates microbial activity in the soil, thereby promoting nitrogen stabilization (Bento et al., 2019). Chu et al. (2020) also observed in their study that the low pH of hydrochar and the presence of carboxyl groups contribute to nitrogen retention in the soil.

Furthermore, the application of sugarcane bagasse hydrochar in the soil led to an increase in soil phosphorus content. As shown in Table (3), the phosphorus content changed from 7.37 mg/kg in the control to 7.67 mg/kg (1%), 8.38 mg/kg (2%), and 10.03 mg/kg (5%). Hydrochar may enhance phosphorus levels in the soil through mechanisms such as pH reduction, phosphorus adsorption, and the adsorption of phosphorus-stabilizing cations (e.g., calcium, iron, and magnesium). Similar findings have been reported by other studies that observed an increase in soil phosphorus following hydrochar application (Bahcivanji et al., 2020).

pH plays a crucial role in improving soil conditions as it can affect nutrient availability and potential toxicity. The pH level can range from acidic to alkaline, and extreme values can limit nutrient accessibility. Hydrochar typically exhibits acidic pH due to the presence of organic acids in its structure or the removal of alkaline elements during production. However, in the current study, after activating the hydrochar with magnesium chloride, its pH slightly increased due to the presence of the alkaline earth metal magnesium.

The results indicated that treatments of 1%, 2%, and 5% engineered sugarcane bagasse hydrochar decreased soil pH by 0.40%, 0.54%, and 1.34% compared to the control, respectively. The reduction in soil pH following hydrochar application may be influenced by the initial pH of the hydrochar and its impact on enhancing soil microbial activity. Previous studies have also attributed the decrease in soil pH to the acidic nature of hydrochar and the presence of carboxylic groups in its structure (Ren et al., 2017; Bento et al., 2019). Additionally, the decrease in soil pH after organic fertilizer application can be attributed to the decomposition of organic matter and the production of carbonic acid and organic acids.

According to the findings of the present study, the application of 1%, 2%, and 5% hydrochar treatments significantly increased soil electrical conductivity (EC) by 33.29%, 51.83%, and 81.82% compared to the control, respectively. The elevated EC in the soil can be attributed to the higher EC of the hydrochar compared to the soil itself.

In Table (3) results showed a significant reduction in soil bulk density following the addition of sugarcane bagasse hydrochar. The decrease in bulk density was observed to be 4.86%, 11.26%, and 16.34% for the 1%, 2%, and 5% treatments compared to the control. This decrease in bulk density can be attributed to the incorporation of lower-density materials into the soil and the increase in soil organic matter resulting from hydrochar application. The presence of soil organic matter promotes the formation of soil aggregates and enhances soil structure stability (Song et al., 2015). Mau et al. (2020) also reported a decrease in soil bulk density associated with the use of hydrochar, which can be attributed to the low density of hydrochar itself. Similarly, other researchers have reported a reduction in bulk density following the application of different types of hydrochar (Abel et al., 2013).

The results of comparing the means showed that the increase of hydrochar at all levels led to a significant increase in soil porosity compared to the control. Soil porosity of 10.6%, 19.39%, and 26.54%, respectively increased in treatments of 1, 2, and 5%. The increase in soil porosity after the application of hydrochar is due to its porous structure. Also, the bulk density in effect the application of hydrochar decreased and it can be an effect on increasing porosity. Abel et al. (2013) attributed the increase in soil porosity to the high specific surface area and porosity of hydrochar (Abel et al., 2013). Shao et al. (2020) stated that hydrochar as a material with a high specific surface area and a porous structure can be used to improve the characteristic soil (Shao et al., 2020).

The results of the mean comparisons revealed a significant increase in soil porosity with the application of hydrochar at all levels compared to the control. The treatments of 1%, 2%, and 5% hydrochar resulted in soil porosity increases of 10.6%, 19.39%, and 26.54%, respectively. This increase in soil porosity can be attributed to the porous structure of hydrochar. Furthermore, the decrease in bulk density resulting from the application of hydrochar can also contribute to the increase in porosity. Abel et al. (2013) attributed the increase in soil porosity to the high specific surface area and porosity of hydrochar. Shao et al. (2020) stated that hydrochar, with its high specific surface area and porous structure, can be utilized to enhance soil characteristics. Mau et al. (2020) mentioned that the addition of hydrochars to the soil increases the presence of secondary pores. Additionally, hydrochars produced at lower temperatures exhibit a greater ability to increase soil porosity. Similar findings have been reported by other researchers regarding the increase in soil porosity following the application of hydrochar (Eibisch et al., 2015).

The effect of sugarcane bagasse hydrochar application on bean plant characteristics

The results from Table (4) indicate that the application of various treatments of engineered sugarcane bagasse hydrochar had a significant impact on the height of the bean plants.

Table 3- Effects of different levels of engineered sugarcane bagasse hydrochar on physical and chemical properties of sandy loam soil ($p < 0.05$)

Parameter	Treatments			
	0% (control)	1%	2%	5%
Bulk density	1.55^{c}	1.44^{b}	1.34^{b}	1.26^{a}
Organic carbon	0.25^{a}	0.28^{a}	0.38^{b}	0.44^{c}
Nitrogen	0.030^{a}	0.034^{ab}	0.035^{b}	0.042^{c}
Porosity	42.54^{a}	47.05^{b}	50.80^{cb}	53.84^{c}
Phosphorus	7.37^{a}	7.67^{a}	8.38^{b}	10.03^{c}
pH	7.45^{b}	7.42^{a}	7.41^{a}	7.35^{a}
EC	2.82^{a}	3.76^{b}	4.29^{c}	5.13^{d}

Table 4- Effects of different levels of engineered sugarcane bagasse hydrochar on bean plant properties ($p < 0.05$)

Parameter	Treatments			
	0% (control)	1%	2%	5%
Plant height (cm)	23.5^{b}	25.6^{b}	20.2^{a}	18.1^{a}
Lateral branches number	3.7^{a}	4.0^{a}	3.7^{a}	3.3^{a}
Leaf number	9.7^{a}	10.0^{a}	9.3^{a}	8.7^{a}
Dry weight of aerial parts (g)	3.5^{a}	3.63^{a}	3.44^{a}	3.32^{a}
Root dry weight (g)	0.564^{b}	0.615^{c}	0.529^{ab}	0.523^{a}

The highest plant height of 25.6 cm was observed with the application of 1% hydrochar, while the application of 2% and 5% hydrochar resulted in a significant decrease in plant height by 14.02% and 23.08%, respectively, compared to the control.

As mentioned, the application of the 1% hydrochar treatment resulted in increased growth parameters of beans. However, higher application of hydrochar in the soil, specifically the 2% and 5% treatments, caused toxicity to the plants and resulted in decreased growth parameters of beans. Melo et al. (2019) also reported similar findings of reduced growth with increased hydrochar application. They observed that the use of hydrochar at a rate of 0.5% improved bean growth, but higher application rates led to plant toxicity.

Fang et al. (2015) conducted a study to investigate the effect of sugarcane bagasse hydrochars produced at different temperatures (200, 250, and 300 °C) on plant height. Their results showed that the application of hydrochars produced at temperatures of 250 and 300 °C resulted in a decrease in plant height (Fang et al., 2015). In the present study, magnesium chloride salt was used to activate hydrochar, which increased its electrical conductivity (EC). As a result of its application to soil, it increased soil salinity. As bean is sensitive to salinity and tolerates soil salinity less than 2 ds/m, its growth parameters were reduced by increasing the dose of hydrochar (Parande et al., 2014). The application of hydrochar at a 1% concentration led to a non-significant increase of 9.09% in the number of lateral branches of the bean plant compared to the control. On the other hand, the application of 5% hydrochar in the soil resulted in a reduction of 9.1% in the number of lateral

Interestingly, the 2% treatment had no significant effect on the number of lateral branches. It was initially expected that the increase in nutrients and improvement in soil properties due to hydrochar application would promote the growth and yield of bean plants. However, this positive effect was observed only at the 1% concentration. It can be inferred that the enhanced water and nutrient retention in the soil, coupled with a high concentration of elements, might have disrupted the nutrient balance in the soil, thereby negatively affecting the growth of bean plants. Furthermore, Bento et al. (2019) mentioned that hydrochar has the ability to release certain toxic compounds such as organic acids and phenols into the soil, which can harm plant growth. Therefore, it is necessary to conduct further studies to determine the optimal and most beneficial dosage of hydrochar for different applications.

Mau et al. (2020) also reached a similar conclusion in their study, stating that although hydrochar positively affects soil moisture and enhances water retention, this factor alone cannot account for the improved growth of lettuce. They stated that hydrochar likely exerts its effects on plant growth through other mechanisms. In terms of leaf number, no significant difference was observed between the effects of the 2% and 5% hydrochar treatments. These treatments resulted in a slight decrease in leaf number (3.45% and 10.34%, respectively). On the other hand, the application of 1% hydrochar led to a 3.45% increase in the number of bean leaves compared to the control. Bargman et al. (2014) conducted a study on spring barley and French beans and identified optimal doses of hydrochar ranging from 2% to 4%. They reported that increasing the hydrochar dosage to 10% resulted in a reduction in plant growth.

The 1% treatment resulted in a 3.8% increase in the dry weight of aerial parts. On the other hand, the addition of hydrochar at 2% and 5% led to a decrease of 1.82% and 5.15%, respectively, in the dry weight of aerial parts compared to the control. Rillig et al. (2010) also found that the addition of hydrochar produced from beetroot residues at a volume of 4% did not significantly impact plant growth, while doses above 10% inhibited plant growth. However, some researchers have reported positive effects of hydrochar on plant growth and performance, attributing it to increased soil nitrogen (Chu et al., 2020). Melo et al. (2019) stated in their research that doses of 10 mg and 60 mg of hydrochar per hectare had the greatest effect on the dry weight of beans and rice, respectively, and further increasing the application dose had a negative correlation with biomass dry weight.

Based on the results presented in Table (4), the application of 1% hydrochar treatment resulted in the highest root dry weight of 0.615 g. This increase in root dry weight was found to be statistically significant compared to both the control group and the other treatments. However, the application of 2% and 5% hydrochar treatments significantly reduced the root dry weight by 6.521% and 7.33%, respectively. Fang et al. (2015) also observed that although hydrochar did not have a significant effect on seed germination, it had a positive impact on root growth. Melo et al. (2019) suggested that the response of biomass to hydrochar application in the soil varies depending on the dosage and type of hydrochar. Long-term field studies are necessary to investigate the interaction between hydrochar, soil properties, and plant growth. The appropriate application of hydrochar as a soil amendment needs to be determined through further research.

Conclusions

The extensive research conducted on the application of hydrochar for soil and plant improvement has demonstrated its positive effects. However, it is important to consider various factors such as biomass type, production temperature, soil type, and application rate of hydrochar, as these variables can influence the outcomes obtained. A comprehensive study that examines the impact of these variables is necessary to determine the most beneficial results. In this particular study, activated hydrochar, obtained after nitrate and phosphate adsorption, was applied to enhance soil and plant growth. The results indicated that the engineered hydrochar had a positive influence on soil parameters, including bulk density, porosity, pH, organic carbon, nitrogen, and phosphorus, thereby improving the physical and chemical conditions of the soil. Consequently, hydrochar can be considered a crucial factor for farmers when selecting fertilizers, as it acts as a soil conditioner. However, when discussing the use of hydrochar as an organic fertilizer for bean plant growth, the expected results were not achieved, most likely due to the use of high doses. Nonetheless, positive effects were observed when applying the hydrochar treatment at 1% concentration.

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References

1- Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M. and Wessolek, G., 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma*, *202*, pp.183-191. doi: 10.1016/j.geoderma.2013.03.003.

2- Azimzadeh, Y., Najafi, N., Reyhanitabar, A., Oustan, S. and Khataee, A., 2021. Effects of phosphate loaded LDH-biochar/hydrochar on maize dry matter and P uptake in a calcareous soil. *Archives of Agronomy and Soil Science*, *67*(12), pp.1649-1664. doi: 10.1080/03650340.2020.1802012.

3- Bahcivanji, L., Gasco, G., Paz-Ferreiro, J. and Méndez, A., 2020. The effect of post-pyrolysis treatment on waste biomass derived hydrochar. *Waste Management*, *106*, pp.55-61. doi: 10.1016/j.wasman.2020.03.007.

4- Bargmann, I., Rillig, M.C., Kruse, A., Greef, J.M. and Kücke, M., 2014. Effects of hydrochar application on the dynamics of soluble nitrogen in soils and on plant availability. *Journal of Plant Nutrition and Soil Science*, *177*(1), pp.48-58. doi: 10.1002/jpln.201300069.

5- Baronti, S., Alberti, G., Camin, F., Criscuoli, I., Genesio, L., Mass, R., Vaccari, F.P., Ziller, L. and Miglietta, F., 2017. Hydrochar enhances growth of poplar for bioenergy while marginally contributing to direct soil carbon sequestration. *GCB Bioenergy*, *9*(11), pp.1618-1626. doi: 10.1111/gcbb.12450.

6- Bento, L.R., Castro, A.J.R., Moreira, A.B., Ferreira, O.P., Bisinoti, M.C. and Melo, C.A., 2019. Release of nutrients and organic carbon in different soil types from hydrochar obtained using sugarcane bagasse and vinasse. *Geoderma*, *334*, pp.24-32. doi: 10.1016/j.geoderma.2018.07.034. doi: 10.1111/sum.12180.

7- Busch, D. and Glaser, B., 2015. Stability of co-composted hydrochar and biochar under field conditions in a temperate soil. *Soil use and management*, *31*(2), pp.251-258.

8- Chen, P., Liu, Y., Mo, C., Jiang, Z., Yang, J. and Lin, J., 2021. Microbial mechanism of biochar addition on nitrogen leaching and retention in tea soils from different plantation ages. *Science of The Total Environment*, *757*, p.143817. doi: 10.1016/j.scitotenv.2020.143817.

9- Chu, Q., Xue, L., Singh, B.P., Yu, S., Müller, K., Wang, H., Feng, Y., Pan, G., Zheng, X. and Yang, L., 2020. Sewage sludge-derived hydrochar that inhibits ammonia volatilization, improves soil nitrogen retention and rice nitrogen utilization. *Chemosphere*, *245*, p.125558. doi: 10.1016/j.chemosphere.2019.125558.

10- De Jager, M., Röhrdanz, M. and Giani, L., 2020. The influence of hydrochar from biogas digestate on soil improvement and plant growth aspects. *Biochar*, *2*, pp.177-194.

11- Eibisch, N., Schroll, R., Fuß, R., Mikutta, R., Helfrich, M. and Flessa, H., 2015. Pyrochars and hydrochars differently alter the sorption of the herbicide isoproturon in an agricultural soil. *Chemosphere*, *119*, pp.155-162. doi: 10.1016/j.chemosphere.2014.05.059.

12- Fang, J., Gao, B., Chen, J. and Zimmerman, A.R., 2015. Hydrochars derived from plant biomass under various conditions: Characterization and potential applications and impacts. *Chemical Engineering Journal*, *267*, pp.253-259. doi: 10.1016/j.cej.2015.01.026.

13- Feng, C., Zhang, S., Wang, Y., Wang, G., Pan, X., Zhong, Q., Xu, X., Luo, L., Long, L. and Yao, P., 2020. Synchronous removal of ammonium and phosphate from swine wastewater by two agricultural waste based adsorbents: Performance and mechanisms. *Bioresource technology*, *307*, p.123231. doi: 10.1016/j.biortech.2020.123231.

14- Gee, G.W. and Or, D., 2002. 2.4 Particle-size analysis. *Methods of soil analysis: Part 4 physical methods*, *5*, pp.255-293. doi: 10.2136/sssabookser5.4.c12.

15- George, C., Wagner, M., Kücke, M. and Rillig, M.C., 2012. Divergent consequences of hydrochar in the plant–soil system: Arbuscular mycorrhiza, nodulation, plant growth and soil aggregation effects. *Applied Soil Ecology*, *59*, pp.68-72. doi: 10.1016/j.apsoil.2012.02.021.

16- Hafshejani, L.D., Hooshmand, A., Naseri, A.A., Mohammadi, A.S., Abbasi, F. and Bhatnagar, A., 2016. Removal of nitrate from aqueous solution by modified sugarcane bagasse biochar. *Ecological Engineering*, *95*, pp.101-111. doi: 10.1016/j.ecoleng.2016.06.035.

17- Islam, M.A., Limon, M.S.H., Romić, M. and Islam, M.A., 2021. Hydrochar-based soil amendments for agriculture: a review of recent progress. *Arabian Journal of Geosciences*, *14*, pp.1-16.

18- Kuo, S. 1996. Phosphorus. In ‘Methods of chemical analysis. Part 3. Chemical methods’.(Eds DL Sparks, AL Page, PA Helmke, RH Loeppert, PN Soltanpour, MA Tabatabai, CT Johnston, ME Sumner) pp. 869–919. *Soil Science Society of America, Inc.: Madison, WI*.

19- Li, F., Zimmerman, A.R., Hu, X. and Gao, B., 2020. Removal of aqueous Cr (VI) by Zn-and Al-modified hydrochar. *Chemosphere*, *260*, p.127610. doi: 10.1016/j.chemosphere.2020.127610.

20- Liu, Y., Ma, S. and Chen, J., 2018. A novel pyro-hydrochar via sequential carbonization of biomass waste: Preparation, characterization and adsorption capacity. *Journal of Cleaner Production*, *176*, pp.187-195. doi: 10.1016/j.jclepro.2017.12.090.

21- Mau, V., Arye, G. and Gross, A., 2020. Poultry litter hydrochar as an amendment for sandy soils. *Journal of Environmental Management*, *271*, p.110959. doi: 10.1016/j.jenvman.2020.110959.

22- Melo, T.M., Bottlinger, M., Schulz, E., Leandro, W.M., de Oliveira, S.B., de Aguiar Filho, A.M., El-Naggar, A., Bolan, N., Wang, H., Ok, Y.S. and Rinklebe, J., 2019. Management of biosolids-derived hydrochar (Sewchar): effect on plant germination, and farmers' acceptance. *Journal of environmental management*, *237*, pp.200-214. doi: 10.1016/j.jenvman.2019.02.042.

23- Nelson, D.W. and Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. *Methods of soil analysis: Part 3 Chemical methods*, *5*, pp.961-1010. doi: 10.2136/sssabookser5.3.c34.

24- Parande, S., Zamani, G., Sayyari, M. and Ghaderi, M., 2014. Effects of silicon on the physiological, quality and quantity characteristics of common bean (Phaseolus vulgaris) under salinity stress. *Iranian Journal Pulses Research*, *5*(2), pp.57-70.

25- Parlavecchia, M., Carnimeo, C. and Loffredo, E., 2020. Soil amendment with biochar, hydrochar and compost mitigates the accumulation of emerging pollutants in rocket salad plants. *Water, Air, & Soil Pollution*, *231*, pp.1-12.

26- Puccini, M., Ceccarini, L., Antichi, D., Seggiani, M., Tavarini, S., Hernandez Latorre, M. and Vitolo, S., 2018. Hydrothermal carbonization of municipal woody and herbaceous prunings: hydrochar valorisation as soil amendment and growth medium for horticulture. *Sustainability*, *10*(3), p.846.

27- Qiao, H., Mei, L., Chen, G., Liu, H., Peng, C., Ke, F., Hou, R., Wan, X. and Cai, H., 2019. Adsorption of nitrate and phosphate from aqueous solution using amine cross-linked tea wastes. *Applied Surface Science*, *483*, pp.114-122. doi: 10.1016/j.apsusc.2019.03.147.

28- Ren, J., Wang, F., Zhai, Y., Zhu, Y., Peng, C., Wang, T., Li, C. and Zeng, G., 2017. Effect of sewage sludge hydrochar on soil properties and Cd immobilization in a contaminated soil. *Chemosphere*, *189*, pp.627-633. doi: 10.1016/j.chemosphere.2017.09.102.

29- Rillig, M.C., Wagner, M., Salem, M., Antunes, P.M., George, C., Ramke, H.G., Titirici, M.M. and Antonietti, M., 2010. Material derived from hydrothermal carbonization: effects on plant growth and arbuscular mycorrhiza. *Applied Soil Ecology*, *45*(3), pp.238-242. doi: 10.1016/j.apsoil.2010.04.011.

30- Schimmelpfennig, S., Müller, C., Grünhage, L., Koch, C. and Kammann, C., 2014. Biochar, hydrochar and uncarbonized feedstock application to permanent grassland—Effects on greenhouse gas emissions and plant growth. *Agriculture, Ecosystems & Environment*, *191*, pp.39-52. doi: 10.1016/j.agee.2014.03.027.

31- Shao, Y., Tan, H., Shen, D., Zhou, Y., Jin, Z., Zhou, D., Lu, W. and Long, Y., 2020. Synthesis of improved hydrochar by microwave hydrothermal carbonization of green waste. *Fuel*, *266*, p.117146. doi: 10.1016/j.fuel.2020.117146.

32- Song, C., Shan, S., Müller, K., Wu, S., Niazi, N.K., Xu, S., Shen, Y., Rinklebe, J., Liu, D. and Wang, H., 2018. Characterization of pig manure-derived hydrochars for their potential application as fertilizer. *Environmental Science and Pollution Research*, *25*, pp.25772-25779.

33- Song, X., Liu, M., Wu, D., Griffiths, B.S., Jiao, J., Li, H. and Hu, F., 2015. Interaction matters: Synergy between vermicompost and PGPR agents improves soil quality, crop quality and crop yield in the field. *Applied Soil Ecology, 89,* pp.25-34. doi: 10.1016/j.apsoil.2015.01.005.

34- Taskin, E., de Castro Bueno, C., Allegretta, I., Terzano, R., Rosa, A.H. and Loffredo, E., 2019. Multianalytical characterization of biochar and hydrochar produced from waste biomasses for environmental and agricultural applications. *Chemosphere*, *233*, pp.422-430. doi: 10.1016/j.chemosphere.2019.05.204.

35- Xia, Y., Luo, H., Li, D., Chen, Z., Yang, S., Liu, Z., Yang, T. and Gai, C., 2020. Efficient immobilization of toxic heavy metals in multi-contaminated agricultural soils by amino-functionalized hydrochar: Performance, plant responses and immobilization mechanisms. *Environmental Pollution*, *261*, p.114217. doi: 10.1016/j.envpol.2020.114217.

36- Yu, S., Xue, L., Feng, Y., Liu, Y., Song, Z., Mandal, S., Yang, L., Sun, Q. and Xing, B., 2020. Hydrochar reduced NH3 volatilization from rice paddy soil: Microbial-aging rather than water-washing is recommended before application. *Journal of Cleaner Production*, *268*, p.122233. doi: 10.1016/j.jclepro.2020.122233.

37- ZHANG, J.H., LIN, Q.M. and ZHAO, X.R., 2014. The hydrochar characters of municipal sewage sludge under different hydrothermal temperatures and durations. *Journal of Integrative Agriculture*, *13*(3), pp.471-482. doi: 10.1016/S2095-3119(13)60702-9.