# Enhancing Soil Health and Plant Growth by Mitigating Soil Contamination with Nanobiochar Amendments

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## ABSTRACT:

The escalating issue of soil contamination in various Egyptian regions is primarily attributed to the use of low-quality irrigation water. This study focused on addressing this concern by employing nano biochar derived from sugarcane bagasse and olive mill waste. The addition rates were 0%, 0.4%, 0.6%, and 0.8% to assess its efficacy in reducing soil contamination. Sugar bagasse, a unique nanostructure with high catalytic activity, is more effective than olive mill waste for soil and plant growth. In addition, the best addition rate, 0.8%, for enhancing soil properties by mitigating soil contamination such as pH, EC, OM and CEC was 7.7, 1.2 $dSm^{-1}$, 1.1% and 28.5 $cmmole.kg^{-1}$, respectively. Nano biochar progressively reduced the levels of the target trace elements, such as Cu, Zn, Pb, Ni and Mo, in the soil over time from 27.3, 12.4, 17.6, 3.9 and 12.6 mg, respectively. kg-1 to 17.5, 7.78, 5.4, 0.95 and 1.82 mg. $kg^{-1}$. Biochars improve soil structure, microbial activity, nutrient retention, and cycling, while decreasing harmful trace elements like Pb, Ni, and Mo. Surface characteristics and reactivity control soil nutrient availability. The soil available Fe concentrations increased from 22.11 to 26.37 mg. $kg^{-1}$ and Mn concentrations increased from 153.9 to 156.17 $mg.kg^{-1}$. Depending on the particular soil variables and agricultural objectives, biochar or nanobiochar may be preferred; however, both treatments offer significant advantages for plant development and soil health.

**Keywords:** Nanobiochar; Soil Health; Soil Contamination.

## INTRODUCTION

Sustainable agriculture and environmental quality are seriously threatened by the deterioration of soil health brought on by pollution from industrial processes, agricultural practices, and urbanization. Contamination of the soil can negatively impact plant development, lower food production, and upset ecological balances. In order to overcome these obstacles, new strategies are needed to improve plant yield and restore soil health. An encouraging approach is to apply changes made of nanobiochar. Because it is made from organic waste and is nanoengineered, nanobiochar has special qualities that can reduce soil pollution and increase soil fertility. By addressing the fundamental problems of soil pollution, this introduction investigates the potential of nanobiochar additions in improving soil health and encouraging vigorous plant development.

As a promising development for sustainable agriculture, biochar has the ability to reduce plant uptake in (TE)-contaminated soils and repair them. This strategy offers a viable means of revitalizing polluted soils and enhancing agricultural resilience by utilizing the complementary advantages of nanotechnology and biochar.To reduce contamination of both water and soil, researchers are investigating the use of biochar resources, frequently in combination with soil amendments. Because of its distinctive qualities, low cost of manufacturing, and carbon-negative status, biochar is a suitable substitute for smart remediation. Through a number of methods, the carbon-rich byproduct of pyrolyzing organic matter, biochar, maximizes the beneficial effects of trace elements while reducing their detrimental effects. It can absorb and bind excess trace elements, lowering their bioavailability and toxicity, according to its porous structure and vast surface area. The cation exchange capacity of biochar enhances the retention and progressive release of nutrients, and its pH modulation neutralizes acidic soils by lowering the solubility of hazardous elements. Furthermore, biochar promotes healthy microbial activity, which can change hazardous substances to less damaging substances. The particular functional groups present on biochar preferentially bind detrimental trace elements, increasing plant protection against toxicity while maintaining the availability of vital nutrients(Qiu et al., 2024). Additionally, biochar could react to the nutrients in the soil by competing with the plants, which would lessen their ability to absorb nutrients. Phosphorus present in the soil is reacted with by biochar as well. Additionally, it has the capacity to precipitate and decrease its availability to plants, which will slow down plant development. According to reports, adding biochar to soil caused organic matter to decompose, which decreased the abundance of certain fungal species, including Ascomycota and Basidomycota. Moreover, nano-biochar has more significant functional groups with carbon and oxygen defects, smaller hydrodynamic radii, and larger negative zeta potentials. Compared to its larger-scale biochar equivalents, these characteristics allow nano-biochar to produce reactive oxygen species (ROS), which improves its adsorption capacities. Hence, nanobiochar has multiple uses, including pesticide remediation, plant protection, and cultivation. It also regularly produces remarkable and enriching results in plant systems.The review papers available currently offer extensive information on the creation of nanobiochar, its mode of action, its uses in the production of sustainable agriculture, and its prospects for the future.

One innovative kind of complicated nanostructured substance is the nanobiochar. Currently, energy-efficient nanotechnology methods and green synthesis techniques are used in the vast majority of nanobiochar production and research. According to studies conducted thus far, nanobiochar is also distinguished by notable physical and chemical variations, including larger pore magnitudes, lower hydrodynamic diameters, more negative zeta potentials, more functional groups that contain oxygen, and carbon imperfections that have the potential to produce reactive organic pollutants (ROS). These characteristics increase the adsorption capacity of nanobiochar and make it more like black carbon in terms of its properties**.** The ball milling method used both agate and stainless steel balls. The weight of the milling balls varies with their diameter and composition. For the pinewood and modified rice husk feedstock materials, 30-45 g stainless steel balls were used, whereas the sugarcane bagasse, bamboo, and hickory wood feedstocks were milled using 180 g agate balls. Aside from the milling process, the rotation speed, ball-to-power mass ratio, and milling time are factors that can influence the final nanobiochar particle size and surface energy**.** The nanoscale production of carbon nanomaterials (NBCs) provides possible solutions for pollutant bioremediation, among other benefits (Dhuldhaj et al., 2023).

In the fields of agriculture, energy, and the environment, carbon nanomaterials—in particular, nanobiochar—are essential for the phytoremediation of contaminants such as organic chemicals and heavy metals. In addition to modifying soil characteristics and removing heavy metals and dangerous substances from the soil, biochar can also increase crop yields. Biochar can reduce the chance of contamination. In recent times, Egypt has witnessed a significant expansion in the planting area of maize (*Zea mays* L.), one of the most significant grain crops.

This study aims to assess how Pb, Ni, and Mo absorption in maize is affected by biochar and nanobiochar derived from OMW and sugarcane bagasse (SCB) and determination the impact of SCB, OMW, and nanobiochar on soil composition, the amount of beneficial TEs present, their toxicity, and their mobility at varying rates of application. The long-term effects of OMW and SCB on maize development should be examined since they can bolster sustainable and ecologically friendly farming practices. This implies that the study should focus on how OMW and SCB influence maize development over an extended period, rather than just short-term outcomes.

## MATERIALS AND METHODS

### Study location

This study was conducted in greenhouses and labs at the Soil Sciences Department, Faculty of Agriculture, Menofia University, Shebin ElKom Menofia Governorate, Egypt, between 2020 and 2023. In this work, two size fractions—regular (bulk) and nano—of biochar were generated from sugarcane bagasse as a starting point (SCB) as well as from olive mill waste (OMW). In the wheat–corn crop system, soil samples were randomly taken at a depth of 0 to 30 cm from five distinct locations in Aghour El Raml, Quesna, Menofia Governorate, Egypt (30°30′ 14″N, 31°8′03″E).. The materials were combined well, allowed to air dry, ground via a 2-mm stainless-steel sieve, and then stored. The remaining amount was stored until the culture (pots) experiment was completed. Tables 1, 2 and 3 list the data acquired from the preliminary soil study. A sample of the sieved soil was obtained, and its chemical and physical properties, as well as the amount of trace elements and necessary nutrients that were accessible, were examined and compared with permissible limits of trace elements in agricultural soil and plant cleared in table 4 and 5 .

FAO/WHO (2011). Summary report of the seventythird meeting of JECFA. Joint FAO/WHO Expert Committee on Food Additives. Geneva

### The synthesis of biochar and nanobiochar

Sugarcane bagasse, or "SCB" (Saccharum officinarum L.), and olive mill waste, or "OMW" (Olea europaea), which were obtained from a nearby facility in Sadat city, Menofia Gavernorate, Egypt, were the sources of the biochar used in this study. The wastes, namely, the SCB, were chopped into pieces of three to five centimeters, cleaned with tap water to remove any dirt, allowed to air dry, and then baked for 48 hours at 70 °C. The two agricultural wastes (OMW and SCB) were subjected to pyrolysis process testing in a small reactor at the Soil Science Department Laboratory, Faculty of Agriculture, Menofia University**.** The reactor was made of stainless steel with a diameter of 10 cm and a height of 40 cm. A muffle furnace provided external heat to the reactor. A K-type thermocouple was used to measure the pyrolysis temperature. The thermochemical process of pyrolysis involves heating biomass to 400 °C (or 550 °C for SCB and OMW) for 90 minutes to produce both wastes at ambient pressure and very little oxygen. Nanobiochar is made by a process called ball-milling. Balls made of agate or stainless steel have both been utilized in ball milling. Agate balls (180 g) were used to mill feed stocks of SCB and OMW. In this work, 180 g of agate balls were ball-milled at 350 °C for 12 hours to prepare the nanobiochar. Table 6 presents the elemental composition of different biochars produced from sugarcane bagasse (SCB) and olive mill waste (OMW), including both bulk and nanotreated biochar. The morphological properties are shown in Fig. 1.

### Incubation experiment

The experiment was set up in a completely randomized design (CRD) consisting of twelve (16) treatment combinations are shown in Fig. 2, namely, SCBB0, SCBB 0.4, SCBB 0.6, SCBB 0.8, SCBN0, SCBN 0.4, SCBN 0.6, SCBN 0.8, OMWB0, OMWB 0.4, OMWB 0.6, OMWB 0.8, OMWN0, OMWN 0.4, OMWN 0.6, and OMWN 0.8, where SCB indicates biochar from sugarcane bagasse, OMW indicates biochar from olive mill waste, B indicates bulk size, N indicates nanosize, and 0, 0.4, 0.6 and 0.8% indicate the application rates.

One hundred grams of soil was weighed into a plastic pot, and 0, 0.4, 0.6, and 0.8 g of amendment were added to the soils at application rates of 0, 0.4, 0.6, and 0.8%, respectively, and thoroughly mixed except for the control, which received no amendment. The amendments were mixed extensively with the soils to ensure uniform dispersion and incubated for 60 days. Throughout the incubation phase, each soil sample was wetted with distilled water at field capacity once per day. After that, the soil from each pot was collected, air-dried, ground, sieved through a 2 mm sieve and kept for chemical analysis.

### Pot Experiment.

A maize plant (*Zea mays*, 3H 33) was used as a test plant in this study, which was conducted in a greenhouse during the growing summer of 2023. We utilized a 48-by-25-cm plastic container with a 30-cm depth and interdiameter. Three kilograms of ready-made soil sample was added to each pot. Ordinary super phosphate (15.5% $P_2O_5$) was used as a P fertilizer in all pots and was blended with the potted soil at a rate of 0.3 g.pot-1 (0.1 g.kg$^{-1}$). Subsequently, the pots were split into two major groups (24 pots). vital group$^{-1}$) to symbolize the two types of agricultural waste (SCB and OMW). Both types of biochar (bulk and small) were represented by two subgroups (12 pots in each major group).

Next, three groups (group$^{-1}$) were created from the pots of each subgroup, each of which represented a different application rate (0, 0.4, 0.6, or 0.8%). Prior to planting, additional biochar was applied and mixed well across the planted soil. This means that 16 treatments were examined in three repetitions. The quartet-shaped seedlings of the validated crop (maize) were then sown in each container. At 65% of the soil WHC, Nile River water from Bahr, Shebin ElKom was used to hydrate every pot. Every three days, irrigation water was supplied based on weight. The plants in each container were thinned to two 10 days after seeding. Twenty days after sowing, all pots were fertilized with N and K fertilizers, such as ammonium nitrate (33% N) and potassium sulfate (48% $K_2O$), at an application rate of 0.15 g pot$^{-1}$ (0.05 g kg$^{-1}$). At 60 days of age, the plants in each pot were harvested above the soil surface and washed with tap water, followed by two rinses with distilled water. Separately, the plant samples were air-dried, oven-dried at 70 °C for 48 hrs, weighed as g.pot$^{-1}$, ground and kept for analysis.

### Extraction of trace elements and determination

At 25 °C, the soil sample was extracted using a solution of DTPA, TEA, and $CaCl_2$. The extraction fluid was buffered to 7.3 ± 0.2 to prevent the sample pH from affecting the extraction process. To extract trace elements from the amended and incubated soils, 10.0 g of sample was weighed in the sample jars; 20.0 mL of DTPA extraction solution (0.005 mol $L^{-1}$) was added, and the mixture was shaken for precisely 2 hours at 25 °C (Lindsay and Norvell, 1978). The extract was filtered through fine-porosity filter paper, and the initial portion of the filtrate was discarded. The filtrate or unfiltered extract was optionally decanted into centrifuge tubes and spun at 3000 rpm until clear (approximately 10 minutes).

### Soil analysis

The seized fine soil sample (>2 mm) was subjected to the following measurements. The particle size distribution (%) was calculated using the international pipette method according to Richards (1954), employing hexametaphosphate as a dispersion agent, and other chemical characteristics were determined according to Cottenie et al. (1982).

### Plant analysis

Based on the methods of Chapman and Pratt (1961), 0.5 g of oven-dried plants was digested on a sandy hot plate at 250 °C with a 10 ml combination of concentrated sulfuric acid and (3:1) perchloric acid until the flask content turned colourless. Subsequently, 100 millilitres of distilled water were added to the digest. The concentrations of trace elements, macronutrients, and micronutrients were examined in aliquots of this digest.

### Statistical analysis

The gathered data were statistically analysed using three-way completely randomized designs with three replicates, as per the computer application Costat statistical software. Duncan’s test was used to compare the mean values. (Costata 6.311; Copyright (C) 1998–2005).

## RESULTS

### Effect of biochar and nanobiochar application on soil chemical properties

The addition of biochar modifies the pH, cation exchange capacity (CEC), electric conductivity (EC), and organic matter content of the soil. Table 7 displays the chemical characteristics of soil that are impacted by biochar derived from two different sources: sugarcane bagasse (SCB) and olive mill waste (OMW). The pH of the OMW-treated soil was greater than that of the SCB-sourced biochar. Table 7 shows that when the addition rate increased, the pH increased. The pH of the control group was 7.6, but following treatment at 0.4, 0.6, and 0.8, the pH levels were 7.7, 7.8, and 7.9, respectively.

Furthermore, there was a slight but noticeable increase in pH when the production process was changed from regular to nanoscale. After treatment for 0.4, 0.6, or 0.8, the pH increased from 7.6 in the control group to 7.8, 7.9, or 7.98, respectively. As shown in Table 7, EC increases as additional rates increase. In the 0.4, 0.6, and 0.8 treatments, the EC was 1.2, 1.4, and 1.6 dSm-1, respectively, compared to 0.9 dSm-1 in the control group. Furthermore, switching from normal to nanoparticle manufacturing enhanced EC.

The EC of the control group was 0.9; however, following the 0.4, 0.6, and 0.8 treatments, the EC was 1.3, 1.6, and 1.8 $dSm^{-1}$, respectively. A number of factors, such as the specific type of biochar, as shown in Table 7, the application rate, particle size, source of agricultural residue, climate, and management strategies, affect how biochar affects soil organic matter (OM). Generally, biochar affects soil organic matter directly and indirectly. In terms of soil stability, biochar is more carbon-rich than other organic compounds and is less prone to breaking down.

The content of organic matter (OM) in the soil increased with increasing addition rate, as shown in Table 7. OM increased from 0.8% in the case–control group to 1.0, 1.2, and 1.4% in the 0.4, 0.6, and 0.8% treatment groups, respectively. Because of its large surface area and porous nature, biochar may help increase the CEC. Because of its porous nature, biochar increases the soil's capacity to hold vital nutrients by creating sites for cation adsorption.

Table 7 illustrates how the CEC increases when additional rates increase. The CEC was 26.5 cmole.kg-1 in the control group and 27.10, 27.70, and 28.60 cmole.kg-1 after the 0.4, 0.6, and 0.8 treatments, respectively. The process of changing the particles from ordinary to nanosized also increased the CEC. The CEC was 26.5 cmole.kg-1 in the control group and 27.91, 28.75, and 29.82 cmole.kg-1 after the 0.4, 0.6, and 0.8 treatments, respectively.

### Effect of biochar and nanobiochar application on available nitrogen, phosphorus and potassium

The data in Fig. 3 show that applying biochar to soils greatly enhanced the amount of accessible nutrients from ordinary to nano soils. The optimal treatment rate was 0.8% biochar. The soil available nitrogen concentrations were 49.40, 52.43, 55.43, and 56.47 mg.kg$^{-1}$ after the 0.4, 0.6, and 0.8% treatments, respectively. After the 0.4, 0.6, and 0.8% treatments, the available P levels in the soil were 4.40, 6.27, 7.93, and 8.53 mg.kg$^{-1}$, respectively. The available K concentrations in the soil were 68.50, 70.67, and 75.30 mg.kg$^{-1}$ after the 0.4, 0.6, and 0.8% treatments, respectively.

### Extracting trace elements (TEs) after incubation

The availability of advantageous trace elements such as Fe and Mn in soils may be greatly increased by using biochar and nanobiochar made from SCB and OMW, as shown in Fig. 4. These biochars improve soil structure, microbial activity, and nutrient retention, which improves the cycling of nutrients and plant uptake. Because of its improved surface characteristics and reactivity, nanobiochar, in particular, has potential as a more effective and focused method for controlling soil nutrient availability. The soil available concentrations of Fe through the bulk SCB were 22.11, 23.53, 25.67 and 26.17 mg. kg$^{-1}$ at application rates of 0, 0.4, 0.6 and 0.8%, respectively; these values increased to 22.11, 24.5, 26.17, and 26.37 mg, respectively. kg$^{-1}$, through nano-SCBs at application rates of 0, 0.4, 0.6 and 0.8%, respectively. OMW, but not SCB, also increased the available concentrations of Fe due to the composition of the raw material. . The soil available concentrations of Fe through the bulk OMW were 22.11, 22.2, 23.37 and 23.87 mg. at application rates of 0, 0.4, 0.6 and 0.8%, respectively; these values increased to 22.11, 22.5, 23.8, and 24.07 mg, respectively. kg$^{-1}$, through nano-OMW at application rates of 0, 0.4, 0.6 and 0.8%, respectively.

The soil available concentrations of Mn through the bulk SCB were 153.9, 155.27, 157.54 and 158.76 mg. at application rates of 0, 0.4, 0.6 and 0.8%, respectively; these values increased to 153.9, 156.17, 158.5 and 159.13 mg, respectively. kg$^{-1}$, through nano-SCBs at application rates of 0, 0.4, 0.6 and 0.8%, respectively. OMW, but not SCB, also increased the available concentrations of Mn due to the composition of the raw material. . The soil available concentrations of Mn through the bulk OMW were 153.9, 153.7, 155.2 and 156.4 mg. kg$^{-1}$ at application rates of 0, 0.4, 0.6 and 0.8%, respectively; these values increased to 153.9, 152.8, 154.5 and 156.8 mg, respectively. kg$^{-1}$, through nano-OMW at application rates of 0, 0.4, 0.6 and 0.8%, respectively.

However, the large surface area and porous structure of nanobiochar make it effective at adsorbing heavy metals. It can immobilize metals by adhering them to their surface, limiting their mobility in the soil and lowering their bioavailability for plants. When biochar is injected into soils, it can have a number of effects on soil characteristics, including the availability of trace elements. The specific implications differ according to the type of biochar used, soil conditions, and presence of heavy metals and toxic trace elements, as shown in Figs. 5 and 6. The results confirm that the application of biochar at different rates affects the available content of TEs and heavy metals such as Cu, Zn, Pb, Ni and Mo, as shown in Figs. 5 and 6. Compared with that of the control, the available concentration decreased with increasing addition rate. The soil available concentrations of Cu, Zn, Pb, Ni and Mo were 28.2, 12.4, 17.6, 3.9 and 12.6 mg, respectively. kg$^{-1}$ in the control treatment. These values fall to 17.5, 7.78, 5.4, 0.95 and 1.82 mg, respectively. kg$^{-1}$ decreased to 16.5, 7.5, 5.2, 0.78 and 1.11 mg/kg at a rate of 0.8% through the bulk SCB and in the nanotreatment, respectively, and the nano-OMW was more effective than the SCB in decreasing the available concentrations of Cu, Zn and Pb, but the nano-SCB was more effective than the OMW in decreasing the available concentrations of Ni and Mo. The values were 14.02, 5.01, 2.9, 1.2 and 1.52 mg. kg$^{-1,}$ respectively, at a rate of 0.8%.

### Effect of sources, types and rates of biochar on maize growth

Table 8 displays the impact of various biochar types and activation techniques on the dry weight of maize planted in polluted soil. The data are organized to compare the effects of bulk and nano biochar; the application rates are given in unspecified units (likely kg/ha or t/ha), and the dry weight of maize is measured in grams. The results presented in Table 8 show that an increase in the dry weight of maize grown in contaminated soil is observed when biochar from the SCB (sugarcane bagasse) and OMW (olive mill waste) sources is applied at various rates. Higher dry weights of maize were associated with the application of SCB biochar at rates of 0.4, 0.6, and 0.8, with the peak effect occurring at a rate of 0.6. This suggests an optimal level for SCB biochar application in enhancing plant growth in contaminated soils. The mean dry weight of maize with SCB biochar application was reported to be 13.24. Conversely, OMW biochar was not associated with a consistent increase in maize dry weight at higher application rates. A slight improvement in dry weight was noted with the initial application, but further increases in the application rate did not correspond to significant changes. The mean dry weight for maize with OMW biochar application is reported to be 12.8, which is lower than that of SCB, indicating a potential difference in efficacy under contaminated soil conditions. The combined effect of these biochar sources on maize growth under the studied conditions is reflected in the overall mean of 15.86. These data highlight the significance of selecting appropriate biochar sources and application rates to optimize plant growth, particularly in soils affected by contamination.

### Effect of sources, types and application rates of biochar on the NPK content (%) of Zea maize plants

The data in Fig. 7 illustrate the effects of sugarcane bagasse biochar (SCB) and olive mill waste biochar (OMW) on the nitrogen percentage (N, P and K%) in maize. The figure shows the impact of biochar sources, specifically (SCB) and (OMW), in both bulk and nano form, on the (N, P and K %) of maize grown in contaminated soil. The use of SCB and OMW biochars, particularly in nano form, can be a sustainable approach for improving soil fertility and crop productivity, especially in contaminated soils. A comparison of SCB and OMW revealed that SCB generally had greater amounts (N, P and K%) across both bulk and nanoforms, indicating that SCB may be a more effective biochar source for enhancing nitrogen availability and uptake in maize. The data revealed that SCB biochar resulted in a greater N content than OMW biochar. This is evident from the overall means, where SCB has a mean N content of 1.56% and OMW has 1.26%, where the P content is 0.11% and 0.08% and the K content is 2.16% and 1.76% for SCB and OMW, respectively. The higher nutrient content in SCB biochar could be attributed to its inherent properties, such as a higher lignin content, which is known to influence the nutrient levels in biochar. This suggests that the type of biochar used can significantly influence the nutrient content of the soil, which in turn affects plant growth. which is known to influence the nutrient levels in biochar. This suggests that the type of biochar used can significantly influence the nutrient content of the soil, which in turn affects plant growth.

Regarding the effect of the biochar type on the N, P and K concentrations in corn plants grown in contaminated soil, it was found from the results presented in Fig. 7 that the mean N, P and K concentrations in the nanobrochar treatments were greater than those in the bulk biochar treatments for both the SCB and OMW sources. The mean of the SCB biochar was greater than that of the OMW biochar for both the bulk and the nanobiochar. Additionally, there was a clear trend indicating that as the rate of biochar application increased, both the nitrogen (N, P and K%) in maize also increased. At the 0% biochar rate (control), the initial N percentage was 0.97%, while the highest biochar rate of 0.8 had the most significant increase, with an N percentage of 1.98%. The mean values across all rates were 1.41% for N. At the 0% rate (control), the initial P% was 0.053%, while the highest biochar rate of 0.8 had the most significant increase, with a P% of 0.144%. At the 0% biochar rate (control), the initial K% was 0.92%, while the highest biochar rate of 0.8 showed the most significant increase, with a K% of 2.82%, demonstrating the overall positive effect of biochar application on nitrogen dynamics in maize. Across all treatments, the application rate of 0.8% resulted in the highest N, P and K%, indicating that higher application rates of biochar, regardless of the source or activation method, are beneficial for nitrogen in maize grown in contaminated soil.

### Effect of the sources, types and application rates of biochar on the micronutrients "Cu, Zn, Mn and Fe" in Zea maize plants mg.kg$^{-1}$".

Fig. 8 illustrates the effects of sugarcane bagasse biochar (SCB) and olive mill waste biochar (OMW) on the copper percentage (Cu Zn, Mn and Fe mg.kg$^{-1}$).

The impact of biochar sources, specifically (SCB) and (OMW), in both bulk and nano forms, on (Cu mg. kg$^{-1}$) of maize grown in contaminated soil. The use of SCB and OMW biochars, particularly in nano form, can be a sustainable approach for improving soil fertility and crop productivity, especially in contaminated soils. A comparison of the SCB and OMW data revealed that the SCB generally had higher Cu concentrations. kg$^{-1}$ both bulk and nano form, indicating that SCB may be a more effective biochar source for enhancing nitrogen availability and uptake in maize. The data revealed that the SCB biochar resulted in a higher Cu content than the OMW biochar. This is evident from the overall means, where SCB has a mean Cu content of 7.58 mg. $kg^{-1}$ and that of OMW was 5.74 mg. $kg^{-1}$ for the SCB and OMW, respectively. The higher nutrient content in the SCB could be attributed to its inherent properties, such as a higher lignin content. Regarding the effect of the biochar type on the Cu mg. According to the results presented in Fig. 8, the mean uptake of kg-1 in Zea maize plants grown in contaminated soil was greater for both SCB and OMW sources than for bulk biochar. For the bulk biochar SCB, the Cu (mg. $kg^{-1}$ were 6.7 mg. $kg^{-1}$, respectively, and in nano form 6.5 $mg.kg^{-1}$.

The data in Fig. 8 illustrate the effects of sugarcane bagasse biochar (SCB) and olive mill waste biochar (OMW) on Zn mg. $kg^{-1}$) and in maize. The data present the impact of biochar on both bulk and nanoform sources, specifically on the (SCB) and (OMW) concentrations of Zn. $kg^{-1}$) of maize grown in contaminated soil. The use of SCB and OMW biochars, particularly in nano form, can be a sustainable approach for improving soil fertility and crop productivity, especially in contaminated soils. A comparison of the SCB and OMW data revealed that the SCB generally had higher Zn concentrations. $kg^{-1}$ across both bulk and nanoforms, indicating that SCB may be a more effective biochar source for enhancing nitrogen availability and uptake in maize. The data revealed that compared with OMW, SCB had a greater Zn content. This is evident from the overall means, where SCB has a mean Zn content of 4.6 mg. $kg^{-1}$ and that of OMW was 3.17 mg. $kg^{-1}$ for the SCB and OMW, respectively. The higher nutrient content in the SCB could be attributed to its inherent properties, such as a higher lignin content. Regarding the effect of the biochar type on the Zn mg. $kg^{-1}$ in Zea maize plants grown in contaminated soil. According to the results presented in Fig. 8, both SCB and OMW sources had greater mean kg-1 values for nanobiochar than for bulk biochar. For the bulk and nano biochar SCB, the Zn (mg. $kg^{-1}$ were 4.04 mg. $kg^{-1}$ and 3.73 mg. $kg^{-1,}$ respectively. The results presented a clear trend indicating that as the rate of biochar application increased, both the nitrogen percentage (Zn mg. $kg^{-1}$) in maize also increased. At a 0 rate (control), the initial Zn (mg. $kg^{-1}$ is 2.7 mg. $kg^{-1}$, when the highest biochar rate of 0.8 had the most significant increase, with a Zn mg. $kg^{-1}$ of 5.2 mg. $kg^{-1}$. Across all treatments, the application rate of 0.8 mg. $kg^{-1}$, indicating higher application rates of biochar.

Fig. 8 illustrates the effects of sugarcane bagasse biochar (SCB) and olive mill waste biochar (OMW) on (Mn mg. $kg^{-1}$) in maize. Fig. 8 presents the impact of biochar sources, specifically (SCB) and (OMW), in both bulk and nano form, on (Mn mg. $kg^{-1}$) of maize grown in contaminated soil. The use of SCB and OMW biochars, particularly in nano form, can be a sustainable approach for improving soil fertility and crop productivity, especially in contaminated soils. A comparison of the SCB and OMW data revealed that the SCB generally had higher Mn concentrations. $kg^{-1}$ across both bulk and nanoforms, indicating that SCB may be a more effective biochar source for enhancing manganese availability in maize. The data revealed that the SCB biochar resulted in a greater Mn content than the OMW biochar. This is evident from the overall means, where SCB has a mean Mn content of 35.47 mg. $kg^{-1}$ and that of OMW was 33.8 mg. $kg^{-1}$ for the SCB and OMW, respectively. The higher nutrient content in the SCB could be attributed to its inherent properties, such as a higher lignin content. Regarding the effect of the biochar type on the Mn mg. $kg^{-1}$ in Zea maize plants grown in contaminated soil. According to the results presented in Fig. 8, both SCB and OMW sources had greater amounts of biochar than did bulk biochar. For the bulk and nano biochar SCB, the Mn mg. $kg^{-1,}$ 34.4 and 34.7 mg. $kg^{-1}$, respectively. The results presented a clear trend indicating that as the rate of biochar application increased, both the percentage of nitrogen (Mn %) in maize also increased. At the 0% rate (control), the initial Mn% was 33.4 mg. $kg^{-1}$, when the highest biochar rate of 0.8 showed the most significant increase, with a Mn mg. $kg^{-1}$ of 35.7 $mg.kg^{-1}$. Among all the treatments, the application rate of 0.8 resulted in the highest Mn mg. $kg^{-1}$ indicates higher application rates of biochar.

Additionally, the data on the impact of biochar sources, specifically (SCB) and (OMW), in both bulk and nano forms, on (Fe mg. $kg^{-1}$) of maize grown in contaminated soil. The use of SCB and OMW biochars, particularly in nano form, can be a sustainable approach for improving soil fertility and crop productivity, especially in contaminated soils. A comparison of the SCB and OMW data reveals that the SCB generally has greater amounts of Fe. $kg^{-1}$ across both bulk and nanoforms, indicating that SCB may be a more effective biochar source for enhancing nitrogen availability and uptake in maize. The data revealed that the SCB biochar resulted in a greater Fe content than the OMW biochar. This is evident from the overall means, where SCB has a mean Fe content of 15.2 mg. $kg^{-1}$ and that of OMW was 13.4 mg. $kg^{-1}$ for the SCB and OMW, respectively. The higher nutrient content in the SCB could be attributed to its inherent properties, such as a higher lignin content. which is known to influence the nutrient levels in biochar. This suggests that the type of biochar used can significantly influence the nutrient content of the soil, which in turn affects plant growth.

Regarding the effect of the biochar type on the Fe mg. $kg^{-1}$ in Zea maize plants grown in contaminated soil. According to the results presented in Fig. 8, both SCB and OMW sources had greater mean kg-1 values for nanobiochar than for bulk biochar. For the bulk and nano biochar SCB, the Fe mg. $kg^{-1,}$ 13.63 and 15.02 mg. $kg^{-1}$ Fe, respectively. The results present a clear trend indicating that as the rate of biochar application increases, the iron percentage (Fe mg. $kg^{-1}$) in maize also increased. At the 0% rate (control), the initial Fe (mg. $kg^{-1}$ is 13.3 mg. $kg^{-1}$, when the highest biochar rate of 0.8 showed the most significant increase, with an increase in Fe. kg-1 of 15.3%. Across all treatments, the application rate of 0.8 resulted in the highest Fe mg. $kg^{-1}$ indicated that higher application rates of biochar, regardless of the source or activation method, are beneficial for iron uptake in maize grown in contaminated soil.

### Effect of the sources, types, and application rates of biochar on the micronutrients "Pb", "Ni", and "Mo" in Zea maize plants mg.$kg^{-1}$".

The mobile species of trace metals in soils, which are consequently phytoavailable, are characterized by the solubility plus exchangeable fractions. The concentrations of plants' migratory species in soils and the elemental contents of those plants are always strongly linked. On the other hand, a variety of plant and soil parameters regulate the intricate energetic and/or nonmetabolic process known as root absorption. The source of trace elements affects their availability significantly, among other soil characteristics. An overabundance of mobile molecules of trace metals can interfere with the processes of preferential adsorption and distribution of trace cations. The effects of olive mill waste biochar (OMW) and sugar-cane bagasse biochar (SCB) on lead (mg. kg-1) in maize are shown in Fig. 9.

The data present the impact of biochar sources, specifically (SCB) and (OMW), in both bulk and nanoforms, on (Pb mg. $kg^{-1}$) of maize grown in contaminated soil. The use of SCB and OMW biochars, particularly in nano form, can be a sustainable approach for improving soil fertility and crop productivity, especially in contaminated soils. A comparison of the SCB and OMW reveals that the SCB generally has higher Pb concentrations. $kg^{-1}$t across both bulk and nanoforms, indicating that OMW may be a more effective biochar source for inhibiting lead availability and uptake in maize.

The data revealed that the SCB biochar resulted in a greater Pb content than the OMW biochar. This is evident from the overall means, where SCB has a mean Pb content of 3.7 mg. $kg^{-1}$ and that of OMW was 2.03 mg. $kg^{-1}$, for the SCB and OMW, respectively. The higher nutrient content in the SCB could be attributed to its inherent properties, such as a higher lignin content. which is known to influence the nutrient levels in biochar. This suggests that the type of biochar used can significantly influence the nutrient content of the soil, which in turn affects plant growth.

Regarding the effect of the biochar type on the Pb mg. $kg^{-1}$ in Zea maize plants grown in contaminated soil, and the results showed that nanobiochar had a greater mean uptake than did bulk biochar for both SCB and OMW sources. For the bulk biochar SCB, the Pb (mg. $kg^{-1,}$ respectively, and in the nano form 2.7 mg. $kg^{-1}$.

The results presented a clear trend indicating that as the rate of biochar application increased, both the (Pb mg. $kg^{-1}$) in maize also increased. At the 0% treatment (control), the initial Pb (mg. $kg^{-1}$ is 5.2 mg. $kg^{-1}$ and decreased with increasing application rate to 2.6, 1.9 and 1.7 mg. At the highest biochar rate of 0.8, kg-1 showed the most significant decrease, and at the highest biochar rate of 0, Pb increased, indicating that higher application rates of biochar, regardless of the source or activation method, are beneficial for lead uptake in maize grown in contaminated soil.

Additionally, the data illustrate the effects of sugarcane bagasse biochar (SCB) and olive mill waste biochar (OMW) on (Ni mg. $kg^{-1}$) in maize. It presents the impact of biochar sources, specifically (SCB) and (OMW), in both bulk and nano forms, on (Ni mg. $kg^{-1}$) of maize grown in contaminated soil. The use of SCB and OMW biochars, particularly in nano form, can be a sustainable approach for improving soil fertility and crop productivity, especially in contaminated soils. A comparison of the SCB and OMW data reveals that the SCB generally contains more Ni. $kg^{-1}$ across both bulk and nanoforms, indicating that SCB may be a more effective biochar source for inhibiting nickel availability in maize. The data revealed that the SCB biochar resulted in a greater Ni content than the OMW biochar. This is evident from the overall means, where SCB has a mean Ni content of 0.52 mg. $kg^{-1}$ and that of OMW was 0.90 mg. $kg^{-1}$ for the SCB and OMW, respectively. The higher nutrient content in the SCB could be attributed to its inherent properties, such as a higher lignin content. which is known to influence the nutrient levels in biochar. This suggests that the type of biochar used can significantly influence the nutrient content of the soil, which in turn affects plant growth.

Regarding the effect of the biochar type on the Ni mg. $kg^{-1}$ in Zea maize plants grown in contaminated soil. The results showed that the mean $Kg^{-1}$ of the nano-biochar treatment group was greater than that of the bulk biochar group for both the SCB and OMW sources. For the bulk and nano biochar SCB, the Ni mg. $kg^{-1}$ are 0.75 mg. $kg^{-1}$ and 0.60 mg. $kg^{-1,}$ respectively.

The results present a clear trend indicating that as the rate of biochar application decreased, the (Ni mg. $kg^{-1}$) in maize also decreased. At the 0% rate (control), the initial Ni (mg. $kg^{-1}$ was 0.0%, when the highest biochar rate of 0.8 showed the most significant increase, with a Ni mg. $kg^{-1}$ Across all treatments, the application rate of 0.8 resulted in a lower Ni mg. $kg^{-1}$, indicating higher application rates of biochar. The data in Fig. 9 illustrate the effects of sugarcane bagasse biochar (SCB) and olive mill waste biochar (OMW) on (Mo mg. $kg^{-1}$) in maize.

The data present the impact of biochar sources, specifically (SCB) and (OMW), in both bulk and nanoforms, on (Mo mg. $kg^{-1}$) of maize grown in contaminated soil. The use of SCB and OMW biochars, particularly in nano form, can be a sustainable approach for improving soil fertility and crop productivity, especially in contaminated soils. When comparing the SCB and OMW, the data reveal that the OMW generally has higher Mo contents. $kg^{-1}$ across both bulk and nanoforms, indicating that OMW may be a more effective biochar source for inhibiting Mo availability in maize. The data revealed that the SCB biochar had a greater Mo content than the OMW biochar. This is evident from the overall means, where the SCB has a mean Mo content of 1.04 mg. $kg^{-1}$ and that of OMW was 1.4 mg. $kg^{-1}$ for the SCB and OMW, respectively. The higher nutrient content in the OMW biochar could be attributed to its inherent properties, such as a higher lignin content. which is known to influence the nutrient levels in biochar. This suggests that the type of biochar used can significantly influence the nutrient content of the soil, which in turn affects plant growth.

Regarding the effect of the biochar type on the Mo (mg. $kg^{-1}$ in Zea maize plants grown in contaminated soil, and the results showed that nanobiochar had a greater mean uptake than did bulk biochar for both SCB and OMW sources. For the bulk and nano biochar SCB, the Mo (mg. $kg^{-1}$, 1.4 and 1.04 mg. $kg^{-1,}$ respectively.

The results also showed a clear trend, indicating that as the rate of biochar application increased (Mo mg. $kg^{-1}$) in maize also decreased. At the 0% rate (control), the initial Mo (mg. $kg^{-1}$ is 1.7 mg. At the highest biochar rate of 0.8, $kg^{-1}$ showed the most significant decrease, with a decrease in Mo. $kg^{-1}$ of 0.88 $mg.kg^{-1}$. Across all treatments, the application rate of 0.8 mg/L Mo was the lowest. kg-1 indicates higher application rates of biochar, regardless of the source.

## DISCUSSION

### Effects of biochar and nanobrochar on soil chemical properties

#### *pH*

As reported by Singh et al.(2022), the smaller particle size of nano biochar, which increases its surface area, is responsible for enhancing its capacity to interact with soil particles and ions. This enhanced interaction is capable of leading to more effective neutralization of acidic ions in the soil, thereby elevating the pH.

According to Hailegnaw et al.(2019), the increased surface area-to-volume ratio of the nanoscale particles in nano biochar increases their reactivity. This increased reactivity can have a more marked influence on soil pH, as biochar is able to interact more effectively with hydrogen ions and other elements that affect soil acidity. As observed by Singh et al.(2022), the probability of smaller particles of nano biochar being more uniformly dispersed throughout the soil is high. This uniform dispersion ensures that the pH-modifying effects of the biochar are applied more consistently across the soil, leading to a higher overall average pH.

Hailegnaw et al.(2019) noted that nano biochar can improve the soil's CEC, which is the ability of the soil to retain and exchange cations (positively charged ions). An enhanced CEC can result in a higher soil pH as more acidic cations are exchanged for alkaline cations.Hematimatin et al.(2024) The properties of biochar, such as ash content, porosity, and inherent mineral content, can vary based on the feedstock and pyrolysis conditions. These varying properties can affect the impact of biochar on soil pH, with nanobiochar potentially possessing a composition that favours an increase in soil pH. In conclusion, the slight increase in soil pH observed with nano biochar compared to bulk biochar can be attributed to its increased surface area, reactivity, and distribution, as well as its potential to enhance soil CEC and its unique physicochemical properties. These factors make nano biochar a more effective agent for modifying soil pH.

### *EC*

Because soil soluble salt is proportional to EC, changes in soil soluble salt can be predicted based on changes in soil solution EC. When biochar is applied, the soil EC increases considerably, presumably due to the soluble ash it contains, which enhances soil base saturation. Biochar can increase soil EC in specific cases. This can occur if biochar emits ions into the soil solution or if it promotes microbial activity, resulting in the synthesis of chemicals that contribute to EC. Furthermore, if biochar contains soluble salts, its addition to soil may increase the EC. Our data indicate that the rate of biochar application is critical for explaining EC variance. However, some studies have indicated that soil EC is negatively correlated (Chausali et al., 2021) or unrelated to the amount of biochar applied. This is mostly because biochar increases soil porosity and increases the leaching of water-soluble nutrient ions to deep soil, hence reducing the amount of soluble ions in the soil(Qiu et al., 2024).

### *OM %*

According to previous findings, applying nanobiochar to soil significantly increases its organic carbon content (Rashid et al., 2023b). Increased Microbial Activity: Biochar's porous nature and wide surface area make it an ideal environment for soil bacteria. This can boost microbial activity in the soil, resulting in faster breakdown of organic compounds. However, the overall effect on soil organic matter concentration will be determined by the balance between stabilizing existing organic matter and decomposing new organic inputs. Biochar can improve soil structure and aggregation, which can have an indirect impact on soil organic matter dynamics. Enhanced soil aggregation can create microenvironments that prevent organic matter degradation and promote its accumulation. Some biochars can affect soil pH (Qiu et al., 2024). Changes in pH can affect organic matter breakdown rates and soil microbial activity, hence influencing soil organic matter concentrations. Biochar has a high cation exchange capacity (CEC), which allows it to retain nutrients in the soil and avoid leaching. Biochar can help plants grow by improving nutrient availability and promoting organic matter accumulation in the soil through root exudates and plant waste. Long-term impacts. The long-term impacts of biochar on soil organic matter dynamics are poorly understood and may vary depending on biochar stability, soil type, and climate. Long-term studies are required to evaluate the persistence of biochar-induced changes in soil organic matter content and quality (Mahmoud et al., 2024). Overall, the impact of biochar on soil organic matter is complex and context specific. While biochar can increase soil organic matter content through stable and nutrient cycling processes, its impact may change depending on the unique features of the soil–plant system and the quality of the biochar used. For example, adding 0.8% nanobiochar to soil increases the organic carbon content. Based on these data, it is proposed that nanobiochar increases soil organic carbon stability while decreasing mineralization. Soil organic carbon stability can be improved in three ways**.** Enhancing soil structure along with chemical and biological stabilization are all necessary components of an integrated strategy to improve SOC stability. These tactics support general soil health, fertility, and resistance to environmental stressors in addition to assisting in sustaining and increasing SOC levels. By storing carbon in soils, these techniques can help create more environmentally friendly agricultural systems and mitigate the effects of climate change(Cha et al., 2016).

### *CEC*

The CEC is used to assess the ability of soil to absorb, retain, and exchange cations, making it an important indicator of soil quality. A higher CEC indicates increased nitrogen fixation potential, which is beneficial for plant development. When in contact with soil, the active groups on the biochar surface, such as -COOH or -OH, react with metal cations in the soil to form metal ion complexes, which results in electrostatic adsorption. These functional groups are negatively charged; hence, biochar has a high CEC, which increases the soil CEC (Tan et al., 2017). Most biochars have a higher CEC than regular agricultural soils. The CEC of biochar is linked to the synthesis of numerous functional groups, including carboxyl and hydroxyl groups, during biomass pyrolysis (Tomczyk et al., 2020). The biochar CEC is determined by two main factors: (a) surface oxidation and (b) the adsorption of highly oxidized organic matter onto the biochar surface (Rodríguez-Vila et al., 2022). Differences in CEC are impacted by feedstock sources as well as any specific functional groups generated during pyrolysis that may alter the surface properties of the biochar. In fact, biochars produced at higher pyrolysis temperatures have greater CECs than identical feedstock-derived products produced at lower pyrolysis temperatures (Rashid et al., 2023b).

## Effects of biochar and nanobrochar on soil fertility

Nitrogen, phosphorus, and potassium are key components of organic molecules in crops and are required by all living species. The majority of the nitrogen, phosphorous, and potassium in the soil are organically bonded. Total nitrogen is commonly used to assess soil fertility, and the availability of nitrogen, phosphorus, and potassium in the soil is directly related to crop development. The addition of biochar increased the available N, P, and K in the analysed soil, which increased the active capacity of the surface area of the studied soils, as did the addition of other nutrients released from biochar to the soil. The results given here are congruent with those obtained by (Rosa et al., 2024). Alkaline nitrogen refers to nitrogen that plants can absorb and use. It is the sum of ammonium nitrogen, nitrate nitrogen, amino acids, amides, and easily decomposable protein nitrogen(Khadem et al., 2021).

## Effect of biochar and nanobrochar on the immobilization of TEs in soil and plants

TE(s) detoxification may be due to TE(s) immobilization in the soil (see also Table 6). Because of its carbonaceous qualities, the sorption of TE(s) on biochar surfaces is part of the rhizosphere's removal of soil pollutants, reducing TE(s) availability to plants (Rizwan et al., 2016). Rashid et al. (2023b) reported that applying BC (80% coniferous and 20% hardwood chips, 450 °C) increased TE(s) immobilization in the soil and the adsorption of TE(s) unique to BC mineral phases. Compared to regular biochar, nanobiochar has clear benefits for lowering the bioavailability of trace elements in soil. The TEs that are significantly more effective at adsorbing and immobilizing are their larger surface area, increased porosity, greater density of functional groups, and stronger chemical interactions. However, to reduce any possible dangers to the environment and human health from nanoparticles, the use of nano biochar needs to be carefully controlled (Rosa et al., 2024).

Biochar serves as a reservoir to increase the availability of vital nutrients. Over extended periods of time, it adsorbs and progressively releases nutrients such as potassium, phosphorus, and nitrogen, increasing their availability to plants. These nutrients are retained in the soil by the high CEC of biochar, which prevents them from evaporating and guarantees that plant roots may still reach them. Additionally, biochar increases soil aeration and structure, which strengthens root systems and improves nutrient uptake. Additionally, biochar increases the diversity and activity of soil microbes, which is important for the cycling and availability of nutrients. It helps with nitrogen fixation and phosphorus solubilization by providing beneficial bacteria with a place to live and a carbon source. The transformation of organic material into forms that plants can readily absorb depends on this microbial activity. Biochar indirectly improves nutrient availability by supporting a healthy soil microbiome (Rashid et al., 2023a).

The organic and mineral components found in BC may play a key role in TE(s) adsorption(Sani et al., 2023). According toCong et al. (2023), the water-soluble part of BC adsorbed significantly more Ni than the HCl-soluble ashes and insoluble silicon oxide solids. Biochar treatment (maple wood at 450 °C) immobilized TE(s), Cu, Zn, and Pb in sandy loam urban soil. Similarly, biochar generated from gigantic Miscanthus lowered the mean cumulative Zn and Cd fluxes, which might be attributed to both lower TE(s) concentrations in the soil solution and decreased drainage(Vejvodová et al., 2020). Rashid et al. (2023b) reported that applying paper sludge biochar (made at 500 °C) to soil and incubating it for 77 days reduced the amount of leached and accessible Ni. Puga et al. (2015a) reported that the application of biochar (sugarcane straw at 700 °C) reduced the concentrations of DTPA-extractable Zn, Pb, and Cd in soil as well as the concentrations of these TE(s) in pore water.

Similarly, Sani et al. (2023) reported that BC (Concarpus waste, 400 °C) significantly reduced AB-DTPA-extractable TE(s) (Mn, Zn, Cd, Cu, and Pb) in soil. In a variety of ways, biochar interacts with nutrients and metals in soil to modify both the availability of critical nutrients and the immobilization of trace elements (TEs). Adsorption is one of the main processes by which metal ions can bind to biochar at many sites due to their porous structure and large surface area. Adsorption can occur physically via van der Waals forces or chemically through the formation of links between metal ions and functional groups on the surface of biochar, such as hydroxyl, carboxyl, and phenolic groups. Because of their dual adsorption capabilities, hazardous metals become immobile in the soil because they are less mobile and less bioavailable (Nauman Mahamood et al., 2023).

Ion exchange is another significant process. Because of its high cation exchange capacity (CEC), biochar can exchange metal ions in the soil solution for cations such as calcium, magnesium, and potassium. This procedure replaces toxic metals with advantageous cations, immobilizing the former and preserving vital nutrients in the soil. Furthermore, the functional groups in biochar can complex or chelate with metal ions to create stable complexes. These complexes help immobilize trace elements since they are less poisonous and bioavailable (Mahmoud et al., 2024). Biochar-facilitated redox processes are also important. The oxidation states of metals can be altered by biochar. For example, hazardous chromium (VI) can be reduced to less harmful chromium (III). Metal toxicity and bioavailability are decreased by this shift in the oxidation state. Moreover, the pH of soil can increase due to the alkaline nature of certain biochars, which can cause metals to precipitate as carbonates or hydroxides. Metals become less mobile and soluble as a result of this precipitation process, which further contributes to their immobilization.

Song et al. (2023) reported that SCB biochar can improve soil fertility by increasing the availability of essential nutrients that are crucial for plant growth. Studies have shown that biochars obtained at higher temperatures, such as SCB, significantly promote the growth of maize by enhancing soil pH and electrical conductivity, which are indicative of improved nutrient availability. Song et al.(2023) demonstrated that the physical properties of SCB biochar, such as increased surface area and porosity, can lead to improved soil structure. This can enhance root penetration and access to nutrients, further contributing to the higher DW observed in maize.

According to Zhou et al.(2023), the application of SCB biochar has been associated with changes in the bacterial community structure and the enhancement of microbial activity in the soil. This can lead to better nutrient cycling and availability for plants, resulting in increased biomass accumulation. Zhou et al.(2023) also noted that SCB biochar may also play a role in mitigating soil toxicity, particularly in contaminated soils. By adsorbing toxic contaminants, SCB biochar can reduce its bioavailability, thus minimizing its negative impact on plant growth.

Yang et al.(2022) noted that SCB biochar can improve soil water retention capacity, which is vital for maize growth, especially under drought-prone or water-limited conditions. Enhanced water retention can lead to a more consistent water supply to maize roots, supporting better growth.

In contrast, OMW biochar may not exhibit the same level of effectiveness in these areas, which could explain the lower DW of maize observed with its application. The specific characteristics of OMW biochar, such as its chemical composition, pH, and nutrient content, may not be as conducive to maize growth as those of SCB biochar. Additionally, the variability in the impact of OMW biochar on plant growth could be due to differences in its interaction with soil chemistry and plant physiology.

The greater DW of maize in the presence of nanobiochar than in the presence of bulk biochar can be attributed to several factors related to the unique properties of nanobiochar. Nanobrochar is produced by reducing the size of biochar to the nanometre level, which significantly enhances its physico-chemical behaviour. Nanobrochar is more stable than its bulk counterpart, which can lead to a more sustained release of nutrients and a longer-lasting effect on soil improvement. Nanobrochar has been shown to have a greater catalytic ability, which can improve the bioavailability of nutrients and enhance plant uptake (Bhandari et al., 2023).

The interaction of nano biochar with soil minerals and organic matter is enhanced due to its increased surface area and number of active sites, which leads to improved nutrient absorption by plants, according to Bhandari et al., (2023) and Ramanayaka et al., (2020). The properties of nano biochar, such as contributing to more efficient regulation of the transport and absorption of vital micro- and macronutrients and reducing the bioavailability of toxic contaminants, have been shown to result in greater biomass accumulation in plants such as maize plants grown in soil amended with nano biochar, as reflected in the increased DW measurements. Furthermore, Martínez-Gómez et al., (2022) showed that cocomposted biochar improved plant height, chlorophyll content, and DW, likely due to changes in soil characteristics and increased nutrient availability. Khadem et al., (2021) showed that the higher nitrogen content in SCB biochar could be due to its higher lignin content, which is known to influence the nutrient levels in biochar. Additionally, biochar can increase nitrogen retention in soil by reducing leaching and gaseous loss and increasing phosphorus availability. This is particularly important for maize cultivation, as nitrogen is a critical nutrient for plant growth and development. Rizwan et al., (2023) demonstrated that in addition to improving soil fertility, biochar application has environmental benefits, such as decreasing nutrient leaching, curbing greenhouse gas emissions, reducing the bioavailability of environmental pollutants, and enhancing agricultural productivity.

The increased efficiency of nanobrodes could be due to their larger surface area and greater porosity, which enhance nutrient retention and availability (Zhao et al., 2022). Khadem et al., (2021) reported that due to their increased surface area and porosity, NBs can enhance nutrient retention and availability, leading to improved soil fertility. These data indicate that both bulk and nanoforms of biochar positively influence nitrogen content and uptake in maize. The nano form of biochar, however, seems to have a slightly more pronounced effect on N uptake at higher application rates, which could be due to its increased surface area and reactivity (Das, 2024). This finding aligns with the findings of Li et al. (2022), who suggested that biochar, especially when used in conjunction with nitrogen fertilizers, can enhance soil nitrogen retention, absorption, and utilization in maize production. Moreover, Gao et al.(2022) showed that the application of biochar promoted nitrogen uptake by maize, improved plant growth performance and potentially increased crop yields. Peng et al.(2021) mentioned that the use of biochar can also contribute to the reduction of nitrogen loss to the environment, thus minimizing the ecological footprint of agricultural practices.

Supporting these observations, Nigussie et al.(2021) showed that biochar application can enhance soil fertility and plant growth, particularly by improving nitrogen uptake and retention in the soil. Sun et al.(2023) demonstrated that biochar is known to increase soil carbon storage and reduce nitrogen loss, suggesting that biochar is a promising strategy for effectively increasing soil productivity. However, Wang ZhiHui et al.(2019) reported that the effectiveness of biochar can vary based on factors such as the type of biochar used, soil properties, and crop type. Guo et al.(2020) noted that higher application rates can significantly increase nutrient content, which is crucial for the growth of maize in contaminated soils. SCB biochar tends to immobilize Cu in the soil, reducing its availability to plants. This is due to the high cation exchange capacity (CEC) and the presence of functional groups that bind to Cu, decreasing its solubility and bioavailability (Rodríguez-Vila et al., 2022). Similar to Cu, SCB biochar can also immobilize Zn in the soil. However, the extent of immobilization can vary depending on the pH and the specific characteristics of the biochar. Generally, biochar increases the pH of acidic soils, which can decrease Zn availability (Raza et al., 2023).

OMW biochar, due to its high organic matter content and specific surface area, can strongly adsorb Cu, thereby reducing its bioavailability. This adsorption is facilitated by the formation of stable Cu-organic complexes (Rodríguez-Vila et al., 2022). The high nutrient content of OMW biochar can influence Zn dynamics. While it can immobilize Zn through similar mechanisms as SCB biochar, the presence of other nutrients and organic compounds might enhance the availability of Zn in some cases, particularly in nutrient-poor soils (L et al., 2024). SCB biochar can improve soil structure by increasing porosity and aeration, which promotes root growth and enhances the root surface area available for nutrient uptake. Improved root development can facilitate greater access to Mn and Fe in the soil (Sayılli et al., 2015). Although SCB biochar generally increases soil pH, which can reduce Mn and Fe availability, it can also buffer pH changes in very acidic soils. In such cases, moderate pH increases can shift Mn and Fe to more available forms without making them completely unavailable, especially in soils that are initially highly acidic (Rodríguez-Vila et al., 2022). SCB biochar contains organic compounds that can form chelates or complexes with Mn and Fe. These complexes can protect Mn and Fe from precipitation and immobilization, keeping them in a soluble form that is easier for maize roots to absorb (Mashwani et al., 2024).

The high CEC of SCB biochar allows it to retain essential nutrients, including Mn and Fe, and release them slowly over time. This slow release can help maintain the consistent availability of these micronutrients for maize uptake throughout the growing season (Mahmoud et al., 2024).

The application rate of biochar significantly affects the uptake of Zn, Mn, and Fe by Zea mays (maize). Low to medium rates generally enhance nutrient availability and uptake by improving soil structure, nutrient retention, and microbial activity. High rates can lead to excessive nutrient adsorption, altered soil pH, and potential nutrient imbalances. Site-specific application, incremental adjustments, and combining biochar with fertilizers are effective strategies for optimizing the benefits of biochar for micronutrient uptake in maize (Sun et al., 2022).

When comparing the effects of sugarcane bagasse (SCB) biochar and olive mill waste (OMW) biochar on reducing nickel (Ni) and molybdenum (Mo) concentrations in plants, several factors need to be considered, including the physicochemical properties of the biochars, the mechanisms of heavy metal immobilization, and the specific interactions with Ni and Mo in the soil–plant system. SCB biochar typically has a large surface area and contains functional groups (such as carboxyl and hydroxyl groups) that can adsorb heavy metals such as Ni and Mo. The structure of SCB biochar may provide effective sites for the adsorption of these metals. Like SCB biochar, OMW biochar has a high surface area and is rich in functional groups that can adsorb heavy metals. The effectiveness can vary based on the specific properties of the biochar produced from OMW (Zafeer et al., 2024).

The availability and mobility of Ni and Mo in soil might be affected by SCB biochar, as it frequently increases the pH of the soil. Elevated pH values have the potential to precipitate Ni and decrease plant absorption. Mo, on the other hand, behaves differently; unless biochar successfully immobilizes it, it becomes more accessible under alkaline conditions, which may boost Mo uptake. The availability of Ni and Mo is further impacted by OMW biochar, which also increases the soil pH (Disha Mishra, Shilpi Jain, Puja Khare, 2023). The effect on Mo may be less favourable because of the higher pH conditions where it is more soluble. The functional groups in SCB biochar can bind Ni and Mo, although the specific chemical properties of SCB biochar may cause variations in binding efficiency. The abundant oxygen-containing functional groups in OMW biochar can chelate Ni and Mo ions, improving immobilization. However, the overall efficacy of the immobilization process is dependent on how the biochar interacts with the individual metals (Mahmoud et al., 2024).

Compared with bulk biochar, nanobiochar generally provides superior performance in reducing Pb, Ni, and Mo concentrations in plants. Its greater surface area, greater porosity, and greater abundance of functional groups make it more effective at immobilizing heavy metals and preventing their uptake by plants. However, the specific outcomes for Mo can be complex due to its unique behavior in soil, and careful management of soil conditions is necessary to optimize the benefits of nano biochar (Mahmoud et al., 2024) and (Wang et al., 2020).

The effectiveness of biochar in decreasing the levels of heavy metals such as lead (Pb), nickel (Ni), and molybdenum (Mo) in plants depends on various factors, including the type and rate of biochar application. Even low rates of biochar can significantly reduce the bioavailability of heavy metals by adsorbing them onto the biochar surface. However, the extent of reduction might be limited compared to higher application rates (Sun et al., 2022). Moderate rates are often optimal for balancing cost and effectiveness. These rates can substantially decrease the uptake of heavy metals by plants by providing sufficient adsorption sites and improving soil properties (Cha et al., 2016). High application rates can further enhance the immobilization of heavy metals but may also lead to other soil amendments, such as altered soil structure and nutrient dynamics, which could affect plant growth (Khan et al., 2024).

## CONCLUSION

This study's findings validated biochar's potential to immobilize hazardous trace elements and heavy metals such as Pb in polluted soils when utilized at normal or nanoscale levels. The relationships among metals, nutrients, and biochar in soil are intricate and varied overall. Because of its capacity to adsorb, exchange ions, form complexes, and participate in redox reactions, biochar is a useful tool for increasing the availability of vital nutrients and immobilizing harmful trace elements. Together, these processes enhance plant development, soil health, and environmental preservation. The soil treated with nanocharcoal has excellent chemical characteristics. The production of nanosized biochar resulted in more pronounced immobilization of TEs compared to the control or routine treatment. As a result, it is argued that applying SCB to polluted soils is a more promising technique for heavy metal remediation than using OMW.

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**Table 1.** Main initial of physical studied soils properties.

| Physical Properties | | | | |
|---|---|---|---|---|
| Particle size distribution (%) | | | Texture | Water Holding Capacity "WHC" (%) |
| Sand | Silt | Clay | | |
| 14.5 | 25 | 60.5 | Clay | 65 |

**Table 2.** Main initial chemical properties of the studied soils.

| Chemical Properties | Values |
|---|---|
| pH (1:2.5) soil : water susp. | 7.66 |
| EC (dSm-1) 1: 5 soil: water extract | 0.84 |
| Soluble ions (meq .l$^{-1}$) | |
| $Na^+$ | 3.93 |
| $K^+$ | 1.71 |
| $Ca^{2+}$ | 1.72 |
| $Mg^{2+}$ | 1.05 |
| $Cl^-$ | 4.85 |
| $CO_3^{2-}$ | 0.00 |
| $HCO_3^-$ | 0.65 |
| $SO_4^{2-}$ | 2.91 |
| OM (%) | 1.46 |
| CEC (cmol/kg) | 26.08 |
| Exchangeable Cations (cmol.kg$^{-1}$) | |
| Na | 7.23 |
| K | 1.25 |
| Ca | 7.84 |
| Mg | 9.70 |
| ESP | 27.72 |

**Table 3.** Trace Elements"TE" concentrations in the studied soils.

| Elements (mg.kg$^{-1}$) | Available | Total |
|---|---|---|
| Cu | 8.29 | 21.44 |
| Zn | 2.4 | 322.4 |
| Mn | 153.9 | 638.6 |
| Fe | 22.11 | 830.36 |
| pb | 7.65 | 47.21 |
| Ni | 0.95 | 22.42 |
| Mo | 2.6 | 89.87 |

**Table 4.** Permissible limits of heavy metals in agricultural soil

| Elements (mg.kg$^{-1}$) | Available (EU, 2002) | Total (EU, 2002) |
|---|---|---|
| Cu | 0.2: 7 | 10 : 20 |
| Zn | 20 | 30 : 80 |
| Mn | 1:50 | 80 : 300 |
| Fe | 2:50 | 25000 : 45000 |
| pb | 10 | 30 : 20 |
| Ni | 0.1 : 0.5 | 20 |
| Mo | 0.1:1 | 10 |

**Table 5.** WHO/FAO standards for heavy metals in plants (zea maize).

| Elements (mg.kg$^{-1}$) | FAO/WHO (2011) |
|---|---|
| Cu | 20 |
| Zn | 10 |
| Mn | 20 : 100 |
| Fe | 48 |
| pb | 0.3 : 5 |
| Ni | 1.5 |
| Mo | 3.2 |

**Table 6.** The Physicochemical analysis of bulk and nano biochar produced from the different feedstock

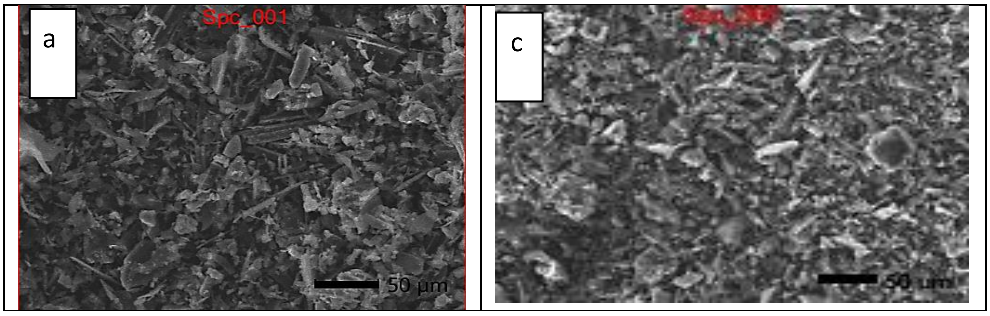
| Physico-chemical analysis of biochar | | Feedstock | | | |
|---|---|---|---|---|---|
| | | Sugarcane bagasse | | Olive mill waste | |
| | | Bulk | Nano | Bulk | Nano |
| pH (1:10) biochar : water susp. | | 8.77 | 8.96 | 9.53 | 9.75 |
| EC (dSm$^{-1}$)1: 10 biochar : water extract | | 230 | 334 | 1125 | 1130 |
| Element content (%) | C | 75.58 | 75.93 | 75.16 | 75.67 |
| | H | 0.19 | 0.25 | 0.42 | 0.51 |
| | O | 21.54 | 20.28 | 21.87 | 21.62 |
| | N | 0.19 | 0.19 | 0.2 | 0.22 |
| | Ca | 0.54 | 0.54 | 0.42 | 0.43 |
| | Mg | 0.22 | 0.32 | 1.41 | 0.26 |
| | K | 2.15 | 1.8 | 1.41 | 1.34 |
| Atomic ratios | O/C | 0.285 | 0.267 | 0.291 | 0.281 |
| | H/C | 0.003 | 0.003 | 0.006 | 0.007 |
| | (O+N)/C | 0.288 | 0.270 | 0.294 | 0.283 |
| | N/C | 0.0025 | 0.0025 | 0.0027 | 0.0029 |
| CEC (Cmole.kg$^{-1}$) | | 33.65 | 35.64 | 31.53 | 32.15 |
| SSA (m$^2$.g$^{-1}$) | | 513.82 | 515.7 | 229.8 | 312.3 |

**Table 7.** Effect of biochar and nano biochar on soil chemical properties.

| Treatments | pH | EC | OM | CEC |
|---|---|---|---|---|
| SCBB0 | 7.6 | $0.9^{d}$ | $0.8^{d}$ | $26.5^{d}$ |
| SCBB0.4 | 7.7 | $1.2^{c}$ | $1.0^{c}$ | $27.1^{bc}$ |
| SCBB 0.6 | 7.8 | $1.4^{b}$ | $1.2^{b}$ | $27.7^{b}$ |
| SCBB 0.8 | 7.9 | $1.6^{a}$ | $1.4^{a}$ | $28.6^{a}$ |
| B Means | 7.8 | $1.3^{b}$ | $1.1^{ac}$ | $27.5^{a}$ |
| SCBN0 | 7.6 | $0.9^{d}$ | $0.8^{d}$ | $26.5^{d}$ |
| SCBN 0.4 | 7.8 | $1.3^{c}$ | $1.0^{c}$ | $27.9^{c}$ |
| SCBN 0.6 | 7.9 | $1.6^{b}$ | $1.1^{b}$ | $28.8^{b}$ |
| SCBN 0.8 | 7.9 | $1.8^{a}$ | $1.2^{a}$ | $29.8^{a}$ |
| N Means | 7.7 | $1.2^{bc}$ | $1.0^{ab}$ | $28.1^{a}$ |
| SCB means | 7.7 | $1.2^{ab}$ | $1.1^{a}$ | $27.8^{a}$ |
| OMWB0 | 7.6 | $0.9^{d}$ | $0.8^{c}$ | $26.5^{d}$ |
| OMWB 0.4 | 7.7 | $1.3^{c}$ | $0.8^{c}$ | $26.6^{c}$ |
| OMWB 0.6 | 7.8 | $1.5^{b}$ | $1.0^{b}$ | $27.2^{b}$ |
| OMWB 0.8 | 7.9 | $1.6^{a}$ | $1.1^{a}$ | $28.1^{a}$ |
| B Means | 7.8 | $1.3^{a}$ | $0.9^{ab}$ | $27.0^{a}$ |
| OMWN0 | 7.6 | $0.9^{d}$ | $0.8^{d}$ | $26.5^{d}$ |
| OMWN 0.4 | 7.7 | $1.5^{c}$ | $0.8^{cd}$ | $27.4^{c}$ |
| OMWN 0.6 | 7.8 | $1.8^{b}$ | $1.0^{b}$ | $28.3^{b}$ |
| OMWN 0.8 | 7.8 | $1.9^{a}$ | $1.4^{a}$ | $29.3^{a}$ |
| N Means | 7.7 | $1.5^{ab}$ | $1.0^{c}$ | $27.6^{c}$ |
| OMWN Means | 7.8 | $1.4^{b}$ | $1.0^{ac}$ | $27.3^{b}$ |
| G Means | 7.7 | $1.3^{a}$ | $1.0^{a}$ | $27.5^{ab}$ |

**Table 8.** Effect of biochar source (SCB and OMW), type (bulk and nano) and application rate on drying. Weight (g.plant$^{-1}$) of maize grown in contaminated soil

| Sources | Rates % | Bulk | Nano | G Means |
|---|---|---|---|---|
| SCB | 0 | 11.23 | 11.53 | 11.38 |
| | 0.4 | 13.00 | 20.33 | 16.67 |
| | 0.6 | 13.67 | 19.50 | 16.59 |
| | 0.8 | 15.07 | 19.00 | 17.04 |
| SCB Means | | 13.24 | 17.59 | 15.42 |
| OMW | 0 | 11.23 | 11.67 | 16.43 |
| | 0.4 | 12.00 | 17.83 | 16.37 |
| | 0.6 | 12.67 | 17.00 | 16.31 |
| | 0.8 | 14.07 | 16.50 | 16.13 |
| OMW Means | | 12.49 | 15.75 | 16.31 |
| G Means | | 12.87 | 16.67 | 15.86 |



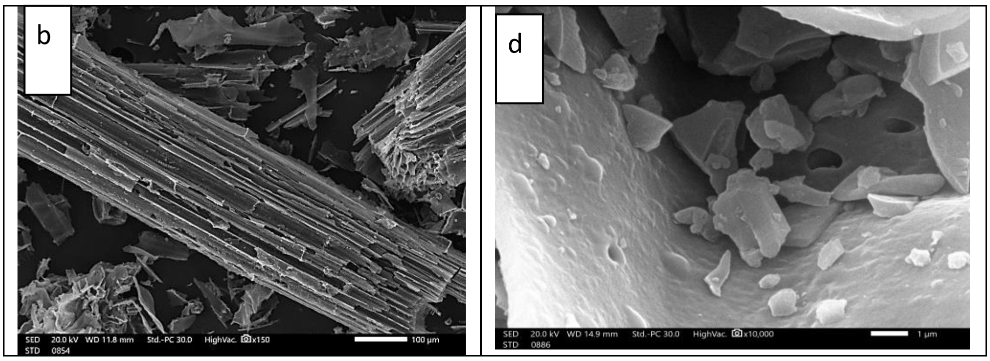


**Figure 1:** SEM images of (a) bulk SCB, (b) nano SCB, (c) bulk OMW, and (d) nano OMW.

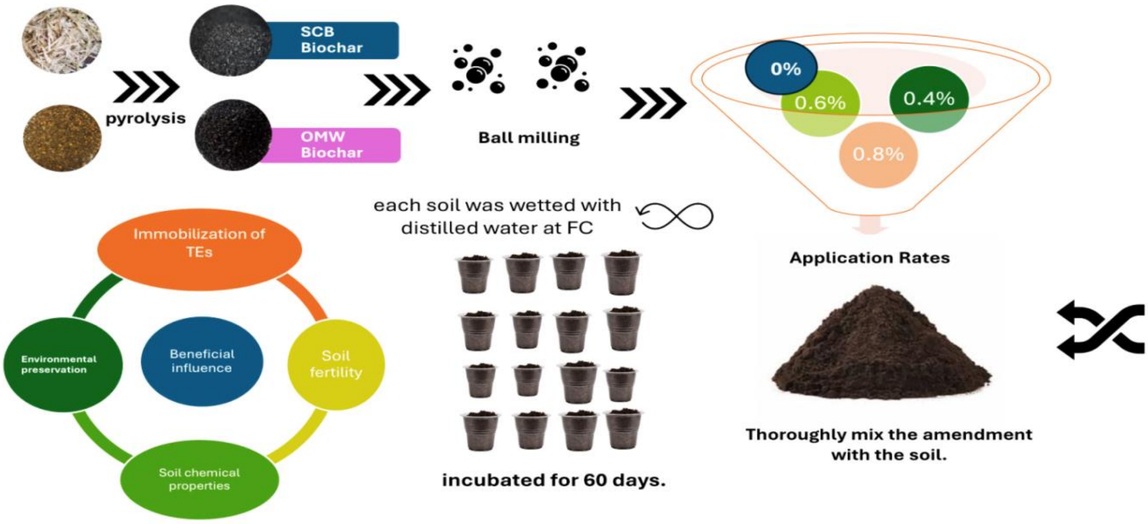


**Figure 2:** Methods and experimental configuration for the biochar treatments.

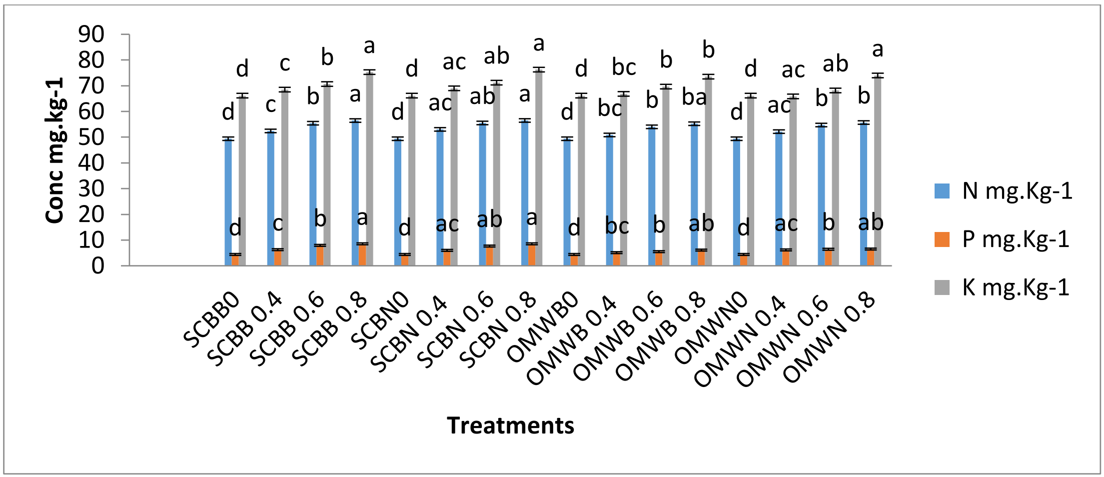


**Figure 3:** Biochar and nanobiochar's effects on the soil available N, P, and K.

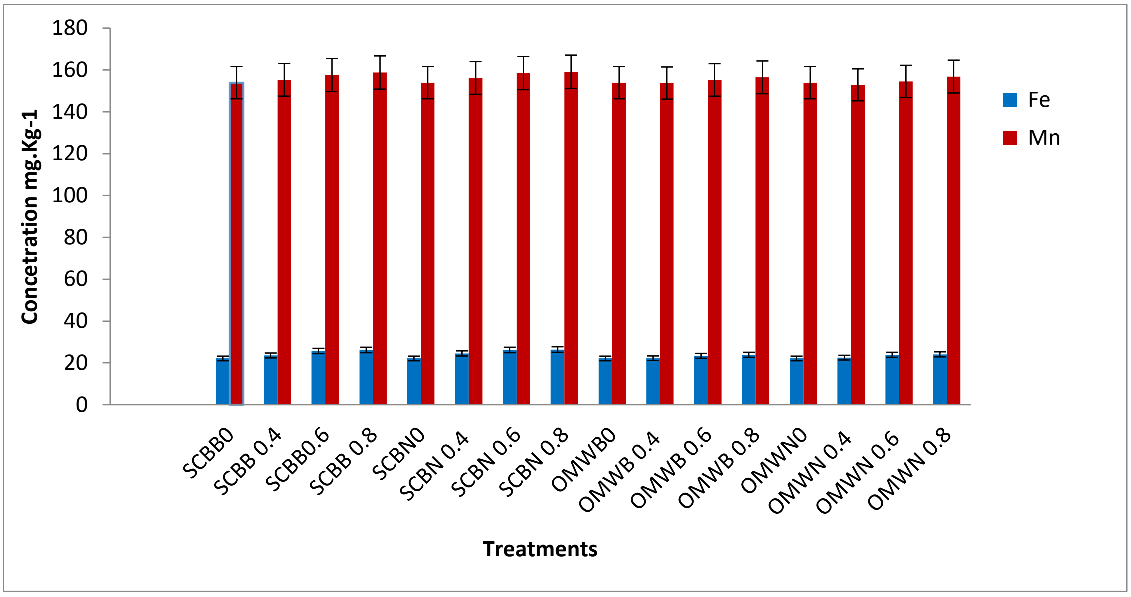


**Figure 4:** Effect of biochar and nanobiochar on available Fe and Mn in the studied soil

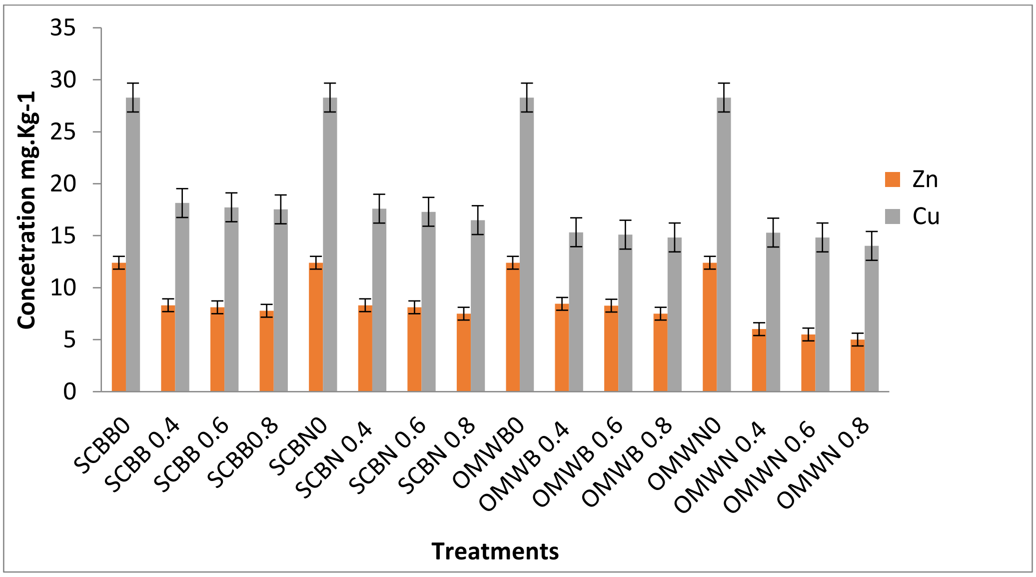


**Figure 5:** Effects of biochar and nanobiochar on available Cu and Zn in the studied soil.

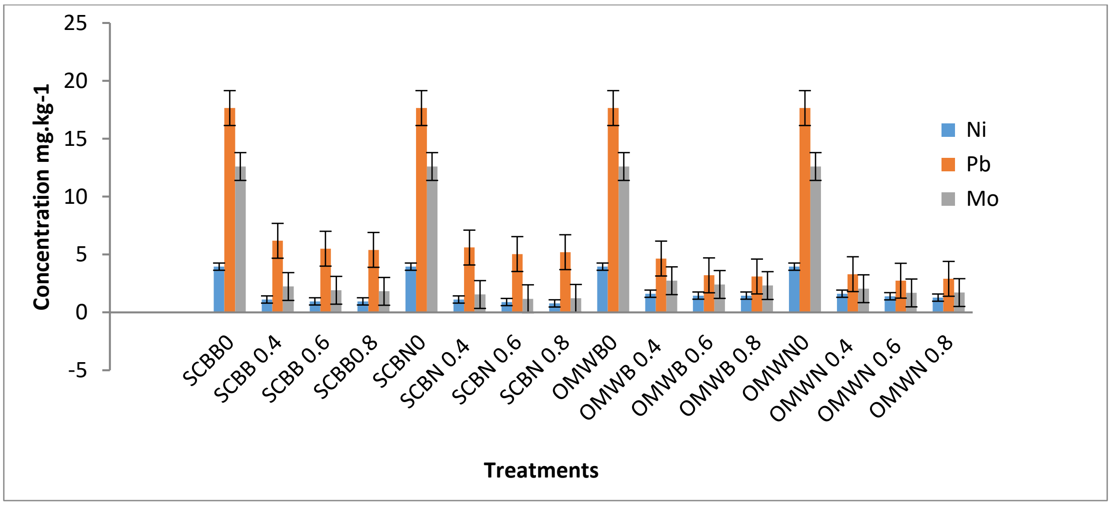


**Figure 6:** Effect of biochar and nanobiochar on available Pb, Ni and Mo in the studied soil.

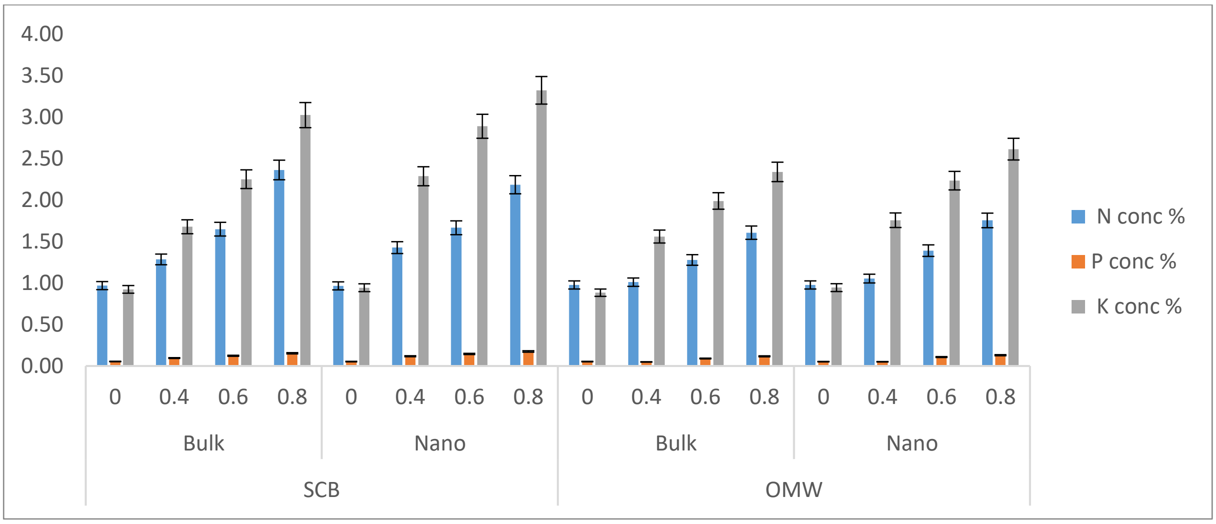


**Figure 7:** Effect of sources, types and application rates of biochar on the NPK content (%) of Zea maize plants

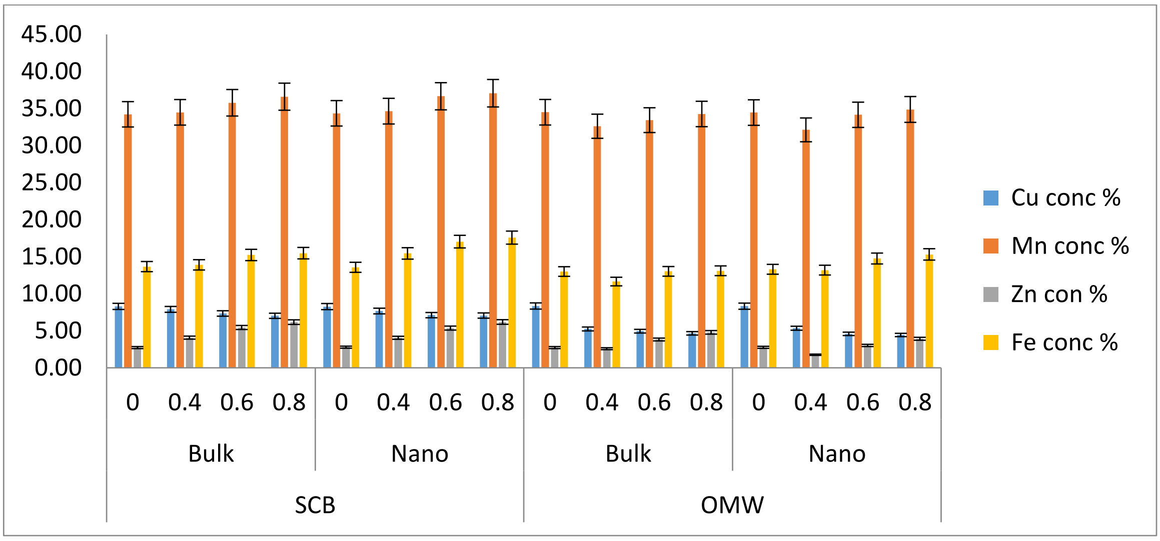


**Figure 8:** Effect of the sources, types and application rates of biochar on the micronutrients Cu, Zn, Mn and Fe mg.kg$^{-1}$”

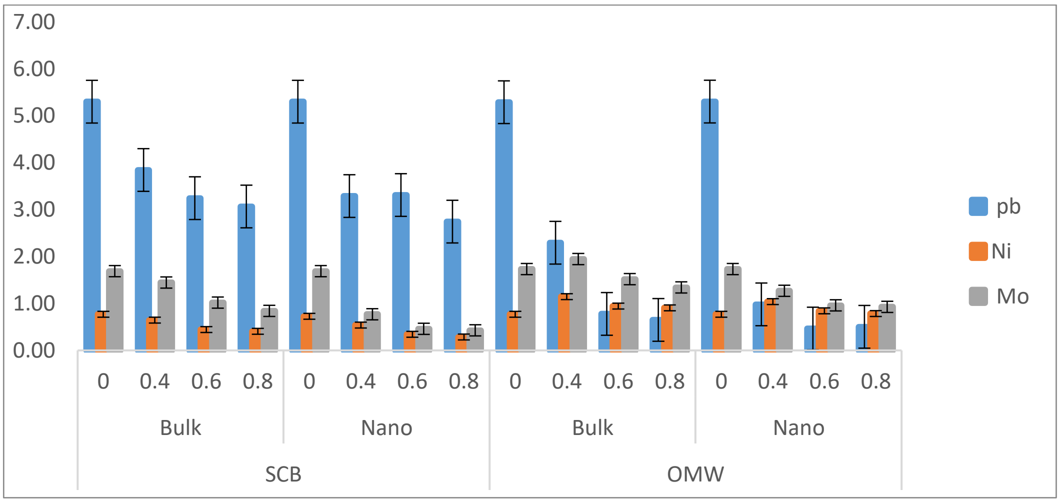


**Figure 9:** Effect of the sources, types and application rates of biochar on the micronutrients Pb, Ni, and Mo in the zea maize plants mg.kg-1”.

# تعزيز صحة التربة ونمو النباتات عن طريق التخفيف من تلوث التربة باستخدام محسنات الفحم الحيوي النانوي

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## الملخص العربي:

ترجع مشكلة تلوث التربة المتصاعدة في مختلف المناطق المصرية في المقام الأول إلى استخدام مياه الري ذات الجودة المنخفضة. ركزت هذه الدراسة على معالجة هذا من خلال استخدام الفحم الحيوي النانوي المشتق من مصاصة قصب السكر ومخلفات تفل الزيتون. وكانت معدلات الإضافة 0%، 0.4%، 0.6%، و0.8% لتقييم فعاليتها في الحد من تلوث التربة. يعد مصاصة قصب السكر بنية نانوية فريدة ذات نشاط تحفيزي عالي، أكثر فعالية من مخلفات تفل الزيتون في التربة ونمو النباتات. بالإضافة إلى ذلك، كان أفضل معدل إضافة عند 0.8٪، لتعزيز خصائص التربة مثل الرقم الهيدروجيني، درجة الأملاح، المادة العضوية و السعة التبادلية الكاتيونية هو 7.7، 1.2 ديسيسيمنز$^{-1}$، 1.1٪ و 28.5 سنتيمول.كجم$^{-1}$، على التوالي.كما قلل الفحم الحيوي النانوى تدريجيًا مستويات العناصر النادرة المستهدفة، مثل النحاس و الزنك و الرصاص والنيكل والموليبدنيم، في التربة بمرور الوقت من 27.3 و12.4 و17.6 و3.9 و12.6 ملجم كجم$^{-1}$ على التوالي إلى 17.5، 7.78، 5.4، 0.95 و 1.82 ملجم كجم$^{-1}$. زادت تركيزات التربة المتاحة من النيتروجين والفوسفور والبوتاسيوم بشكل ملحوظ، كما زاد توافر العناصر النادرة المفيدة مثل الحديد والمنجنيز في التربة. يعمل الفحم الحيوي على تعزيز بنية التربة، والنشاط الميكروبي، والاحتفاظ بالمغذيات، ودورة المغذيات.تتحكم الخصائص السطحية وتفاعلية الفحم النانوي في توافر مغذيات التربة. زادت تركيزات الحديد المتاحة في التربة من 22.11 إلى 26.37 ملجم. كجم$^{-1}$ ,زادت تركيزات المنجنيز من 153.9 إلى 156.17 ملجم كجم$^{-1}$. اعتمادًا على متغيرات التربة والأهداف الزراعية، قد يكون من المفضل استخدام الفحم الحيوي أو الفحم الحيوي النانوي؛ ومع ذلك، فإن كلاهما يوفران مزايا كبيرة لنمو النبات وصحة التربة.

**الكلمات الاسترشادية:** الفحم الحيوي النانوى , صحة التربة , تلوث التربة.