



Production, characterization and application of charcoal on soil nutrients enhancement and remediation of soil toxic metals

Ufuoma Ugbune¹ · Great Iruoghene Edo^{1,2,3} · Jude Oghenenyore Avwenaghegha⁴ · Ufuomaeke Stephen Oghoje⁵

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Abstract

The paper examines the effect of charcoal prepared from oil palm trunks on nutrient enhancement and remediation of toxic metals in contaminated soil. The test soils were obtained from two different waste dump sites in Benin City, using a standard method of sampling. The physicochemical properties and nutrient of test soils and charcoal were investigated. The performance of charcoal on soil physicochemical properties and nutrients was also assessed. The charcoal showed a remarkable pH, EC (electrical conductivity) and nutrient level. The result of control soils of this research revealed that the soil was mostly sandy-clay. The concentration of macro-nutrients in the control soil particularly nitrogen was below the critical level of some crop nutrients, indicating soil nutrient imbalance. Soil amendment with the charcoal revealed an increased in pH, electrical conductivity and nutrients. Toxic metal partitioning studies indicate that the charcoal additives resulted in the redistribution of arsenic, cadmium, and lead from the metal poisonous phase (exchangeable and carbonate phase) to the less poisonous phase (residual phase). The result of toxic metals mobility showed decrease trend as the rate of charcoal added was increased, signifying possible reduction in bioavailability of the toxic metals at a higher concentration of charcoal additive. This implies the reduction of environmental threats and contamination by toxic metals on farmers, microorganisms, and crops. The rate of 40% amendment (application) shows a remarkable reduction (over 90%) of toxic metals and nutrient enhancement. Thus, charcoal has shown to be a green option for nutrient improvement and remediation of toxic metals in contaminated soil.

Keywords Soil · Toxic metal remediation · Charcoal · Nutrients enhancement · Environmental contamination

Introduction

Soil is regarded as an important natural resource which supplies the essential mineral elements needed for plant growth and crops productivity. Soil quality is generally known as one of the vital ingredients for sustainable agriculture and

global food sufficiency. Hence soil quality plays an important factor in deciding healthy soil that could provide enough nutrients for both plant and soil micro-organisms. It is not just having nutrients present in the soil as mineral elements, it also hinges on access to those nutrients (M. Tahat, M. Alananbeh, A. Othman, & I. Leskovar, 2020). Macronutrients and micronutrients can be locked away from plant and soil micro-organisms because of different soil physical, chemical and biological properties that influence accessibility and availability of soil nutrients. These properties include moisture content, conductivity, porosity, pH, temperature, and competitive demand by microorganisms (Bhattacharyya & Furtak 2022). There are essential (mineral) nutrients plant required in order to grow healthy. These nutrients dissolved in soil water and are assimilated by plants through their plant roots. They are not always sufficient of these nutrients in the soil for plant to grow properly (Jacoby, Peukert, Succuro, Koprivova, & Kopriva, 2017). These mineral nutrients are classified into two groups, macro-nutrients and micro-nutrients. Macro-nutrients are nitrogen, phosphorus,

✉ Great Iruoghene Edo
greatiruo@gmail.com

¹ Department of Chemistry, Faculty of Science, Delta State University of Science and Technology, Ozoro, Nigeria

² Department of Petroleum Chemistry, Faculty of Science, Delta State University of Science and Technology, Ozoro, Nigeria

³ Department of Chemistry, College of Sciences, Al-Nahrain University, Baghdad, Iraq

⁴ Department of Physics, Faculty of Science, Delta State University of Science and Technology, Ozoro, Nigeria

⁵ Department of Chemistry, Faculty of Science, Delta State University, Abraka, Nigeria

potassium, calcium, magnesium, and sulphur e.t.c. Previous reports have shown that these nutrients are generally deficient in soils because plants utilize large amounts of them for their growth survival and food production (Huntley 2023). Micro-nutrients are also required for plants and biochemical metabolism for growth but they are needed in only small (micro) amount (S. Kumar, Kumar, & Mohapatra, 2021a, 2021b). These nutrients or elements are sometimes referred to as minor elements or trace elements. Example of micro-nutrients are copper, manganese, zinc, nickel, iron, and carbon (Bhattacharya et al. 2016). Other elements or metals present in soil are the toxic metals such as lead, cadmium, arsenic, mercury e.t.c., which are directly introduced into soils through due to human activities and could be poisonous even at low concentrations (Zhao et al. 2022). Toxic metals cannot not be biodegraded and could maintain ecological circle in soils (Dixit et al. 2015). Toxic metals contamination can have different consequences such as damage of ecosystem, reduction of agricultural productivity, loss of ground water resources quality and threat to human and animal health (Mitra et al. 2022). Many studies have documented that wastes dump is a source of toxic metals and nutrients in soil. The study by Alengebawy et al., (2021) in India found alarming concentration of lead and cadmium contamination in soil, exceeding safe limits by 5 times for lead and 11 times for cadmium. In the same vein, Onakpa et al., (2018) also proclaimed the accumulation of some toxic metals in crops grown within waste dumpsites environment in Benin City, Nigeria.

In African and some other places in the world smallholder farmers use wastes dumpsites for crops cultivation without remediation or nutrient enhancement (Agbeshie et al. 2020). Toxic metals in these soils need remediation for adequate soil restoration. In situ remediation (immobilization) have demonstrated to be low cost option for efficient remediation for toxic metals in contaminated soils and, may provide long term remediation result through the establishment of stable minerals complexes (Agbeshie et al. 2020). This procedure is aimed at limiting the toxic metals solubility and bioavailability without getting rid of them from contaminated soils (Kapahi & Sachdeva 2019). It is a protocol that employs the additive of chemical (amendments, additives or chemical immobilizing/stabilizing agents) to contaminated soil in order to immobilize/ limit the available partition of the toxic metals in soil (Raffa et al. 2021). Incorporating non charcoal immobilizing agents such as cow bone, and phosphate rock to soil polluted with toxic metals have been reported to decreased the level of metals to 13.7% and 10.3% respectively (Liang et al. 2014). Thus, these non charcoal immobilizing agent can cause secondary pollutants such contamination of ground water through leaching. However, stabilizing / immobilizing and, nutrient enrichment agent like charcoal that is carbonized between 450– 700 °C could

be better option in addressing this gap (Edo et al. 2024a, b, c).

Physical, chemical and biological properties of charcoal are different from uncharred biomass in soil and are known to undergo modification over time as a result of weathering processes, reaction with others oil mineral and microorganism's interaction (Hardy & Dufey 2017). Charcoal is unique in soil environment due to its unique physical (Edo et al. 2024a, b, c), chemical and, biological properties and the nature of their contact with soil and plant population (Edo et al. 2024a, b, c). Many benefits emanate from the physical properties of charcoal (Ogheneoruese et al., 2022). Array of pore sizes within the charcoal feedstock results in a wide surface area and low bulk density (Edo et al. 2024a, b, c). Charcoal addition can change the soil physical properties, this include the structure, density, and pore size distribution (Ugbune et al. 2024), with significant implications for soil workability, aeration, water holding capacity and plant growth (Samuel et al. 2023). It has been documented that charcoal amendment to soil may multiply the overall net soil surface area and, the attendant effects include the increase in soil water holding capacity, nutrient retention and soil aeration, especially in fine-texture soils. Charcoal has a bulk density much lower than that of mineral soils, therefore, application of charcoal to soil could decrease the overall total bulk density of the soil which is generally beneficial for plant growth (Gao et al. 2020). Charcoal composed of some mineral matter (ash) and, surface charge at a reduced pH values (Tomczyk et al. 2020). These properties make charcoal capable of withhold certain nutrients, (potassium, calcium, magnesium etc.). The neutralizing influence of charcoal could also improve nutrients availability in soil close to plant roots (rhizosphere). This is visible when charcoal interacts with the growing plant (Mastrolonardo et al. 2019). The pore volume of charcoal can be affected by the way it is processed. Therefore charcoals do not have negative effects on nutrient cycling in the soil environment (Adeyemo et al. 2023). Charcoal can withhold some nutrients, this hinders nutrients from being transported to the aquifer in soil environment (Schoonover & Crim 2015). This could decrease the amount of fertilizer required to achieve maximum agricultural benefits. The charred biomass can decontaminates soil water by absorbing toxic compounds that prevent microbial growth. Charcoal prepared at a lower temperature have a high a cation exchange capacity, while those prepared at a higher temperature have reduced or no exchange capacity (Roshan et al. 2023). This implies that charcoal for soil application should not be prepared at high temperature (Qurat-ul-Ain et al. 2021). Charcoals used for soil amendment are usually alkaline in nature. Therefore, their application would normally raise soil pH and could also correct the pH of acidic soils for optimal crops production. The pH of charcoal is mostly in the range 4 to 12 depending

on the biomass used and the pyrolysis temperature (Hamidi et al. 2021a). This implies that effect of charcoal addition to soil could modify its pH, increase nutrients level and carbon storage of the soil as well as filtration of moving soil water (Tsolis & Barouchas 2023). Research has shown that charcoal incorporation to soil may be more necessary as it can improve soil organic carbon, increase bioavailability plant nutrients and thereby improve plant growth, physical, chemical and biological properties of soil (Singh Yadav et al. 2023). Charcoal enhances the soil texture and ecology, improve its ability to hold fertilizer and released them at a slow rate. Charcoal biomass has been considered to be better than other organic manure in terms of nutrients composition and its sterility at higher temperature (Samoraj et al. 2022).

Charcoal has greater capacity for metals adsorption, hence it could limit metals transports in contaminated soil (Golia et al. 2022). However, the reaction between charcoal and, metals is pH dependent (Golia et al. 2022). The mechanism of metal removal with charcoal treatment may be attributed to the electrostatic interactions, precipitation and other reactions (Wang et al. 2023). The introduction of charcoal to soil increases soil surface negative charge, it would limit the zeta factors thereby improving the attraction the positive charge metals and soils (Ramezanzadeh et al. 2023). Raising soil pH due to charcoal treatment may lead to decrease in metal transport in soil and improvement on soil health. The objectives study are to: (1) determination of the nutrient levels of waste dump soils (2) determination of selected physiochemical properties and toxic metals levels in the wastes dump soil (3) evaluation of efficiency of charcoal on nutrients and toxic metals bioavailability.

Materials and methods

Soil sampling, charcoal production and experimental design

Composite soil samples were obtained from two wastes dump sites after a careful removal of the surface debris. The samples were dried at ambient laboratory temperature (28 °C), sieved through a 2 mm mesh and were preserved in polythene bag and properly labeled for characterization and further treatment with the charcoal.

Oil palm trunks were collected from oil palm plantation in Mosogar, Nigeria. The oil palm trunks were dried and carbonized at 550 °C temperature (Edo et al. 2022). The carbonized oil palm trunks (charcoal) was allowed to cool overnight (Edo et al. 2022), crushed and passed through 2 mm mesh. Nutrients level of charcoal was determined using standard methods (Edo et al. 2022), and metal content was determined using AAS (VGP, 2010 model).

A kilogram (1 kg) of the thoroughly mixed air dried soils containing 0, 10, 20, 30 and 40% of the pulverized charcoal and were placed in 5 plastic pots for each sites soil. They samples were mixed thoroughly and arranged in green house within the laboratory environment using randomized complete block design (RCBD) and the soil were stirred two times a weeks for stabilization while maintaining the water holding capacity at 50% of field capacity prior characterization.

Determination of physico-chemical properties of soil and charcoal

The samples pH were measure using Black method (Gessesse & Khamzina 2018). Electrical conductivity was assessed following Hergenrather method (Hergenrather 2009). The hydrometer method as describe by de la Peña, et al., (2022) was used for particle sizes distribution. Method of Hergenrather, (2009) was used to evaluate the organic carbon content. An analytical method as prescribed by Van-Waardhuizen, (2022) was used to determine CEC. The level of phosphorus was obtained using the Olsen method (Tóth et al. 2014). Nitrogen content was determined by Amanullah et al., (2020) method. Toxic metals were evaluated using sequential extraction protocols in order to assess the level of toxic metals in the following operational phase (fractions). These forms are exchangeable, carbonate-bond, Fe–Mn oxide, organic/ sulphide, and residual fraction. The details procedure has been described (Al-Mur 2020). The concentration of macro-nutrients and toxic metals were determined using atomic absorption spectrometer (Buck Scientific VGP 210, USAs).

Determination of bioavailability/ mobility of toxic metals in soil

Toxic metals bioavailability in soil was determined using mobility factor, MF (Otabor 2019).

$$MF = \frac{F1 + F2 + F3}{F1 + F2 + F3 + F4 + F5} \times \frac{100}{1} \quad (1)$$

where F1–F5 = percentage of geochemical forms toxic metal.

Determination of environmental risk factor (ERF) of toxic metals

In order to confirm the potential threat of toxic metals to soil organisms, environmental risk factor (ERF) was adopted (Robert et al. 2015).

$$ERF = CSQV - C_i/CSQV \quad (2)$$



where CSQV = Concentration of soil quality value (toxic metal concentration in fifth partition of soil which is equivalent to the background/pre-industrial concentration).

Ci = Toxic metal concentration in the first four partitions of soil.

It is pertinent to note that when $ERF < 0$, it implies that there is potential threat to soil organisms; the reverse is the case when $ERF > 0$ = no potential threat to soil organisms recorded.

Determination of contamination factor (CF) for soil

The contamination factor (CF) was determined as;

$$CF = \frac{\text{Toxic metal concentration in soil}}{\text{Background concentration of Toxic metal in soil}} \quad (3)$$

(Alengebawy et al. 2021).

It is important to note that when $CF > 1$, it indicates that the soil is contaminated by a given toxic metal. Further, if $CF < 1$, $1 < CF < 3$, $3 < CF < 6$ and $CF > 6$ is an indication of zero, moderate, considerable and high contamination by a toxic metal respectively.

Quality assurance and data processing

All chemical used for sample extraction and chemicals analysis were of analytical grade. Standard procedures and methods were employed in soil sampling and in the laboratory analyses to ensure quality and reliable results for the study. Averaging of triplicate data were done. Anova was used to examine the statistical significant difference between control sample and treated samples. Required calculation were made using standard equations while data presentation were done using relevant tables and, statistical bar charts and, graph.

Results

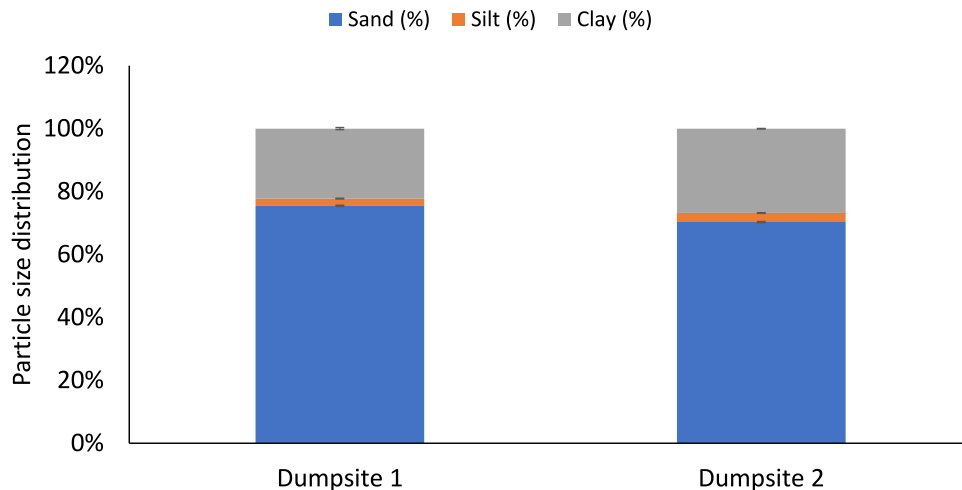
The results of soil texture from the two different wastes dumpsite sites are presented in Fig. 1

The results revealed Soil texture of sample collected from wastes dumpsites revealed that the soil is predominantly sandy loam. With the order of, sand > clay > silt. The amount of organic matter in the soils was quite significant.

Physical properties of oil palm trunks charcoal

The result of the ash content of charcoal revealed $6.63 \pm 0.08\%$, the ash of charcoal include inorganic constituents (calcium, magnesium and inorganic carbonates). The ash content the charcoal used in this study is greater than woody charcoal earlier reported (less than 4% (Rocchi et al. 2023)). The higher ash content could be connected to the nature of the feedstock and, the carbonization temperature. Introduction of materials with higher ash content into nutrients deficient and poisonous metals soils have been documented by many researchers to increased macro-nutrients and poisonous metals complexation due to increase in soil pH (Adamczyk-Szabela & Wolf 2022). The result of moisture content of charcoal shows $23.40 \pm 0.24\%$, this value is higher than woody charcoal earlier documented (Haider et al. 2022). Higher moisture content of charcoal is an indication of large pore size of charcoal (Schneider et al. 2020), large pore size of charcoal aid in the adsorption of metals (Ilomuanya et al. 2017). The physicochemical properties charcoal suggest that charcoal is advantageous in soil remediation and, nutrients enhancement. Similar studies have shown that inclusion of biomass to soil can immobilize soil pollutants including toxic metals (Kozioł et al. 2024). Besides, soil organic matter (SOM) is a key enhancer of soil

Fig. 1 Soil texture of wastes dump soil



moisture, a vital condition for soil microorganism growth and diversities (G. Wang et al. 2022) (Fig. 2).

Effect of charcoal application on soil pH, electrical conductivity and cation exchange capacity

Generally, pH is one of the physicochemical properties which affect the presence, retention, transport of nutrients and heavy metals in soil. Several micro-organisms are active at moderate pH (Yan et al. 2023). The most conducive pH range for of many plant growth and productivity was between 5.5 to 7.0, though many plants have adjusted to thrive at pH value outside this range (Penn & Camberato 2019). Soil pH in this study was found to be 7.01 ± 0.01 (waste dump site 1) and 7.32 ± 0.02 (wastes dumpsite 2), suggesting slightly alkaline. It has been documented that alkalinity controls the availability of essential nutrients and immobility of non-nutrients in soil (Alkharabsheh et al. 2021). At high pH, none essential nutrients

are adsorbed on the clay colloids and not available for plant uptake (Neina 2019).

In this study, soil treated with 40% charcoal was observed to have the highest pH value while the lowest value were found in soil amended with 5% (Fig. 3). The rise in pH after charcoal application could be attributed to the release of free bases such as potassium ion, calcium ion and magnesium into the soil solution by ash of charcoal thereby increasing the pH status of the soil and readily providing available nutrients for plant usage (Oni et al. 2019). This implies that, charcoal could be function as liming substance. Protonation of oxygen containing functional groups of charcoal feedstock could be the main mechanisms for the increase of soil pH after carbonized feedstock application (Nkoh et al. 2021). Soil texture may also contribute to in the increase of soil pH. Sultan et al. (Sultan et al. 2020) reported a greater increase in pH in sandy and loamy soils than in clayed soils with charcoal application. Since wastes dumpsite soil in this study was

Fig. 2 Physicochemical properties of charcoal, soil and the rate of amendments for site 1

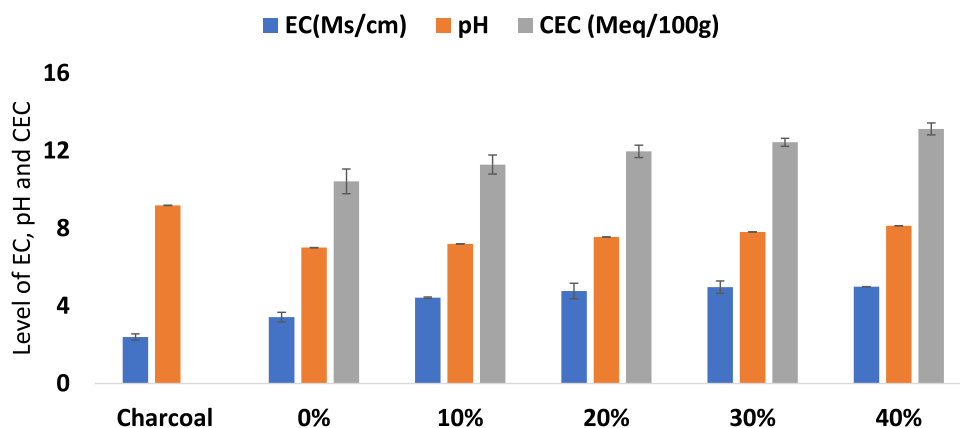
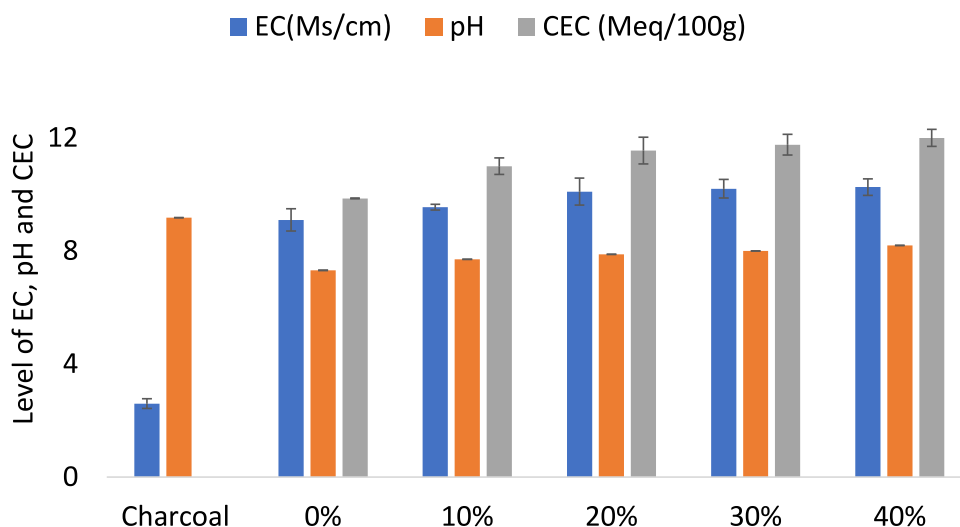


Fig. 3 Physicochemical properties of charcoal, soil and the rate of amendments for site 2



mostly sandy loamy, the level of pH might be attributed to the soil texture.

Electrical conductivity (EC) is the concentration of ions from water-soluble salts in soils and it is an indication of the ability of an aqueous solution to carry an electric current. The electrical conductivity of the wastes dumpsite soil, unamended soil is 3.43 ± 0.24 ms/cm (waste dumpsite 1) and 9.10 ± 0.34 ms/cm (waste dumpsite 2), this is an indication of moderate EC. The moderate EC is an indication that alkaline metal ions were present in the soil.

The EC result shows a gradual increase as the rate of charcoal application increases from 5 to 40% (Fig. 3). This increase may be due to the liming property associated with carbonates salts present in ash components of charcoal which change EC level of the soil.

Cation exchange capacity (CEC) of soils can be described as extent of how well some nutrients (cations) are bound to the soil. CEC is predominantly dependent upon soil texture and organic matter content. However, the greater the clay and organic matter in the soil the greater the CEC (Jeon et al. 2023). CEC maintain adequate quantities of available plant calcium ion, magnesium ion and potassium ion in soil. CEC in addition with total organic carbon and soil texture are among several components of soil that affect availability and transport of metals with increase in pH, CEC is a key properties of soil quality and fertility. The soil (control) CEC was 10.43 ± 0.60 Meq/100 g and 9.80 ± 0.01 Meq/100 g for waste dumpsite 1 and waste dumpsite 2 respectively. CEC of the control soil is within the range of waste dump soil (Oluwatuyi et al. 2020). The CEC level in the control soil (i.e.0% charcoal application) buttressed the presence of organic matter in the wastes dumpsites soils.

Charcoal application to wastes dumpsite soils gave a higher CEC result compared with that of the control (0%) (Fig. 3) Soil amended with charcoal gave a higher CEC values which gradually increased as charcoal amendment rate increases (Fig. 3). Thus charcoal improved the nutrient holding capacity of the soil. The increase in CEC may be due to rapid oxidation of the charcoal surfaces and absorption of organic acids by the charcoal, resulting to rise in negative charges on the soil surface.

Earlier work of Yang et al., (2019) proved that there were development of carboxylic—C and aromatic hydroxyl functional groups in charcoal surface during oxidation. This might also add to increase in soil CEC. The improvement of soil CEC in the presence of charcoal was in line with the report of Yang et al., (2019), which reported highest level of CEC in carbonized feedstock treated soil.

Effect of charcoal application on macro and micro-nutrients of soil

Many researchers have revealed that wastes dumpsites soil contains soil macro- nutrients greater than the surrounding

soil as a result of the presence of household and industrial wastes at the dumpsites (Asare & Száková, 2023). The levels of carbon content in the soils were 3.39 ± 0.04 and $3.21 \pm 0.05\%$ dumpsites 1 and 2 respectively. The presence of organic carbon in the soil could be attributed to the decay of organic wastes in the soils. For nitrogen, the values were 0.21 ± 0.00 and $0.26 \pm 0.04\%$ for the dumpsite 1 and 2 respectively. The level of nitrogen in the soils was below the critical nutrient level of 3.00% for agricultural soils (Mng'ong'o et al. 2021).

Phosphorus content in the soils was 100.43 ± 5.75 ppm and 73.41 ± 1.50 ppm dumpsites 1 and 2 respectively. The higher value of phosphorus is desirable because plant need them in higher quantity. The level of potassium, calcium, magnesium, sodium at dumpsite 1 was 0.23 ± 0.04 meq/100 g, 7.24 ± 0.06 meq/100 g, 2.72 ± 0.55 meq/100 g, 0.11 ± 0.00 meq/100 g respectively. While level of potassium, calcium, magnesium, sodium for dumpsite 2 is 0.37 ± 0.01 meq/100 g, 7.20 ± 0.06 meq/100 g, 2.48 ± 0.08 meq/100 g and, 0.11 ± 0.00 meq/100 g respectively.

Thus, the soils are rich in macro-nutrient except nitrogen. The low level of nitrogen in the soils may be due to the emission of nitrogen in the form of nitrous oxide from the soils. While higher levels of the other macro-nutrients in the dumpsite soils may be attributed to the decomposition of domestic wastes in the dumpsite.

Charcoal has an impact on soil macro- nutrients availability in two ways, nutrients addition and nutrient holding (Hamidi et al. 2021b). The results (Fig. 4 and Fig. 5) revealed that application of charcoal at different amendment rate (0%,10%, 20% and 40%) lead to increase in the available macronutrients, revealing a significant difference ($p < 0.05$) between control soil and treated. The concentration of organic carbon increased gradually as the rate of charcoal increased. Charcoal also improved soil nitrogen, therefore enhances the nitrogen concentration of the soils (Fig. 4 and Fig. 5).

The rise in soil nitrogen after treatment may be ascribed to the presence of nitrogen in the charcoal, while that of organic carbon is due to the numerous amount of carbon-organic in charcoal. These findings is in line with the study of Orozco-Ortiz et al., (2021) who reported higher concentration of carbon and nitrogen at the ancient tera preta compared with adjacent soils. The level of available phosphorus of the soils also improved as the rate of charcoal application increased. Concentration of phosphorus, Potassium, calcium, magnesium and sodium also gave higher values after application of the charcoal (Fig. 4 and Fig. 5). This could be attributed to the presence of the mineral elements found in ash of the charcoal. The ash content of charcoal feedstock helps in the rapid release of the occluded macro-nutrient like phosphorus, calcium, nitrogen, magnesium and

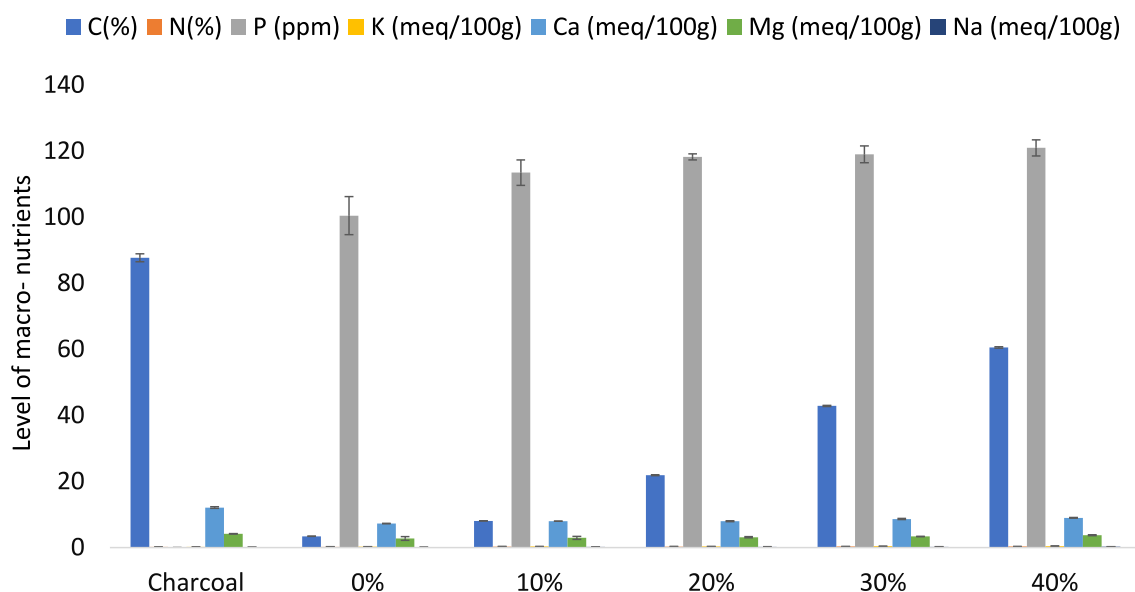


Fig. 4 Macro-nutrient level of charcoal, soil and the rate of amendments for site 1

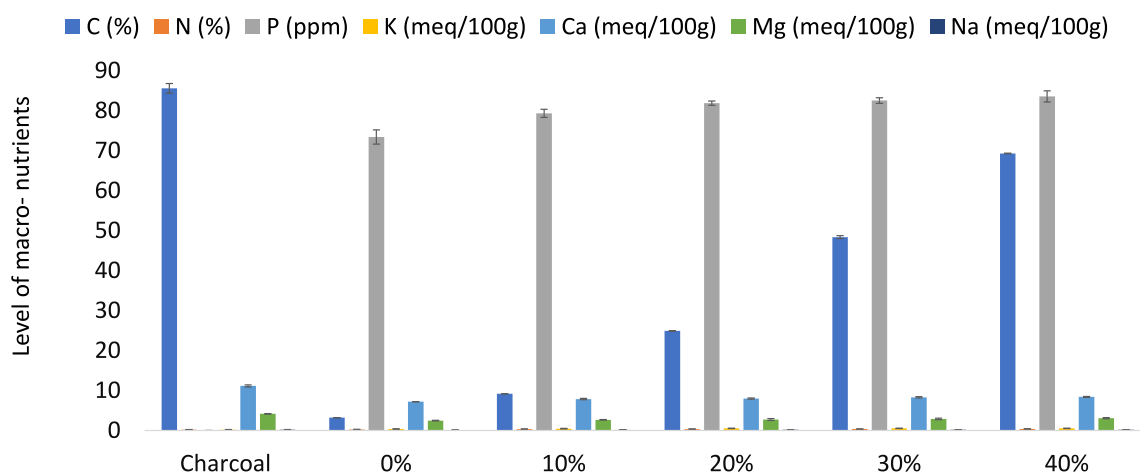


Fig. 5 Macro-nutrient level of charcoal, soil and the rate of amendments for site 2

sodium into soil solution for plant utilization (Hamidi et al. 2021a). Charcoal application also affect nutrient availability by changing soil pH, since charcoal typically has higher pH than soil, it can function as a liming agent resulting in overall increases in pH. Higher soil pH increases nutrients availability and reduces the proportion of aluminum and hydrogen ions occupying cation exchange site.

Zinc, copper, manganese are micro-nutrient that plant need in little quantity, micro- nutrients concentration of the control soil follow the order: $Zn > Cu > Mn > .$ The availability of these metals in the soil may be connected to the presence of industrial and, medical wastes in the

wastes dumpsites. Addition of charcoal to soils could improve the micro-nutrients levels of soils compared to control soil. In this study, application of 40% charcoal gave the highest concentration while the lowest was observed in 10% rate treatment (Fig. 6 and Fig. 7). This improvement of micro-nutrients in the soil is due to the presence of Zn, Cu, Mn and Cr in the charcoal feedstock. This observation is in line with previous work of Paramisparam et al., (2021), which reported that ash of carbonized feedstock contains micro-nutrients for crop utilization. However, the micro-nutrients levels of the soils after charcoal application is within the permissible level for agricultural soils.



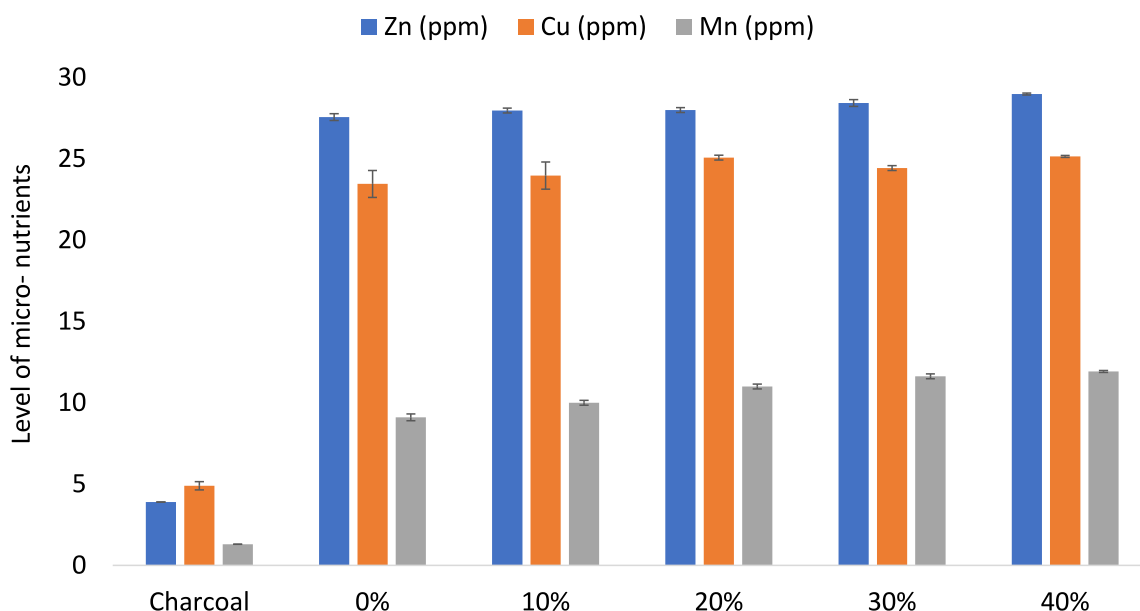


Fig. 6 Effect of charcoal application on micro-nutrients of waste dump soil for site 1

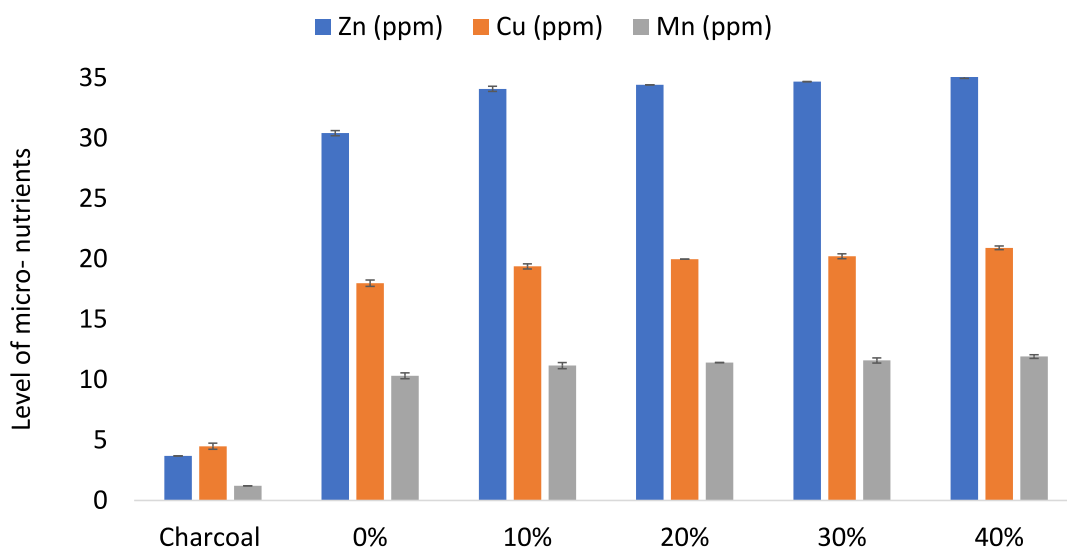


Fig. 7 Effect of charcoal application on micro-nutrients of waste dump soil for site 2

Effect of charcoal on toxic metal soil fractionation, concentration and mobility

The behavior of toxic metals in soils depend on the concentration of toxic metals and the forms of the metals. Partitioning of metals in soils is a useful key to understand the chemistry of these toxic metals (Ugbune et al. 2023). Toxic metal partitioning studies indicated the charcoal application led to the redistribution of amount arsenic, cadmium and lead in the metal poisonous phase (exchangeable and carbonate phase) to less poisonous phase (residual phase).

This distribution pattern could be attributed to charcoal tendency of increasing the soils pH (Fig. 2 and Fig. 3) thus facilitating the precipitation and complexation of toxic metals. The residual phase of toxic metals is known to be less reactive and most stable and less bioavailable since is constituted into the crystal lattice of clay minerals and silicate, therefore not freely released into soil solution (Li et al. 2022).

This results is identical with the work of (Wyszkowski et al. 2022), which revealed that when soil pH was altered due to carbon feedstock application, metals were reduced in

the exchangeable and carbonate form. Previous research of Paramisparam et al.(Wyszkowski et al. 2022), proposed that change of exchangeable partition to low available organic partition through complexation reaction can be added to the significant reduction of extractable toxic metal in charcoal treated soil. Toxic metals adsorption in this fraction could depress arsenic, cadmium and lead in exchangeable pool leading to reduction in the bioavailable and transport of toxic metals in the studied soils (Figs. 8, 9, 10, 11, 12 and 13). According to Devi & Bhattacharyya, (2018), the first two partitions (exchangeable and Carbonate) is highly mobile and bioavailable.

The effect of charcoal application on metals concentrations is depicted on Fig. 14. The result showed that the concentration of cadmium at dumpsite soils were above the permissible level of 3 mg/kg for agricultural soils (FAO/WHO, 2001, USEPA, 2002).

However, on application of 40% charcoal, the concentration of the cadmium was reduced from 5.1 mg/kg to 2.36 mg/kg (40% application). Charcoal also decrease the concentration of arsenic and lead as the rate of charcoal increases from 10 to 40% (Fig. 14), Showing a significant difference ($p < 0.05$) between control soil and treated soil across all study toxic metals Toxic metal reduction in this

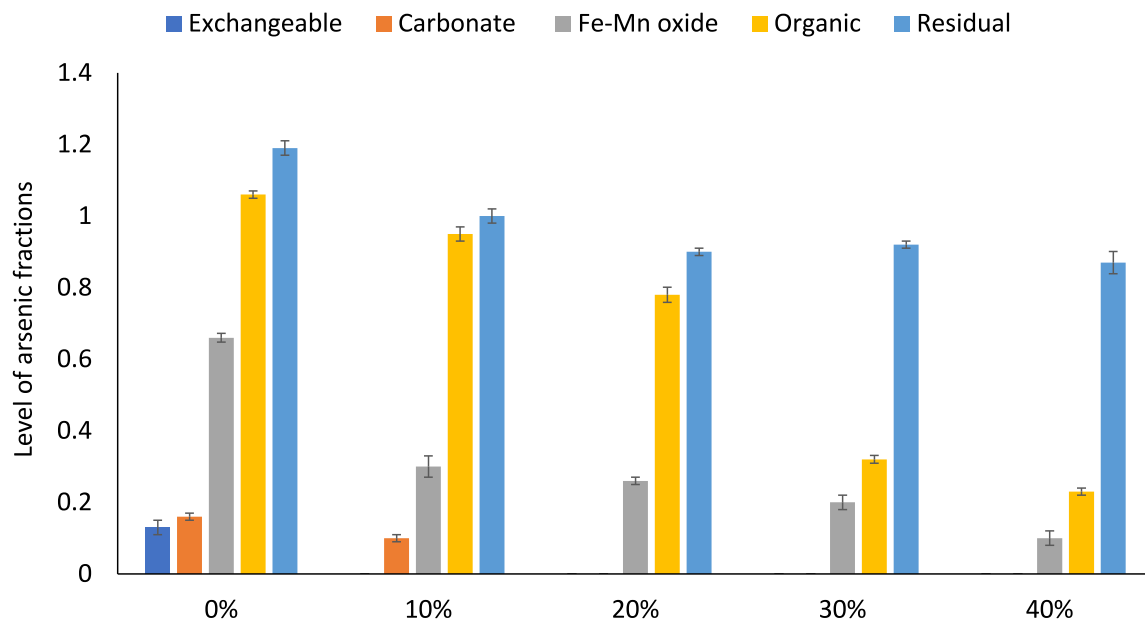


Fig. 8 Effect of charcoal on arsenic fractionation on waste dump soil for site 1

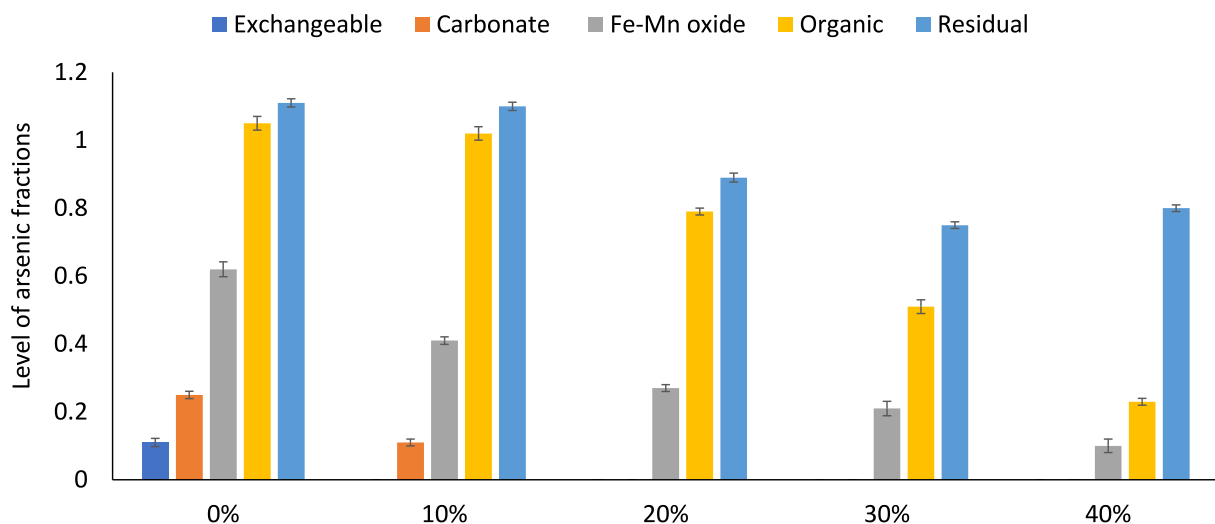


Fig. 9 Effect of Charcoal on Arsenic Fractionation on Waste Dump Soil for Site 2



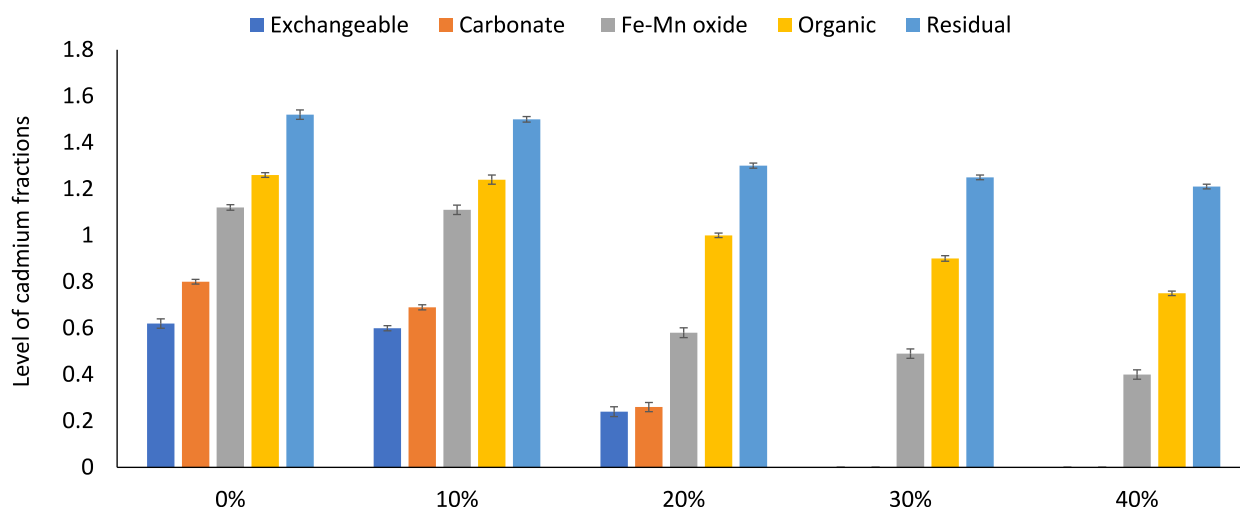


Fig. 10 Effect of charcoal on cadmium fractionation on waste dump soil for site 1

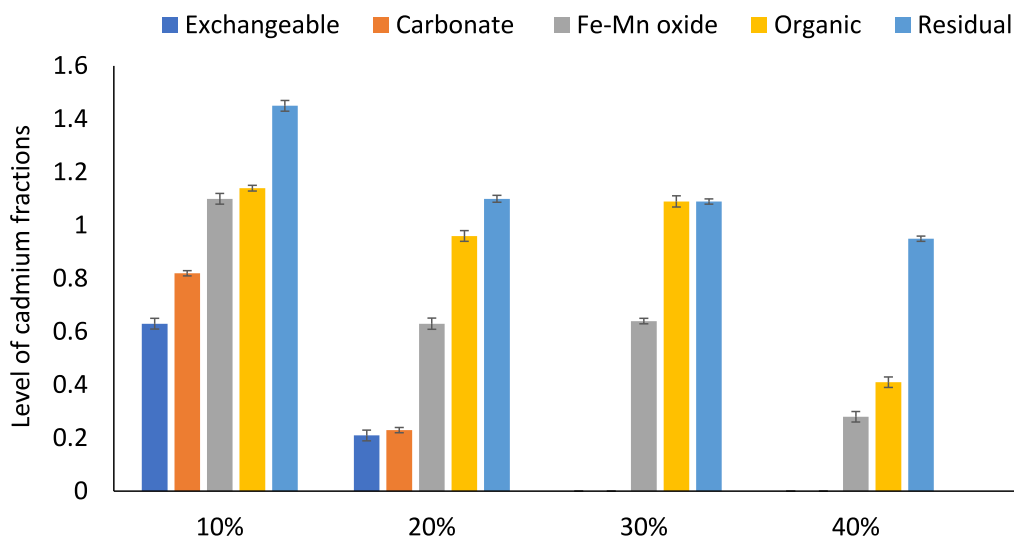


Fig. 11 Effect of charcoal on cadmium fractionation on waste dump soil for site 2

study is 1.5 fold higher than the result earlier reported by (Adeyemo et al. 2017) in toxic metal soils treated with manure. This reduction is due to the interaction between toxic metals and charcoal, electrostatic attraction and metals ion exchange (Kumar et al. 2021a, b). The porous nature of charcoal is also an important factor that aid the fixation of the toxic (Zellner et al. 2019). The Adsorption of toxic metal on the negative site of charcoal also an important reaction in the soil solution that help in toxic metal reduction (Dwiew-juah et al. 2020).

Other mechanism of charcoal reduction activities of toxic metals in soil is by dissolution- precipitation of mineral constituents (Chen et al. 2023). Increase in soil pH by ash of charcoal is also mechanism that lead to toxic metals

reduction, this mechanism speed up the reaction of toxic metals ions with -OH , PO_4^{3-} , CO_3^{2-} to form hydroxide, carbonate or phosphate precipitation which effectively solidify the toxic metal pollutants.

In the same vein, complexation reaction of toxic metals with charcoal in soil environment is also important reaction that assist in the reduction of toxic metals, this is an indication that the study metals react with the hydroxyl functional group and carbonate of charcoal to formed metal complexes, such as metal hydroxyl carbonate, $[\text{Mx}(\text{OH})_g(\text{CO}_3)_x]$. Numerous studies have demonstrated that the reaction of toxic metal ions with oxygenic functional groups like carboxyl group (-COOH), amino- group (-NH_2), and hydroxyl group (-OH) on charcoal surface make great contributions

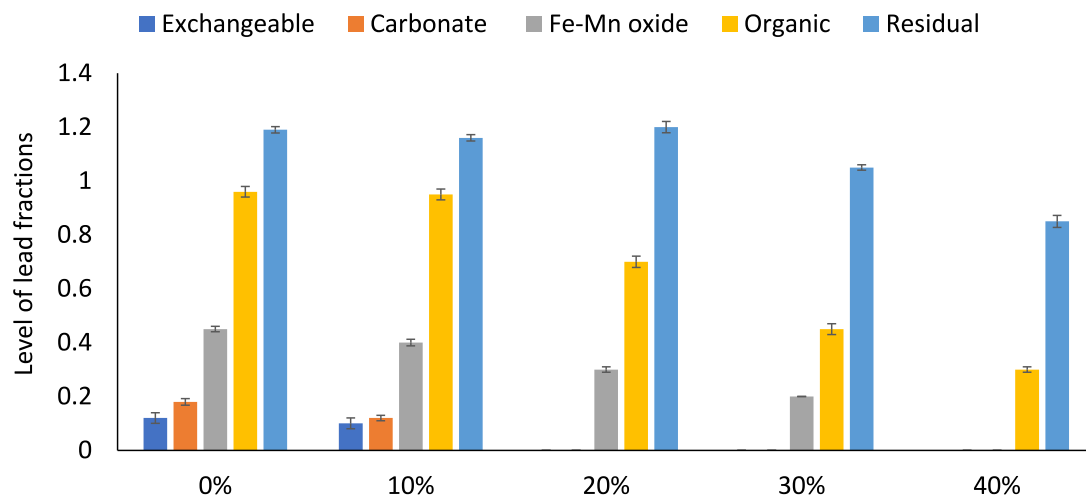
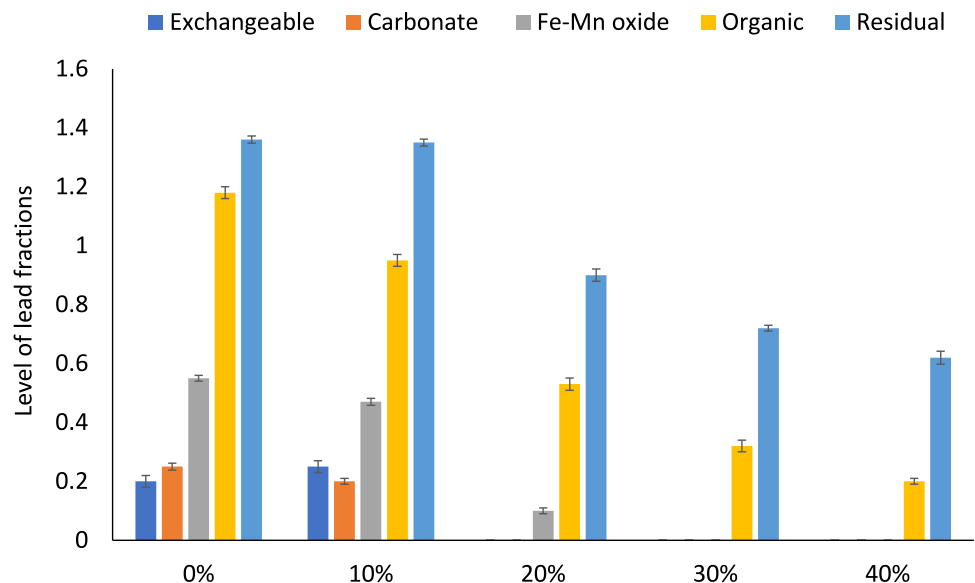


Fig. 12 Effect of charcoal on lead fractionation on waste dump soil for site 1

Fig. 13 Effect of charcoal on lead fractionation on waste dump soil for site 2



to the adsorption of heavy metal ions (ÇELEBİ & SÖĞÜT, 2022).

The mobility factor describes the potential mobility of a metal. Generally, some metallic forms are more strongly bound to soil or charcoal components than others. High mobility factor has been reported as a symptom of relative high liability and biological availability of metals in soil (Asmoay et al. 2019). In this present study, the mobility factor (MF) was calculated using five step schemes (Eq. 1).

The toxic metal mobility in the control soil revealed that toxic metals were mobile while significant reduction ($P < 0.05$) in the metals mobility was observed as the rate of charcoal application to the contaminated soils increased (Table 1). This could be attributed to the ability

of charcoal to enhance soil pH. pH is the most important parameter that control the mobility of metals in soil. Similarly, Antonangelo (Antonangelo et al. 2021), suggested in their study that raising the pH could be one mechanisms by which metal mobility was reduced by carbonized feedstock.

In this present assay, the increase in the soils pH by charcoal application enhanced the adsorption of metals because it increased the negative charges of the soil by the charcoal particles. It is likely that slightly CEC increase after charcoal application also contributed to the metal immobilization because extractability of metals is known to correlate with CEC (Domingues et al. 2020).



Fig. 14 Effect of charcoal on toxic metal concentration on waste dump soil

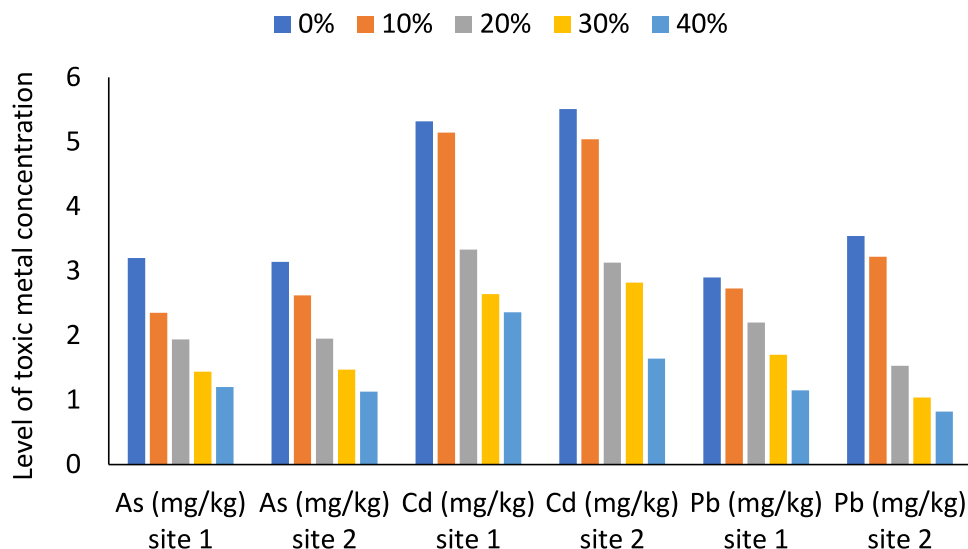


Table 1 Effect of charcoal on mobility of toxic metals in dumpsite soil

		Rate of amendment (%)					
Toxic metals	Waste dumpsites	0	10	20	30	40	
As	1	9.06 ± 0.22	4.24 ± 0.20	0 ± 0.00	0 ± 0.00	0 ± 0.00	
	2	11.46 ± 0.2	4.20 ± 0.20	0 ± 0.00	0 ± 0.00	0 ± 0.00	
Cd	1	26.69 ± 0.30	25.1 ± 0.24	5.02 ± 0.40	0 ± 0.00	0 ± 0.00	
	2	28.68 ± 0.30	26.79 ± 0.22	14.06 ± 0.39	0 ± 0.00	0 ± 0.00	
Pb	1	10.34 ± 0.20	8.06 ± 0.10	0 ± 0.00	0 ± 0.00	0 ± 0.00	
	2	12.71 ± 0.20	13.98 ± 0.30	0 ± 0.00	0 ± 0.00	0 ± 0.00	

Effect of charcoal on environmental risk factor (ERF) and contamination factor (CF) for toxic metals in soil

The potential threats of toxic metals on living organisms in the control soil and charcoal amended soils were evaluated in terms of environmental risk factor (ERF, Eq. 2). The ERF values for the soils for arsenic, cadmium and lead is presented in Figs. 15, 16, 17, 18, 19, 20. The highest values of ERF of the metals were found in 40% charcoal treatment while the lowest values were found at 10% treatment, displaying a significant difference ($p < 0.05$) between control soil and treated soil across all study toxic metals for ERF. Thus, as the rate of charcoal application increased the potential threat to living organism begin to decrease. Therefore charcoal application to toxic metal contaminated soils would be effective way to manage the potential threat of such toxic metals to farmers, soil micro-organism and crops (Edo et al. 2024d).

However, environmental contamination is described as the presence of toxic substances in the environment. In this study, contamination factor (CF) was calculated based on the Eq. 3 described by Custodio et al., (2022). Results of the CF for the control soil and charcoal amended soils are presented

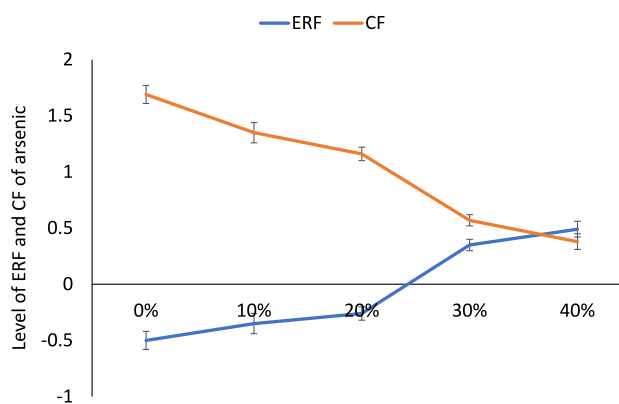


Fig. 15 Effect of charcoal application on ERF and, CF of arsenic waste dump soil for site 1

in Figs. 15, 16, 17, 18, 19, 20. The CF values were higher and lower for charcoal treatment at 10 and 40% respectively. This indicated that as the rate of charcoal application to the soils increased, the CF for the toxic metals decreased, demonstrating a significant difference ($p < 0.05$) between control soil and treated soil across all study toxic metals for CF. Contamination factor of control soil showed that most of

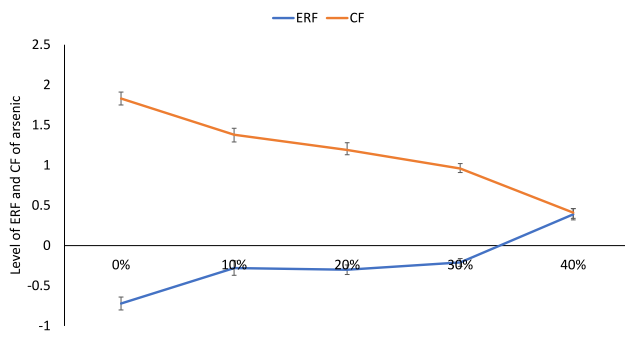


Fig. 16 Effect of charcoal application on ERF and, CF of arsenic waste dump soil for site 2

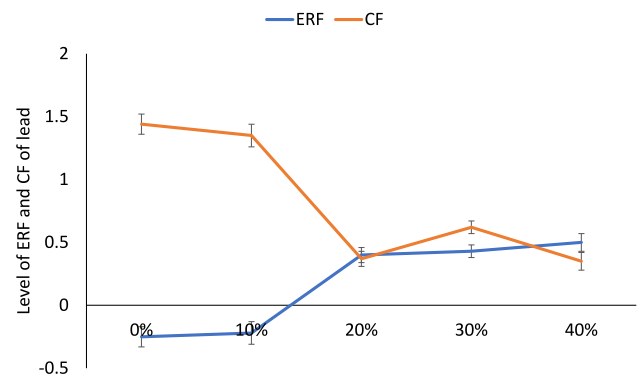


Fig. 19 Effect of charcoal application on ERF and, CF of lead waste dump soil for site 1

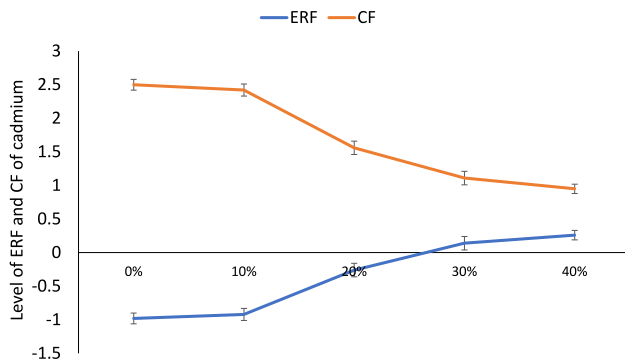


Fig. 17 Effect of charcoal application on ERF and, CF of cadmium waste dump soil for site 1

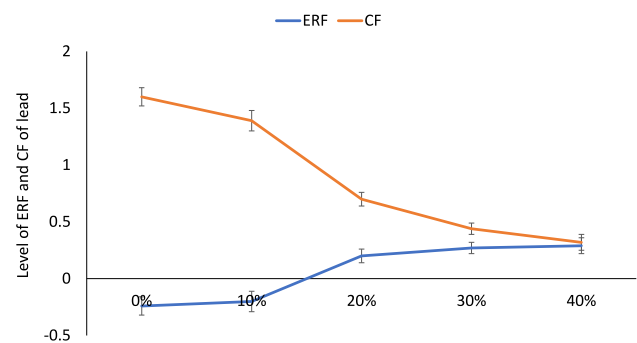


Fig. 20 Effect of charcoal application on ERF and, CF of lead waste dump soil site 2

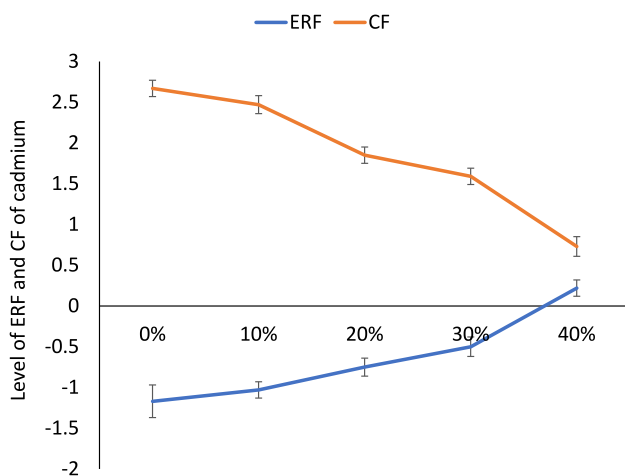


Fig. 18 Effect of charcoal application on ERF and, CF of cadmium waste dump soil for site 2

the metals are moderately contaminated the dumpsites soils. Thus, charcoal was very effective in decreasing CF of soils. This is in agreement with the result obtained from ERF and mobility factor. Therefore, it could be concluded that

charcoal is an excellent soil amender to check the contamination factor of wastes dumpsite soils.

Conclusion and future research

The texture of the study soils was sandy loam with appreciable level of pH and nutrients. The concentration of toxic metals in soil before treatment were above the permissible levels for agricultural soils. The Charcoal was found to contained remarkable quantities of macro and micro nutrients. It also improved soils pH, cation exchange capacity, electrical conductivity and macro-nutrients. The study also revealed that application of charcoal could affect the partition or redistribution of toxic metals within the exchangeable, carbonate and residual phase. Furthermore, the mobility factor indicated reduction of toxic metals mobility as the rate of charcoal increased. Environmental risk factor and ecological health factor were indicative that application of charcoal to toxic metals contaminated soil could be a better option for remediation and nutrients enhancement of such soils. Therefore, the study has established



that charred oil palm trunks could enhanced soil nutrients, decreased soil environmental risk and increased soil ecological health for better soil quality and agricultural potentiality particularly for food production. However, further study is necessary to fully understand long term effect of palm oil trunk charcoal treatment on soil polluted with toxic metals.

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Author contributions UU, GE, JA, UO, were responsible for the conception and design of the study; UU, GE performed data collection. UU, GE performed data analysis and drafted the article. UU, GE supervised the study, contributed to data analysis, interpretation, and critical revisions. All authors approved the final manuscript.

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Data availability All data will be made available upon reasonable request.

Material availability All data will be made available upon reasonable request.

Declarations

Conflict of interest The authors have no competing interests.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

References

- Adamczyk-Szabela, D., Wolf, W.M.: The impact of soil pH on heavy metals uptake and photosynthesis efficiency in *Melissa officinalis*, *Taraxacum officinalis* *Ocimum basilicum*. *Molecules* **27**(15), 4671 (2022). <https://doi.org/10.3390/molecules27154671>
- Adeyemo, A.A., Adeoye, I.O., Bello, O.S.: Adsorption of dyes using different types of clay: a review. *Appl. Water Sci.* **7**(2), 543–568 (2017). <https://doi.org/10.1007/s13201-015-0322-y>
- Adeyemo, A.J., Ayorinde, A.S., Awodun, M.A., Oyun, M.B.: Nutrients status and soil microbial biomass C and N in charcoal production sites of derived savannah forest of southwestern Nigeria. *Sci. Afr.* **20**, e01684 (2023). <https://doi.org/10.1016/j.sciaf.2023.e01684>
- Agbeshie, A.A., Adjei, R., Anokye, J., Banunle, A.: Municipal waste dumpsite: impact on soil properties and heavy metal concentrations, Sunyani Ghana. *Sci. Afr.* **8**, e00390 (2020). <https://doi.org/10.1016/j.sciaf.2020.e00390>
- Alengebawy, A., Abdelkhalek, S.T., Qureshi, S.R., Wang, M.-Q.: Heavy metals and pesticides toxicity in agricultural soil and plants: ecological risks and human health implications. *Toxics* **9**(3), 42 (2021). <https://doi.org/10.3390/toxics9030042>
- Alkharabsheh, H.M., Seleiman, M.F., Battaglia, M.L., Shami, A., Jalal, R.S., Alhammad, B.A., Almutairi, K.F., Al-Saif, A.M.: Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: a review. *Agronomy* **11**(5), 993 (2021). <https://doi.org/10.3390/agronomy11050993>
- Al-Mur, B.A.: Geochemical fractionation of heavy metals in sediments of the Red Sea Saudi Arabia. *Oceanologia* **62**(1), 31–44 (2020). <https://doi.org/10.1016/j.oceano.2019.07.001>
- Amanullah, Ullah, H., Soliman Elshikh, M., Alwahibi, M. S., Alkahtani, J., Muhammad, A., Khalid, S., Imran. (2020). Nitrogen contents in soil, grains, and straw of hybrid rice differ when applied with different organic nitrogen sources. *Agriculture*, **10**(9), 386. <https://doi.org/10.3390/agriculture10090386>
- Antonangelo, J.A., Sun, X., Zhang, H.: The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. *J. Environ. Manage.* **277**, 111443 (2021). <https://doi.org/10.1016/j.jenvman.2020.111443>
- Asare, M.O., Száková, J.: Are anthropogenic soils from dumpsites suitable for arable fields? Evaluation of soil fertility and transfer of potentially toxic elements to plants. *Plant Soil* **486**(1–2), 307–322 (2023). <https://doi.org/10.1007/s11104-023-05870-6>
- Asmoay, A.S.A., Salman, S.A., El-Gohary, A.M., Sabet, H.S.: Evaluation of heavy metal mobility in contaminated soils between Abu Qurqas and Dyer Mawas Area, El Minya governorate, Upper Egypt. *Bull. National Res. Centre* **43**(1), 88 (2019). <https://doi.org/10.1186/s42269-019-0133-7>
- Bhattacharya, P.T., Misra, S.R., Hussain, M.: Nutritional aspects of essential trace elements in oral health and disease: an extensive review. *Scientifica* **2016**, 1–12 (2016). <https://doi.org/10.1155/2016/5464373>
- Bhattacharyya, S.S., Furtak, K.: Soil–plant–microbe interactions determine soil biological fertility by altering rhizospheric nutrient cycling and biocrust formation. *Sustainability* **15**(1), 625 (2022). <https://doi.org/10.3390/su15010625>
- ÇELEBI, M., SÖĞÜT, E.G.: High-efficiency removal of cationic dye and heavy metal ions from aqueous solution using amino-functionalized graphene oxide, adsorption isotherms, kinetics studies, and mechanism. *Turk. J. Chem.* **46**(5), 1577–1593 (2022). <https://doi.org/10.55730/1300-0527.3462>
- Chen, H., Jiang, H., Nazhafati, M., Li, L., Jiang, J.: Biochar: an effective measure to strengthen phosphorus solubilizing microorganisms for remediation of heavy metal pollution in soil. *Front. Bioeng. and Biotechnol.* (2023). <https://doi.org/10.3389/fbioe.2023.1127166>
- Custodio, M., Espinoza, C., Orellana, E., Chanamé, F., Fow, A., Peñaloza, R.: Assessment of toxic metal contamination, distribution and risk in the sediments from lagoons used for fish farming in the central region of Peru. *Toxicol. Rep.* **9**, 1603–1613 (2022). <https://doi.org/10.1016/j.toxrep.2022.07.016>
- de la Peña, P., Thomas, M., Molefyane, T.R.: Particle size distribution: an experimental study using southern African reduction methods and raw materials. *PLoS ONE* **17**(12), e0278867 (2022). <https://doi.org/10.1371/journal.pone.0278867>
- Devi, U., Bhattacharyya, K.G.: Mobility and bioavailability of Cd Co, Cr, Cu, Mn and Zn in surface runoff sediments in the urban catchment area of Guwahati India. *Appl. Water Sci.* **8**(1), 18 (2018). <https://doi.org/10.1007/s13201-018-0651-8>
- Dixit, R., Wasiullah, D.M., Pandiyan, K., Singh, U., Sahu, A., Shukla, R., Singh, B., Rai, J., Sharma, P., Lade, H., Paul, D.: Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. *Sustainability* **7**(2), 2189–2212 (2015). <https://doi.org/10.3390/su7022189>
- Domingues, R.R., Sánchez-Monedero, M.A., Spokas, K.A., Melo, L.C.A., Trugilho, P.F., Valenciano, M.N., Silva, C.A.: Enhancing cation exchange capacity of weathered soils using biochar: feed-stock Pyrolysis conditions and addition rate. *Agronomy* **10**(6), 824 (2020). <https://doi.org/10.3390/agronomy10060824>



- Duwiejuah, A.B., Abubakari, A.H., Quainoo, A.K., Amadu, Y.: Review of biochar properties and remediation of metal pollution of water and soil. *J. of Health and Pollut.* (2020). <https://doi.org/10.5696/2156-9614-10.27.200902>
- Edo, G.I., Makinde, M.G., Nwosu, L.C., Ozgor, E., Akhayere, E.: Physicochemical and pharmacological properties of palm oil: an approach for quality, safety, and nutrition evaluation of palm oil. *Food Anal. Methods* (2022). <https://doi.org/10.1007/s12161-022-02293-4>
- Edo, G.I., Itoje-akpokinio, L.O., Obasohan, P., Ikpekor, V.O., Samuel, P.O., Jikah, A.N., Nosu, L.C., Ekokotu, H.A., Ugbune, U., Oghrro, E.E., Emakpor, O.L.: Impact of environmental pollution from human activities on water, air quality and climate change. *Ecol. Front.* (2024). <https://doi.org/10.1016/j.ecofro.2024.02.014>
- Edo, G.I., Samuel, P.O., Jikah, A.N., Ekokotu, H.A., Ugbune, U., Oghrro, E.E.A., Emakpor, O.L., Essaghah, A.E.A., Ainyanbhor, I.E., Ojulari, A.E., Okoronkwo, K.A., Owheruo, J.O.: Petroleum discovery, utilization and processing in the World and Nigeria: a comprehensive literature review. *Sustain. Chem. Eng.* (2024). <https://doi.org/10.37256/sce.5120243970>
- Edo, G.I., Samuel, P.O., Oloni, G.O., Ezekiel, G.O., Ikpekor, V.O., Obasohan, P., Ongulu, J., Otunuya, C.F., Opiti, A.R., Ajakaye, R.S., Essaghah, A.E., Agbo, J.J.: Environmental persistence, bioaccumulation, and ecotoxicology of heavy metals. *Chem. and Ecol.* (2024). <https://doi.org/10.1080/02757540.2024.2306839>
- GI Edo, PO Samuel, AN Jikah, E Yousif, PN Onyibe, AR Opiti, VO Ikpekor, GO Ezekiel, BE Thomas, SO Eboh, HA Ekokotu, UU, Ephraim EA Oghrro, IE Ainyanbhor, PO Akpogheli, JO Owheruo, AEA Essaghah, LD Ekpeko, EF Isoje, JJ Agbo. (2024). Sensitivity ecology and evolution, toxicology organism assessment model in the use of chemical applications for the management of toxic substances. *Ecological Frontiers*. <https://doi.org/10.1016/j.ecofro.2024.06.001>
- Gao, J., Liu, D., Yakun, X., Chen, J., Yang, Y., Dong Xia, Y., Ding, W.X., Wennian, Xu.: Effects of two types of activated carbon on the properties of vegetation concrete and *Cynodon dactylon* growth. *Sci. Reports* **10**(1), 14483 (2020). <https://doi.org/10.1038/s41598-020-71440-w>
- Gesse, T.A., Khamzina, A.: How reliable is the Walkley-Black method for analyzing carbon-poor, semi-arid soils in Ethiopia? *J. Arid Environ.* **153**, 98–101 (2018). <https://doi.org/10.1016/j.jaridenv.2018.01.008>
- Golia, E.E., Aslanidis, P.S.C., Papadimou, S.G., Kantzou, O.-D., Charotodipomenou, M.-A., Lakiotis, K., Androudi, M., Tsiropoulos, N.G.: Assessment of remediation of soils, moderately contaminated by potentially toxic metals, using different forms of carbon (charcoal, biochar, activated carbon) Impacts on contamination, metals availability and soil indices. *Sustain. Chem. and Pharmacy* **28**, 100724 (2022). <https://doi.org/10.1016/j.scp.2022.100724>
- Haider, F.U., Wang, X., Farooq, M., Hussain, S., Cheema, S.A., Ul Ain, N., Virk, A.L., Ejaz, M., Janyshova, U., Liqun, C.: Biochar application for the remediation of trace metals in contaminated soils: Implications for stress tolerance and crop production. *Eco-toxicol. and Environ. Saf.* **230**, 113165 (2022). <https://doi.org/10.1016/j.ecoenv.2022.113165>
- Hamidi, N.H., Ahmed, O.H., Omar, L., Ch'ng, H.Y.: Combined use of charcoal, Sago Bark Ash, and urea mitigate soil acidity and aluminium toxicity. *Agronomy* **11**(9), 1799 (2021a). <https://doi.org/10.3390/agronomy11091799>
- Hamidi, N.H., Ahmed, O.H., Omar, L., Ch'ng, H.Y.: Soil nitrogen sorption using charcoal and wood ash. *Agronomy* (2021b). <https://doi.org/10.3390/agronomy11091801>
- Hardy, B., Dufey, J.E.: The resistance of centennial soil charcoal to the “Walkley-Black” oxidation. *Geoderma* **303**, 37–43 (2017). <https://doi.org/10.1016/j.geoderma.2017.05.001>
- Hergenrather, K.: Photovoice as community-based participatory research: a qualitative review. *Am. J. Health Behav.* (2009). <https://doi.org/10.5993/AJHB.33.6.6>
- Huntley, B.J.: Soil, water and nutrients. In: Huntley, B.J. (ed.) *Ecology of angola*. Springer International Publishing, Cham (2023)
- Ilomuanya, M., Nashiru, B., Ifudu, N., Igwilo, C.: Effect of pore size and morphology of activated charcoal prepared from midribs of *Elaeis guineensis* on adsorption of poisons using metronidazole and *Escherichia coli* O157:H7 as a case study. *J. Microsc. and Ultrastruct.* **5**(1), 32 (2017). <https://doi.org/10.1016/j.jmau.2016.05.001>
- Jacoby, R., Peukert, M., Succurro, A., Koprivova, A., Kopriva, S.: The role of soil microorganisms in plant mineral nutrition—current knowledge and future directions. *Front. in Plant Sci.* (2017). <https://doi.org/10.3389/fpls.2017.01617>
- Jeon, I., Chung, H., Kim, S.H., Nam, K.: Use of clay and organic matter contents to predict soil pH vulnerability in response to acid or alkali spills. *Heliyon* **9**(6), e17044 (2023). <https://doi.org/10.1016/j.heliyon.2023.e17044>
- Kapahi, M., Sachdeva, S.: Bioremediation options for heavy metal pollution. *J. Health and Pollut.* **9**(24), 191203 (2019). <https://doi.org/10.5696/2156-9614-9.24.191203>
- Kozioł, A., Paliwoda, D., Mikiciuk, G., Benhadji, N.: Biochar as a multi-action substance used to improve soil properties in horticultural and agricultural crops—a review. *Agriculture* **14**(12), 2165 (2024). <https://doi.org/10.3390/agriculture14122165>
- Kumar, M., Seth, A., Singh, A.K., Rajput, M.S., Sikandar, M.: Remediation strategies for heavy metals contaminated ecosystem: a review. *Environ. and Sustain. Indic.* **12**, 100155 (2021a). <https://doi.org/10.1016/j.indic.2021.100155>
- Kumar, S., Kumar, S., Mohapatra, T.: Interaction between macro- and micro-nutrients in plants. *Front. Plant Sci.* (2021). <https://doi.org/10.3389/fpls.2021.665583>
- Li, Q., Wang, Y., Li, Y., Li, L., Tang, M., Hu, W., Chen, L., Ai, S.: Speciation of heavy metals in soils and their immobilization at micro-scale interfaces among diverse soil components. *Sci. Total Environ.* **825**, 153862 (2022). <https://doi.org/10.1016/j.scitotenv.2022.153862>
- Liang, Y., Cao, X., Zhao, L., Arellano, E.: Biochar- and phosphate-induced immobilization of heavy metals in contaminated soil and water: implication on simultaneous remediation of contaminated soil and groundwater. *Environ. Sci. Pollut. Res.* **21**(6), 4665–4674 (2014). <https://doi.org/10.1007/s11356-013-2423-1>
- Mastrolonardo, G., Calderaro, C., Coccozza, C., Hardy, B., Dufey, J., Cornelis, J.-T.: Long-term effect of charcoal accumulation in hearth soils on tree growth and nutrient cycling. *Front. Environ. Sci.* (2019). <https://doi.org/10.3389/fenvs.2019.00051>
- Mitra, S., Chakraborty, A.J., Tareq, A.M., Emran, T.B., Nainu, F., Khuro, A., Idris, A.M., Khandaker, M.U., Osman, H., Alhumaydhi, F.A., Simal-Gandara, J.: Impact of heavy metals on the environment and human health: novel therapeutic insights to counter the toxicity. *J. King Saud University – Sci.* **34**(3), 101865 (2022). <https://doi.org/10.1016/j.jksus.2022.101865>
- Mng'ong'o, M., Munishi, L.K., Blake, W., Comber, S., Hutchinson, T.H., Ndakidemi, P.A.: Soil fertility and land sustainability in Usangu Basin-Tanzania. *Heliyon* **7**(8), e07745 (2021). <https://doi.org/10.1016/j.heliyon.2021.e07745>
- Neina, D.: The role of soil pH in plant nutrition and soil remediation. *Appl. Environ. Soil Sci.* **2019**, 1–9 (2019). <https://doi.org/10.1155/2019/5794869>
- Nkoh, J.N., Baquy, M.A.-A., Mia, S., Shi, R., Kamran, M.A., Mehmood, K., Xu, R.: A critical-systematic review of the interactions of biochar with soils and the observable outcomes. *Sustainability* **13**(24), 13726 (2021). <https://doi.org/10.3390/su132413726>



- Ogheneoruese Onoharigho, F., Oyinegeri Akpodimo, E., Edo, G.I.: The effect of uncontrolled dumping of solid waste on groundwater in Osun State, Nigeria. *Fine Chem. Eng.* (2022). <https://doi.org/10.37256/fce.3220221668>
- Oluwatuyi, O.E., Ajibade, F.O., Ajibade, T.F., Adelodun, B., Olowoselu, A.S., Adewumi, J.R., Akinbile, C.O.: Total concentration, contamination status and distribution of elements in a Nigerian State dumpsites soil. *Environ. and Sustain. Indic.* **5**, 100021 (2020). <https://doi.org/10.1016/j.indic.2020.100021>
- Onakpa, M.M., Njan, A.A., Kalu, O.C.: A review of heavy metal contamination of food crops in Nigeria. *Ann. of Global Health* **84**(3), 488–494 (2018). <https://doi.org/10.29024/aogh.2314>
- Oni, B.A., Oziegbe, O., Olawole, O.O.: Significance of biochar application to the environment and economy. *Ann. of Agric. Sci.* **64**(2), 222–236 (2019). <https://doi.org/10.1016/j.aos.2019.12.006>
- Orozco-Ortiz, J.M., Peña-Venegas, C.P., Bauke, S.L., Borgemeister, C., Mörchen, R., Lehndorff, E., Amelung, W.: Terra Preta properties in Northwestern Amazonia (Colombia). *Sustainability* **13**(13), 7088 (2021). <https://doi.org/10.3390/su13137088>
- Otabor, K.E.: Chemical speciation and mobility study of some heavy metals in soils around municipal solid waste dumpsites in Benin City metropolis. Nigeria. *SN Appl. Sci.* **1**(12), 1649 (2019). <https://doi.org/10.1007/s42452-019-1700-0>
- Paramisparam, P., Ahmed, O.H., Omar, L., Ch'ng, H.Y., Johan, P.D., Hamidi, N.H.: Co-application of charcoal and wood ash to improve potassium availability in tropical mineral acid soils. *Agronomy* **11**(10), 2081 (2021). <https://doi.org/10.3390/agronomy11102081>
- Penn, C., Camberato, J.: A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture* **9**(6), 120 (2019). <https://doi.org/10.3390/agriculture9060120>
- Qurat-ul-Ain, Shafiq, M., Capareda, S. C., & Firdaus-e-Bareen. (2021). Effect of different temperatures on the properties of pyrolysis products of *Parthenium hysterophorus*. *Journal of Saudi Chemical Society*, 25(3), 101197. <https://doi.org/10.1016/j.jscs.2021.101197>
- Raffa, C.M., Chiampo, F., Shanthakumar, S.: Remediation of metal/metalloid-polluted soils: a short review. *Appl. Sci.* **11**(9), 4134 (2021). <https://doi.org/10.3390/app11094134>
- Ramezanzadeh, H., Zarehaghi, D., Baybordi, A., Bouket, A.C., Oszako, T., Alenezi, F.N., Belbahri, L.: The impacts of biochar-assisted factors on the hydrophysical characteristics of amended soils: a review. *Sustainability* **15**(11), 8700 (2023). <https://doi.org/10.3390/su15118700>
- Robert, P., Torres, V., García, P., Vergara, C., Sáenz, C.: The encapsulation of purple cactus pear (*Opuntia ficus-indica*) pulp by using polysaccharide-proteins as encapsulating agents. *LWT Food Sci. Technol.* **60**(2), 1039–1045 (2015). <https://doi.org/10.1016/j.lwt.2014.10.038>
- Rocchi, L., Campioni, R., Brunori, A., Mariano, E.: Environmental certification of woody charcoal: a choice experiments application. *Forest Policy Econ.* **154**, 103042 (2023). <https://doi.org/10.1016/j.forpol.2023.103042>
- Roshan, A., Ghosh, D., Maiti, S.K.: How temperature affects biochar properties for application in coal mine spoils? A Meta-Anal. *Carbon Res.* **2**(1), 3 (2023). <https://doi.org/10.1007/s44246-022-00033-1>
- Samoraj, M., Mironiuk, M., Witek-Krowiak, A., Izydorczyk, G., Skrzypczak, D., Mikula, K., Baśladyńska, S., Moustakas, K., Chojnacka, K.: Biochar in environmental friendly fertilizers - prospects of development products and technologies. *Chemosphere* **296**, 133975 (2022). <https://doi.org/10.1016/j.chemosphere.2022.133975>
- Samuel, P.O., Edo, G.I., Oloni, G.O., Ugbune, U., Ezekiel, G.O., Essaghah, A.E.A., Agbo, J.J.: Effects of chemical contaminants on the ecology and evolution of organisms a review. *Chemistry and Ecology* (2023). <https://doi.org/10.1080/02757540.2023.2284158>
- Schneider, A., Hirsch, F., Bonhage, A., Raab, A., Raab, T.: The soil moisture regime of charcoal-enriched land use legacy sites. *Geoderma* **366**, 114241 (2020). <https://doi.org/10.1016/j.geoderma.2020.114241>
- Schoonover, J.E., Crim, J.F.: An introduction to soil concepts and the role of soils in watershed management. *J. Contemp. Water Res. & Educ.* **154**(1), 21–47 (2015). <https://doi.org/10.1111/j.1936-704X.2015.03186.x>
- Singh Yadav, S.P., Bhandari, S., Bhatta, D., Poudel, A., Bhattarai, S., Yadav, P., Ghimire, N., Paudel, P., Paudel, P., Shrestha, J., Oli, B.: Biochar application: a sustainable approach to improve soil health. *J. Agric. and Food Res.* **11**, 100498 (2023). <https://doi.org/10.1016/j.jafr.2023.100498>
- Sultan, H., Ahmed, N., Mubashir, M., Danish, S.: Chemical production of acidified activated carbon and its influences on soil fertility comparative to thermo-pyrolyzed biochar. *Sci. Rep.* **10**(1), 595 (2020). <https://doi.org/10.1038/s41598-020-57535-4>
- Tahat, M.M., Alananbeh, K.M., Othman, Y.A., Leskovar, D.I.: Soil health and sustainable agriculture. *Sustainability* **12**(12), 4859 (2020). <https://doi.org/10.3390/su12124859>
- Tomczyk, A., Sokołowska, Z., Boguta, P.: Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Rev. Environ. Sci. and Bio/technol.* **19**(1), 191–215 (2020). <https://doi.org/10.1007/s11157-020-09523-3>
- Tóth, G., Guicharnaud, R.-A., Tóth, B., Hermann, T.: Phosphorus levels in croplands of the European Union with implications for P fertilizer use. *Eur. J. Agron.* **55**, 42–52 (2014). <https://doi.org/10.1016/j.eja.2013.12.008>
- Tsolis, V., Barouchas, P.: Biochar as soil amendment: the effect of biochar on soil properties using VIS-NIR diffuse reflectance spectroscopy, biochar aging and soil microbiology—a review. *Land* **12**(8), 1580 (2023). <https://doi.org/10.3390/land12081580>
- Ugbune, U., Avwenaghegha, J.O., Edo, G.I.: Geochemical distribution and ecological risk level of inorganic pollutant of River Ethiopia sediment. *Dutse J. Pure and Appl. Sci.* **9**(3a), 187–193 (2023). <https://doi.org/10.4314/dujopas.v9i3a.19>
- Ugbune, U., Edo, G.I., Avwenaghegha, J.O., Kpomah, B.: Studies of biochar prepared with different temperatures on sorption of urban wastes leachate. *Proc. Indian Natl. Sci. Acad.* (2024). <https://doi.org/10.1007/s43538-024-00332-8>
- VanWaardhuizen, L. (2022). Jackson V. P., Holland J. M., & Miller Arline J. R. (Eds.) (2021). *African Americans in the human sciences*. Lexington Books. ISBN 978-1-7936-4894-5 (hardcover). 306 pp. *Family and Consumer Sciences Research Journal*, 50(3), 255–258. <https://doi.org/10.1111/fcsr.12433>
- Wang, G., Ren, Y., Bai, X., Su, Y., Han, J.: Contributions of beneficial microorganisms in soil remediation and quality improvement of medicinal plants. *Plants* **11**(23), 3200 (2022). <https://doi.org/10.3390/plants11233200>
- Wang, B., Lan, J., Bo, C., Gong, B., Ou, J.: Adsorption of heavy metal onto biomass-derived activated carbon: review. *RSC Adv.* **13**(7), 4275–4302 (2023). <https://doi.org/10.1039/D2RA07911A>
- Wyszkowski, M., Wyszkowska, J., Kordala, N., Borowik, A.: Effects of coal and sewage sludge ashes on macronutrient content in maize (*Zea mays* L.) grown on soil contaminated with eco-diesel oil. *Materials* **15**(2), 525 (2022). <https://doi.org/10.3390/ma15020525>
- Yan, Q., Fang, H., Wang, D., Xiao, X., Deng, T., Li, X., Wei, F., Liu, J., Lin, C.: Transfer and transformation characteristics of Zn and Cd in soil-rotation plant (*Brassica napus* L and *Oryza sativa* L) system and its influencing factors. *Sci. Reports* **13**(1), 7393 (2023). <https://doi.org/10.1038/s41598-023-34377-4>
- Yang, X., Wan, Y., Zheng, Y., He, F., Zebin, Y., Huang, J., Wang, H., Ok, Y.S., Jiang, Y., Gao, B.: Surface functional groups of carbon-based adsorbents and their roles in the removal of heavy



- metals from aqueous solutions: a critical review. *Chem. Eng. J.* **366**, 608–621 (2019). <https://doi.org/10.1016/j.cej.2019.02.119>
- Zellner, T., Prasa, D., Färber, E., Hoffmann-Walbeck, P., Genser, D., Eyer, F.: The use of activated charcoal to treat intoxications. *Dtsch. Arztebl. Int.* (2019). <https://doi.org/10.3238/arztebl.2019.0311>
- Zhao, H., Wu, Y., Lan, X., Yang, Y., Wu, X., Du, L.: Comprehensive assessment of harmful heavy metals in contaminated soil in order to score pollution level. *Sci. Rep.* **12**(1), 3552 (2022). <https://doi.org/10.1038/s41598-022-07602-9>

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