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Physicochemical characterization of biochar and study of their effect on the bioavailability of heavy metals in soil from Burkina Faso

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Abstract: The use of municipal waste as fertilisers contributes to contaminating the soil with heavy metals. The main objective of this study is to determine the ability of different types of biochar to immobilize heavy metals from contaminated soils. To do this, the biochar was made with cotton stalks and then physically activated at 500 °C and chemically with calcium chloride at 2 M. Thus, each biochar was applied in increasing doses of 0 t/ha, 2.5 t/ha and 5 t/ha. The trial consisted of an experimental block factorial setup with three replicates. Analyses of the heavy metal levels (cadnium, lead, zinc and copper) in the soil indicated zero cadmium levels for the control treatment, which recorded a content of 1.03 mg/kg. For copper, the levels ranged from 190.53 to 139.82 mg/kg. As for lead, the concentrations ranged from 79.72 to 61.93 mg/kg. In addition, zinc levels ranged from 321.79 to 152.21 mg/kg. The addition of 5 t/ha of chemically activated biochar resulted in the best reduction in heavy metal bioavailability compared to the control. The analytical results also showed that chemically activated biochar adsorbed nitrogen, phosphorus and potassium from the soil in contrast to other types of biochar which released them into the soil solution. The use of these materials could provide a palliative solution to the problem of bioaccumulation of heavy metals while improving soil fertility.

1. Introduction

Soil contamination by heavy metals is a global environmental problem that threatens human health, ecological balance and puts a strain on the sustainability of thriving agriculture. Thus, heavy metals, such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As) and copper (Cu) can persist in soils for long periods of time, leading to their accumulation in the food chain, while endangering the quality of food (Akartasse *et al.*, 2017; Ghulam *et al.*, 2021; El Hammari *et al.*, 2023; Koua *et al.*, 2026). This is due to their solubility, which makes them much more mobile in the soil. These heavy metals are thought to come mainly from industrial effluents, greenhouse gas emissions, and the use of agricultural chemicals in large quantities today (Nouri *et al*., 2016, Nimi *et al*., 2025). Thus, through the mobility of heavy metals, soils are impacted in terms of loss of fertility, structural degradation, loss of organic matter, acidification and probably possible leaching of the main nutrients that are generally replaced on the exchange complex by metals and metalloids (Adou *et al*., 2026). Even at low concentrations in soil, cadmium (Cd), mercury (Hg) and arsenic (As) are highly toxic to plants. Thus, the consumption of these plants by humans causes health problems. Indeed, heavy metals are known to harm organisms, even at low concentrations (Karim *et al*., 2019; Sanou *et al*., 2021 & 2022). According to Guo *et al.* (2020), the assimilation of heavy metals in the organs of the human or animal body, even at insignificant concentrations, can lead to cardiovascular, pulmonary, immunological, neurological and endocrine disorders and cancers. More specifically, risks to human health include headaches, liver, kidney, hematopoietic, gastrointestinal system diseases and nerve toxicity (Sanou *et al*., 2020 & 2022). On the other hand, cations such as Cu, Zn, Fe, Mn, Mo, Ni and Co have a primary role in plant metabolism. Therefore, it is crucial to develop effective and accessible methods to reduce their bioavailability in contaminated soils. This is how several soil decontamination techniques have been implemented to eliminate or reduce heavy metals in soils. These include physical, chemical and biological processes (Dhaliwal et al., 2020). Physical techniques mainly include soil washing, thermal desorption, and total or partial replacement of contaminated soil with clean soil to reduce the concentration of pollutants. Chemical techniques involve vitrification technology, chemical leaching, chemical fixation and electrokinetic remediation. As for biological techniques, they include treatment by bioremediation which uses microorganisms such as bacteria and fungi, and phytoremediation which uses plant species (use of different plants) or the combination of the two for the decontamination of agricultural land (Senou *et al*., 2019, Dhaliwal *et al*., 2020, Gholizadeh & Hu, 2021). Although these techniques have improved soil quality, it must be recognized that they are very expensive and require sufficient time to give satisfactory results. Given the pressure on land, farmers cannot therefore suspend their agricultural activities while waiting for a total decontamination of their fields. It is therefore imperative to find other techniques that are less expensive, effective for soil treatment and adapted to producers. As a result, the application of biochar is an alternative and accessible technique for farmers, which can be considered for the remediation of soils contaminated by heavy metals (Hidetoshi *et al*., 2009, Luke *et al*., 2011, Diatta *et al*., 2026). Indeed, biochar, a solid product resulting from the pyrolysis or gasification of biomass (Gholizadeh *et al*., 2020, Zhang *et al*., 2020), can be mixed with soil contaminated by metals to prevent the transfer of the latter from the soil to crops (Liang *et al*., 2017, He *et al*., 2019). Biochar, depending on the origin of the biomass and the production conditions, could be a porous coal with a high cation exchange capacity and alkaline properties. (Ahmad *et al*., 2014; Salahat *et al.,* 2023), allowing it to adsorb heavy metals present in the soil through the complexation of metal ions on its external and internal surface (Tan *et al*., 2017, Zhu *et al*., 2017). The work of Beesley *et al*. (2010) and Laird *et al*. (2009) showed that activated biochar, thanks to its high affinity for metals and metalloids and its ability to raise soil pH, could be an interesting alternative to allow farmers to continue their activities on contaminated soils while reducing the bioaccumulation of heavy metals by crops. According to Jiang *et al*. (2012), the use of biochar for soil amendment reduces the bioavailability of trace metals and improves soil fertility. Zhang *et al*. (2024) also demonstrated that adding biochar to saline soil can effectively increase the activity of soil urease and alkaline phosphatases, which are needed to make potassium and soil organic matter more available, thereby promoting rice production yield. The use of biochar for soil remediation is no longer to be demonstrated, however, the use of ecological, abundant, renewable precursor material for its production would constitute the basis for an added value of this material, while having an overview of its influence on certain soil parameters. This work aims to study the effect of biochar and its activation on the physicochemical properties and bioavailability of some heavy metals in a soil in Burkina Faso. It will be a question of developing biochar, physically activated by calcination at 500 °C, then chemically at 400 °C with calcium chloride ($CaCl_2$) as the activating agent. Then, the physicochemical characteristics of the different types of biochar will be determined. Finally, the effect of biochar on the adsorption capacity of heavy metals (Cd, Cu, Pb and Zn) and the physicochemical properties of soils will be studied.

2. Materials and methods

2.1 Study Materials

The study was carried out within the Training and Research Center of Nazi BONI University (11°9'51.326' north latitude and 4°18'54.538' west longitude), located in sector 20 of the city of Bobo-Dioulasso in Burkina Faso. The biochar used was developed from cotton stalks produced in an experimental field of the Institute of Environment and Agricultural Research (I.N.E.R.A) in Farako-Bâ in Burkina Faso. The choice of cotton stalks as raw material was justified by their availability in quantity and quality. The soil taken for growing lettuce in pots comes from the Dogona market garden area in Bobo Dioulasso. It is very rich in organic matter inherited from the city's household and industrial waste. It is blackish, a color inherited from incinerated waste and/or by the richness of the soil in organic matter. According to Kissou *et al*. (2014), these soils are classified among techno sols.

2.2 Experimental methods

2.2.1 Production and activation of biochar

The production of biochar from biomass first begins with lighting the oven. This step involves building inside the kon-tiki oven, a square open chimney from wood stacked in the middle of the oven about three-quarters of the way up the oven. The bottom of the oven lined with cotton stalks is on fire. About ten minutes later, the chimney which was now engulfed in flames was deconstructed and the embers spread at the bottom of the oven. After this step, the oven is filled where the biomass is piled on the embers to the brim of the oven. Once the flames resume, cotton stalks are added as needed. The operation was suspended 30 minutes later when there was no more flame and a layer of incandescent biochar had formed. Finally, the glowing biochar is drained from the oven and then extinguished with clean water before being dried. Part of the biochar produced has undergone physical activation and chemical activation. The activation aimed to improve the adsorption properties of heavy metals by biochar. The procedure followed for physical activation is that of Omlin *et al*. (2010). For the purpose of the experiment, one kilogram of dry biochar was taken and soaked in distilled water for twenty-four hours. After bleeding, it was introduced into an oven set at 500°C for a period of five (05) hours. Once removed from the oven, the biochar was soaked in distilled water and then dried. The technique used for chemical activation is that of Nadia Morin-Crini *et al*. (2017). To do this, one kilogram of biochar was taken and then soaked in two liters of calcium chloride solution ($CaCl_2$) with a concentration of 2 mol.L^{-1} for 24 hours. The whole thing was put in the oven set at a temperature of 400 °C. After five hours, the activated biochar was cooled and washed with distilled water before being dried.

2.2.2 Setting up the experimental device

The experimental design that was set up was a block factorial design comprising seven (07) treatments and three (03) repetitions or blocks. Two factors were studied, namely the type and doses of biochar provided. Regarding the type of biochar, they were physically activated biochar (BAP), chemically activated biochar (BAC) and non-activated biochar (BNA). As for the doses provided, they were 2.5 tonnes per hectare and 5 tonnes per hectare. The control is represented by a treatment without addition of biochar. The system included 21 plots distributed between the three (03) blocks. Each plot consisted of four pots, so 84 pots in total. The treatments were referenced as follows: T0D0: control without biochar addition; T1D1: 2.5 tonnes of chemically activated biochar (BAC); T1D2: 5 tonnes of chemically activated biochar (BAC); T2D1: 2.5 tonnes of physically activated biochar (BAP); T2D2: 5 tonnes of physically activated biochar (BAP); T3D1: 2.5 tonnes of non-activated biochar (BNA); T3D2: 5 tonnes of non-activated biochar (BNA).

2.2.3 Physicochemical characterization of biochar

2.2.3.1 pH at point of zero charge

The pH at the point of zero charge (pH_{PZC}) is the pH for which the adsorbent (biochar) is electrically neutral in solution allowing an elucidation of the role played by the charge carried by the surface of the adsorbent in the adsorption process. The pH at the point of zero charge is determined using the Lopez-Ramon method cited by I. Sanou *et al.* (2024). For this process, dried biochar is agitated for 72 h with 20 mL of 0.1 mol. L^{-1} NaCl solutions with a pH between 2 and 10. After filtering each solution using Whatman filter paper, a new pH reading is obtained. Curve representing the final pH as a function of the initial pH is plotted. The pH of the solution for which curve crosses first bisector corresponds to the pH_{PZC} ($pH_{final} = pH_{initial}$).

2.2.3.2 Iodine number

The microporosity of adsorbent materials can be evaluated by their ability to bind iodine molecules (Amadou Kiari *et al*., 2026). Iodine indices are determined by the standard method described by Ahmed *et al.* (2012). To do this, 0.05 g of biochar was added to an Erlenmeyer flask containing 15 ml of a 0.1 N iodine solution and the mixture was stirred for 4 min then filtered. 10 ml of filtrate was titrated with standard sodium thiosulfate solution using 2 drops of starch solution as indicator. The iodine number was then calculated using the **equation 1**:

$$\mathbf{I}_d = \frac{(\mathbf{V_b} - \mathbf{V_S}) \times \mathbf{N} \times \mathbf{126{,}9} \times (\frac{\mathbf{15}}{\mathbf{10}})}{m} \qquad \textbf{Eqn. 1}$$

With: $\mathbf{I_d}$: the iodine number in mg/g; $\mathbf{V_b}$: the volume (mL) of sodium thiosulphate ($Na_2S_2O_3$) poured during the blank test (without activated carbon); **Vs**: the volume (mL) of sodium thiosulphate ($Na_2S_2O_3$) applied during the test with biochar; **N**: the normality of the sodium thiosulphate solution (mol/L); **126.9**: the atomic weight of iodine (g/mol); **m**: the mass of biochar (g).

2.2.3.3 Specific surface area

The efficiency of an adsorbent material is essentially oriented towards its surface, both internal and external. The higher the specific surface area of a solid, the more it has the opportunity to spread sufficiently while occupying more space, thus allowing a significant accumulation of a given substance. According to Omlin *et al*. (2010), a material has a good adsorbent power when it has a specific surface area between 500 and 1500 m^2/g. Thus, biochar, chemically, physically and non-activated, have been characterized in terms of specific surface area using the methylene blue (BM) adsorption method described by Kouadio *et al.* (2019). The method consists in studying the adsorption of methylene blue, by the same given mass of the adsorbent, by variation in the concentration of the BM solution, in order to determine the value of the maximum adsorption capacity of the monolayer from the Langmuir isotherm. The specific area is determined from the **equation 2**:

$$S_{BM} = \frac{Q_0 \times S \times N_A}{M_{BM}} \qquad \textbf{Eqn. 2}$$

With, S_{BM}: specific surface area determined using BM as adsorbate ($m^2.g^{-1}$); Q_0: maximum adsorption capacity ($mg.g^{-1}$); **S**: area occupied by a molecule of BM (175 $Å^2$); N_A: Avogadro's number; M_{BM}: molar mass of BM (319.853 g/mol).

2.2.4 Analysis of the level of heavy metal contamination of soil and biochar

Analyses of the heavy metal content of soil and biochar samples concerned copper (Cu), lead (Pb), cadmium (Cd) and zinc (Zn). The method used is that of flame atomic absorption spectrometry after hot wet mineralization with aqua regia (1/3 HNO_3+HCl) according to the AFNOR Standard NF U44-041 (1985).

2.2.5 Statistical analysis of the data : Comparison of means

The data collected was captured and processed using the Microsoft Office Excel 2016 spreadsheet. Statistical analyses were performed using R software version 4.3.1. Shapiro Wilk's normality tests, and Levene's homoscedasticity tests were also used. The analysis of variance (ANOVA) was performed at the 5% probability level when the data did not follow a normal distribution. The Krusla-Wallis test was used when the data did not meet the assumptions of parametric tests. When these tests showed significant differences, the means were contrasted with Tukey's Honest Significant Difference (HSD) test at the 5% level (parametric test) or the DUNN test (nonparametric test).

3. Results and discussion

3.1 Results

3.1.1 Physicochemical characteristics of biochar

The adsorption capacity of a biochar depends on several parameters, including its physicochemical properties. The **Table 1** presents the physicochemical characteristics of the different biochar. The analysis of this table shows that the value of the pH at the point of zero charge obtained from the curves in **Figure 1** of the BAP substrate is significantly higher (8.86) than those of the other substrates, which record values of 7.01 and 7.78 respectively for BAC and BNA. As for the iodine value, BAP also has the highest value at 1877 $mg.g^{-1}$ compared to BAC and BNA, which obtained values of 1618 and 945 $mg.g^{-1}$, respectively.

Table 1. Physicochemical characteristics of biochars

Parameters	BAC	BAP	BNA
pH_{PCN}	7.01	8.86	7.78
I_d ($mg.g^{-1}$)	1618	1877	945
S_{BM} ($m^2.g^{-1}$)	1285	1013	875
pHeau	6.65	7.85	9.94
COT (%)	40.72	44.2	46.66
MO (%)	73.13	80.66	84.4

In contrast, BAC has the largest specific area of methylene blue (1285 m^2. g^{-1}) compared to other substrates which were 875 and 1013 $m^2.g^{-1}$ for BNA and BAP respectively. This indicates that chemical activation improves the functionality of the surface better than the physical one. Similar results were obtained by Boshir *et al*. (2016) in their work to improve the preparation and application of modified biochar for better removal of contaminants from water and wastewater. As for the pH of the BNA, it is higher at the level of 8,86 compared to the BAC and BAP whose values were 7,01 and 7.78. As for the percentages of organic carbon (TOC) and organic matter (OM), the BNA presents the highest percentages while the lowest percentages were recorded at the BAC level.

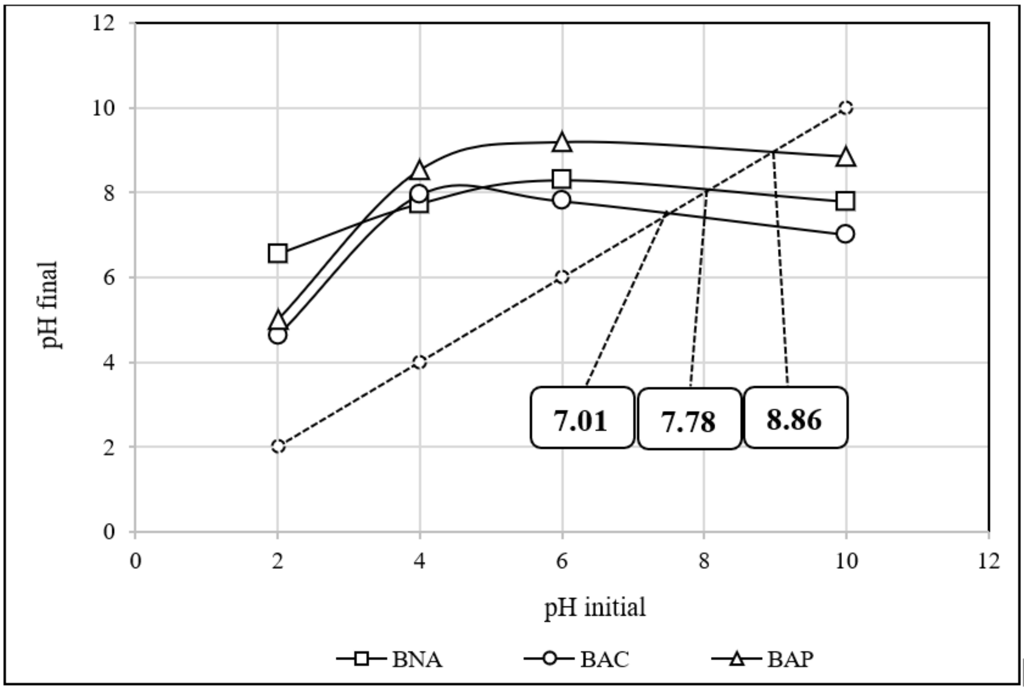

Figure 1. pH curves at the point of zero charge

3.1.2 Heavy metal content in different types of biochar

The results of analysis of heavy metal contents in the different types of biochar are presented in **Figure 2**. For initial biochar (**BI**), the Cd and Pb contents are zero in all samples. Regarding Cu, the contents vary from 3.25 mg/kg to 1.88 mg/kg respectively for chemically activated biochar (BAC) and non-activated biochar (BNA). In terms of Zn, the contents vary between 5.68 mg/kg and 4.05 mg/kg respectively for chemically activated biochar (BAC) and non-activated biochar (BNA). For post-harvest biochar (**BAR**), the analysis of variance did not find a significant difference between the treatments in terms of cadmium even though the levels varied between 6.35 and 7.79 mg/kg. The same goes for copper where the contents were between 87.24 and 75.46 mg/kg. As for lead and zinc, the levels between the treatments were statistically different. In terms of lead, they varied between 35.56 and 51.48 mg/kg for the T1D2 and T1D1 treatments respectively. For zinc, a minimum content of 158.78 mg/kg was obtained on the T3D2 treatment and a maximum of 184.75 mg/kg recorded on the T3D2 treatment. From the dose of 2.5 t/ha of biochar to the dose of 5 t/ha of biochar, the trends are downward with regard to heavy metal contents (Cd, Cu, Pb and Zn). In addition, the contents of heavy metals adsorbed by the different types of biochar revealed values below the threshold limit according to the AFNOR Standard NF U44-041 (1985). Comparison of the heavy metal contents in the initial biochar and those of the post-harvest biochar showed an increase in the concentrations of cadmium, copper, lead and zinc in the biochar after harvest.

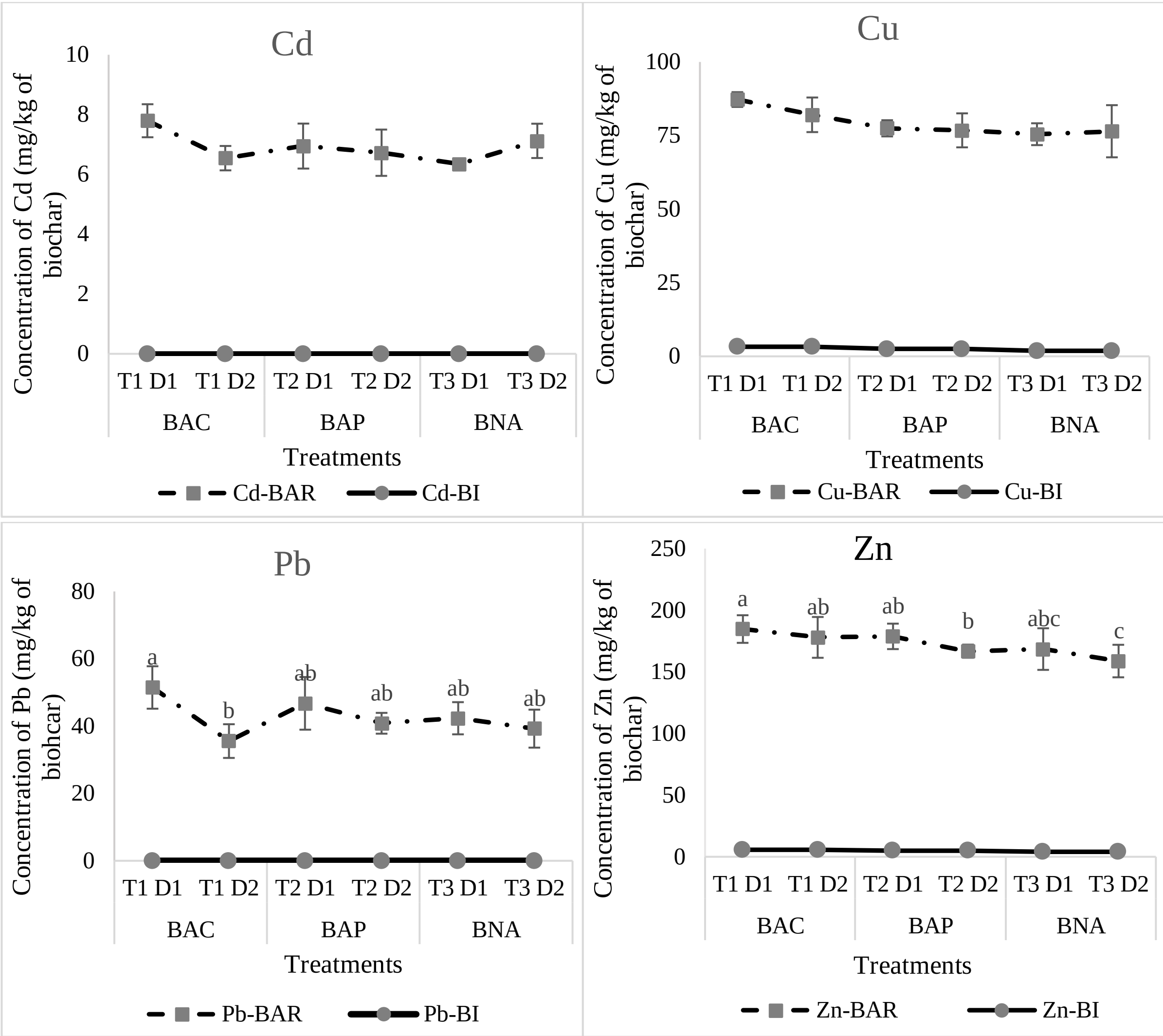

Figure 2. Heavy metal content in different types of biochar

3.1.3 Variation of chemical parameters of different types of biochar after harvest

The variations of the chemical parameters of the different types of biochar after harvest are given in **Figure 3**. The analysis of variance revealed a significant variation in the values by post-harvest treatment. At the level of chemically activated biochar, the water pH value increased by 0.01 and 0.25 following the T1D1 and T1D2 treatments. For the case of physically activated and non-activated biochar, the water pH decreased. However, the decrease in non-activated biochar which was of the order of -3.09 and -3.16 respectively for the T3D2 and T3D1 treatments is less compared to the physically activated biochar whose decrease varied between -1.07 and -1.14 for the T2D2 and T2D1 treatments. Likewise for the case of organic carbon (COT), the analysis of variance revealed significant variations in the percentages according to the treatments. However, for all treatments, COT percentages decreased in post-harvest biochar compared to pre-sowing biochar. This reduction is from -5.82 to -8.66% for the T1D1 and T3D1 treatments respectively. The least reductions were recorded at the level of chemically activated biochar followed by physically activated biochar then non-activated biochar.

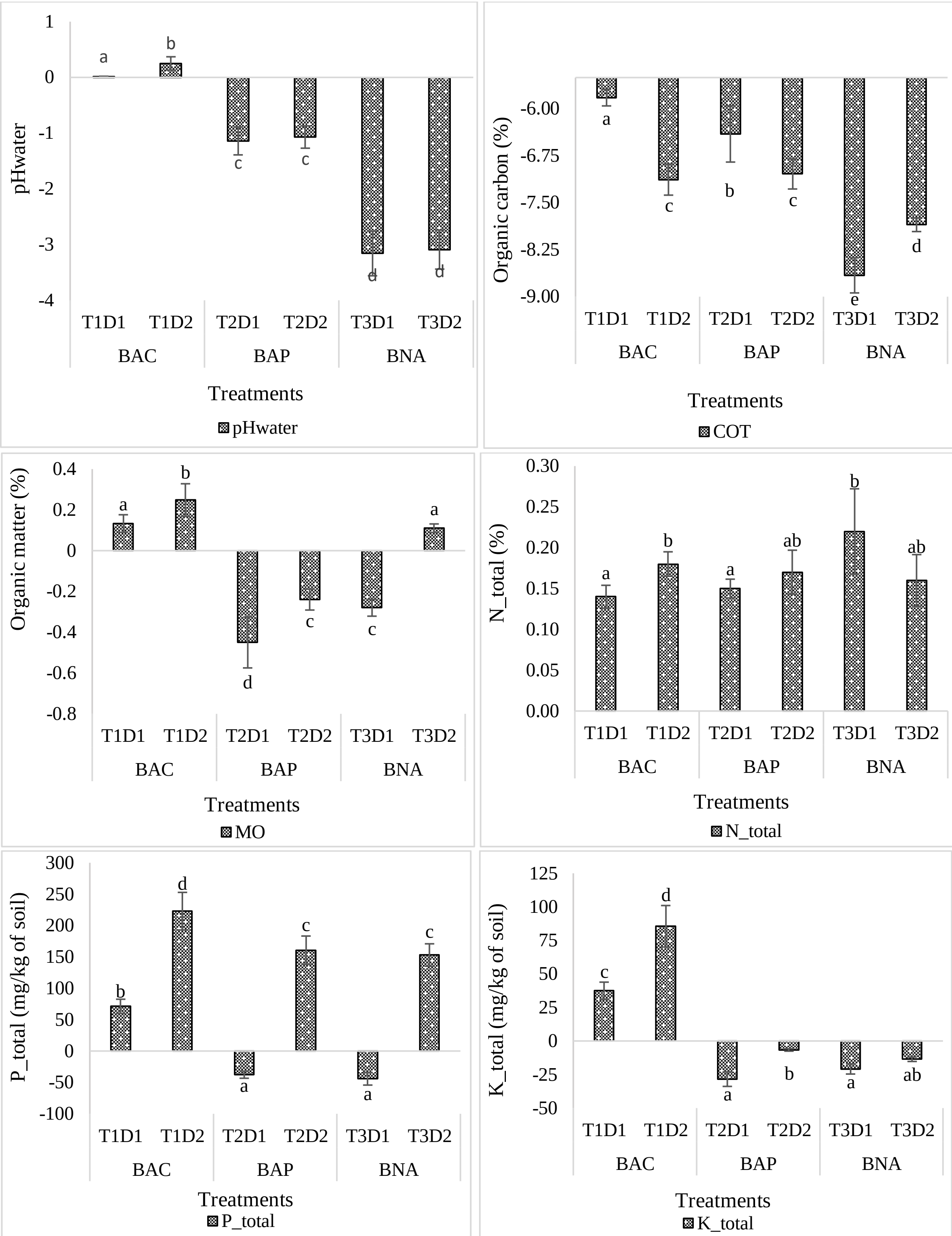

Figure 3. Variation of the chemical parameters of different types of biochar

The analysis of variance carried out at the level of the percentage of organic matter (OM) showed a significant difference between the treatments. For chemically activated biochar, the percentage of OM increased by 0.13% at the T1D1 treatment level and by 0.25% at the T1D2 level. As for treatments T2D1, T2D2 and T3D1, their percentage of organic matter decreased by -0.45, -0.24 and -0.28% respectively. For T3D2 organic matter content increases of 0.11%. Regarding total nitrogen, the variation is positive and statistically different between treatments. It is between 0.14 and 0.22 mg/kg respectively for the T1D1 and T3D1 treatments. However, the increase is less in chemically and physically activated biochar compared to non-activated biochar. The results of the analysis of variance carried out for total phosphorus showed a significant difference between the treatments. At the level of chemically activated biochar, the variation in contents was positive, the increase was between 71.28 mg/kg at the T1D1 treatment and 221.90 mg/kg at the T1D2 treatment. As for the treatments which experienced declines, the levels varied between -37.69 and -44.14 mg/kg respectively for the T2D1 and T3D1 treatments. Regarding the total potassium contents, they increased by 37.43 and 85.45 mg/kg following the T1D1 and T1D2 treatments. For the case of physically activated and non-activated biochar, the contents experienced a drop of between -28.43 and -6.69 mg/kg respectively for the T2D1 and T2D2 treatments.

3.1.4 Heavy metal levels in soils

The heavy metal contents in the initial (SI) and post-harvest (SAR) soils are shown in **Figure 4**. In the initial soils, the heavy metal contents were 12.96 mg/kg, 214.34 mg/kg, 86.72 mg/kg and 371.79 mg/kg respectively for Cd, Cu, Pb and Zn. These contents were all higher than those of the soils after harvest.

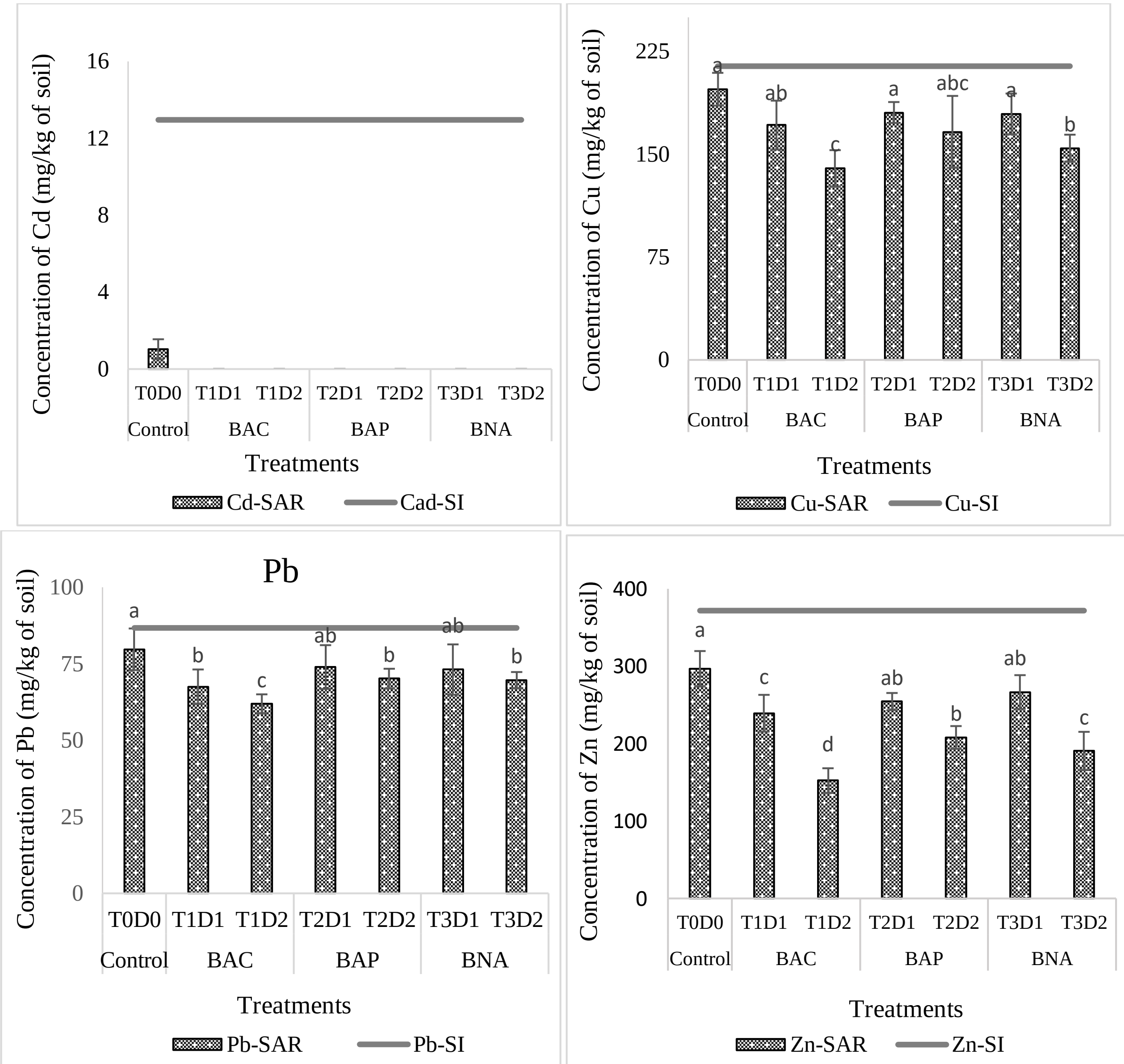

Figure 4. Concentration of Cd, Cu, Pb and Zn in the soil

The results of the analyzes indicated for the latter case, zero cadmium levels with the exception of the control treatment which recorded a level of 1.03 mg/kg of soil. For the Cu, the analysis of variance at the 5% threshold revealed a significant difference between the treatments. The highest content was 190.53 mg/kg of soil and was obtained on the T0D0 treatment, the lowest content recorded on the T1D2 treatment was 139.82 mg/kg of soil. The results obtained from the analysis of variance on lead indicated significant differences. They were between 79.72 and 61.93 mg/kg of soil respectively on the T0D0 and T1D2 treatments. Concerning zinc, the T0D0 and T1D2 treatments obtained the maximum (321.79 mg/kg) and minimum (152.21 mg/kg). The heavy metal contents are higher in soils that did not receive biochar, followed by those that received 2.5 t/ha of biochar, then those that received 5 t/ha of biochar. Trends showed that soils amended with chemically activated biochar were the least contaminated after harvest compared to soils amended with physically activated biochar and non-activated biochar. As for the order of abundance of metallic elements in the soil, zinc was the most concentrated followed by copper, lead and cadmium.

3.2 Discussion

3.2.1 Physicochemical characteristics of biochar

Analysis of the physicochemical characteristics of biochar reveals that chemical activation improves their micro and mesoporosity. This could be explained by the destructuring of the structure of the raw materials by the activating agent (calcium chloride) by making them extrudable. Similarly, the increase in surface area by heat treatment is explained by the decomposition of the oxygen groups initially present on the surface of the biochar. Activation increases the adsorption capacity of iodine in biochar, whether chemical or physical. Moreover, all our developed biochar have developed high iodine values compared to the 521 $mg.g^{-1}$ obtained by Jaward *et al.* (2019) for their orange biochar (citrus sinensis) Peelngs chemically activated by sulfuric acid in favor of methylene blue adsorption. Only non-activated biochar (BNA) with its iodine value of 945 $mg.g^{-1}$ has a value below 955.953 and 1070 $mg.g^{-1}$ obtained by Mohammed *et al.* (2007). According to Kouadio *et al.* (2019) for an adsorbent material to have the capacity to adsorb small molecules, its iodine number must at least be between 600 and 1100 $mg.g^{-1}$. It should be noted that all the biochar developed meet its conditions. These data reveal that the biochar produced have a strong capacity in the attachment of small molecules, making these biochar microporous materials. Physical activation leads to essentially microporous materials, which explains the highest index obtained from BAP biochar. This is due to the rise in temperature (500 °C) (Girgis *et al.*, 2002). Compared to non-activated biochar (BNA), iodine number and specific surfaces evolve in the same direction (they increase with activation). Our results corroborate those of some authors such as Maazou *et al.* (2017) and Balogoun *et al.* (2015).

For pH at the zero charge point (pH_{PZC}), all three types of biochar yielded values greater than 7, indicating the alkaline nature of the biochar produced. Thus, biochar will behave like acids in pH media lower than different pH_{PZC}, where the surfaces of the materials will be positively charged and predisposed to favorable binding of negatively charged species. On the other hand, they will behave as bases in media with a pH higher than pH_{PZC} for each biochar developed, where the surfaces will this time be negatively charged for a better fixation of the positively charged adsorbates (I. Sanou *et al.*, 2024), which could be the case for the adsorption of heavy metals in cationic form such as Cu^{2+}, Pb^{2+}, Zn^{2+}, Cd^{2+}. Mobarak *et al.* (2024), recorded values of 6.14 and 7.65 for biochar derived from rubber seed shells. For these authors, the difference in pHPZC values indicates that the prepared biochar has different surface properties, suggesting that they can exhibit different adsorption behaviors towards the charged species, depending on the pH of the solution (Mobarak *et al.*, 2024).

3.2.2 Trace metal element content in soils

Analyses of heavy metal concentrations in the initial soil revealed cadmium (Cd), copper (Cu) and zinc (Zn) concentrations above the limit thresholds given by the AFNOR Standard NF U44-041 (1985). The presence of Cd, Cu and Zn in high levels indicates contamination of the soil by these heavy metals (N'Dri *et al*., 2024) which represent a real danger for humans, animals and the environment (A. Sanou *et al*., 2024; Fort *et al*., 2024). Similar results were obtained by Senou *et al*. (2023a), they found heavy metal concentrations (Cd, Cu, Pb and Zn) above the toxicity threshold. The contamination of the site's soil with metals could be explained by the fact that producers use municipal waste as fertilizer in vegetable production. After the harvest, the heavy metal contents in the various treatments decreased. Nevertheless, zinc levels were still above the contamination threshold. The drop in heavy metal levels could be explained by the leaching of metal ions out of the pots. Indeed, according to Adriano (2001), Cd and Zn are the most soluble and mobile among the four metals studied. On the other hand, this decrease could be explained by the adsorption of heavy metals by biochar or their phytoextraction by lettuce. A study by Senou *et al*. (2023b) on heavy metal translocation showed higher levels of cadmium, copper, lead and zinc in post-harvest soils compared to pre-sowing soils. The discrepancy in the results between these studies could be due to the contamination of irrigation water with heavy metals, which contributed to increased levels. In addition, after the removal of biochar from soils after harvest, the results indicated that heavy metal levels were higher in the treatments that did not receive biochar followed by the treatments that received 2.5 t/ha of biochar and then those that received 5 t/ha of biochar. The explanation could come from the fact that biochar has this ability to capture heavy metals. An evaluation of the performance of different types of biochar by Omlin *et al*. (2010) showed that a doubling of the dose resulted in an almost double abatement effect. Also, trends showed that soils amended by chemically activated biochar are the least contaminated compared to soils amended by physically activated biochar and non-activated biochar. Indeed, chemically activated biochar has a larger specific surface area and is therefore more available and favorable to the adsorption process than physically activated or non-activated biochar (Gueye, 2008). In addition, according to Tseng *et al*. (2005) chemical activation changes the chemical composition of the biochar surface and makes it more reactive with cations. Physically activated biochar has many pores but does not have a highly reactive surface like that of chemically activated biochar. This could help reduce its performance in adsorbing metal ions into the soil solution, but not less than unactivated biochar which has poorly cleared pores.

3.2.3 Trace metal content in biochar

Analyses of the heavy metal content of biochar removed from the soil after harvest consistent the results of Omlin *et al*. (2010) on the effectiveness of different types of biochar. Thus, the adsorption of cadmium, copper, lead and zinc was higher than the chemically activated biochar followed by the physically activated biochar and then the non-activated biochar. In order of abundance, zinc was the most adsorbed by biochar, followed by copper, lead and cadmium. This correlates with the order of abundance at the initial ground level. From this observation, the adsorption of one heavy metal to another could depend on its content in the initial soil. Regarding heavy metals in biochar before planting, only copper and zinc were detected during the analysis. The presence of copper and zinc in biochar is explained by the fact that cotton, which was the plant used for the production of biochar, needs these metallic elements for their basal metabolism, unlike cadmium and lead, which have no use for the plant cell (Behanzin *et al*. 2014).

3.2.4 Chemical parameters of different types of biochar

The analysis of the pHwater of the different types of initial biochar gave pHwater varying between 6.65 and 9.94 respectively for the chemically activated biochar and the non-activated biochar. According to El-Naggar *et al*. (2019) biochar contains high concentrations of alkaline ash. The results also showed that biochar is rich in carbon and organic matter, so when they are added as amendments, it is likely that they lose carbon particles under the action of water. The results of this study are similar to those obtained by El-Naggar *et al*. (2019) and Guo *et al.* (2020), they showed that the addition of biochar as an amendment to the soil reduced its carbon contents. Regarding mineral elements, the contents increased only in chemically activated biochar. This could be explained by the very high fixing power of BAC compared to other types of biochar. The mineral elements would be weakly adsorbed by the latter, facilitating their leaching by irrigation water. Unlike BAC, there could be strong bonds with mineral elements. According to Abhijeet *et al.* (2023) activation increases the potential of biochar for the adsorption of heavy metals and environmental remediation. Thanks to these potentials, chemically activated biochar can trap soil nutrients more effectively and more if the dose is high to the detriment of the soil.

Conclusion

The main objective of this present study was to determine the capacity of different types of biochar to immobilize heavy metals from contaminated soils. It appears from the results obtained that the contents of cadmium (Cd), copper (Cu) and zinc (Zn) in the initial soil are higher than the threshold limit given by the AFNOR NF U44-041 (1985) standard, unlike the soil after harvest. Analysis of the biochar samples (unactivated, chemically and physically activated) revealed that they adsorbed heavy metals during the cultivation period. However, chemically activated biochar was most effective at trapping cadmium, copper, lead and zinc. Based on the doses provided, the analyzes showed that the higher the dose of biochar, the greater the quantity of heavy metals retained. Regarding the chemical parameters, the analysis of variance showed significant differences. Chemically activated biochar was the most effective in retaining nutrients followed by physically activated biochar and then non-activated biochar. In short, this study made it possible to compare the effectiveness of different types of biochar and their effects on the bioavailability of heavy metals in the soil. The results obtained could positively influence decision-making during intervention by the government on contaminated sites through the training of producers in the manufacture and use of biochar as an organic amendment. However, certain avenues of research are worth exploring. This concerns in particular the study of the effect of biochar on the bioaccumulation of heavy metals by certain hyperaccumulator plants, the physicochemical parameters of the soils and the short and long term agronomic performances.

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