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Pig manure digestate-derived biochar for soil management and crop cultivation in heavy metals contaminated soil

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Abstract

Management of heavy metal-contaminated soil under drought and other harsh hydrological conditions is critical for protecting soil ecosystem services. In this study, we examined the effect of pig manure digestate-derived biochar as a soil amendment (15 t ha^{-1}) with N fertilizer (180 kg ha^{-1}) on soil and plant heavy metal levels and nutrient availability under various moisture regimes (optimal moisture ~15%, drought condition ≤5%, and flooded condition ≥35% wt.). It was observed that biochar applications significantly decreased heavy metals in the spring wheat plants, lowering Cr by 90%, Ni by 50%, Cd by 9% and Pb by 34% compared to non-biochar (control) treatments. However, the pig digestate-derived biochar increased heavy metals in soil under all moisture regimes, increasing soil Cr by 21%, Ni by 43%, Cu by 55%, Zn by 70%, and Pb by 12%. The availability of macroelements also increased with the biochar applications under the optimum moisture regimes in both soil and plants, increasing Mg^{2+} by 11%, P by 4%, K^+ by 50%, and Ca^{2+} by 56% in the soil, and Mg^{2+} by 13%, P by 69%, K^+ by 29, and Ca^{2+} by 39% in plants. Biochar addition also improved chlorophyll fluorescence (CF) levels in the crop for the entire season (12^{th} to 62^{nd} day) and the aboveground crop biomass and dry matter contents both increased. Consequently, the use of pig manure digestate-derived biochar with N fertilizer under normal moisture conditions was able to reduce heavy metal availability to plants and thus could be used in contaminated soils to maintain better crop growth and development.

KEYWORDS
biochar, crop yield, heavy metals, land degradation, soil moisture

1 | INTRODUCTION

Industrial and agricultural activities have detrimentally affected the natural environment (Kumar et al., 2021). The substantial amount of heavy metals (HMs) released to soils through anthropogenic activities has become a global concern because of their detrimental impact on food security and human health (Girault et al., 2016; Kumar et al., 2021; Salam, Shaheen, et al., 2019). If they are transmitted through the human agri-food continuum, HM exposure can cause diseases such as cancer (Rashmi et al., 2020). Therefore, adequate action must be taken to diminish the impact of HMs in polluted soils. The use of biochar as an organic amendment is an economical and efficient way to treat hazardous substances such as HMs by lowering their bioaccumulation and availability in contaminated soils (Zhou et al., 2021).

Biochar is a black, porous carbon product that is produced through pyrolysis of organic remains such as manures, animal digestates, forests and plants residues, and other wastes under limited oxygen conditions at 200–900°C (Kumar et al., 2021; Yan et al., 2020). It has the ability to stabilize HMs by processes such as surface adsorption, ion exchange and precipitation as a result of its multiple surface functional groups, high specific surface area, alkalinity and cation exchange capacity (CEC) (Bandara et al., 2020). It is particularly effective in lowering Pb and Cd availability in soil (Chen et al., 2018; Wang et al., 2021).

To assess the effectiveness of biochar to stabilize HMs in contaminated soils, researchers have used sequential leaching procedures and discharge kinetics (Kumar et al., 2021; Wang et al., 2020). For example, Ahmad et al., 2016 reported on soya bean stover and pine-needle-derived biochar (produced at 300 and 700°C) applied at a dosage rate of 10% wt. They found it lowered the exchangeable carbonate fraction up to 79% and bound fractions of HMs, for example Pb in an alkaline, contaminated loam soil, whereas the organic matter and residual HMs fractions increased by up to 41%. One study showed that sheep manure-derived biochar and vermicompost-derived biochar (300–500°C) substantially reduced heavy metal concentration in plants (Boostani et al., 2019). It was concluded that biochar amendments significantly lowered carbonate (10%–11%) and exchangeable (10%–20%) forms of soil HMs. Additionally, rice straw-derived and rapeseed residue-derived biochar amendment at 5% (wt.) substantially lowered the easily accessible fractions of HMs, for example Pb and Cu in polluted and partially acidic soils (Salam, Bashir, et al., 2019).

Soil moisture content influences the allocation of HMs among soil phases, with impacts on soil pH, soil redox potential, transition in Fe oxides, decomposition and conversation of soil organic matter (Qi et al., 2014; Shaheen et al., 2019). However, there is limited published literature regarding the impact of soil hydrothermal conditions on the chemical forms of HMs and their adsorption in contaminated soils. In one study, the influence of different soil field capacities (FC) on HM availability in a naturally contaminated soil was observed to be lowest at 40% and highest at 80% of soil FC (Salam, Shaheen, et al., 2019). A percentage of soil HMs was transfigured from an exchangeable fragment to a less labile fragment (iron oxide phase) after incubation with water. They reported that after 180 days of water incubation, the release of HMs was restrained and reduced leaching of Cu, Zn, Cd and Pb by as much as 2%–8% (Yang et al., 2016).

The high surface area, porous structure of biochar also impacts soil moisture and, therefore, H_2SO_4-modified biochar with higher surface area has emerged with improved performance in this area (Lau et al., 2017). Numerous field studies and pot experiments have identified biochar's ability to improve crop yields and build up C stocks in several soil types, especially in nutrient-poor soils (Ali et al., 2021; Khadem et al., 2021). It is reported that due to its porous structure, biochar increases microbial activity and nutrient supply in soil and decreases nutrient loss (Ayaz et al., 2021; Egamberdieva et al., 2016). As a result of a liming effect (Köster et al., 2021), biochar encourages the provision of major macro- and micronutrients needed for plant growth (Ahmed et al., 2016; El-Bassi et al., 2021; Mandal et al., 2020). For example, one study showed that the application of rice- and cowpea-derived biochar (68 t ha^{-1}) enhanced crop biomass by 20% and 50%, respectively (Ali et al., 2021; Ayaz et al., 2021; Egamberdieva et al., 2016).

Soil contamination and degradation is a serious global issue and a threat to the United Nations' sustainable development goals (SDGs) (Hou, 2021). The shared aim of the global scientific community is to overcome the challenges of hunger, poverty, inequality, etc. (SDG, U. N., 2019). Our current research work on biochar allies with SDGs 2, 12 and 13 to end hunger, responsible consumption and production, and climate action, respectively, through increased food security, improved nutrition and sustainable agriculture (Mancini et al., 2019).

We hypothesized that the biogeochemical reallocation of HMs, the degree of HMs discharge and thus bioaccumulation may differ after applying biochar under the different soil hydrological conditions. Therefore, the objective of this research was to investigate the influence of biochar derived from pig manure digestate applied at 15 t ha^{-1} under three types of soil moisture regimes—optimal moisture (W—water content ≥15%), drought condition ($W \leq 5\%$) and flooded condition ($W \geq 35\%$) and their interactions on soil HMs release in soil and plant uptake.

2 | MATERIALS AND METHODS

2.1 | Experimental site and design

Endocalcaric Epigleyic Cambisol soil (WRB-IUSS, 2014) was obtained from the top 0–20 cm layer of a field at the Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry (55°23′49″N 23°51′40″E). The soil was air-dried and passed through a 2-mm mesh sieve. Pig manure digestate-derived biochar was manually mixed with soil at the rate of 15 t ha^{-1} and synthetic nitrogen (N) fertilizer in form of ammonium nitrate applied at a rate of 160 kg ha^{-1} (applied on day 20 after sowing). Small-sized plastic pots 27 cm diameter and 25 cm height were filled with 10 kg of soil. The pots were installed with closed-loop irrigation control system to control irrigation and soil moisture regimes. A randomized complete block design (RCBD) experiment was designed with six treatments and three replications each, for example M1B1 = (Soil and Biochar + Normal moisture regime, $W \geq 15\%$), M2B1 = (Soil and Biochar + drought condition, $W \leq 5\%$), M3B1 = (Soil and biochar + excess of moisture, $W \geq 35\%$), M1B0 = (Soil and No biochar + Normal moisture regime, $W \geq 15\%$), M2B0 = (Soil and no biochar + drought, $W \leq 5\%$ condition), M3B0 = (Soil and no biochar with excess of moisture, $W \geq 35\%$ condition). Ten seeds of spring wheat crop were sown in each pot. After two weeks, each pot was thinned and six healthy plants were left in the pots.

2.2 | Production and characterization biochar and soil

Pig manure waste was collected from an active farm. The manure was air-dried for 48 h and manually ground. The feedstock was heated at 550°C in a cylindrical furnace for 5–6 h under anaerobic conditions to produce biochar (Boostani et al., 2019). Physiochemical properties of the biochar and soil were analysed by standard laboratory methods. Soil and biochar (pH) and EC analysis was analysed as a 1:5 (vol vol^{-1}) soil mixture in 1 M KCl solution (Buneviciene et al., 2020) and extracted to distilled water (Yang et al., 2016). Cation exchange capacity was determined by the updated ammonium-acetate method (Gaskin et al., 2008). Thermo analysis of the feedstock during thermal decomposition was tested at the Lithuanian Energy Institute with thermal analyser (Netzsch Jupiter STA 449 F3). The biochar pyrolysis process was applied with a 35°C min^{-1} heating rate at the temperature range 40–900°C. To create an inert atmosphere, N2 carrier gas (60 ml min^{-1}) was used. Specific surface area was measured using Sear's method (Sears, 1956).

2.3 | Heavy metals and major nutrient analysis in soil and biochar

Dried soil and biochar samples (1 g) were mixed with 25 ml 0.1 M $CaCl_2$ solution and shaken for 2 h on an orbital shaker before being centrifuged for 15 min. The final solution was filtered and HMs analysed (Ni, Cr, Cd, Pb, Cu, Zn) using an ICP-OES (Optima 2000, PerkinElmer Co.). Soil and biochar samples were dissolved with $HF–HClO_4–HNO_3$, filtered, and then analysed by ICP-OES (Carignan & Tessier, 1988) for heavy metal fractions. Extractable nutrients P, K, Ca and Mg were measure by ICP-OES after DTPA extraction (Zaccheo et al., 2017).

2.4 | Crop biomass and dry matter analysis

Plants were harvested after 2 months. The aboveground biomass fresh weight was determined. Plants were separated into leaves, stems, roots and ear and for weighing. The aboveground dry biomass was determined after drying in an oven at 70°C until constant weight. The final grain yield was calculated by as the total number of ears per pot, the number of grains per ear and the average grain weight (Vitkova et al., 2017).

2.5 | Statistical analysis

All data sets were normally distributed and were subsequently subjected to analysis of variance (ANOVA) followed by the least significant difference (LSD) test. All data analyses were carried out using Statistix 8.1 and GraphPad PRISM 8 software. The ranked coefficient analysis was performed using R-studio software.

3 | RESULTS

3.1 | Effect of biochar on soil heavy metals

Heavy metal (HM) contents varied in soil under different treatments and moisture regimes. The biochar amendment significantly enhanced Cr content in soil (by 12.35%, $p \leq .01$) compared to no biochar amendment (Figure 1a). Biochar application and optimal moisture significantly increased ($p \leq .01$) Ni by 59.67% and 80%, Cu by 19.90%, 38.90%, Zn by 18.93%, 41.01% and Pb by 16.02%, 38.8% in soil compared no biochar application and drought condition, respectively (Figure 1b,c,d,f). However, Cd content decreased in soil under drought conditions compared to 15% and 35% moisture regimes (Figure 1e), whereas no significance was recorded after biochar application. The factorial interaction of treatments also showed significant variation among all treatments.

The flooded moisture condition with 15 t ha^{-1} of biochar (M3B1) significantly enhanced the Cr content by 21% ($p \leq .05$) in soil compared to non-biochar treatments under optimal moisture regime (Figure 1a). Ni content was substantially increased by 42.96%

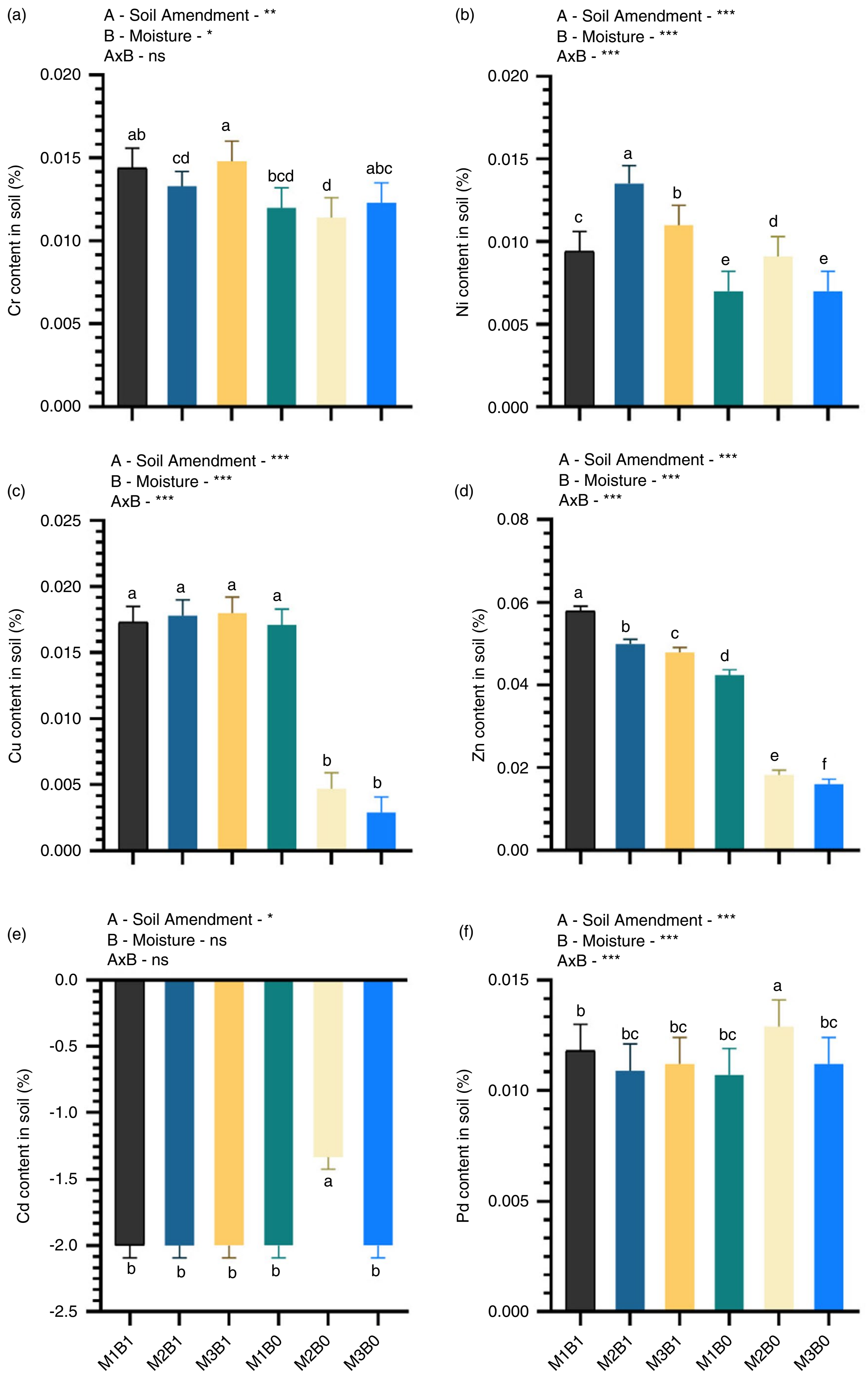
(a)
A - Soil Amendment - **
B - Moisture - *
AxB - ns
Cr content in soil (%)
0.020
0.015
0.010
0.005
0.000
ab
cd
a
bcd
d
abc
(b)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Ni content in soil (%)
0.020
0.015
0.010
0.005
0.000
c
a
b
e
d
e
(c)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Cu content in soil (%)
0.025
0.020
0.015
0.010
0.005
0.000
a
a
a
a
b
b
(d)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Zn content in soil (%)
0.08
0.06
0.04
0.02
0.00
a
b
c
d
e
f
(e)
A - Soil Amendment - *
B - Moisture - ns
AxB - ns
Cd content in soil (%)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
b
b
b
b
a
b
(f)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Pd content in soil (%)
0.015
0.010
0.005
0.000
b
bc
bc
bc
a
bc
M1B1
M2B1
M3B1
M1B0
M2B0
M3B0

FIGURE 1 The interactive effect of moisture and biochar on soil heavy metals, for example (a) Chromium, (b) Nickel, (c) Copper, (d) Zinc, (e) Cadmium and (f) Lead. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001), respectively

($p \leq .05$) with biochar amendment under drought condition (M2B1) compared to all no biochar treatments and M1B1 (Figure 1b). All biochar-treated soils under all types of moisture regimes significantly (by 55.36%, $p \leq .05$) enhanced Cu content in soil compared to non-biochar treatments (Figure 1c), except the M1B0 treatment where Cu content was similar to the biochar-amended treatments. Zn content in soil significantly increased by 70.46% ($p \leq .05$) in the biochar treatment under optimal moisture regime (M1B1) compared to non-biochar treatments with drought (M2B0) and flooded (M3B0) conditions (Figure 1d). However, soil Cd content decreased during the experiment period under different moisture regimes with biochar amendments compared to drought condition without biochar (M2B0) application (Figure 1e). Pb was the only heavy metal found to be significantly higher in soil (by 12.40%, $p \leq .05$) under drought condition without biochar (M2B0) application (Figure 1f). Overall, pig manure-derived biochar amendments with different moisture regimes enhanced the content of all heavy metals in soil, except Cd.

3.2 | Effect of biochar on plant heavy metals

The biochar amendment reduced Cd, Pb, Cr and Ni contents in crops; however, the strength of this influence depended on the moisture regime (Figure 2). Biochar application under optimal moisture conditions (M1B1) caused 88.9% lower Cr content than under drought (M2B1) or moisture excess (M3B1) conditions. Biochar application reduced Ni content in crops under all moisture regimes, especially in drought conditions. Biochar amendment was most beneficial for Cd and Pb content reduction in crops under optimal and excess moisture conditions. An effect of biochar over no-biochar was registered only for reduction of Ni and Pb accumulation in crops. Whereas in treatments with biochar application, Cu and Zn accumulation in crop tended to rise compared to no-biochar treatments. Figure 2 reflects that biochar significantly immobilized Cr, Ni and Pb content in plants under different moisture regimes and enhanced Cu and Zn content in biochar-treated plants under drought condition (M2B1).

3.3 | Effect of biochar on major elements in soil

Biochar application affected major elements, although this was dependent on soil moisture content. On average, P and Ca content was substantially higher (46.63% and 13.38%, respectively, $p \leq .01$) with biochar amendment compared to non-biochar application. However, the effect of biochar on soil K and Mg content was not so high (5.81% and 3.34%, respectively). Drought and moisture excess decreased biochar contribution for accumulation of soil elements. Biochar application under optimal moisture had a significant ($p \leq .001$) effect on increasing P, K, Mg and Ca content (by 37.34%, 9.39%, 12.68% and 11.10%, respectively), compared to drought and flooded conditions without biochar application (Figure 3). The factorial interaction of treatments revealed substantial effect on soil major elements. Optimum moisture regime at 15 t ha^{-1} of biochar application significantly ($p \leq .001$) enhanced soil P, K, Mg and Ca content (by 49.79%, 13.29%, 10.53% and Ca 29.11%, respectively), compared to no biochar under optimum moisture condition. These results indicate that the interaction of biochar and optimal moisture (15%) in treatment M1B1 could be a good strategy to improve soil major element accumulation.

3.4 | Effect of biochar on major elements in plants

Biochar as soil amendment increased crop nutrient accumulation. Data averaged across soil moisture regimes revealed that biochar caused significantly higher P content in plants (36.60%, $p \leq .01$) compared to non-biochar treatments. Mean data showed that moisture had no significant influence on plant P content (Figure 4a). The rest of the major elements, that is K, Mg and Ca were significantly ($p \leq .01$) affected by both factors (biochar and moisture). Plant K, Mg and Ca content in treatments M1B1, M2B1 and M3B1 were higher by 18.13% + 3.91%, 3.71% + 14.28% and 17.29% + 27.17%, respectively, compared to treatments M1B0, M2B0 and M3B0 (Figure 4b–d). The best results were obtained after biochar amendment under optimum moisture regimes (M1B1). In this treatment, P, K, Mg and Ca contents were higher by 55.62%, 68.95%, 3.80% and 38.52%, respectively, compared to the same moisture

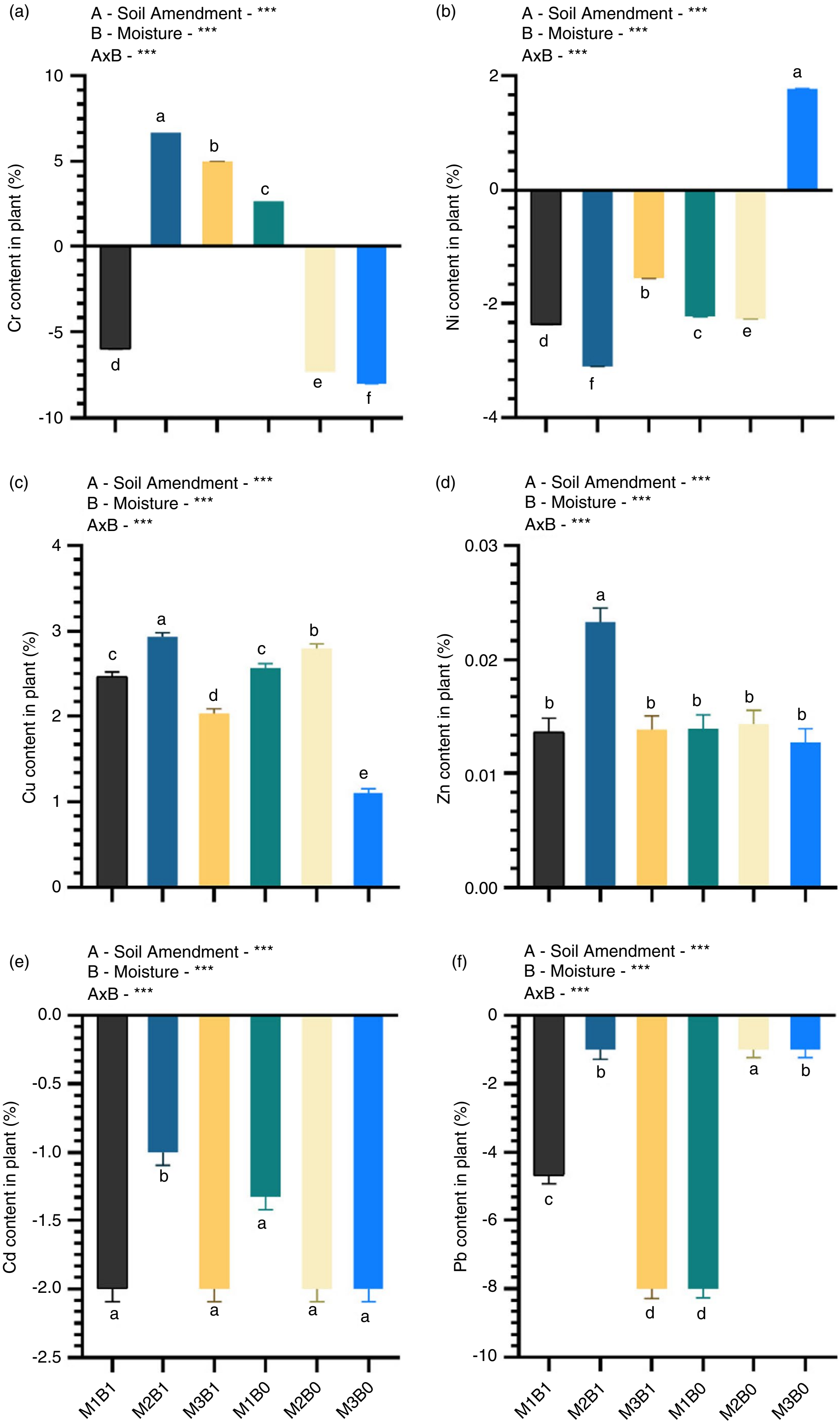
(a)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Cr content in plant (%)
(b)
Ni content in plant (%)
(c)
Cu content in plant (%)
(d)
Zn content in plant (%)
(e)
Cd content in plant (%)
(f)
Pb content in plant (%)
M1B1
M2B1
M3B1
M1B0
M2B0
M3B0

FIGURE 2 The interactive effect of moisture and biochar on plants heavy metals, for example (a) Chromium, (b) Nickel, (c) Copper, (d) Zinc, (e) Cadmium and (f) Lead. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001), respectively

condition with no biochar application (Figure 4a–d). It is concluded that biochar application under moisture ≤5% and 15% (treatments M1B1 and M2B1) could improve major element accumulation in plants compared to non-biochar treatments.

3.5 | Impact of biochar on chlorophyll fluorescence and chlorophyll index

The influence of different moisture regimes on chlorophyll fluorescence (CF) during the whole season was insignificant; however, biochar substantially ($p \le .01$) increased CF throughout the season, for example on day 12th, 20th, 27th, 34th, 47th and 62nd (i.e. by 21.29%, 20.21%, 23.95%, 10.44%, 14.52% and 9.28%, respectively) compared to non-biochar treatments (Figure 5a). Moisture regimes did not highlight significant differences under biochar application (Figure 5a).

Similarly, the effect of different moisture regimes on chlorophyll index (CI) was non-significant; however, biochar amendment substantially ($p \le .01$) increased CI on day 12th, 20th, 27th, 34th, 47th and 62nd (by 21.50%, 9.20%, 21.56%, 6.64%, 13.96%, and 20.35%, respectively), compared to non-biochar treatments (Figure 5b). These results reflect that biochar application irrespective of moisture regimes can impact both CF and CI.

3.6 | Impact of biochar on aboveground biomass and dry matter content

Biochar application to the soil as an amendment significantly *($p \le .001$)* enhanced aboveground biomass

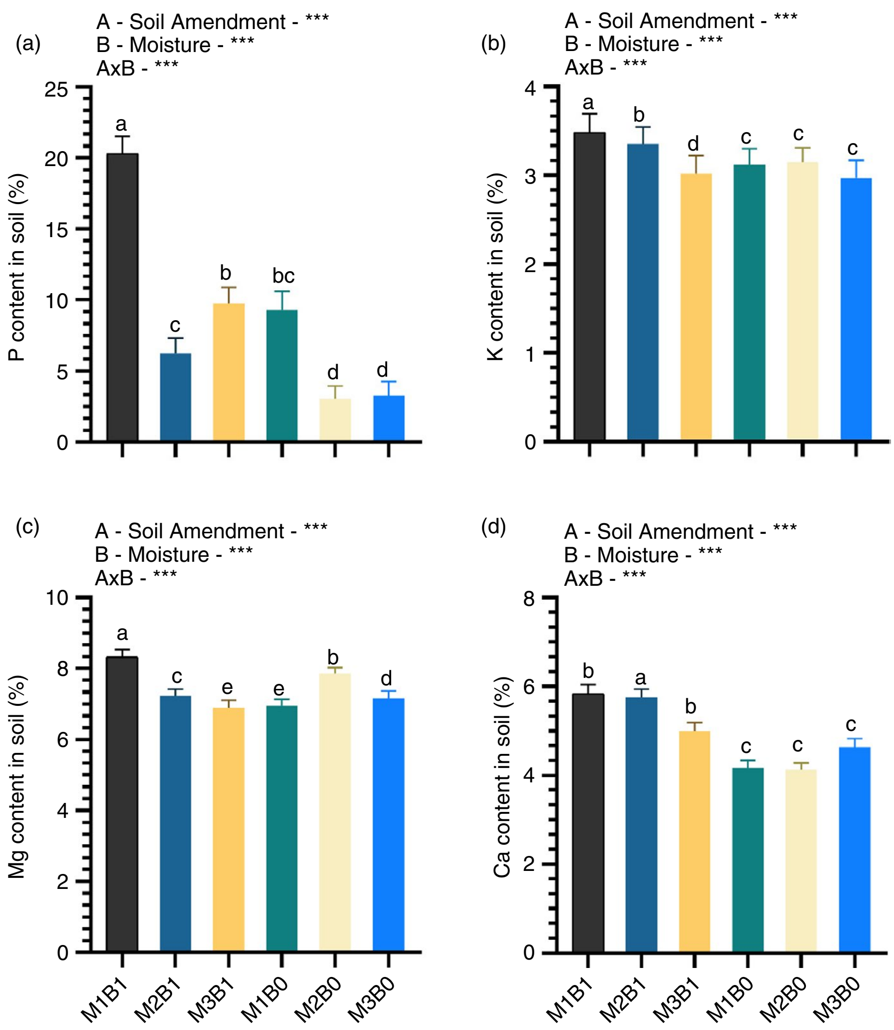

FIGURE 3 The interactive effect of moisture and biochar on major elements in soil, for example (a) Phosphorus, (b) Potassium, (c) Magnesium and (d) Calcium. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001) respectively

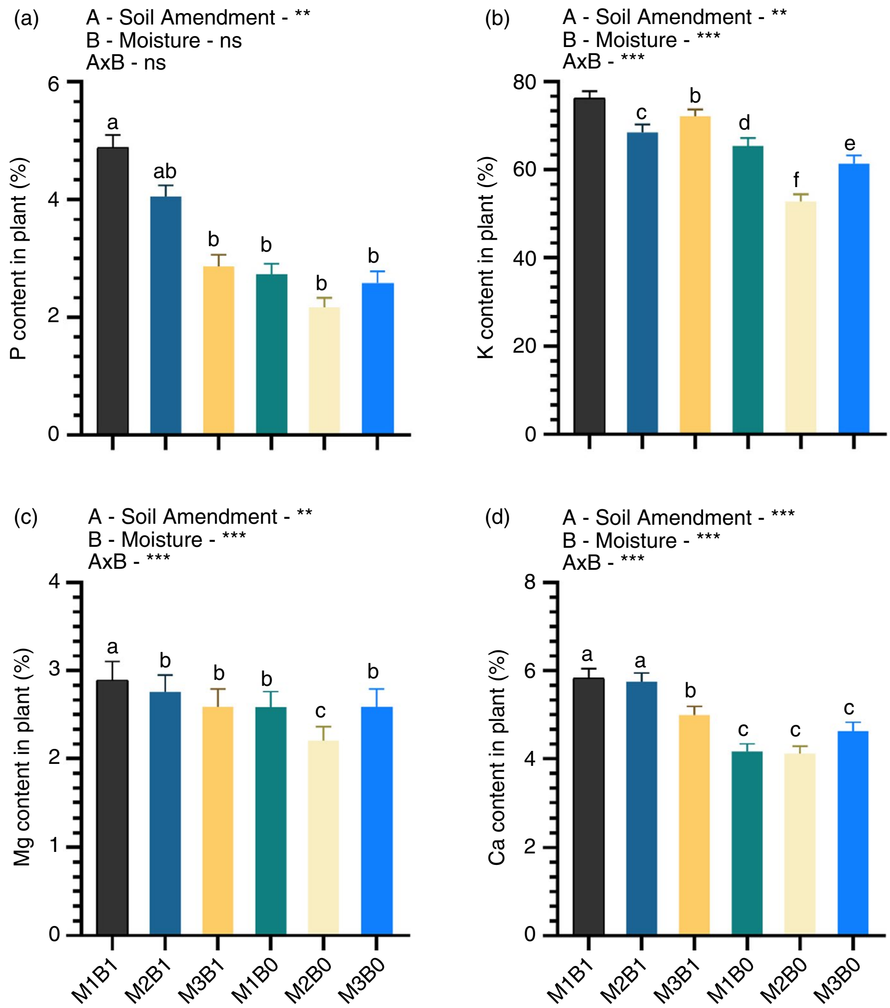

FIGURE 4 The interactive effect of moisture and biochar on major elements in plants, for example (a) Phosphorus, (b) Potassium, (c) Magnesium and (d) Calcium. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001) respectively

(AGB) and dry matter content (DMC) irrespective of different moisture regimes. Factorial interaction in treatments M1B1, M2B1 and M3B1 significantly ($p \leq .05$) enhanced AGB compared with that in M1B0, M2B0 and M3B0 (by 71.87%, 66.66% and 68.64%), respectively (Figure 6). Similarly, the combination of biochar and moisture (M1B1, M2B1 and M3B1) caused significantly ($p \leq .05$) higher DMC (by 45.83%, 55.17% and 40.90%, respectively) compared with that in M1B0, M2B0 and M3B0 (Figure 3b). Thus, it indicates that biochar amendment under different moisture conditions could improve biomass, compared to no biochar applications.

3.7 | Relationship among heavy metals and major elements of soil and plant

A ranked coefficient analysis was performed among the heavy metals and major elements of soil and plants (Figure 7). All variables were significantly and positively correlated with each other. An exception was Pb, which showed negative relationship with Ca contents in plants. While Cr content in soil showed positive significant correlation with soil Cu, Zn, K and P content. Similarly, Cr content in plants showed significant positive correlation with soil Cr, Cu, Zn, Ni, Cr, K and P contents and plant K contents.

4 | DISCUSSION

4.1 | Response of biochar on heavy metals in soil and plants

The pig manure digestate-derived biochar used was rich in heavy metals (Table 1) which has also influenced heavy metal content in soil (Figure 1). Previously, it was reported that traditionally weaned pigs were fed pharmacological heavy metals (Hill et al., 1996; Smith et al., 1997), which may have led to higher heavy metal content in biochar and thereby biochar treatments significantly increased heavy metal content in the soil (Figure 1). Beesley et al. (2015)

reported that refurbishing of heavy metal–contaminated bases may be considered appropriate for soil amendment, particularly where the impact is the accessibility of certain metals. The evident case is Zn, Ca, Cu, etc. a vital plant nutrient and essential element to strengthen fodder but, in large, a toxin.

Our results showed that Cd content in soil was lowered (Figure 1). The exchangeable Cd content response to pH is essential to understand the influence of biochar on the bioavailability of Cd. It is reported that increase in soil pH causes hydrolysis of heavy metal cations to form oxides, which lowers the soil exchangeable Cd content (Chen et al., 2020). Furthermore, several studies have documented that biochar amendment can substantially affect the absorption and reabsorption of heavy metals in soil (Wang & Zhou, 2003; Yuan et al., 2011). Biochar application adds large amount of organic matter into soil which has active groups, thus facilitating chelation and complexation with Cd as ligands, which consequently reduces the Cd availability in soil (Zhu et al., 2008).

Biochar reduced heavy metals in plants (Figure 2) which was confirmed by Liu, Huang et al. (2021) where sewage sludge biochar (500–550°C) and broiler litter-derived biochar (700°C) substantially reduced heavy metals in plants due to the fact of splitting of metals from exchangeable form to less bioavailable organic bond proportion. The positive side that biochar immobilize heavy metals was attributed to enhancing the absorptive capacity of soil by altering the physical and chemical characteristics, as well by means of dynamoelectric attraction, cation and anion exchange, and physical absorptivity (He et al., 2019). Other sorption factors influenced by biochar include soil organic and mineral matter content, soil pH and CEC.

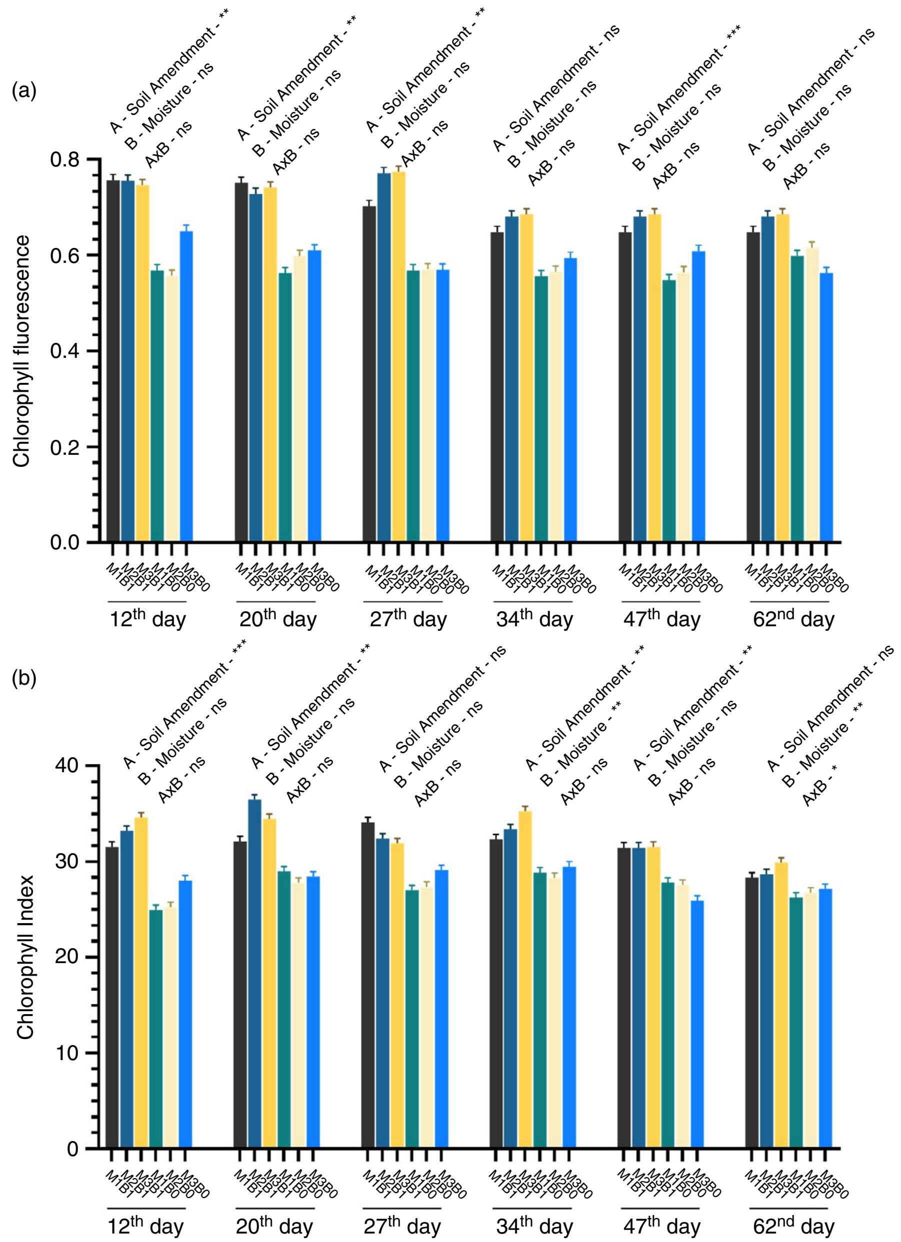

FIGURE 5 The interactive effect of moisture and biochar on (a) chlorophyll fluorescence and (b) SPAD chlorophyll index. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001) respectively

4.2 | Effect of biochar on major elements in soil and plants

Several studies have documented that moisture conditions can significantly impact the soil nutrients and plant, morphological properties and biological variables (Ghanbary et al., 2018; Jafarnia et al., 2018). The current research indicates that major elements in soil and plants were positively affected under biochar treatment (M2B1) compared to non-biochar treatments under the same moisture regimes (Figures 3 and 4). Consequently, the negative effects of comparative moisture regimes are bounded by biochar application. Various reasons were reported for the ameliorative behaviour of biochar, that is application of biochar enhances fine pore structure, improves surface area (Kalus et al., 2019) and increases soil aeration and porosity which leads to strengthening the soil bulk density (Bd) and water holding capacity (WHC) (Chang et al., 2021; Guo et al., 2021; Xie et al., 2021).

Plant nutrient uptake and soil nutrient absorption (Mg, P and K) was substantially improved via biochar amendment under optimal moisture regimes (Figure 4). This is because of the biochar's richness in major nutrients which were released into soil after mineralization (Farhangi-Abriz & Ghassemi-Golezani, 2021; Plaimart et al., 2021); improvement in soil microbial density and WHC and reduction in nutrient lost could be attributed as the secondary impacts of biochar amendment (Kanthle et al., 2016; Tian et al., 2018). Similar results were reported by Farrar et al. (2021) where bamboo-derived biochar remarkably increased trace elements in plants and soil. Our results were also in line with those of Ref. (Liu et al., 2020; Zhang et al., 2020) who indicated that biochar application enhanced trace elements Mg, P and K in soil and plants.

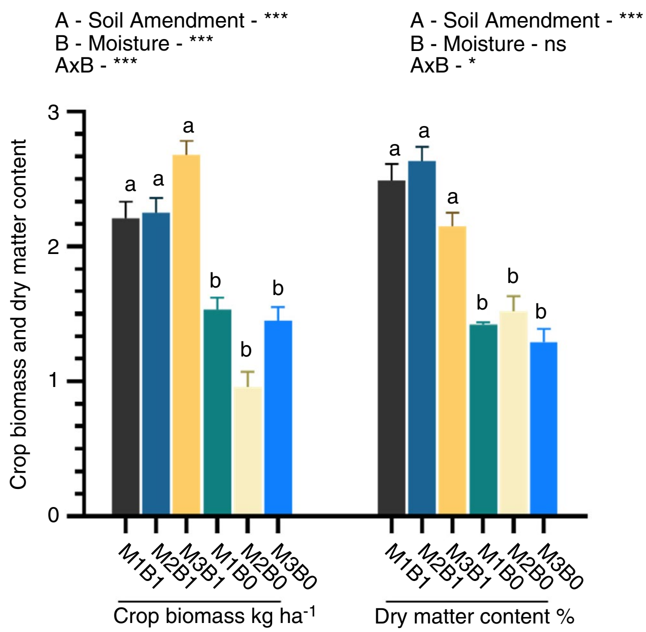

FIGURE 6 Response of moisture regimes and biochar on crop biomass and dry matter content under different moisture regimes. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001) respectively

4.3 | Impact of biochar on chlorophyll fluorescence and chlorophyll index

The effects of soil moisture condition on plants depends on its severity and plant genotypic condition (Vijayaraghavareddy et al., 2020). In the current research, physiological properties such as chlorophyll fluorescence and chlorophyll index significantly increased with each time interval under biochar treatments M1B1, M2B1 and M3B1, thus lowering the adverse effect of drought stress compared to non-biochar treatment (Figure 5). When a plant is subjected to drought conditions, it closes the stomata to maintain homeostasis and consequently lowering leaf transpiration. Stomata closure could provoke a deterioration in the photosynthetic rate under drought conditions (Hereme et al., 2020).

Major elements (P, K and Mg) can induce the transformation of photosynthetic electrons (Saccon et al., 2020) and regulate osmotic potential (Hafeez et al., 2017; Walter & Rajashekhar Rao, 2015). Biochar application could substantially enhance nutrient fraction in leaves (Hafez et al., 2020; Tanazawa et al., 2021); therefore, biochar application can mitigate these adverse consequences and ameliorate the chlorophyll fluorescence and chlorophyll index (Paneque et al., 2016; Subhan et al., 2014). Furthermore, photosynthetic activity can be severely influenced by soil hydrological condition and stress injury (Lyu et al., 2016). Previously, it was indicated that biochar amendment altered soil hydrological condition for plants by improving WHC and increasing the leaf water condition (Gao et al., 2020; Liu, Wei et al., 2021). Consequently, in this work, it was recorded that biochar application to soil could lower the adverse impact of waster stress on the photosynthesis.

4.4 | Influence of biochar on aboveground biomass and dry matter content

Biochar has been proposed as a potential soil amendment to improve soil quality and increase aboveground biomass (Banik

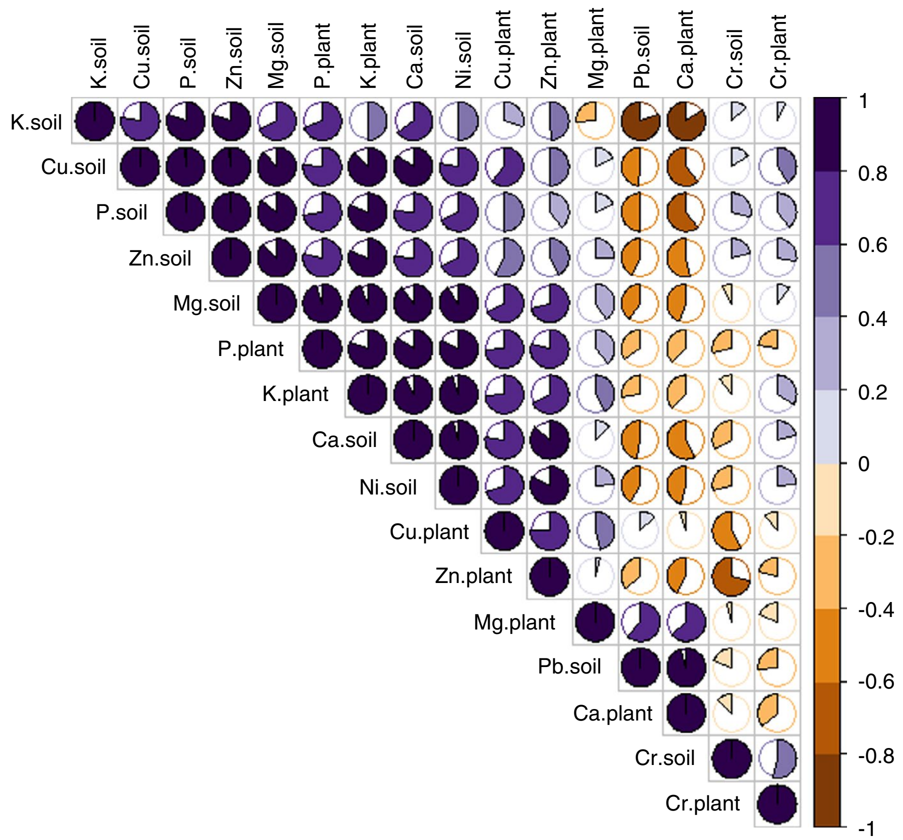

FIGURE 7 Correlation rank coefficient among major elements and heavy metals in soil and plant

TABLE 1 Physiochemical properties of soil and biochar prior to experiment

Physiochemical properties	Soil	Biochar
pH	7.5	9.1
Ash content (%)	–	32.21
Moisture wt. (%)	–	2.52
Volatiles wt. (%)	–	56.73
Residual mass (char formed) wt. (%)	–	40.75
Cr (%)	0.0113	0.0112
Ni (%)	0.010	0.014
Cu (%)	0.003	0.216
Zn (%)	0.020	0.444
Cd (%)	0.0001	0.0001
Pb (%)	0.011	0.002
Mg (%)	7.33	13.07
P (%)	0.31	18.11
K (%)	3.21	14.27
Ca (%)	10.12	75.51

et al., 2021; Elias et al., 2020) and dry matter content (Yakubu et al., 2020) particularly on degraded or highly weathered tropical soils. In the current study, pig manure digestate-derived biochar treatments (M1B1, M2B1 and M3B1) significantly enhanced aboveground biomass and dry matter compared to non-biochar treatments (Figure 6). These results were in line with Feng et al. (2021) ; Gupta et al. (2020) who applied corn straw-derived biochar and rice straw-derived biochar (5 Mg ha^{-1}) enhance crop biomass, respectively.

When biochar is applied, there is mutually reinforcement among the soil pH and ions released from biochar, which ultimately improve crop yields (Feng et al., 2021; Pulka et al., 2020). Simply put, it has ability to strengthen deteriorated soil and enhance crop production by upgrading soil quality (Zahra et al., 2021). Numerous studies have reported that biochar amendment to soil lowers soil bulk density (Chang et al., 2021; Liang et al., 2021), enhances and retains soil nutrients and organic matter content, and significantly improves soil microbiota plant growth and fruit quality (Arif et al., 2021; Jin et al., 2021; You et al., 2021).

5 | CONCLUSION AND RECOMMENDATION

The conclusions of this study are as follows:

1. Pig manure digestate-derived biochar could be a potential soil amendment for soil and plant quality improvement. At the first growing stages of spring

wheat, it significantly decreased heavy metal concentration in plants, lowering Cr by 90%, Ni by 50%, Cd by 9% and Pb by 34% compared to non-biochar treatments. However, the pig manure digestate biochar also increased heavy metals in soil under all moisture regimes, for example (Cr 21%, Ni 43%, Cu 55%, Zn 70% and Pb 12% content, respectively).
2. Biochar application significantly improved major elements (P, K, Mg and Ca) in both soil and plants under different moisture regimes. The highest concentration of those elements was found under the optimal soil humidity, while drought and flooded regimes may be the reason of loss of those elements, especially flooded soils which have high risk for leaching.
3. Plant vitality may be described by their chlorophyll fluorescence and chlorophyll index. After adding biochar to the soil, these improved throughout the growing interval (from day 12 to 62), which led to enhanced aboveground biomass and dry matter content.

For future work, we hypothesize that using different dosses of biochar as a soil amendment could have more significant results in highly contaminated and degraded soils. Further experiments are needed to analyse the long-term effect on soil and on crop quality and productivity.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

All authors contributed to this research paper. Muhammad Ayaz had the idea for the article; performed practical and the literature search, data preparation, analyses and figures; and wrote the first draft. Dalia Feizienė and Vita Tilvikienė critically revised the work and contributed to writing and editing; Urte Stulpinaitė performed laboratory work; and Kashif Akhtar, Edita Baltrėnaitė-Gedienė, Monika Toleikienė, Modupe Doyeni, Nerijus Striug, Sahib Alam and Rashid Iqbal helped in biochar preparation and contributed to article conception, critical revision and editing of drafts. All authors read and approved the final version of the manuscript.

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