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Synergistic Effect of Biochar and Organic Fertilizers on Tomato Growth, Fruit Quality, and Yield in Heavy Metals-Contaminated Soil

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ABSTRACT

This study presents a novel, integrative approach to remediating heavy metal-contaminated soils by evaluating the synergistic effects of biochar in conjunction with multiple organic fertilizers such as farmyard manure (FYM), spent mushroom compost (SMC), and leaf mould (LM) on the growth, yield, and fruit quality of tomato (Solanum lycopersicum). Unlike previous research, which has predominantly assessed these amendments in isolation, our work systematically explores their combined application, offering new insights into their interactive effects on both plant productivity and heavy metal mitigation. The experiment was conducted at the Agriculture Research Station (Merged Areas) District Bajuar during the 2022 and 2023 growing seasons, utilizing a randomized complete block design (RCBD) with two factors: biochar applied at 0.0%, 1.0%, 1.5%, and 2.0% (w/w), and organic fertilizers (FYM, SMC, LM) at 2% and 3% (w/w) concentrations. Tomato seedlings (cv. Rio Grande) were transplanted into soils sourced from mining-affected sites, characterized by elevated levels of heavy metals. Results demonstrated that biochar application, particularly at 2%, significantly improved key agronomic and quality parameters, including plant height (67.53 cm), leaf area (41.68 cm2), and yield (9.45 t ha^{-1}). Notably, biochar treatments also enhanced ascorbic acid, lycopene, and carotenoids, while markedly reducing the accumulation of toxic metals in fruit tissues (2.55 mg kg-1), which remains within the maximum permissible limit set by the WHO. Organic fertilizers further contributed to these improvements, with 3% FYM yielding the highest plant height and fruit yield, and 3% SMC optimizing ascorbic acid, total phenolic content, and lycopene levels alongside a pronounced reduction in fruit heavy metal concentrations (2.39 mg kg-1) which remains within the maximum permissible limit set by the WHO. The combined application of 2% biochar with 3% FYM resulted the most substantial gains in plant growth and yield, whereas the pairing of 2% biochar with 3% SMC maximized fruit quality indices.This dual amendment strategy showed better results than using biochar or organic fertilizers alone, clearly demonstrating a synergistic effect in increasing tomato yield and reducing heavy metal uptake. The results highlight that applying 2% biochar together with 3% organic fertilizer (either FYM or SMC) is an effective and sustainable way to boost tomato growth, quality, and yield while minimizing heavy metal contamination in polluted soils.

INTRODUCTION

Agricultural soils worldwide are increasingly threatened by heavy metal contamination, a challenge that not only impairs plant growth but also poses significant risks to food safety and human health. Heavy metals such as cadmium (Cd) and lead (Pb) disrupt essential physiological and biochemical processes in plants. Cadmium, for instance, interferes with photosynthesis, nutrient uptake, and water absorption, resulting in stunted growth and reduced yields. Similarly, lead toxicity can inhibit root elongation and key enzymatic activities, further compromising plant metabolism (Benavides et al., 2005).

The contamination of agricultural soils with heavy metals is a growing concern for global food security, as it adversely affects both crop productivity and the safety of agricultural produce. Tomato (*Solanum lycopersicum*) cultivation on contaminated soils is particularly problematic because tomatoes are prone to accumulating heavy metals in their tissues, including the edible fruits, thereby introducing these toxic elements into the food chain (Tyagi et al., 2014). Although the highest concentrations of heavy metals are often found in leaves and stems, significant amounts can also accumulate in the fruits, increasing the risk to consumers. The root system is the primary site for heavy metal uptake, with metals absorbed alongside water and nutrients and subsequently translocated to aerial parts, making both leaves and fruits unsafe for consumption (Shahid et al., 2014; Yadav, 2010). Additionally, heavy metal stress can hinder reproductive development in tomatoes, leading to fewer flowers, reduced fruit set, and smaller fruit size, which collectively diminish yield and quality (Rizwan et al., 2016).

To address these challenges, the use of soil amendments such as biochar and organic fertilizers has gained attention as a sustainable remediation strategy. Biochar, produced through the pyrolysis of organic materials, has emerged as an effective phyto-stabilization technology. It can immobilize heavy metals, reduce their mobility and bioavailability, and improve soil physical and chemical properties, including nutrient retention (Fellet et al., 2011). Alongside biochar, organic amendments such as farmyard manure (FYM), spent mushroom compost (SMC), and leaf mould (LM) can further improve soil structure and fertility, bind heavy metals, and enhance plant growth (Park et al., 2011; Ahmad et al., 2014).

Despite the demonstrated benefits of these amendments when used individually, there is limited research on their combined effects. Exploring the synergistic potential of biochar and diverse organic fertilizers may offer a more effective and sustainable approach to mitigating heavy metal toxicity in contaminated soils while improving crop yield and quality. This study aims to evaluate the interactive effects of biochar and multiple organic fertilizers on tomato growth, fruit quality, and heavy metal accumulation in contaminated soils, providing practical insights for safer and more productive tomato cultivation.

MATERIALS AND METHODS

Experimental Site and Plant Material

This experiment was conducted at the Agriculture Research Station (Merged Areas) District Bajuar Pakistan, during the 2022 and 2023 growing seasons. The study aimed to evaluate the synergistic effects of biochar and organic fertilizers on tomato (*Solanum lycopersicum* L. cv. Rio Grande) growth, fruit quality, and yield in heavy metal-contaminated soil. Tomato seeds were sown in January 2022 to raise seedlings for transplantation. The seeds were sown in raised nursery beds in the third week of January using a 1:1:1 mixture of silt, garden soil, and compost as the growing medium. Beds were covered with polythene sheets to maintain optimal germination conditions. Seedlings at the 3–4 leaf stage were transplanted into experimental units containing the prepared soil mixtures.

Heavy Metals Contaminated Soil Collection

Soil was collected from vegetables growing fields in Prang Ghar, Mohmand agency, which included soil mixtures from chromites, soapstone, and manganese mines, known for high levels of heavy metals. The soils from different sites were thoroughly mixed to ensure homogeneity and used as the contaminated growth medium for the experiment.

Preparation and Sourcing of Amendments

Biochar was produced from hardwood (Mulberry) via pyrolysis and sourced from the Department of Environmental Sciences, University of Peshawar. Farmyard manure (FYM) and leaf mould (LM) were obtained from the ornamental plant nursery, Department of Horticulture, while spent mushroom compost (SMC) was collected from the mushroom house, Department of Plant Pathology, the University of Agriculture Peshawar.

Experimental Setup

Plastic bags (30 cm height × 15 cm width) were filled with a 2:1 mixture of garden soil and contaminated soil and weight to 5 kg. Biochar was incorporated at rates of 0.0%, 1.0%, 1.5%, and 2.0% (w/w), while organic fertilizers (FYM, SMC, LM) were each applied at 2% and 3% (w/w) concentrations. Each treatment combination was thoroughly mixed with the soil before transplanting the tomato seedlings. The experiment was arranged in a Randomized Complete Block Design (RCBD) with two factors: biochar levels (0, 1.0%, 1.5%, and 2.0%) and organic fertilizers (FYM, SMC, and LM at 2% and 3%) for each treatment. The tomato seedlings were transplanted into pots with contaminated soil, and the treatments were replicated three times, with 28 treatments, resulting in 84 experimental units and 420 plants in total.

Studied Attributes

A comprehensive set of morphological, physiological, yield and quality parameters were measured to assess the effects of biochar and organic fertilizers on tomato plants grown in heavy metal-contaminated soil. Leaf area (cm^2) was determined using a leaf area meter (C1-202 Area Meter, USA), while leaf chlorophyll content was quantified with a SPAD chlorophyll meter (SPAD-502, Minolta, Japan) to evaluate the photosynthetic potential of the plants. Fruit yield ($t\ ha^{-1}$) was calculated by summing the total fruit weight harvested from each experimental unit and extrapolating to a per-hectare basis. Fruit firmness (N/m^2), an important indicator of postharvest quality, was measured using a pressure tester following the method described by Pocharski et al. (2000). Nutritional quality attributes were also assessed: ascorbic acid content (mg $100g^{-1}$) was determined using the indophenol titration method according to AOAC (2006); lycopene and total carotenoids (mg $100g^{-1}$) were estimated spectrophotometrically following the protocols of Scott (2001), Fish et al. (2002), and Srivastava and Kumar (2004), respectively. Total phenolic content was measured using the Folin-Ciocalteu reagent method (Mazumdar and Majumder, 2003), and antioxidant activity (%) was evaluated by the DPPH radical scavenging assay as described by Huang et al. (2005). To assess food safety, heavy metal concentrations (Pb, Cd and Cr) in tomato fruits were analyzed. Fruits were oven-dried, ground to a fine powder, and digested with a mixture of nitric and hydrochloric acids, followed by quantification using atomic absorption spectrophotometry (Richard, 1954). These parameters provided a holistic evaluation of plant growth, fruit quality, and heavy metal mitigation under different amendment treatments.

Statistical Analysis

Data were analyzed using Analysis of Variance (ANOVA) with Statistix 8.1 software, and significant differences were determined using the Least Significant Difference (LSD) test (Steel et al., 1997).

RESULT AND DISCUSSION

Plant Height (cm)

Tomato plants treated with biochar showed a significant increase in plant height compared to the control. The tallest plants (67.53 cm) were recorded with 2% biochar, followed by 64.34 cm and 63.32 cm with 1.5% and 1.0% biochar, respectively. The control treatment (without biochar) had the shortest plants (58.09 cm). Regarding organic fertilizers, the tallest plants (68.51 cm) were observed with 3% farmyard manure (FYM), followed by 64.98 cm with 3% spent mushroom compost (SMC) and 2% FYM. The shortest plants (59.79 cm) were found in the control without organic amendments (Table 1). The interaction between biochar and organic fertilizers was significant, with the maximum plant height (72.10 cm) recorded for the combination of 2% biochar and 3% FYM, followed by 71.02 cm with 1.5% biochar and 3% FYM. The lowest height (57.86 cm) was observed in the combined control without amendments (Fig I). The increase in plant height due to biochar application is attributed to improvements in soil water retention, nutrient availability, and microbial activity, which collectively promote better plant growth (Bista et al., 2019; Joseph et al., 2021). Organic fertilizers enhanced soil fertility and nutrient supply, further supporting growth (Hameeda et al., 2019; Gul and Whalen, 2016). The significant interaction between biochar and organic fertilizers indicates a synergistic effect, where biochar improves soil physical and chemical properties, and organic fertilizers supply essential nutrients and stimulate microbial populations, resulting in enhanced tomato growth. This combined amendment approach effectively mitigates heavy metal stress and supports sustained plant development (Bista et al., 2019; Joseph et al., 2021; Hameeda et al., 2019).

Leaf Area (cm²)

Leaf area significantly increased with biochar application. The maximum leaf area (41.68 cm^2) was recorded with 2% biochar, followed by 38.51 cm^2 with 1.5% biochar. The control without biochar had the smallest leaf area (33.74 cm^2). Among organic fertilizers, 3% FYM produced the largest leaf area (43.42 cm^2), followed by 41.21 cm^2 with 3% SMC. The control without fertilizers showed the lowest leaf area (30.70 cm^2) (Table 1). The combination of 2% biochar and 3% FYM resulted in the highest leaf area (48.84 cm^2), followed by 47.37 cm^2 with 2% biochar and 2% FYM. The lowest leaf area (28.60 cm^2) was recorded in the combined control (Fig II).

Biochar improves soil structure and nutrient availability while reducing soil toxicity, which promotes leaf expansion and overall vegetative growth. Organic fertilizers enhance soil fertility and water retention, further contributing to increased leaf area. The synergistic effect observed with combined biochar and organic fertilizer application provides optimal soil conditions for tomato growth, resulting in larger leaf areas and improved plant performance (Sharma and Bhalla, 1993; Sugel et al., 2011).

Chlorophyll Content (SPAD)

Chlorophyll content increased significantly with biochar application. The highest chlorophyll content (38.73 SPAD) was observed with 2% biochar, followed by 37.15 SPAD with 1.5% biochar. The control had the lowest chlorophyll content (32.86 SPAD). Among organic fertilizers, 3% FYM yielded the highest chlorophyll content (38.41 SPAD), followed by 37.03 SPAD with 3% SMC. The control without organic fertilizers had the lowest value (33.52 SPAD) (Table 1). The combination of 2% biochar and 3% FYM resulted in the highest chlorophyll content (48.84 SPAD). Biochar enhances soil pH, moisture retention, and nutrient availability, particularly nitrogen, which is essential for chlorophyll synthesis. Additionally, biochar reduces heavy metal toxicity, positively influencing chlorophyll production (Lehmann & Joseph, 2015; Spokas, 2010). Organic fertilizers supply vital nutrients and improve soil health, further boosting chlorophyll content. The combined application synergistically enhances nutrient availability and soil structure, supporting improved photosynthetic capacity (Kavita and Subramanian, 2007; Yadav et al., 2007).

Tomato Fruit Yield (t ha⁻¹)

Fruit yield significantly increased with biochar application. The highest yield (9.45 t ha^{-1}) was recorded with 2% biochar, followed by 8.95 t ha^{-1} with 1.5% biochar. The control had the lowest yield (8.18 t ha^{-1}). Among organic fertilizers, 3% FYM produced the highest yield (9.57 t ha^{-1}), followed by 9.11 t ha^{-1} with 3% SMC. The control without organic fertilizers had the lowest yield (7.94 t ha^{-1}) (Table 1). The combination of 2% biochar and 3% FYM resulted in the highest fruit yield (10.63 t ha^{-1}), followed by 10.37 t ha^{-1} for 2% biochar and 3% SMC. The combined control treatment had the lowest yield (6.58 t ha^{-1}) (Fig III). Biochar enhances soil nutrient retention, water-holding capacity, and microbial activity, mitigating heavy metal toxicity and promoting better plant health and fruit production (Chen et al., 2018; Smith et al., 2018). Organic fertilizers improve soil fertility and structure, supporting enhanced yield. The synergistic interaction between biochar and organic fertilizers optimizes soil conditions and nutrient availability, resulting in significantly higher fruit yields compared to individual treatments or controls. These findings are consistent with previous reports on the benefits of organic amendments in heavy metal-contaminated soils (Gupta et al., 2019; Jones and Brown, 2020).

Tomato Fruit Firmness (N/m²)

The application of biochar to heavy metal-contaminated soil significantly increased tomato fruit firmness compared to the control. The highest fruit firmness (3.21 N/m^2) was observed in plants treated with 2% biochar, followed by (2.95 N/m^2) with 1.5% biochar. The control treatment (without biochar) exhibited the lowest fruit firmness (2.50 N/m^2) (Table 1). The use of organic fertilizers (FYM, SMC, and LM) also had a positive effect on fruit firmness. The highest value (3.20 N/m^2) was recorded in tomato plants treated with 3% SMC, followed by 3.18 N/m^2 with 3% FYM, while the control group showed the lowest firmness (2.58 kg N/m^2)(Table 1). The combined application of 2% biochar with 3% SMC yielded the highest fruit firmness (3.75 N/m^2), closely followed by 3.74 N/m^2 in plants treated with 2% biochar and 2% SMC. The lowest firmness (2.09 N/m^2) was observed in the combined control treatment without amendments (Fig IV). The increase in fruit firmness with biochar is likely due to improved soil structure, nutrient availability, and reduced heavy metal stress, supporting better fruit development. Organic fertilizers, especially SMC and FYM, provide essential nutrients that strengthen cell walls and enhance firmness. The combined use of biochar and organic fertilizers further boosts soil fertility and microbial activity, resulting in healthier plants and firmer fruit. These results align with previous studies (Haider et al., 2022; Lehmann et al., 2015; Younis et al., 2015), confirming that integrated amendments improve tomato fruit quality and shelf life, particularly in contaminated soils (Johnson et al., 2019).

Ascorbic Acid (mg 100g^{-1})

The application of biochar at various concentrations significantly increased ascorbic acid content in tomato fruits grown on heavy metal-contaminated soil. The highest ascorbic acid content (23.55 mg 100g^{-1}) was observed with 2% biochar, followed by 22.23 mg 100g^{-1} with 1.5% biochar, while the untreated control had the lowest value (20.31 mg 100g^{-1}). Organic fertilizers also significantly enhanced ascorbic acid levels; the highest value (23.21 mg 100g^{-1}) was recorded with 3% SMC, followed by 22.92 mg 100g^{-1} with 3% FYM, compared to 21.18 mg 100g^{-1} in the control (Table 2). The combined application of biochar and organic fertilizers showed a synergistic effect, with the highest ascorbic acid content (26.90 mg 100g^{-1}) in fruits from plants treated with 1.5% biochar and 3% SMC, and a similar value (26.33 mg 100g^{-1}) with 2% biochar and 3% FYM. The lowest ascorbic acid (18.25 mg 100g^{-1}) was observed in the combined control (Fig V). The increase in ascorbic acid with biochar and organic fertilizer application is likely due to improved soil health, nutrient availability, and reduced heavy metal stress, all of which support better fruit nutritional quality. Biochar enhances nutrient retention and reduces metal toxicity, while organic fertilizers supply essential nutrients and further alleviate stress. The synergistic effect of combined treatments leads to the highest ascorbic acid content, consistent with previous findings (Meena et al., 2014; Yin et al., 2021; Zhou et al., 2019) that highlight the benefits of integrated soil amendments for improving crop nutritional value in contaminated soils.

Total Phenolic Content (TPC) in Tomato Fruit (mg/g)

The application of biochar significantly increased the total phenolic content (TPC) in tomato fruits grown on heavy metal-contaminated soil. The highest TPC (31.53 mg/g) was observed with 2% biochar, followed by 30.77 mg/g with 1.5% biochar, while the control group had the lowest TPC (27.74 mg/g). Organic fertilizers also influenced TPC, with the highest value (30.62 mg/g) found with 3% spent mushroom compost (SMC), followed by 30.31 mg/g with 3% farmyard manure (FYM); the control treatment had the lowest TPC (28.64 mg/g) (Table 2). The combined application of 2% biochar and 3% SMC resulted in the highest TPC (34.58 mg/g), followed by 33.35 mg/g with 2% biochar + 2% SMC, while the combined control treatment had the lowest TPC (27.85 mg/g) (Fig VI). The enhancement of TPC with biochar and organic fertilizers is likely due to improved soil health, nutrient availability, and mitigation of heavy metal stress, which together promote the synthesis of antioxidant compounds like phenolics. Biochar improves soil aeration and nutrient retention and adsorbs heavy metals, reducing their uptake and oxidative stress, which supports higher phenolic accumulation in fruit. Organic fertilizers such as SMC and FYM further enrich soil organic matter, reduce heavy metal bioavailability, and enhance microbial activity, all of which contribute to increase TPC. These amendments help mitigate heavy metal-induced oxidative stress and promote the production of secondary metabolites, including phenolics. Increased TPC in tomatoes enhances antioxidant activity and nutritional value, as phenolic compounds play a key role in neutralizing reactive oxygen species and supporting human health (La-Vecchia, 1998-2004; Willcox et al., 2003). These findings are consistent with previous studies, which reported that crops treated with biochar and organic fertilizers generally exhibit improved quality attributes, including phenolic content, compared to conventional practices (Vinha et al., 2014; Worthington, 2001).

Lycopene Content in Tomato (mg/100g)

The application of biochar at various concentrations significantly increased the lycopene content in tomato fruits grown on heavy metal-contaminated soil. The highest lycopene content (14.89 mg/100g) was observed with 1.5% biochar, followed closely by 2% biochar (14.84 mg/100g), while the control treatment had the lowest lycopene content (12.74 mg/100g). Organic fertilizers also significantly influenced lycopene content, with the highest value (15.27 mg/100g) found in tomatoes fertilized with 3% SMC, followed by 3% FYM (15.25 mg/100g), and the lowest in the control group (13.23 mg/100g) (Table 2). The interaction between biochar and organic fertilizers showed a significant positive effect, with the highest lycopene content (17.36 mg/100g) recorded in fruits from plants treated with 2% biochar and 3% FYM combined, whereas the combined control group had the lowest (12.39 mg/100g) (Fig VII). The observed increases in lycopene content with biochar application can be attributed to improved soil health, mitigation of heavy metal toxicity, and stimulation of secondary metabolite production, including lycopene, which acts as a potent antioxidant. Biochar enhances soil structure and nutrient retention, and its stress-mitigating effects may amplify lycopene synthesis under heavy metal stress. Organic fertilizers such as FYM and SMC provide essential nutrients, improve soil structure, and reduce the bioavailability of heavy metals, supporting plant growth and mitigating oxidative stress. This leads to improved root development and nutrient uptake, both of which are necessary for lycopene production. Lycopene is a powerful antioxidant associated with health benefits, including reduced risks of prostate cancer and cardiovascular diseases (Barber and Barber, 2002). The combination of biochar and organic fertilizers, particularly 2% biochar with 3% FYM, appears to have a synergistic effect, resulting in the highest lycopene content and thus improving the nutritional quality and health benefits of tomatoes. These results highlight the importance of integrated soil amendments for enhancing crop quality under contaminated conditions.

Carotenoids Content in Tomato (mg/kg)

The application of biochar significantly influenced carotenoid content in tomato fruit grown on heavy metal-contaminated soil. Carotenoid content increased with biochar levels up to 1.5%, with the highest value (7.21 mg/kg) observed at 1.5% biochar. At 2% biochar, carotenoid content slightly decreased to 7.12 mg/kg. The control treatment (without biochar) produced tomatoes with lower carotenoid content (5.88 mg/kg). Organic fertilizers also enhanced carotenoid content, with the highest value (7.67 mg/kg) recorded for 3% spent mushroom compost (SMC), followed by 6.97 mg/kg with 3% farmyard manure (FYM). The control group showed lower carotenoid content (5.86 mg/kg) (Table 2). The combination of 1.5% biochar and 3% SMC resulted in the highest carotenoid content (8.38 mg/kg), while the combined control group had the lowest (5.06 mg/kg) (Fig VIII). Biochar improves soil water holding capacity, cation exchange, and nutrient uptake, which together support carotenoid synthesis and fruit quality. The optimal biochar dose (1.5%) enhanced carotenoid content by improving soil health and reducing heavy metal toxicity, while a higher dose (2%) led to a slight decline, possibly due to complex soil-plant interactions. Organic fertilizers (FYM, SMC and LM) supply nutrients and boost microbial activity, stimulating carotenoid and antioxidant production, especially under stress. SMC and FYM, rich in organic matter, were particularly effective. Carotenoids act as antioxidants with important health benefits, and their synthesis is promoted by improved soil conditions and reduced metal stress. The synergistic effect of biochar and organic fertilizers, especially the combination of 1.5% biochar and 3% SMC, yielded the highest carotenoid content, confirming that integrated amendments are most effective for enhancing fruit nutritional quality under contaminated conditions.

Lead (Pb) Concentration in Tomato Fruit (mg kg^{-1})

The addition of biochar to contaminated soil significantly reduced the Pb concentration in tomato fruit. The highest Pb concentration (2.96 mg kg^{-1}) was recorded in the control group (untreated soil), while 1% biochar reduced Pb to 2.85 $^{mg/kg}$, and 2% biochar further decreased Pb concentration to 2.55 mg kg^{-1}. Organic fertilizers also influenced Pb concentrations in tomato fruit. The highest Pb concentration (3.15 mg kg^{-1}) was found in the control treatment. Treatment with 2% leaf mold (LM) led to a Pb concentration of 2.88 mg kg^{-1}, while the application of 3% FYM resulted in the lowest Pb concentration (2.39 mg kg^{-1}) (Table 3).The combined application of biochar and organic fertilizers significantly reduced Pb concentrations. The lowest Pb concentration (2.12 mg kg^{-1}) was recorded in plants treated with 2% biochar and 3% FYM, which is within the WHO permissible limit (0.1-2.8 mg kg^{-1}) (Fig IX). Biochar reduced Pb uptake by adsorbing and immobilizing Pb ions in the soil, increasing soil pH, and providing a high surface area for Pb binding. These mechanisms decrease Pb bioavailability and promote its precipitation as less soluble compounds. Organic fertilizers such as FYM, SMC, and LM further reduced Pb bioavailability by increasing soil organic matter and pH, and enhancing microbial activity, which together immobilized Pb and limited its uptake. The combined use of biochar and organic fertilizers showed a synergistic effect, significantly lowering Pb concentrations in tomato fruit and improving plant resilience. These findings are consistent with previous research by Chen et al. (2018), supporting the effectiveness of these amendments for reducing heavy metal accumulation and improving food safety in contaminated soils.

Cadmium (Cd) Concentration in Tomato Fruit (mg kg^{-1})

Biochar significantly reduced the Cd concentration in tomato fruit grown on heavy metal-contaminated soil. The control treatment (untreated) had the highest Cd concentration (0.83 mg kg^{-1}), while the addition of 1% biochar reduced it to 0.74 mg kg^{-1}. The lowest Cd concentration (0.53 mg kg^{-1}) was observed in tomatoes from plants amended with 2% biochar. Organic fertilizers also influenced Cd concentrations. The highest Cd concentration (0.82 mg kg^{-1}) was found in control-treated plants. Treatment with 2% leaf mold (LM) resulted in a concentration of 0.72 mg kg^{-1}, and the addition of 3% spent mushroom compost (SMC) led to the lowest Cd concentration (0.56 mg kg^{-1}) (Table 3). The interaction of biochar and organic fertilizers significantly reduced Cd concentrations in tomato fruit. The highest concentration (1.03 mg kg^{-1}) was found in the control treatment, while the combination of 2% biochar and 3% SMC resulted in the lowest Cd concentration (0.43 mg kg^{-1}). The WHO's maximum permissible Cd concentration for tomato fruit is 0.1-0.91 mg kg^{-1} (Fig X). The results from biochar and organic fertilizer treatments, such as 2% biochar and 3% SMC (0.53 mg kg^{-1} and 0.56 mg kg^{-1}), fall within the acceptable limits. Biochar application significantly reduced Cd accumulation in tomato fruit by immobilizing Cd in the soil. Its high surface area and functional groups (carboxyl, hydroxyl, phenolic) adsorbed Cd ions, lowering their bioavailability, while increased soil pH promoted the formation of less soluble Cd compounds. Biochar also enhanced microbial activity and altered root exudates, further limiting Cd uptake, consistent with Eissa (2019). Organic fertilizers such as SMC, LM, and FYM also reduced Cd bioavailability by increasing soil organic matter, forming stable Cd complexes, and supporting beneficial microbes, as reported by Nie et al. (2018) and Xu et al. (2018). The combined use of 2% biochar and 3% SMC showed the greatest reduction in Cd concentration in tomato fruit, demonstrating a synergistic effect on improving soil quality and minimizing Cd uptake. These results support the use of biochar and organic fertilizers as effective, sustainable solutions for reducing heavy metal contamination in crops and improving food safety.

Chromium (Cr) Concentration in Tomato (mg kg^{-1})

Biochar significantly reduced Cr concentration in tomato fruit grown on heavy metal-contaminated soil. The control treatment (untreated soil) had the highest Cr concentration (2.10 mg kg^{-1}). As biochar concentration increased, Cr levels decreased, with the lowest value (1.19

mg kg^{-1}) observed in plants treated with 2% biochar. Organic fertilizers also reduced Cr accumulation in tomatoes. The highest Cr concentration (1.92 mg kg^{-1}) was observed in the control group, and the application of 3% SMC led to the lowest Cr concentration (1.32 mg kg^{-1}) (Table 3). The combined application of 2% biochar and 3% SMC resulted in the lowest Cr concentration (1.07 mg kg^{-1}), which is within the WHO permissible limit (0.2-2.0 mg kg^{-1}) (Fig XI). Biochar reduced Cr concentration in tomato fruit by adsorbing Cr ions due to its high surface area and porous structure, decreasing their mobility and bioavailability. The increase in soil pH and altered redox conditions from biochar application further reduced Cr solubility and promoted the formation of stable metal-organic complexes. Organic fertilizers such as FYM, SMC, and LM also lowered Cr accumulation by increasing soil organic matter, which adsorbed Cr and formed stable complexes via humic and fulvic acids. Enhanced microbial activity from these amendments further immobilized Cr through biosorption and reduction processes. The combined use of biochar and organic fertilizers provided a synergistic effect, significantly reducing Cr uptake and improving soil and plant health. Overall, these amendments effectively immobilized Cr in contaminated soils, reduced its uptake by tomatoes, and contributed to safer food production and improved plant resilience.

Table 1

Vegetative and yield attributes of tomato plant as affected by biochar and organic fertilizers (FYM, SMC and LM) grown on heavy metals contaminated soil.

Biochar Levels (%) (B)	Plant height (cm)	Leaf Area (cm^2)	Chlorophyll Content (SPAD)	Fruit yield (t ha^{-1})	Fruit firmness (N/m^2)
Control (0)	58.09 c	33.74c	32.86 d	8.18 c	2.50 c
1.0	63.32 b	36.18 bc	34.94 c	8.48 b	2.76 bc
1.5	64.34 b	38.51 b	37.15 b	8.95 b	2.95 ab
2.0	67.53 a	41.68 a	38.73 a	9.45 a	3.21 a
LSD (P<0.05)	1.41	1.125	1.12	0.31	0.24
Organic Fertilizers (OF)					
Control (0)	59.79 d	30.70 d	33.52 d	7.94 c	2.58 ab
FYM (2%)	64.09 b	39.54 b	36.39 bc	8.91 b	2.86 ab
FYM (3%)	68.51 a	43.42 a	38.41 a	9.57 a	3.18 ab
SMC (2%)	62.21c	34.24 cd	35.87 bc	8.81 b	2.73 b
SMC (3%)	64.57 b	41.21 ab	37.03 ab	9.11 ab	3.20 a
LM (2%)	61.21cd	35.51 c	34.96 cd	8.46 bc	2.73 b
LM (3%)	62.22 d	38.07 c	35.26 c	8.57 bc	2.89 ab
LSD (P<0.05)	1.87	1.488	1.48	0.41	0.31
Interaction (B x OF)	Fig I	Fig II	NS	Fig III	Fig IV

FYM = Farm Yard Manure, SMC = Spent Mushroom Compost, LM = Leaf Mould.
LSD = Least significant difference.

Table 2

Qualitative attributes of tomato plant as affected by biochar and organic fertilizers grown in contaminated soil.

Biochar Levels (%) (B)	Ascorbic acid (mg $100g^{-1}$)	Total Phenolic Contents (mg GAE/100g)	Lycopene (mg $100g^{-1}$)	Carotenoids (mg kg^{-1})
Control (0)	20.31 c	27.74 c	12.74 b	5.88 c
1.0	21.21bc	28.84 bc	13.95 b	6.64 b
1.5	22.23 b	30.77 a	14.89 a	7.21 a
2.0	23.55 a	31.53 ab	14.84 a	7.12 a
LSD (P<0.05)	1.10	1.07	0.81	0.29
Control (0)	21.18 b	28.64 b	13.23 c	5.86 d
FYM (2%)	21.45 ab	29.46 ab	13.67 bc	6.46 c
FYM (3%)	22.92 a	30.31 a	15.25 a	6.97 b
SMC (2%)	21.60 ab	30.04 a	14.49 ab	6.90 b
SMC (3%)	23.21 a	30.62 a	15.27 a	7.67 a
LM (2%)	21.04 ab	29.54 ab	13.45 bc	6.52 c
LM (3%)	21.38 ab	29.43 ab	13.39 c	6.62 bc
LSD (P<0.05)	1.45	1.32	1.07	0.38
Interaction (B x OF)	Fig V	Fig VI	Fig VII	Fig VIII

FYM = Farm Yard Manure, SMC = Spent Mushroom Compost, LM = Leaf Mould.
LSD = Least significant difference.

Table 3

Heavy metal (mg kg^{-1}) concentration in tomato plant as affected by biochar and organic fertilizers grown on contaminated soil.

Biochar Levels (%) (B)	Lead (Pb) (mg kg^{-1})	Cadmium (Cd) (mg kg^{-1})	Chromium (Cr) (mg kg^{-1})
0 (Control)	2.96 a	0.83 a	2.10 a
1.0	2.85 ab	0.74 b	1.68 b
1.5	2.72 b	0.62 c	1.34 c
2.0	2.55 c	0.53 d	1.19 c
LSD (P<0.05)	0.08	0.04	0.12
Organic Fertilizers (OF)			
0 (Control)	3.15 a	0.82 a	1.92 a
FYM (2%)	2.94 ab	0.71 bc	1.68 ab

FYM (3%)	2. 43 c	0.64 d	1.42 cd
SMC (2%)	2.83 b	0.65 cd	1.43 cd
SMC (3%)	2.39 c	0.56 e	1.32 d
LM (2%)	2.88 ab	0.72 ab	1.75 a
LM (3%)	2.77 b	0.64 d	1.54 bc
LSD (P<0.05)	0.11	0.06	0.16
Interaction (B x OF)	**Fig X**	**Fig XI**	**Fig XII**
Max. Permissible Value	0.1-2.8 mg/kg	0.1-0.91 mg/kg	0.2-2.0 mg/kg

FYM = Farm Yard Manure, SMC = Spent Mushroom Compost, LM = Leaf Mould.
LSD = Least significant difference.

Figure I

Interaction between biochar and organic fertilizer on the plant height (cm) of tomato grown on heavy metals contaminated soils.

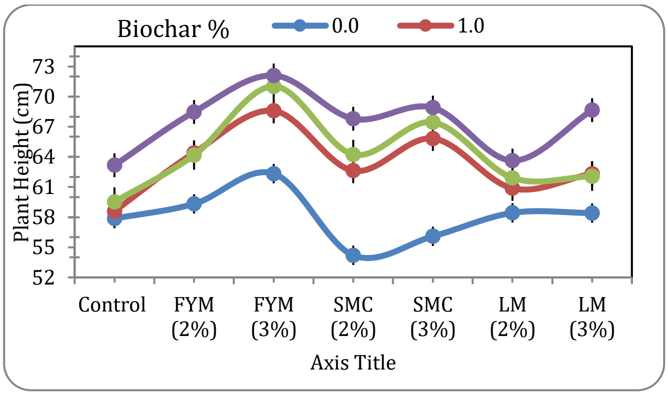


Figure II

Interaction between biochar and organic fertilizer on the Leaf area (cm²) of tomato grown on heavy metals contaminated soils.

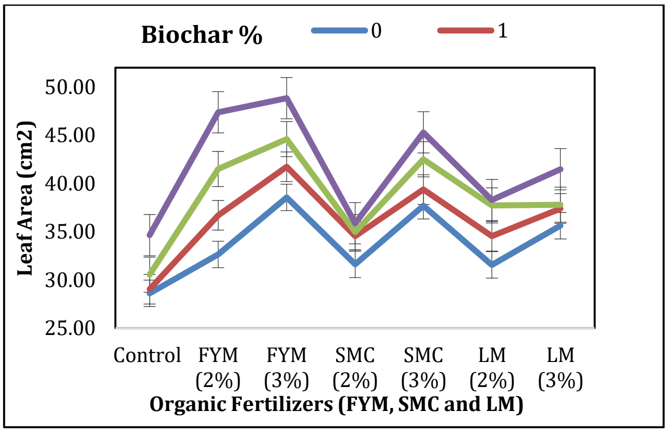


Figure III

Interaction between biochar and organic fertilizers on fruit yield (t ha⁻¹) of tomato.

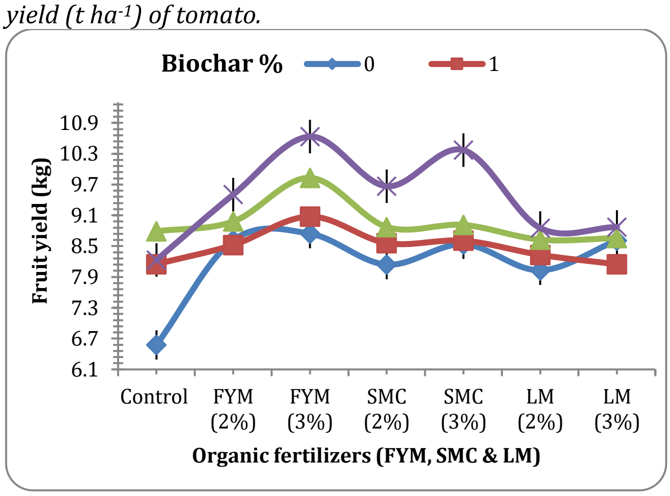


Figure IV

Interaction between biochar and organic fertilizer on fruit firmness (N/m²) of tomato.

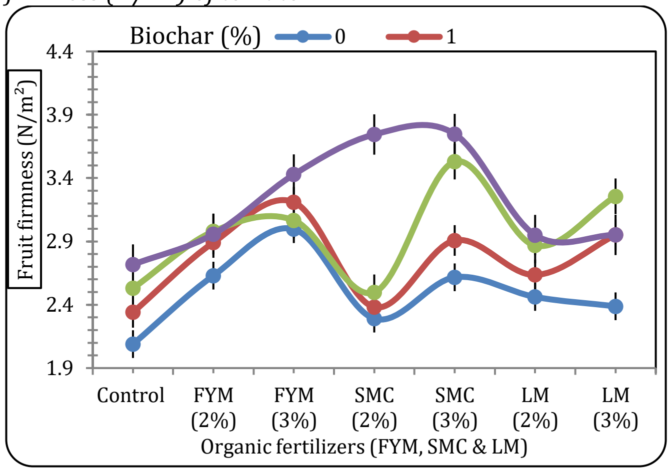


Figure V

Interaction between biochar and organic fertilizer on ascorbic acid (mg 100g⁻¹)of tomato.

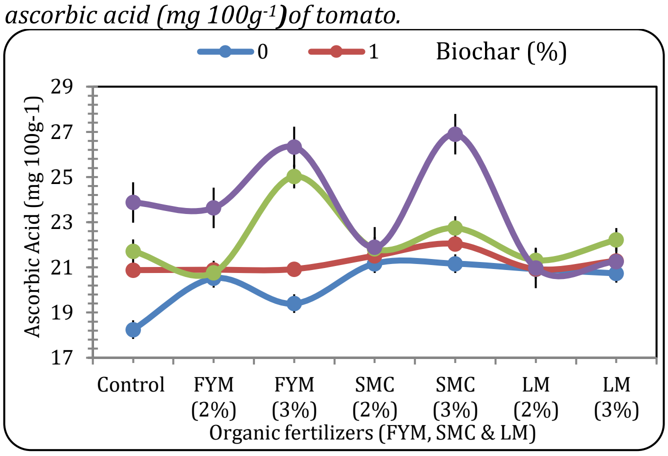


Figure VI

Interaction between biochar and organic fertilizer on total phenolic contents (mg GAE/100g) of tomato.

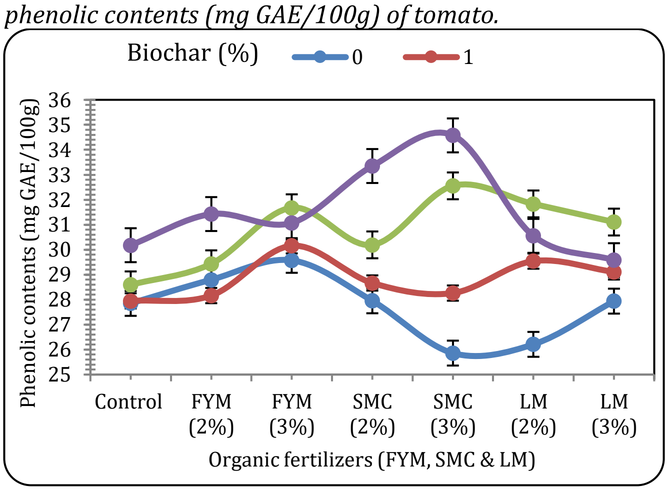


Figure VII

Interaction between biochar and organic fertilizer on lycopene contents (mg 100g-1) of tomato.

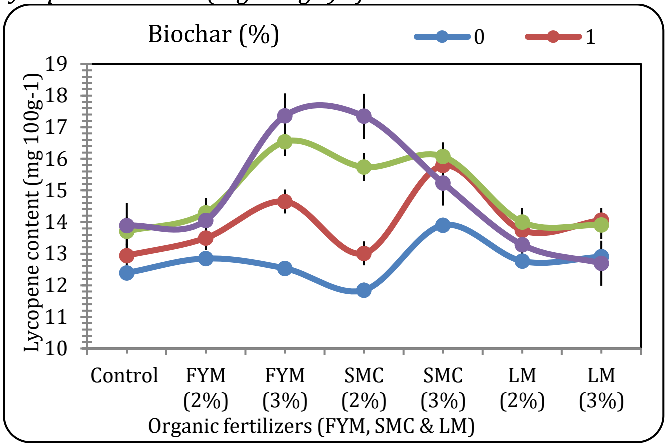


Figure VIII

Interaction between biochar and organic fertilizer affects carotenoids (mg kg-1) of tomato.

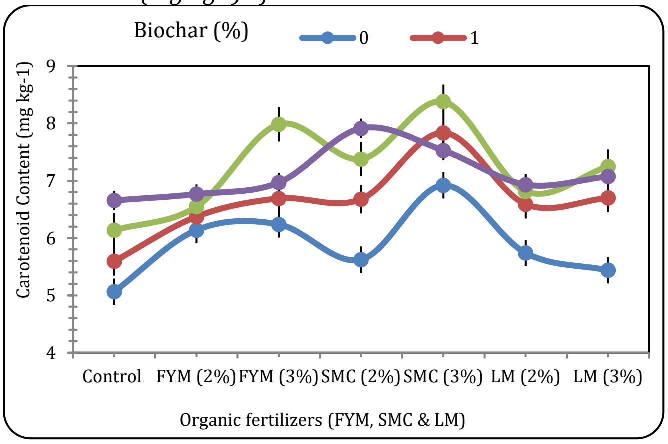


Figure IX

Interaction of biochar and organic fertilizer on lead (Pb) Concentrations (mg kg-1) in tomato fruit.

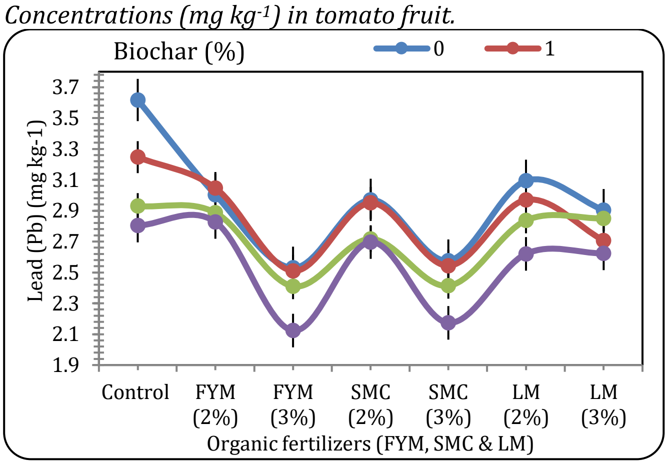


Figure X

Interaction of biochar and organic fertilizer on cadmium (Cd) concentrations (mg kg-1) in tomato fruit.

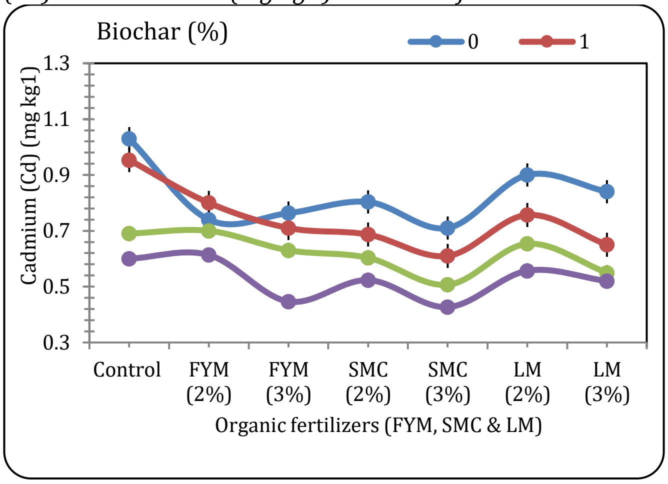
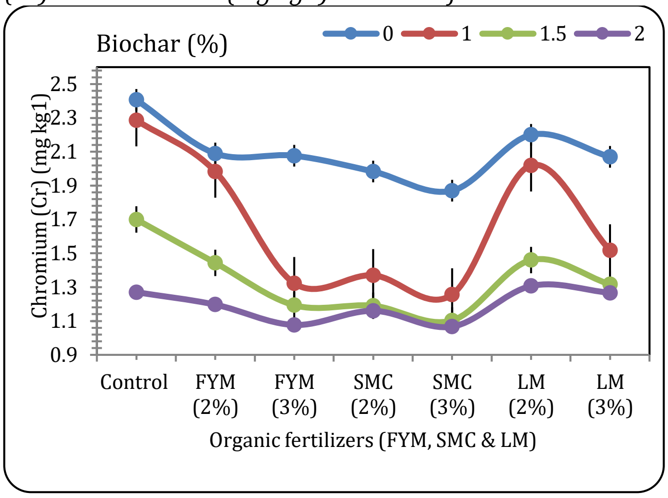


Figure XI

Interaction of biochar and organic fertilizer on chromium (Cr) concentrations (mg kg-1) in tomato fruit.



CONCLUSIONS

The significant findings of present research concluded that the tomato crop cv. Rio Grande, grown on heavy metal contaminated soil should be fertilized with 2% biochar for better growth, to get maximum fruit yield and to improve the quality attributes with less accumulation of heavy metals. The organic fertilizer i-e 3% FYM should be added to contaminated soil to obtain better vegetative growth and maximum fruit yield. The 3% SMC should be added to contaminated soil to improve the quality attributes and also minimize the accumulation of heavy metals in tomato fruit.

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