Journal of Soils and Sediments
https://doi.org/10.1007/s11368-025-04077-9

SOILS, SEC 1 • SOIL ORGANIC MATTER DYNAMICS AND NUTRIENT CYCLING • RESEARCH ARTICLE

Comparative assessment of biochar and vermicompost on chromium bioavailability and stress alleviation in tomato (*Solanum lycopersicum*)

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Received: 29 November 2024 / Accepted: 25 June 2025
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Abstract

Purpose Chromium (Cr) toxicity is a significant threat to food and nutritional security. This study investigated the comparative effect of different organic amendments to immobilize Cr and mitigate its toxic effects on tomatoes.

Methods Plants were stressed with Cr (0, 25, 50, and 100 mg kg^{-1}) in a pot experiment, alone or in combination with various organic amendments viz. biochar (5% BC), iron-enriched biochar (0.5% Fe-BC), farmyard manure (5% FYM), and vermicompost (5% VC).

Results Cr toxicity at 25 and 50 ppm significantly reduced plant growth, membrane stability and relative water contents while plants did not survive at 100 ppm Cr. Cr-induced oxidative damage increased by 1.9- and 2.7-fold under 25 and 50 ppm Cr, respectively. However, application of organic amendments effectively alleviated Cr stress in tomato, with VC showing the most pronounced effect on growth. Tomato plants supplemented with VC under Cr stress exhibited a substantial increase in shoot length (2.3-fold), fresh weight (2.0-fold) and membrane stability (1.7-fold), respectively as compared to the stressed plants grown without VC. Notably, the addition of organic amendments enabled the plants to withstand the toxicity of 100 ppm Cr. Organic amendments improved stress tolerance in tomato primarily due to reduced Cr uptake and increased antioxidant enzyme activities (SOD = 3.11-fold, CAT = 1.14-fold, POD = 2.95, and APX = 1.76-fold).

Conclusions These findings underscore the potential of various organic amendments in mitigating Cr toxicity in plants, with VC demonstrating superior performance. Future research should focus on exploring optimal application and long-term effects of these amendments on soil health and crop productivity.

Keywords Biochar · Chromium · Iron enriched biochar · Tomato · Vermicompost

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Published online: 31 July 2025

1 Introduction

Heavy metal (HM) accumulation in terrestrial ecosystems is a major global challenge that negatively affects agricultural productivity and human well-being. Among HMs, chromium (Cr) is the 24th most readily available metal on the Earth's surface and is ranked 17th among the most toxic chemicals by the Agency for Toxic Substances and Disease Registry (Tumolo et al. 2020; Wilbur et al. 2012). When present above threshold levels, Cr is hazardous, exhibiting carcinogenic, mutagenic, and teratogenic properties (Liu et al. 2008). Cr enters the soil via natural processes such as volcanic eruptions and rock weathering, and through anthropogenic activities like mining, biosolid application, wastewater discharge, fuel combustion, smelting operations, and the use of certain agrochemicals (Bhatt et al. 2022).

Plants grown in Cr-contaminated soils can uptake and accumulate Cr within their cellular tissues, compromising cell integrity by damaging proteins, DNA, and membrane lipids (Wilbur et al. 2012; Moreira et al. 2018). Accumulated Cr in plant tissues can lead to physiological and biochemical disorders such as reduced chlorophyll production, impaired micro-, and macronutrient uptake, and decreased net photosynthetic activity, ultimately causing leaf chlorosis and nutrient imbalance (Panda and Choudhury 2005; Ali et al. 2023). Excessive Cr exposure causes oxidative stress by triggering overproduction of reactive oxidative species (ROS), including singlet oxygen species ($^1O_2$), hydroxyl groups ($OH^·$), hydrogen peroxide (H_2O_2) and superoxide ($O_2^{\bullet -}$) radicals. These ROS damage proteins and lipids, disrupt bio-membranes, and impair the antioxidant defense system (Nagajyoti et al. 2010). Plants minimize the harmful impacts of ROS by enhancing the activity of an intricate antioxidant defense system (Farooq et al. 2019; Moreira et al. 2018; Saleem et al. 2022).

The immobilization and detoxification of HMs through the incorporation of highly sorptive inorganic and organic compounds is an emerging and promising remedial approach (Antoniadis et al. 2018). Organic amendments offer advantages over inorganic amendments due to their cost-effectiveness, biodegradability, and ability to improve soil health (Bolan and Duraisamy 2003). Vermicompost (VC), a humus like organic material derived from the digestion processes of earthworms, is particularly beneficial for soil health compared to conventional compost or commercial soil amendments (Pande et al. 2007). VC possesses desirable attributes such as high nutrient composition, significant cation exchange capacity, suitable porosity, adequate air exchange, excellent water retention, and enhanced microorganism activities (Bolan and Duraisamy 2003). Moreover, VC contains humic acid which alters the fractional distribution of HMs. The carboxylic acid functional groups within VC participate in proton transfer reactions between metal cations and weak organic acids, thereby reducing HM bioavailability (Pande et al. 2007). Consequently, researchers regard VC as an eco-friendly and sustainable soil amendment.

Similarly, farmyard manure (FYM) serves as a vital organic amendment that improves physical, chemical, and physical characteristics of soil (Kumar et al. 2021). When well-processed, FYM acts as an excellent soil conditioner with multiple ecosystems benefits and serves as an important feedstock for VC production (Dheeba et al. 2015).

Biochar (BC), a solid carbon-rich material with substantial aromaticity, is produced through the thermo-chemical transformation of biomass under restricted oxygen supply. BC application improves fertility, water holding capacity, and other physico-chemical and biological properties of soil. Due to its slow decomposition rate, BC also reduces greenhouse gas emissions (e.g., methane and carbon dioxide), thus store C for a prolonged period (Chen et al. 2020; Rafiq et al. 2017). The resultant improvement in soil health enhances crop growth and productivity (Bashir et al. 2020; Rafiq et al. 2017). Importantly, BC's unique surface morphology and high sorption capacity contribute to reducing HM bioavailability (Ambika et al. 2022; Bashir et al. 2020; Diao et al. 2021). Recent reports suggest that surface modifications of BC with essential nutrients impart multiple advantages over pristine BC. For example, adding sulfur (S) to rice husk BC was reported to improve its mercury (Hg) adsorptive capacity by approximately 70% (Ambika et al. 2022; El-Naggar et al. 2022). Similarly, iron (Fe) is an essential mineral, and its deficiency can cause stunted growth and a significant decrease in plant productivity (Mallick 2021; Kumar et al. 2013). The inclusion of Fe nanoparticles on the surface of BC is reported to improve crop development and yield (Sun et al. 2020). Previous research has shown that Fe-BC significantly reduces metal ion (Cd, Cr, Pb, and Cu) bioavailability along the reaction mechanism for Cr (VI) adsorption in a combination of surface participation, complexation and reduction (Dong et al. 2021; Qiao et al. 2017; Dad et al. 2021; Yang et al. 2021). Another research indicated that the addition of Fe-BC could transform more Cr (VI) into Cr (III), that is beneficial to improve the plant biomass and the Cr accumulation capacity of *L. hexandara* (Qingxia et al. 2024).

To this end, several reports demonstrated the positive effects of BC in soil remediation and improving plant growth under multiple abiotic stresses viz. salinity, HM toxicity, drought etc. Likewise, research has been performed to compare the performance of BC with other amendments e.g., activated C, highlighting its environmental benefits and cost-effectiveness (Alhashimi and Aktas 2017). However, the comparative efficiency of BC with other organic amendments in inhibiting or mitigating Cr stress has not yet been examined, necessitating further investigation. Considering these gaps, the objectives of the present study were to investigate (1) the effects of BC, Fe-BC, FYM, and VC amendments on tomato growth under Cr toxicity, (2) the biochemical and physiological responses of tomato plants to Cr toxicity under different organic amendments, and (3) the comparative efficiency of BC, Fe-BC, and VC for reducing Cr toxicity in tomato.

2 Materials and methods

2.1 Soil and amendment characterization

We collected loamy soil from a nursery (111°53′E, 28°51′N) in Islamabad City, Capital Territory, Pakistan. Prior to analysis, larger debris including stones, were removed and the soil was sieved through a 2-mm sieve. The processed soil was then brought to the laboratory for the analysis of different physico-chemical parameters analysis. The pH of the soil sample was 6.8, determined using a pH meter (1:2.5 soil:water ratio) (Hanna, Nusfalau, Romania). Electrical conductivity (EC; 0.25 dS m^{-1}) was measured using an electrochemical analyzer (InoLab pH/Cond 720, Germany) in a 1:5 (w/v) soil−water suspension. Other characteristics were determined by using standard methods described by Waqas et al. (2014). The organic matter in the soil was 12 g kg^{-1}, the exchangeable sodium (Na^+) was 1.2 cmol(+) kg^{-1}, the available phosphorus was 28 mg kg $^{-1}$, and the extractable potassium was 220 mg kg^{-1}.

Organic amendments used in this experiment like cow dung based FYM and VC were kindly provided by the Department of Agronomy, University of Agriculture, Faisalabad, Pakistan and their preparation method and characteristics have been reported in previous report by Yasir et al. (2009). Carbon rich, BC and Fe-BC were prepared by slow pyrolysis of rice husks having properties like high surface area, porosity, nutrient content, and stability (Yan et al. 2022), and technique used to synthesize BC and Fe-BC was as per our previous studies (Dad et al. 2021; Khan et al. 2022). All the four amendments were thoroughly characterized using different analytical techniques. Scanning electron microscopy was used to examine the morphology and surface characteristics of the amendments (Fig. 1). The phase structures were studied by using energy dispersive X-ray (EDX) (Bruker D8 Advance) analysis (Fig. 2). A thermogravimetric analyzer (TGA) (Tescan Vega 3, Brno, Czech Republic) was used to characterize the materials by measuring their mass change with changing temperature (Fig. 3a). Fourier transform infrared spectroscopy (PerkinElmer Spectrum Two) was used to investigate the functional group variations of the BC before and after modification as well as for VC and FYM samples (Fig. 3b).

2.2 Plant growth conditions and treatment plan

Tomato (*Solanum lycopersicum*) seeds were disinfected by soaking in 2% NaClO for 15 min and subsequently washed multiple times with deionized (DI) water. The experiment included four Cr treatment levels (0, 25, 50, and 100 mg kg^{-1}) of Cr, and combinations of four organic amendments: (5% BC, 0.5% Fe-BC, 5% FYM, and 5% VC). A total of twenty (20) treatment combinations were made by mixing the calculated amounts of $K_2Cr_2O_7$ solution with 5.0 kg of soil in plastic made containers (20.0 cm wide,

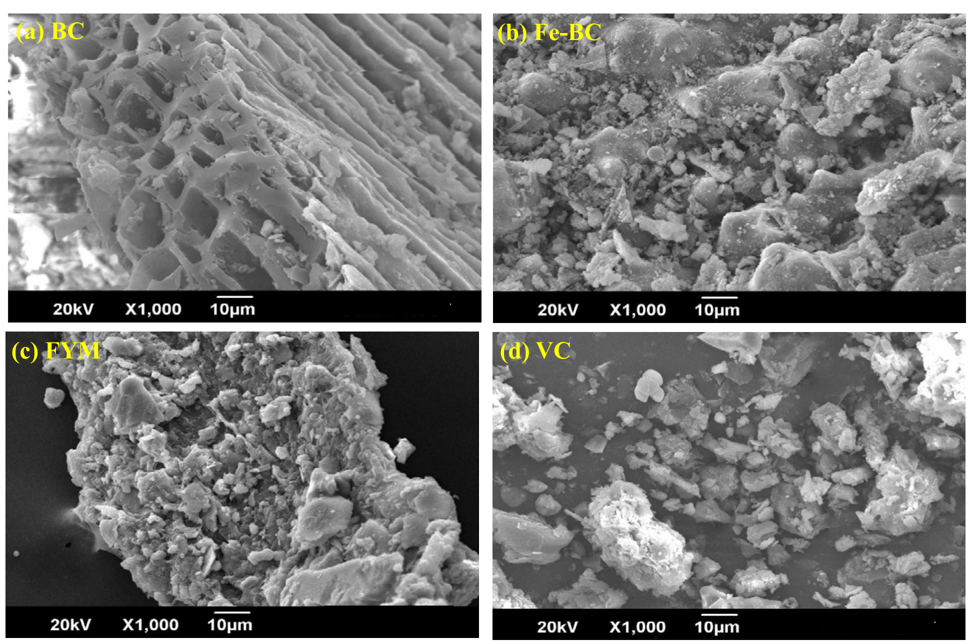


Fig. 1 Scanning electron microscopy (SEM) images of (**a**) biochar (BC), **b** Fe-biochar (Fe-BC), **c** farmyard manure (FYM), and (**d**) vermicompost (VC)

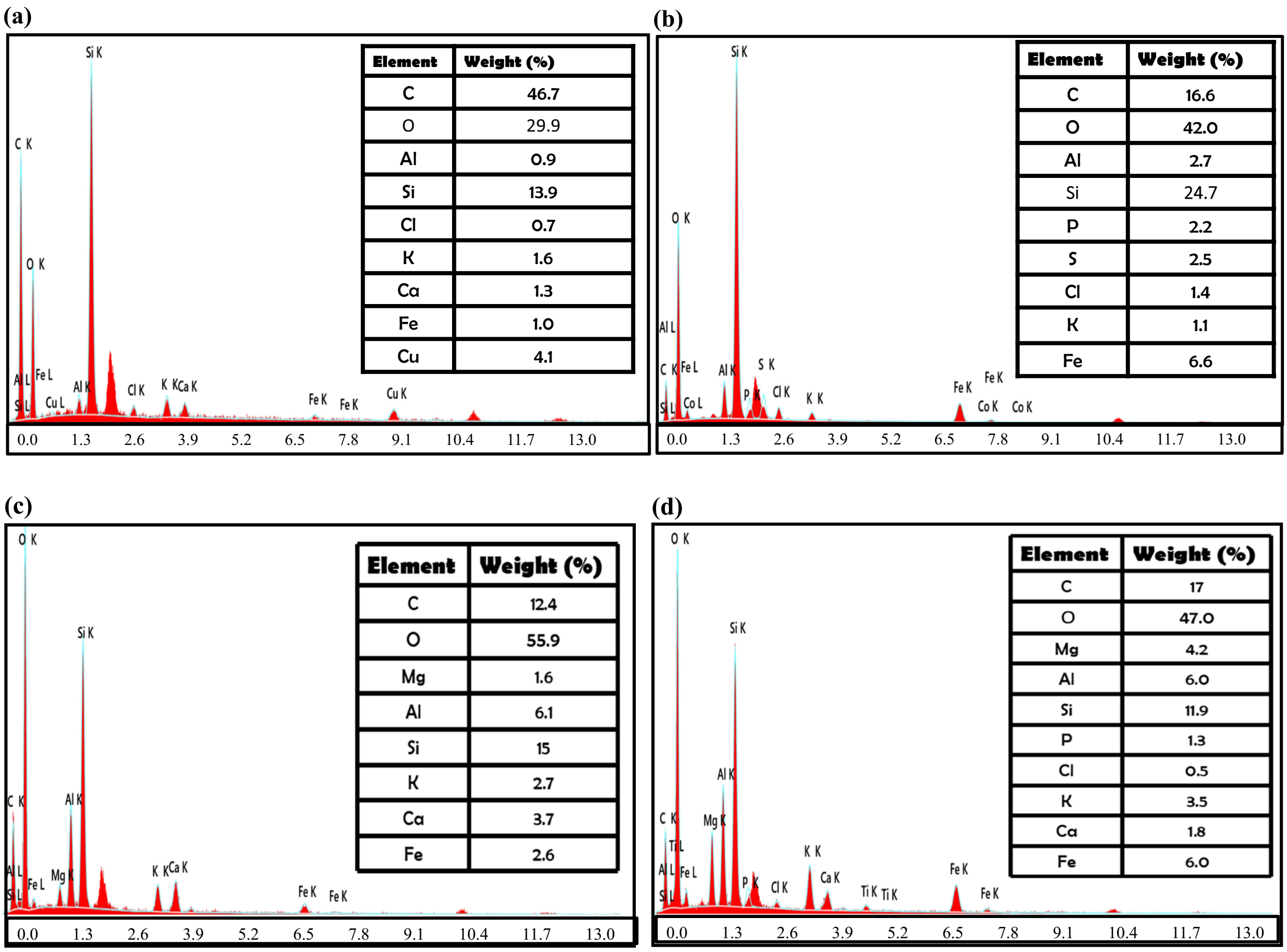


Fig. 2 Energy dispersive X-ray (EDX) analysis of (**a**) biochar (BC), **b** Fe-biochar (Fe-BC), **c** farmyard manure (FYM), and (**d**) vermicompost (VC)

15.0 cm bottom diameter, 22.0 cm top diameter). The treated soil was irrigated to maintain 70%field capacity and incubated it at 25 °C for 15 d to attain equilibrium. Three-week-old tomato seedlings were then transplanted (four plants per pot) and cultivated under greenhouse conditions. Each of the 20 treatments was replicated four times. Leaves from 80 d old tomato plants were used to evaluate the response of plants to Cr and/or organic amendments in terms of growth, physiological and biochemical parameters.

2.3 Plant harvest, growth and Cr content analyses

The above-ground biomass (shoots and leaves) were separated, initially air dried, followed by oven drying at 75 °C for 48 h until constant dry weight to measure shoot dry weight (SDW) (Rafiq et al. 2017). Plant Cr concentration in the dried samples (0.5 g) was determined after acid digestion with 15 mL of an acid mixture (H_2SO_4, $HClO_4$ and HNO_3; 1:1:5) at 160 °C (Khan et al. 2008). Post digestion, the samples were cooled to room temperature, filtered and diluted to a final volume of 50 mL using double DI water. The atomic absorption spectrophotometer (AAS) (Analytic-Jena NOVA 800D, Germany) was used to determine the Cr concentrations in plant tissues (Khan et al. 2008).

2.3.1 Relative water content (RWC)

The RWC was measured according to Sairam et al. (2002) by using fresh leaf samples. A 0.5 g leaf sample was taken and soaked in 10 mL DW for 24 h at room temperature under low light conditions to obtain the soaked or turgid weight (SW). The samples were dried for 48 h in an oven at 65 °C until a constant dry weight (DW), and the RWC was calculated via the following equation:

$$RWC = \frac{FW - DW}{SW - DW} \times 100 \quad (1)$$

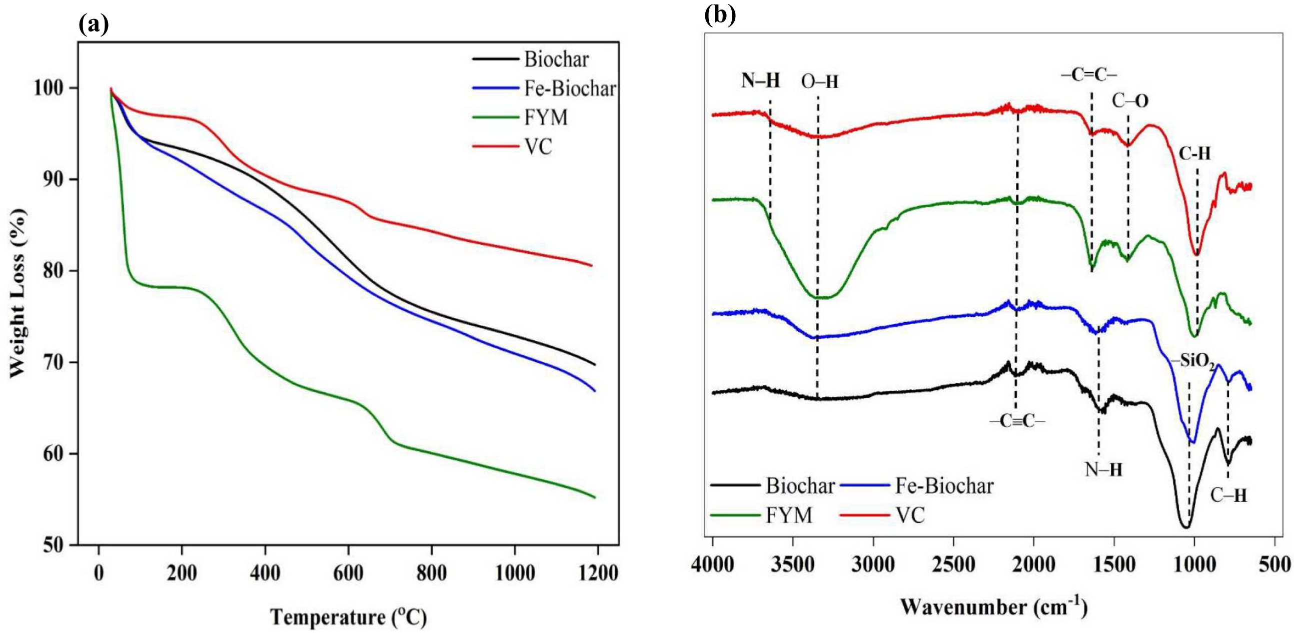


Fig. 3 Thermogravimetric analysis (**a**) and Fourier Transform Infrared Spectroscopy (FTIR) images (**b**) of biochar (BC), Fe-biochar (Fe-BC), farmyard manure (FYM) and vermicompost (VC)

2.3.2 Membrane stability index (MSI)

The MSI was recorded by measuring the EC of leaf leachates at two different temperatures, 40 and 100 °C, then the MSI was computed (Sairam et al. 2002). Briefly, 0.1 g of each leaf sample was cut into two equal-sized circular sections and placed into test tubes containing 10 mL of DI. Before measuring the differing electrical conductivities of C1 and C2, using an EC meter, one set of test tubes was held at 40 °C and the second set at 100 °C in a water bath for approximately 30 min. The following formula was used to calculate the MSI:

$$MSI = 1 - \frac{C1}{C2} \times 100 \quad (2)$$

2.3.3 Total chlorophyll content (TCC)

Total chlorophyll content (TCC) was recorded using a SPAD-502P chlorophyll meter (Minolta, Osaka, Japan). Readings were noted from the fully expanded youngest leaves, and the average of the multiple readings was recorded one day prior to harvesting.

2.3.4 Hydrogen peroxide (H_2O_2) content

H_2O_2 contents were quantified following the method given by Islam et al. (2008). 0.5 g fresh leaf samples frozen in liquid nitrogen were extracted using 0.1% v/v trichloroacetic acid (TCA). The leaf extract was cold centrifuged at 19,000 × g for 20 min. Subsequently, 1 mL of the supernatant was combined with 1 mL each of potassium phosphate buffer (10 mM) and potassium iodide (2 M) solution. The pH of the solution was adjusted to 7.0. A UV−Vis spectrophotometer was used to record the final solution absorbance at 390 nm. The standard H_2O_2 curve was used to calculate the H_2O_2 content.

2.3.5 Antioxidant enzyme activities

The youngest, fully developed leaves at the top were used to measure the antioxidant enzyme activity. Using a precooled mortar and pestle stored in liquid nitrogen, 250 mg of frozen leaf was ground in 0.1 M phosphate buffer (pH 7.0). After that, the mixture was cold centrifuged for 30 min at 15,000 rpm. Following centrifugation, the supernatant was obtained to measure the activities of different antioxidant enzymes.

The superoxide dismutase (SOD) activity was measured in accordance with the protocol described by Dhindsa and Matowe (1981) and expressed as one unit of SOD activity. Catalase (CAT) activity was determined using Aebi's (1984) methodology using spectrophotometer at 240 nm and reported as the number of H_2O_2 moles destroyed min^{-1} g^{-1} protein. The guaiacol peroxidase (POD) activity was assessed using the protocol described by Hemeda and Klein (1990) using spectrophotometer at 470 nm. The amount of guaiacol oxidized (min^{-1} g^{-1} protein) was used to measure POD activity. While APX (ascorbate peroxidase) activity was measured in accordance with Rangani et al. (2016). The amount of oxidized ascorbate was calculated using an extinction value of 2.8 mM^{-1} cm^{-1}, and the activity of APX was assessed by measuring the decrease in absorbance for one minute at 290 nm.

2.4 Statistical analysis

Four independent replicates of the experiment were conducted using a RCBD (completely randomized block design). Using the SigmaPlot v12.0 statistical program (Systat Software Inc., Chicago, IL, USA), the dataset was subjected to a two-way ANOVA and Tukey's test ($P=0.05$). The results are presented as the mean and standard error (SE) (Steel and Torrie 1980). PCA (principal component analysis) was performed using PAST3 V3.14 to characterize the variation patterns among treated and control plants. The plant parameters, owing to possession of different units, were normalized about mean using z-scores. The standard normalized data was used to transform the original variables into the corresponding principal component space. The loadings and scores for the computed PCs are given in Table S1 and S2, respectively.

3 Results

3.1 Characterization of the amendments

The SEM images representing surface morphological properties of BC, Fe-BC, FYM, and VC are shown in Fig. 1. The surface of the rice husk BC resembled a honeycomb with interconnecting holes of varying diameters (Fig. 1a). BC exhibited a well-developed porous structure with consistent patterns, highlighting a wide range of shapes in the meso, macro, and micropores. Furthermore, the porous surface texture of BC could be the result of volatile matter evaporation from rice husk during pyrolysis (Ahmad et al. 2012). According to Guo and Chong Lua (1998), the correctly arranged porous structure of BC possesses a high BET (Brunauer−Emmett−Teller) surface area and good adsorptive capacity. Compared to BC, Fe-BC had a rougher surface and moderately altered pore structures (Fig. 1b). Due to the deposition of Fe, many tiny flocculent solid particles of various sizes were found on the outer layers and in the pore space; these particles were scattered, disordered, and partially intersecting (Yang et al. 2021; Zhu et al. 2019). The morphology of the FYMs, as shown in Fig. 1c, revealed uneven surfaces with a porous surface structure, indicating a good capacity to adsorb Cr ions in an aqueous environment (Idrees et al. 2016; Yan et al. 2021). SEM examination additionally provided important information on the surface morphology of VC. The open pores visible in VC are represented by the black dots between the particles (Fig. 1d). It has interconnected particles with fewer pores and a reduced porosity (Priya et al. 2020).

The EDX results of BC indicate C (46.7%), O (29.89%) and some amount of minerals. The EDX of Fe-BC indicated that C, O and Si were the key elements, and mineral fractions particularly Fe (6.6%) could be detected. These findings demonstrated that carbon was the primary skeleton with oxygen in the BC specimens, which might be derived from O_2-containing functional groups (e.g., -COOH and -OH) or oxide-containing metal particles of minerals (e.g., carbonates, phosphates, and sulfates) (Biagini et al. 2008). EDX analysis revealed that the surface of Fe-BC was coated with Fe_2O_3 particles since it has a mixture of components (C, O, Si, Mg, Ca, and Fe) found in both BC and Fe-BC. The basic chemical makeup of Fe-BC exhibits enhanced Fe on the surface due to Fe_2O_3 deposition, and a greater O concentration compared to that of BC (Viglašová et al. 2020). Furthermore, the EDX mapping of the Fe-BC shows the presence of Fe, indicating that Fe was effectively deposited on the BC's outermost layer. While the results agree to our previous study (Khan et al. 2022) indicating successful Fe deposition (48%) on BC surface confirmed using XRF analysis, additional techniques like XPS or XRD should be employed to validate phase identification of Fe oxides. The content of the mineral elements in VC varies depending on the VC source and production process. Some of these elements can be released and become part of the soil when applied in the field, which contributes to increased fertility. Figure 2d shows an EDX spectrum of a VC sample. A greater quantity of the elements C, K, Ca, O, and Si, possibly in the form of salts such as carbonates and silicates (CO_3^{2-}, SiO_4^{4-}), were observed in this spectrum. Other elements such as Fe, Mg, and Al, are part of the inorganic pool of this VC (Ahamad et al. 2023; Martinez-Balmori et al. 2013). Elemental mapping of the FYM showed that C, O, and Si are present throughout the entire structure and could facilitate metal adsorption. The morphology of the FYMs, as shown in Fig. 2c, revealed an uneven surface with a porous structure, indicating a greater capacity to adsorb Cr ions in an aqueous environment (Mian et al. 2021). Additionally, SEM provides important information on the surface morphology of VC. The open pores visible in VC (Fig. 1d) are represented by the black dots between the particles. It has interconnected particles with fewer pores and reduced porosity. The results showed higher concentrations of C, O, and Si in all four amendments, with variations between each amendment. These findings suggest that each organic amendment possesses distinct physical and chemical properties that may affect its performance in different applications.

The mass loss was recorded between the inflection points of the TGA curves (Karathanasis and Harris 2015).

As shown in Fig. 3a, the TGA curves demonstrated the thermal stability of BC and Fe-BC. Under inert (N2) gas, the initial weight loss for both BC and Fe-BC occurred approximately at 100 °C. Nevertheless, Fe-BC demonstrated more stability than BC, as it lost less weight at 100 °C. The increased thermal stability of Fe-BC than BC can be ascribed to the impregnation of Fe, which possibly improved the BC structure, preventing early volatilization and enhancing its overall thermal resistance. While BC possibly lacked the reinforcing impact of Fe, it demonstrated slightly less thermal stability. A significant weight loss may also be caused by moisture impregnation from the environment during handling and storage (Tareq et al. 2019; Zhang et al. 2012). Under atmospheric conditions, the initial mass losses for FYM and VC were 85 ℃ and 120 ℃, respectively (Fig. 3a). These mass percentage increases could be attributed to higher levels of volatile materials in the initial waste blend (Lim et al. 2014). The progressive decrease in mass loss during the vermicomposting process implies net mineral formation and degradation. Compared to pre-vermicompost materials, the final VC exhibited lower mass loss, indicating greater maturity. This increased thermal stability in VC can be understood by mass loss owing to desiccation, oxidation, and decomposition (Bhat et al. 2017; Khatun et al. 2019). The increased carbohydrate molar complexity and aromaticity of VC contributed to a greater proportion of heat-resistant chemicals (Ravindran et al. 2013; Khatun et al. 2019).

Furthermore, FTIR was used to identify the functional groups in the different organic amendments (Fig. 3b). Biomass used for BC is a heterogeneous material with multiple peaks caused by organic component bonding. Its peaks at 3420–3200 cm^{-1}, 1100–1000 cm^{-1}, and 995–675 cm^{-1} indicated O–H stretching, Si–O-Si stretching, and C-O stretching, respectively (Cantrell et al. 2012; Pütün et al. 2005). These functional groups could efficiently enhance the adsorption rate of pollutants i.e., Cr (VI) (Diao et al. 2018). SiO_2 is a prominent component of the chemical structure of rice and has recalcitrant property. Although new functional groups were not introduced by Fe modification, it caused slight shifts in the FTIR absorption peaks as well as noticeable changes in peak intensities. Specifically, decrease in the intensity of -COO and -OH peaks indicate their surface interactions with Fe(III), possibly due to surface complexation and ligand exchange. These results are similar to our previous findings (Khan et al. 2022), where the doping of BC with Fe caused formation of C = O functional group and broad O–H stretching, highlighting structural changes after Fe addition. Moreover, the decrease in peak intensities may be ascribed to Fe oxide coating, partially covering surface functional bands on the BC plane while preserving key adsorption sites (Qian et al. 2017). Despite this, the surface of Fe-BC still exhibited an abundance of hydroxyl and carboxyl groups, which encouraged heavy metal adsorption (Agwupuye et al. 2022; Qian et al. 2017). Likewise, the abundant aromatic carbon supplied electrons, which may increase the potential for redox reactions (Wang et al. 2016). Altogether, these results indicate that Fe doping induced changes in surface chemistry of BC, without any significant disruption in the core functional groups involved in metal immobilization.

Furthermore, the FTIR spectra of VC and FYM demonstrates distinct functional groups involved in Cr sorption through different mechanisms. Figure 3b shows a sharp wide band between 3200 and 3500 cm^{-1}, specifically at 3355 cm^{-1}, corresponding to the stretching band of (-OH) groups from phenol, alcohol, and carboxyl functional groups, as well as adsorbed molecules of water. These functional groups containing oxygen serve as key heavy metal adsorption sites (Pandey and Pitman 2003; Amir et al. 2010; Simkovic et al. 2008; Kumar et al. 2013). Furthermore, the FTIR peak at 3609 cm^{-1} corresponds to N–H stretching indicating the involvement of amine group in metal complexation (Idrees et al. 2016). The peak at 1634.71 cm^{-1} represents C = O stretching from carboxylates and the presence of lignin-related structures, known to form strong complexation with heavy metals such as Cr (Elakiya and Arulmozhiselvan 2021). Likewise, the peak at 1549.85 cm^{-1} corresponds to C = C aromatic structures formed during the mineralization of proteins, hemicellulose, and celluloses. This humification process increases compost maturity as well as stability of organic matter, thereby contributing to poly-condensed structures capable of metal ions adsorption via π-electron interactions (Huang et al. 2006; Elakiya and Arulmozhiselvan 2021). In another study, FTIR spectra revealed increased in absorbance at 1453.31 cm^{-1}, 1421.63 cm^{-1}, and 1053.95 cm^{-1}, as well as the appearance of minor new peaks at approximately 1634.71 cm^{-1} and 1514.87 cm^{-1}, demonstrate the presence of oxidized benzyl structures and aromatic ethers from lignin-like structures, characteristics of humified compost materials providing additional metal binding sites via cation-π interactions and chelation (Ammar et al. 2014; Quadar et al. 2022). While the strong bands at 1002 cm^{-1} to 909 cm^{-1}, specifically at 998 cm^{-1}, remained linked with the C-H stretching of the alkene group observed in the FTIR spectra of VC (Elakiya and Arulmozhiselvan 2021).

3.2 Growth of plants as affected by Cr and various organic amendments

Effects of different concentrations of Cr (25, 50, 100 ppm) alone or in combination with organic amendments (5% VC, 0.5% Fe-BC, 5% BC, 5% FYM) on the SL, FW, and DW of tomato plants were observed in a pot experiment (Fig. 4a-c). The results demonstrated that the SL, DW, and FW of the plants significantly decreased at elevated levels

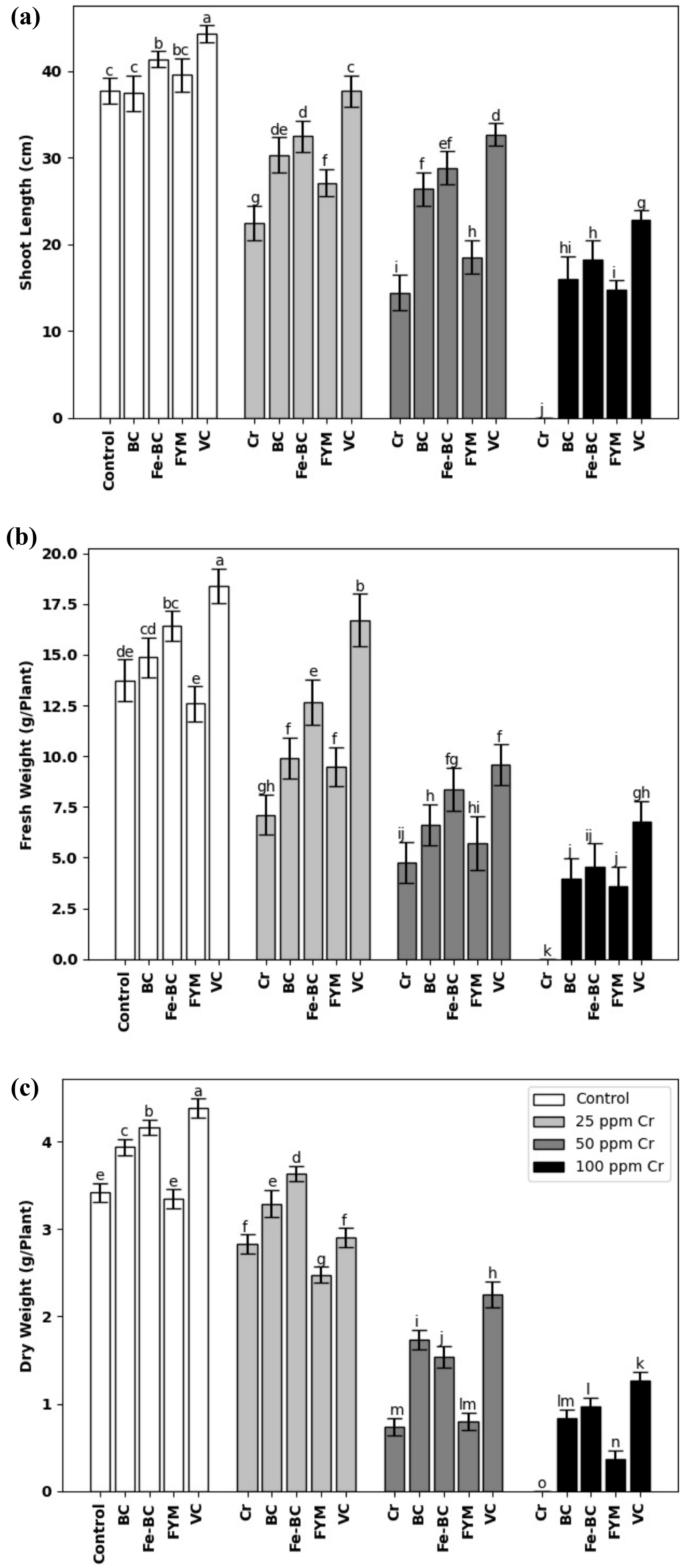


Fig. 4 Effects of chromium (Cr) levels and organic amendments on: **a** shoot length (SL), **b** fresh weight (FW), and (**c**) dry weight (DW) of tomato plants. The values are the means ± SE of four independent replicates. Different lower-case letters represent significant differences between different treatments at $p < 0.05$

of Cr, and all the values significantly ($p < 0.05$) increased in response to the mixed treatment of Fe-BC and VC with different Cr concentrations. As is evident from the data (Fig. 4), extreme declines in SL, DW, and FW were noted in plants receiving 50 ppm Cr dose, while 100 ppm Cr was found fatal for the plants. Also, notable decreases of 40—61%, 48—65%, and 17—78% at 25–50 ppm Cr were observed in SL, FW, and DW, respectively, compared to those in control. Interestingly, plants were able to survive at 100 ppm Cr with the application of all four amendments. In soil amended with Fe-BC, decreases of only 48%, 33%, and 28% were noted, and for VC, decreases of only 60%, 49%, and 37% were noted in the SL, FW, and DW of tomato plants exposed to 100 ppm Cr, respectively, compared to those in the control. Further amendment results showed that at the 50 ppm Cr stress level, FYM and BC increased SL by 1.28- and 1.83-fold, FW by 1.19- and 1.38-fold, and DW by 1- and 2.34-fold, respectively than the 50 ppm Cr-stressed plants raised without any amendment. Compared with 50 ppm Cr only, a significant increase of 2- and 2.27-fold in SL, 1.75- and 2.0-fold in FW, and 2.61- and 2.99-fold in DW, was recorded with the application of Fe-BC and VC along with 50 ppm Cr, respectively (Fig. 4a, b, c).

3.3 Effect of Cr and organic amendments on RWC, MSI, and TCC

Increasing levels of Cr had a detrimental impact on the RWC and MSI of tomato plant leaves (Fig. 5a, b), similar to the trend observed for SL and plant biomass, where higher levels of Cr had devastating impacts on plant characteristics. A decrease in the percentage of RWC (13%, 31%, and 100%) and MSI (22%, 52%, and 100%) for 25, 50 and 100 ppm Cr, respectively, was observed. However, the combination of Cr and organic amendments resulted in a considerable increase in RWC and MSI in the leaves. The soil amendment treatment results showed that at 25 and 50 ppm Cr, the RWC significantly increased (by 1.1- and onefold, respectively) with Fe-BC and by 1.12- and 1.19-fold, respectively, with VC (the greatest increase observed). Similarly, the MSI significantly increased by 1.16- and 1.3-fold with Fe-BC and 1.21- and 1.73-fold with VC at 25 and 50 ppm Cr, respectively. On the other hand, at the 100 ppm Cr stress level, a 57% and 67% decrease in RWC and a 58% and 62% decrease in MSI were observed in response to Fe-BC and VC, respectively, than the control.

We observed a substantial decrease in TCC of tomato leaves with an increasing concentration of Cr (Fig. 5c). The respective reductions in the pigment concentration in the tomato leaves were reported to be 24%, 49%, and 100% at 25, 50 and 100 ppm Cr, respectively, than the control. The combined application of amendments and Cr improved the TCC more efficiently than the Cr treatment alone. Shared applications of amendments with 25 and 50 ppm Cr enhanced the levels of TCC by 1.18- and 1.4-fold with Fe-BC and 1.52- and 1.87-fold with VC, respectively. At the 100 ppm Cr stress level, a 45% and 80% decrease in TCC was observed in response to Fe-BC and VC, respectively, compared to those in the control.

3.4 Plant Cr uptake and oxidative stress

The Cr contents in the plant tissues increased with increasing doses of Cr in the pots, as shown in Fig. 6a. The application of Cr in combination with organic amendments decreased the metal concentration regardless of its concentration. Interestingly, compared with the other amendments, the VC amendment was more effective at overcoming Cr contamination, and FYM had non-significant effect on Cr contamination. Cr concentrations in plants significantly decreased by 39% with Fe-BC and 52% with VC at 50 ppm Cr. At 100 ppm Cr in the pots, the Cr concentration in the plant tissues decreased by 29% and 49% with Fe-BC and VC, respectively.

All the Cr levels increased the H_2O_2 accumulation than to non-stressed control. The greatest increase in H_2O_2 (1.94- and 2.71-fold) at 25 and 50 ppm Cr, respectively, than that of the control was observed. The application of Cr in combination with amendments had significantly less effect on the H_2O_2 content than did the control treatment or the individual application of Cr. The combined application of amendments and 25 and 50 ppm Cr significantly increased the levels of H_2O_2 by 0.75- and 0.81-fold with Fe-BC and 0.5- and 0.47-fold with VC, respectively. Overall, a comparison of treatments revealed that H_2O_2 contents were greater after the individual application of Cr than after the combined application of Cr and amendments (Fig. 6b).

3.5 Activities of antioxidant enzymes

Effect of various treatments on the activities of antioxidant enzymes was assessed by analyzing the activity of SOD, CAT, POD, and APX. The results demonstrate that as the Cr concentration in the soil medium increased, so did the activities of antioxidant enzymes. We observed the greatest increase in antioxidant enzymes activity under Cr (25 and 50 ppm) stress (Fig. 7a, b, c, and d). SOD, APX, POD, and CAT activities increased by 1.58/2.61-fold, 1.17/2.07-fold, 1.62/2.12-fold, and 1.25/1.53-fold, respectively, at 25 and 50 ppm Cr compared to controls. The combined application of Cr and amendments (Fe-BC and VC) significantly lowered the antioxidant activity. The application of amendments in combination with 25 and 50 ppm Cr increased SOD

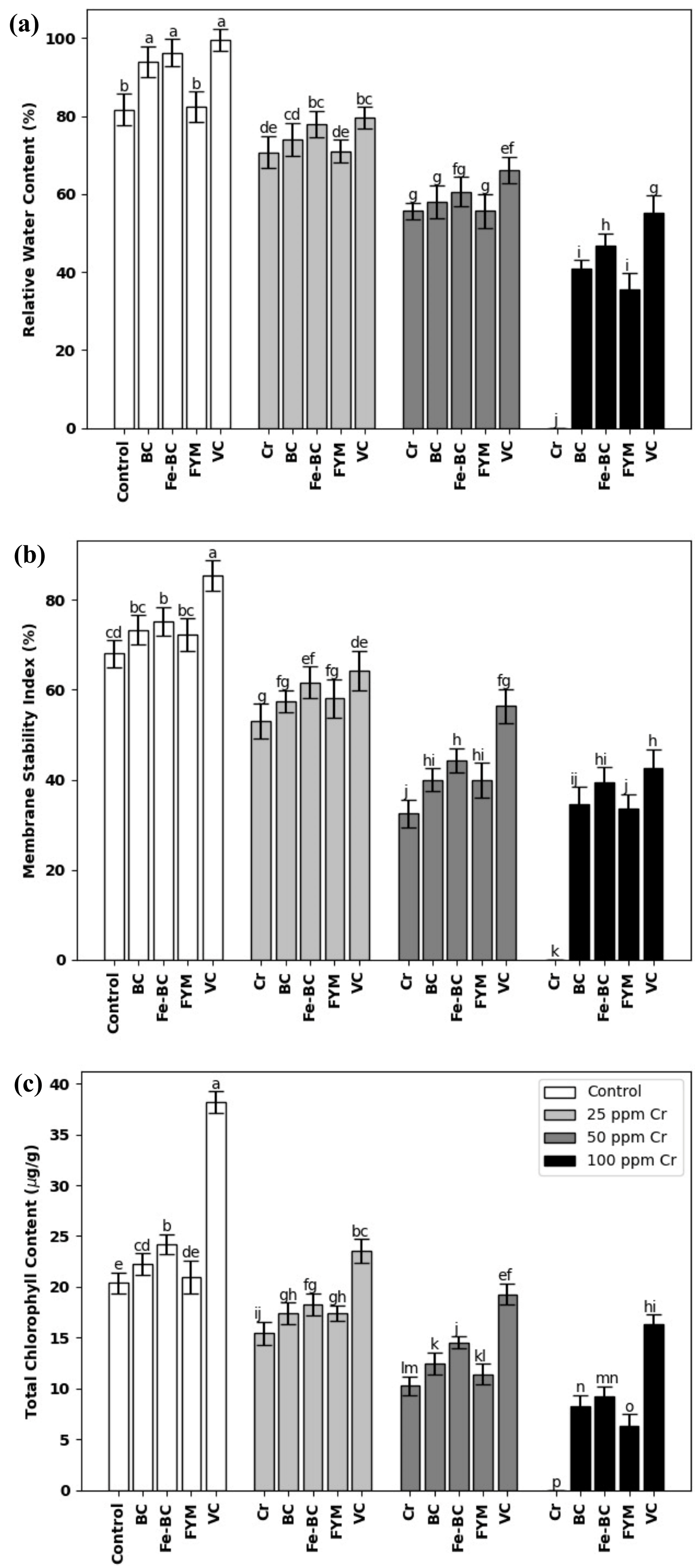
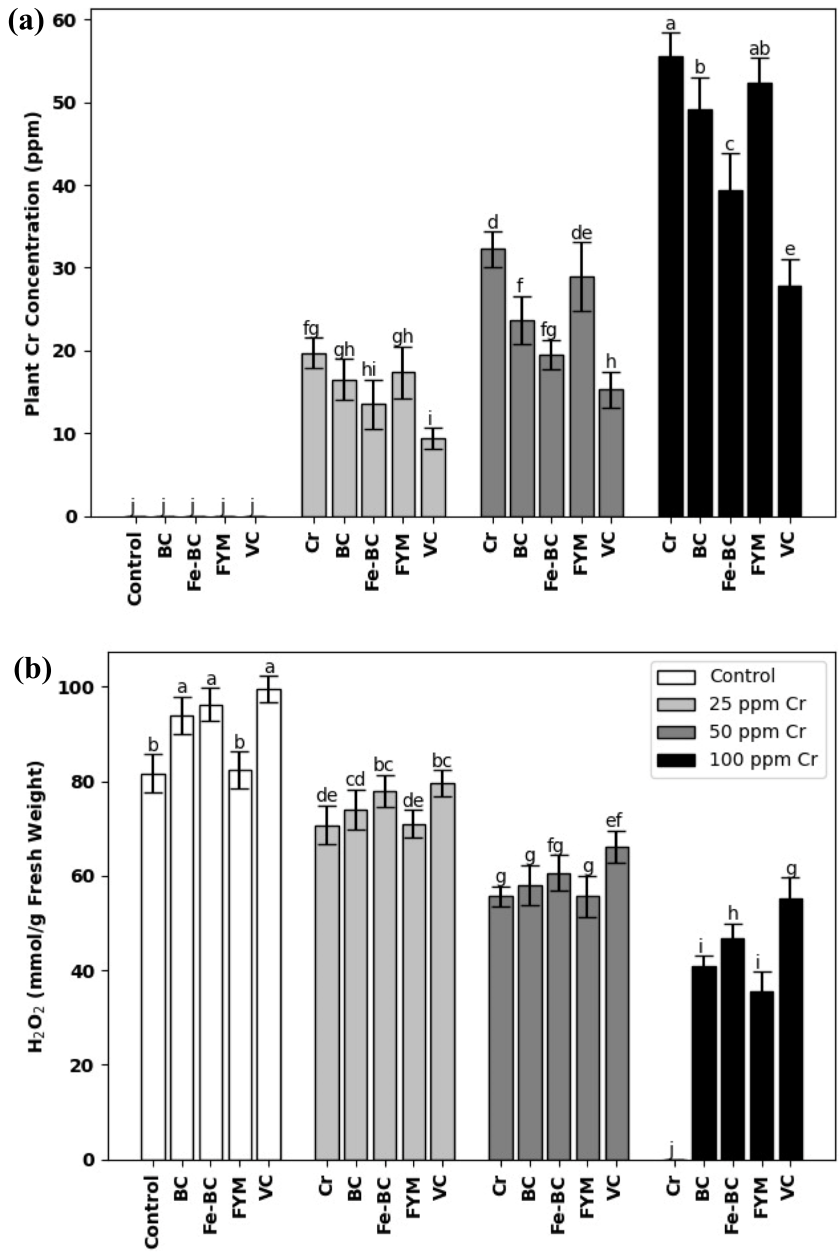


Fig. 5 Effects of chromium (Cr) levels and organic amendments on: **a** relative water content (RWC), **b** membrane stability index (MSI), and (**c**) total chlorophyll content (TCC) of tomato plants. The values are the means ± SE of four independent replicates. Different lower-case letters represent significant differences between different treatments at $p < 0.05$

Fig. 6 Effects of Cr levels and organic amendments on (**a**) Cr concentration and (**b**) H_2O_2 accumulation in tomato plants. The values are the means ± SE of four independent replicates. Different lower-case letters represent significant differences between different treatments at $p < 0.05$



activity by 0.75- and 0.78-fold, CAT activity by 0.74- and 0.76-fold, POD activity by 0.71- and 0.84-fold and APX activity by 0.63- and 0.81-fold with Fe-BC, respectively. Similarly, with the application of VC, a limited increase in SOD activity (0.53- and 0.67-fold), CAT activity (0.59- and 0.56-fold), POD activity (0.63- and 0.75-fold), and APX activity (0.39- and 0.55-fold) was observed with Cr (25 and 50 ppm, respectively). At the 100 ppm Cr stress level, increases in SOD (3.11 and 2.64)-fold, CAT (1.41 and 1.05)-fold, POD (2.95 and 2.23)-fold, and APX (1.71 and 1.46)-fold were observed in response to Fe-BC and VC, respectively, compared to those in the control.

3.6 Principal component analysis (PCA)

As demonstrated in PCA biplot (Fig. 8), the correlation matrices included PC1 (81.9%) and PC2 (15.4%), which link growth, physiological and biochemical data in tomato plants to different organic amendments under Cr stress. On PC1, parameters with the highest positive loadings include H_2O_2, SOD, APX, CAT, and plant Cr contents – which altogether suggests association of Cr-induced oxidative damage and the plant's antioxidant defense response under different treatments. Importantly, the strongest contribution of plant Cr contents along PC1 clearly separates Cr-treated plants from

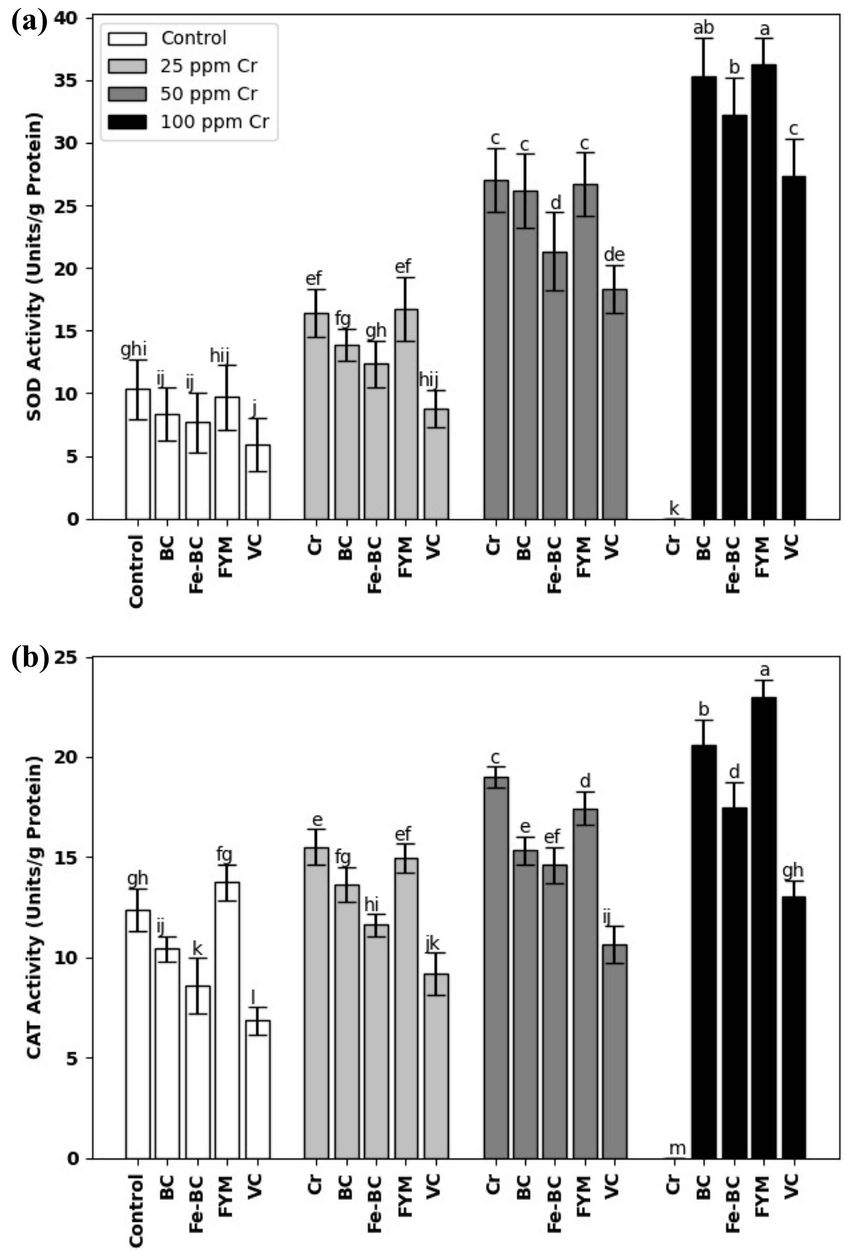
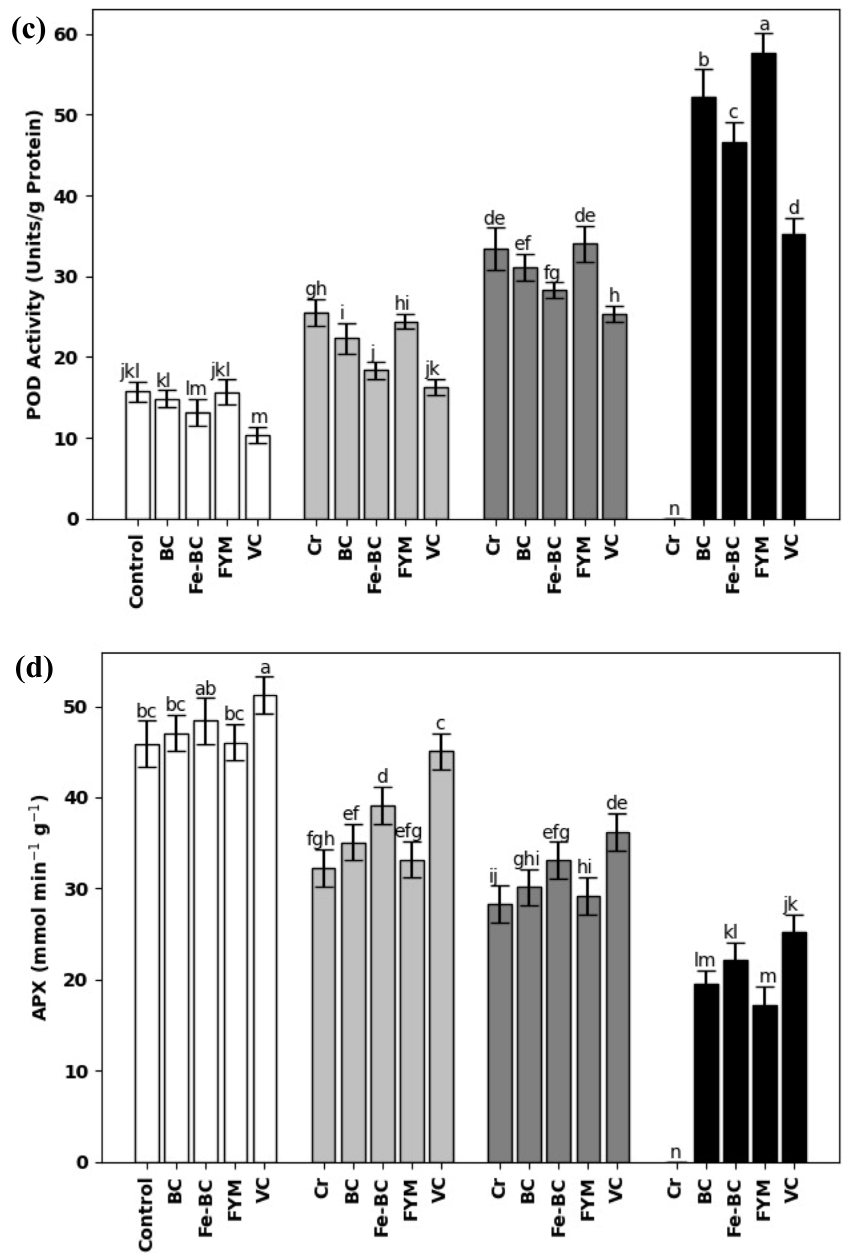


Fig. 7 Effects of Cr concentration and organic amendments on the activity of (**a**) superoxide dismutase (SOD) (**b**) catalase (CAT), (**c**) peroxidase (POD), and (**d**) ascorbate peroxidase (APX) activities in tomato leaves. The values are the means ± SE of four independent replicates. Different lower-case letters represent significant differences between different treatments at $p < 0.05$

other treatments. Contrarily, parameters with the highest negative loadings on PC1 include FW, DW, TCC, SL, MSI, and RWC – representing key plant growth and physiological variables that decrease with increase in Cr accumulation in plant tissues, thereby confirms Cr toxicity effects on tomato performance. On the other hand, the strong positive loading of CAT on PC2 contributes to distinct antioxidant response across different treatments. Whereas other antioxidant markers (SOD, SOD, and APX) cluster tightly, indicating coordinated defense response against Cr-induced oxidative stress.

Biologically, the matrices of correlations revealed a strong negative association between plant Cr contents and physiological variables (FW, DW, TCC, SL, MSI, and RWC), indicating that increase in accumulation of Cr is detrimental to plant vigor. In contrast, the PCA biplot clearly shows a positive correlation between Cr accumulation and oxidative stress markers including H2O2, SOD, APX, POD, and CAT, demonstrating that Cr phytotoxicity induces a distinct biochemical defense response. It is further evident by the spatial separation of oxidative stress markers from the growth-related attributes on opposite side of PCA biplot. Overall, the PCA underscores the significance of organic amendments in improving tomato resilience against Cr stress through immobilization as well as modulation of physiological and biochemical pathways to mitigate oxidative damage.

Fig. 7 (continued)



4 Discussion

Industrial use of heavy metals (HMs) has caused global soil pollution. Heavy metal contamination from industry has expanded rapidly in Pakistan due to lack of policies and the improper enforcement of existing ones (Song et al. 2022). It is well known that insufficient OM and excessive Cr accumulation might affect soil structure, resulting in decreased agricultural yields (Saleem et al. 2022). Chromium accumulates in plant tissues, directly polluting the food web and endangering the well-being of animals and humans (Ali et al. 2023). This highlights the need to develop reliable strategies to mitigate Cr toxicity and accumulation in plants.

In the present study, the effectiveness of four organic amendments (FYM, BC, Fe-BC, and VC) to reduce Cr toxicity in tomato was compared. The results revealed that the plant growth (FW, DW, and SL) decreased with increasing Cr stress, indicating its interference with normal physiological and cellular functions by causing oxidative damage, and hindering photosynthesis (Farooq et al. 2019; Khan et al. 2023). Chromium-induced toxicity was more pronounced at elevated levels of Cr (25 ppm, 50 ppm), while no growth was observed at 100 ppm Cr, which might be ascribed to cell cycle disruption and reduced plant growth (Gardea-Torresdey et al. 2005; Singh et al. 2013; Monteiro et al. 2018; Riaz et al. 2019; Mushtaq et al. 2022) (Fig. 4). Cr stress likely reduces the surface area of the roots for penetration

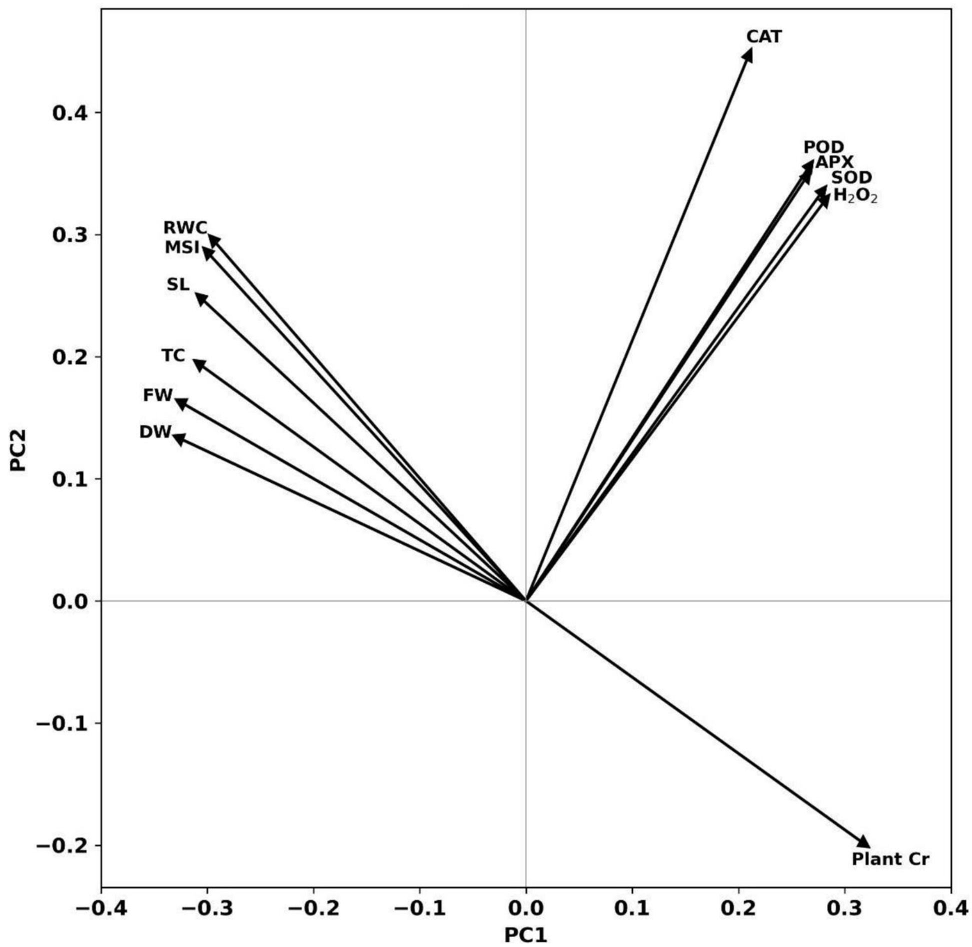


Fig. 8 Comparison of different variables using principal component analysis (PCA), with and without different Cr and amendment levels. Hydrogen peroxide (H_2O_2), total chlorophyll content (TCC), shoot length (SL), fresh weight (FW), dry weight (DW), relative water content (RWC), membrane stability index (MSI), superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), ascorbate peroxidase (APX), and chromium (Cr)

in the soil and the plant's capacity to look up the soil surface for moisture and nutrients (Ahemad 2015; Naz et al. 2023). The exposure of seedling roots to Cr most likely is reported to cause tissue collapse and, as a result, an inability to absorb both nutrients and water, ultimately stunted growth in plants (Ali et al. 2023; Singh et al. 2013). Furthermore, Cr localization in vacuoles, particularly in the parenchyma and xylem wall structures, may influence how cells function and attenuate their aqueous potential (Paredes et al. 2009; Vannini et al. 2011). These toxic effects of Cr could be attributed to structural defects and chlorosis of plant tissues (Sharma et al. 2020).

Organic amendments improved plant growth, with the most effective treatments given in the following order: VC > Fe-BC > BC > FYM. According to Ogbonna (2012) and Rekaby et al. (2020), using processed organic materials boosted maize stems in length, the total number of leaves, and leaf length, and pigment content. Khan et al. (2021) reported a similar trend, revealing that humic acid treatment increased Zinnia plant height. Organic substrates are known to restrict Cr solubility and mobility in soils, inhibit its uptake and transport by plants, thus influencing physiological responses contributing to plant resilience under Cr stress (Guo et al. 2018). Table 1 summarizes key mechanisms of Cr immobilization including physico-chemical properties and biological contributions though which each amendment reduces Cr mobility and toxicity in soil–plant systems.

A decreased Cr bioavailability with BC application observed in this study is in agreement with previous reports, highlighting its potential in improving soil characteristics and metal immobilization (Alhashimi and Aktas 2017). BC primarily immobilizes Cr via surface complexation with functional groups and precipitation with mineral ions (e.g., Ca and Mg). Moreover, its alkaline nature, high surface area and porous matrix collectively contribute to reducing Cr solubility. BC-mediated microbial transformation further reduces its availability to plants (Alhashimi and Aktas 2017; Bashir et al. 2020; Diao et al. 2021; Qian et al. 2017). Jiang et al. (2020) reported similar findings in terms of improved plant growth by applying BC to lead (Pb)-contaminated soil. Houben et al. (2013) showed a reduction in the accessible fraction of zinc (Zn), cadmium (Cd), and Pb due to BC (10%) treatment. Alhashimi and Aktas (2017) conducted a meta-analysis to compare BC and activated C, demonstrating BC's economic feasibility and environmental sustainability. However, more

Table 1 Summary of sorption mechanisms of organic amendments for Cr immobilization, including physico-chemical features and biological processes through which each amendment reduces Cr mobility and toxicity in soil–plant systems

Organic amendment	Key Cr immobilization mechanisms	Physico-chemical features	Biological processes	References
Biochar (BC)	- Adsorption via surface area and porosity - Surface complexation (–OH and –COOH functional groups) - Precipitation via mineral components (e.g., Ca and Mg)	- Porous matrix and high surface area - Alkaline pH reduces solubility of Cr(VI) - Rich in ash/carbon contents	- Increases microbial diversity and habitat - Stimulate microbial transformation of Cr(VI)	Alhashimi and Aktas (2017); Bashir et al. (2020); Diao et al. (2021); Qian et al. (2017)
Fe-BC	- Surface complexation with Fe oxides - Redox-mediated transformation of Cr(VI) - Enhances electrostatic complexation	- High Fe oxide contents and surface reactivity - Better structural/thermal stability	- Promote microbial activity via Fe-mediated pathways	Dong et al. (2021); Khan et al. (2022); Yang et al. (2021)
Vermicompost (VC)	- Chelation by fulvic/humic acids - Cation exchange via organic (–COOH and phenolic) functional groups - Microbial-mediated Cr speciation	- High CEC, nutrient rich - Rich in fulvic/humic substances and microbial biomass—Moderate porosity	- Promotes microbial biomass and enzymes - Stimulate microbial transformation of Cr(VI)	Elakiya and Arulmozhiselvan (2021); Ahamad et al. (2023)
Farmyard Manure (FYM)	- Sorption by organic matrix - Adsorption with hydroxyl and phenolic groups - Organic coating on soil particles - Dissolved organic carbon mediated Cr retention	- Moderate organic C and variable CEC - Lower ash content than BC or VC	- Boost microbial activity via enhanced nutrient supply - May increase enzymatic Cr(VI) transformation	Idrees et al. (2016); Kumar et al. (2021)

investigations are required to assess long-term benefits of BC in comparison with other organic amendments in different soil conditions.

Furthermore, the addition of Fe-BC in this study resulted in improved growth of plants and enhanced physiological parameters. This improvement could be ascribed to the high Fe oxide contents and surface reactivity, which not only enhance thermal and structural stability but also promote redox-mediated Cr(VI) transformation (Dong et al. 2021; Khan et al. 2022; Yang et al. 2021). Because of its high porosity and surface area, Fe-BC may generate perfect conditions for soil microorganisms and increased CEC (cation exchange capacity) by binding important cations and anions (Ebrahimi et al. 2021). It can alter soil properties (soil texture, permeability, structure, volume, and particle size distribution) and produce favorable conditions for growing plants (Ebrahimi et al. 2021; Li et al. 2018). Likewise, the improvement in soil aggregation and microbial diversity is reported to promote nutrient absorption and root growth (Ebrahimi et al. 2021). Furthermore, high ash content in organic amendments enhances their capacity to adsorb heavy metals like Cr, limiting its accessibility and harmful influence on plant growth and development (García-Gómez et al. 2018).

VC immobilizes metal ions via ion exchange and complexation (Ahamad et al. 2023). VC-induced biological processes including microbial transformation and increased enzymatic activity play key role in reducing Cr toxicity (Table 1). Furthermore, the availability of essential crop nutrients is influenced by organic amendments like VC, (Cheng 2003; Skjemstad et al. 2002). In this study, the increased plant growth under Cr stress is most likely due to the VC role in increasing the mineral supply, which stimulates plant growth (Méndez et al. 2017; Ebrahimi et al. 2021). Furthermore, high CEC of VC, abundant humic and fulvic substances, and enhanced microbial biomass increase crop productivity and yield under stressful conditions (Elakiya and Arulmozhiselvan 2021; Ahamad et al. 2023).

Contrarily, FYM was the least effective strategy to improve Cr tolerance of tomato. Nevertheless, FYM addition contributes to Cr retention through microbial stimulation and dissolved organic carbon (DOC) mediated pathways (Idrees et al. 2016; Kumar et al. 2021). DOC contents of organic amendments improve nutrient cycling and soil health by facilitating microbial activity (Ebrahimi et al. 2021). It has been reported that DOC also reduces metal bioavailability by forming metal complexes with organic matrix, hydroxyl and phenolic groups (Idrees et al. 2016; Kumar et al. 2021). However, moderate CEC and lower ash contents limit FYM capacity to immobilize Cr in comparison to BC and VC (Idrees et al. 2016). In this study, the non-significant variation in plant stress tolerance between FYM and other organic amendments highlights the significance of amendment-specific properties such as stability, functional group composition, and microbial synergy in governing Cr immobilization efficiency.The results revealed that the RWC, MSI, and TCC of the plants significantly decreased with increasing levels of Cr compared to those of the control plants (Fig. 5). However, Fe-BC and VC significantly increased the RWC, MSI, and TCC of plants by reducing the harmful impacts of increasing Cr levels. Plants grown on FYM-supplemented soil showed nonsignificant increases in RWC, MSI, and TCC. The VC-amended soil showed the greatest increase in RWC, MSI, and TCC. Photosynthetic pigments, or chlorophyll, are molecules that collect light energy at a specific wavelength, which is required for photosynthesis and are impacted by Cr stress. Reduced photosynthetic pigments could be caused by impaired enzyme activities involved in pigment production and decreased absorption of nitrogen (N) and magnesium (Mg) and nitrogen (N) due to Cr toxicity (Adejumo et al. 2016; Nelson and Cox 2008). Furthermore, this could be related to increased ROS generation, which decreases the plants photosynthetic capacity under Cr exposure (Asgher et al. 2018). Its accumulation may also decrease energy utilization, diminishing the activity of photosynthetic pigments (Yruela 2005). Similarly, Cr toxicity drastically reduced the rate of photosynthesis (A) regarding the CO_2 fixation rate while also negatively impacting the activity of carbon-fixing catalysts and the electron transporter chain (Liu et al. 2008). Decreased assimilation of CO_2 may also correlate with decreased stimulation-capturing efficiency and PS-II quantum yields (Singh et al. 2017). Additionally, Cr-induced irregularities had a comparable effect on the transpiration rate of plants that could be ascribed to lower water permeability and higher diffusive impedance (Gopal et al. 2009). Stomata, which include distinct cells known as guard cells, regulate their closure and opening (Wang and Blatt 2011). These stomatal apertures undergo gas exchange instead of water loss and are influenced by toxic Cr (Singh et al. 2017). Our findings are similar to those of previous research (Chen et al. 2023; Danish et al. 2019; Gopal et al. 2009), which indicated that plants exposed to Cr stress have worse physiological and photosynthetic performance. The bioaccumulation of harmful Cr may reduce nutrient uptake or cell osmotic potential, generating a discrepancy in stomatal activity and thus compromising plant photosynthetic processes and growth (Chanda and Parmar 2003). Moreover, Cr toxicity in photosynthetic pigments may reduce the size of the peripheral part of the antenna complex, causing protein breakdown or destabilization and resulting in enzyme inactivation, all of which might lead to a decrease in chlorophyll concentration (Rai et al. 2014). Reduced chlorophyll synthesis, chloroplast ultrastructure disorganization, suppression of electron flow routes, and decreased enzymatic functioning of the Calvin cycle could explain the reduced plant photosynthetic rates observed in this study. The synthesis of electrons in photochemical reactions may not be efficient for carbon assimilation; the diversion of electrons from PS-I to Cr (VI) on the electron-donating side could play a role in reducing the rate of photosynthesis (Liu et al. 2008; Singh et al. 2013). Chromium-induced irregularities in chloroplast ultrastructure could also be generated by a poorly formed lamellar framework with broadly dispersed thylakoids and few grana (Paiva et al. 2009).

Plant water status can be determined using RWC, that is described as a plant physiological response to stress. The reduction in RWC (Fig. 5a) could be ascribed to the smaller root surface area, which might reduce the plant's ability to absorb water from the soil's outermost layer. Furthermore, Cr toxicity in plants may reduce longitudinally dispersed water circulation by narrowing the vascular channel (Shanker et al. 2005). Similarly, RWC decreased in plants subjected to mild or severe Cr stress (Shanker et al. 2005). A lower RWC in leaf tissue is caused by a reduction in turgor pressure, a limitation in the absorption of accessible water, and a restriction in roots water uptake under harsh conditions. Plants use a decrease in RWC in tissues to reduce numerous metabolic processes and conserve energy for life (Sarker and Oba 2018). In the current study, a substantial increase in RWC was recorded in the Cr-stressed plants grown with the organic amendments (Fig. 5a). The increase in RWC by organic substrates was possibly owing to their role in stimulating the hydration level which induces biochemical reactions in plant tissues and the subsequent growth and yield of the crops (Rekaby et al. 2020). Like our findings, Feizabadi et al. (2021) also reported that VC increased the RWC of various canola cultivars.

Reactive oxygen species are naturally occurring by products of cellular activity. Parvez et al. (2020) identified free radicals such as radicals containing hydroxy (•OH), and anionic superoxide (O_2•) as well as nonradical molecules like singlet oxygen ($^1O_2$) and peroxides of hydrogen (H_2O_2). Chromium stress causes increased ROS generation in plants due to the disruption of homeostasis in cells (Saleem et al. 2022). Excessive ROS generation induces oxidative damage in plants, particularly cell membrane breakdown and electrolyte leakage (Ahemad 2015; Saleem et al. 2022). ROS activity during Cr stress causes lipid oxidation, protein structural changes, the deposition of groups of sulfhydryl (-SH) groups in amino acids and their deactivation, fading, or loss of pigmentation, such as chloroplasts and carotenoid pigments, and overall damage to the photosystem (Hasanuzzaman et al. 2020). Unsurprisingly, increased activities of APX, POD, CAT, and SOD enzymes in the leaves of plants have been detected in Cr-contaminated soils, indicating their role in ROS detoxification, which is in accordance with recent findings (Figs. 6 and 7) (Chen et al. 2023; Singh et al. 2013). Increased APX activity may aid in the scavenging of H_2O_2 and its conversion to water by employing ascorbate as an electron carrier (Bashir et al. 2020). Additionally, the enhanced activity of CAT decreased the Cr-induced oxidative damage to the stroma and thylakoid chloroplast functions (Paredes et al. 2009). Increased activity of SOD most likely generated primary resistance to damage from oxidation and altered O_2^- to H_2O_2, which then promoted water utilization by APX and CAT enzymes (Bashir et al. 2020; Rai et al. 2014.). The negative effects of Cr on the activities of antioxidant enzymes were also modulated by the application of organic amendments. Because of their substantial water-holding capacities and advancements in both chemical and physical qualities, VC and BC promote nutrient uptake by roots, resulting in a faster photosynthetic rate. In the presence of OM, the major components that facilitate photosynthesis, especially P, are discharged into the root zones (Bashir et al. 2020; Pande et al. 2007). The incorporation of VC and BC as organic amendments improved the biochemical attributes of *B. integerrima* and its ability to cope with metal stress by increasing the contents of organic materials, phenolic compounds, and enzymes that produce antioxidants under moderate to severe stress (Khosropour et al. 2022).

5 Conclusions and recommendations

The results of the current study suggested that the application of organic amendments could alleviate overall Cr toxicity in tomato plants and improve their growth. The harmful effects of Cr on plants were negated significantly by 0.5% Fe-BC and 5% VC treatments, but effect of 5% FYM treatment was not significant. The application of 50 ppm Cr caused pronounced reductions in plant growth, MSI, RWC, and TCC, while plants did not survive at the highest Cr concentration, i.e., 100 ppm. Cr-induced oxidative damage reduced overall plant growth as indicated by a 2.7-fold increase in H_2O_2 accumulation. The addition of organic amendments to the growth medium effectively improved plant growth characteristics. Decreased oxidative stress due to enhanced antioxidant activity was regarded as the major mechanism responsible for improved plant growth in the presence of organic amendments. Interestingly, plants were able to withstand the highest level of Cr (100 ppm) with the application of soil organic amendments, and VC was the most effective amendment. Organic amendments are known to exert multiple beneficial impacts on soil properties associated with increased organic matter contents, improved nutrient retention and microbial diversity. Furthermore, surface properties of different organic amendments provide exchange sites for heavy metal immobilization and ultimately contribute to plant stress tolerance. While the present study provides valuable insights into organic soil amendments (Fe-BC and VC) as a cost-effective strategy for reducing Cr uptake, several limitations need to be acknowledged. (1) The use of advanced complementary techniques like X-ray photoelectron spectroscopy (XPS) or X-ray diffraction (XRD) is recommended to enhance the robustness of mineralogical interpretations of this study. (2) Future studies involving post-harvest soil and root Cr content data will facilitate complete understanding of Cr translocation and residual contamination. (3) Researchers should conduct further studies to test the efficiency of organic soil amendments in large-scale field experiments on Cr-polluted soils. (4) Additional research is needed to understand how VC and (Fe)-BC affect multiple secondary metabolites groups as well as antioxidant enzyme activity in various plant species to better understand their significance for agricultural productivity. (5) Also, plant parameters for tomatoes, including growth indicators (biomass and plant height), physiological traits (chlorophyll content, photosynthetic rate etc.) and yield attributes (fruit number, size and nutritional quality) are vital to evaluate the efficacy of such soil amendments. (6) Future research shall also explore the molecular mechanisms underlying these responses, assess the long-term impacts of amendments on plant–microbe interactions, and develop sustainable practices to enhance yield and resilience in diverse environmental conditions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11368-025-04077-9.

Data availability Data will be made available on request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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