Plant and Environment
https://journals.pagepal.org/index.php/PlantandEnvironement
ISSN (Online), 2788-7553; (Print), 2788-7545
https://doi.org/ 10.54219/plantenviron.06.02.2025.276



Organic Amendments and Biochar Alleviate Chromium Stress in Mungbean (*Vigna radiata*)

Ayesha Shahid[1], Amina Rashid[1], Hamna Bashir[2] and Muhammad Tahir Shehzad[3]

[1]Department of Agronomy, University of Agriculture Faisalabad, 38040, Faisalabad, Pakistan
[2]Ham Organics (PVT) Limited, 39100, Nankana Sahib, Pakistan
[3]Institute of Soil and Environmental Science, University of Agriculture Faisalabad, 38040, Faisalabad, Pakistan

Article Info

Keywords:
Chromium stress; organic amendments; mungbean; soil remediation; heavy metal immobilization
Date:
Received: 12 August 2025
Accepted: 26 November 2025
Published: 15 December 2025

Volume: Vol. 06 (02)

Copyright: © 2025 by the authors. This article is distributed under the Creative Commons Attribution (CC BY) license, allowing for open access and sharing under specified terms and conditions. (https://creativecommons.org/licenses/by/4.0/).

Abstract

*Chromium (Cr) contamination poses serious risks to crop productivity and food safety due to its toxicity and persistence in soil-plant systems. This study evaluated the comparative effectiveness of different organic amendments in mitigating Cr stress in mungbean (*Vigna radiata*). A pot experiment was conducted under controlled conditions using soil spiked with 25 ppm Cr and treated with cow dung manure, poultry manure, farmyard manure, biochar, and lignite at 2% (w/w), arranged in a completely randomized design with three replications. Growth and yield attributes, along with chromium fractionation and speciation in soil and plant tissues, were assessed using standard analytical techniques. Relative to the Cr-stressed control, cow dung manure increased shoot length by 45.7%, root length by 110.2%, shoot dry weight by 243.2% and seed number by nearly 68-fold, while reducing exchangeable Cr by 43% and soil Cr (VI) concentration by 42.4%. Poultry and farmyard manures showed moderate improvements, whereas biochar and lignite had limited or negative effects. Cow dung also decreased total Cr accumulation in roots and shoots by 63.5% and 82.8%, respectively, and enhanced Cr immobilization by increasing organic-bound and residual fractions. The superior performance of cow dung is attributed to its balanced nutrient composition, organic matter enrichment, and stimulation of microbial Cr (VI) reduction to less toxic Cr (III). These findings demonstrate that nutrient-rich organic amendments, particularly cow dung, effectively mitigate chromium toxicity and improve plant performance under contaminated conditions. Field-scale validation is recommended to confirm the long-term applicability and sustainability of this remediation strategy.*

1. Introduction

Heavy metal contamination has become a significant environmental and agricultural challenge due to rapid industrialization, urbanization and intensive anthropogenic activities. Among these contaminants, chromium (Cr) is of particular concern because of its high toxicity, persistence and potential for bioaccumulation in food crops (Angon et al., 2024). Accumulation of Cr in edible plant parts can enter the human and animal food chain, posing serious health risks including chronic toxicity, organ damage and immune dysfunction. Pulses like mungbean (*Vigna radiata*), which are critical for protein security and soil fertility through nitrogen fixation, are vulnerable to Cr stress, making remediation research in these crops highly relevant for both food safety and sustainable agriculture (Das et al., 2023). Chromium exhibits primarily two oxidation states in the

Corresponding Author: Amina Rashid Email: aminauaf1@gmail.com
©2025, PagePal Pvt. Ltd. (https://journals.pagepal.org/index.php/PlantandEnvironement)

environment: trivalent [Cr (III)] and hexavalent [Cr (VI)]. Cr (III) is an essential micronutrient at trace levels, which is involved in glucose and lipid metabolism but can be phytotoxic in excess (Ijaz et al., 2023a; Qureshi et al., 2024). Cr (VI) on the other hand, very soluble, mobile, and carcinogenic, percolates through plant tissues causing oxidative stress with excess generation of reactive oxygen species (ROS) (Sharma et al., 2020). This subsequently leads to lipid peroxidation, damaging proteins and DNA inhibiting photosynthesis, disrupting membrane integrity and interfering with enzymatic and nutrient uptake. Cr (VI) contamination is mainly anthropogenic, from leather tanning, electroplating and metal refining industries; pigment and fertilizer production and small sources from coal combustion and waste incineration; with negligible natural inputs from weathering of ultramafic rocks (Ijaz et al., 2023b; Kierczak et al., 2021). These activities often lead to Cr (VI) concentrations that exceed safety limits for drinking water and soil, necessitating immediate remediation interventions.

Mitigation of chromium toxicity by conventional chemical methods is often expensive, energy-intensive, and disturbing to the ecosystem (Qureshi et al., 2024). Organic amendments are an alternative approach that can be both cost-effective and environmentally friendly. These materials improve the soil structure, nutrient cycling, and immobilization of heavy metals by sorption, complexation, and electron-donor-driven microbial reduction (Khaliq et al., 2023). For instance, biochar obtained from pyrolysis possesses high porosity, surface area, and density of functional groups, leading to Cr (VI) adsorption and microbial reduction to Cr (III) (Amalina et al., 2022). Compost- and vermicompost-rich humic substances and microbial biomass may complex and detoxify heavy metals, whereas farmyard manure (FYM) improves the organic matter content, pH and nutrient availability for binding metals to soil particles (Enebe and Erasmus, 2023; Rupa et al., 2023). Owing to the nitrogen, phosphorous, and minerals present in poultry manure, these contribute towards buffering capacity and sustain microbial populations capable of enzymatic Cr (VI) reduction (Amin et al., 2023). Lignite, a carbon-rich material, is another amendment that could lead to immobilization (Chafik et al., 2025; Shakeel et al., 2021).

A significant amount of research has been conducted on organic amendments, but almost all studies have concentrated on cereals and fodder crops grown in pot conditions, largely ignoring pulses such as mungbean (Diatta et al., 2024). The strategic importance of Cr remediation research is underlined by the nutritional and ecological impact of mungbean (Ali et al., 2020). To date, comparative studies on various amendments, including cow dung, poultry manure, FYM, biochar and lignite are few and far between especially regarding the effectiveness of these amendments in ameliorating exchangeable Cr and supporting growth under Cr stress. Further study on these differences is critical to design targeted remedial strategies thereby contributing to sustainable soil remediation. Pot experiments, while valuable for mechanistic understanding have limitations in simulating field conditions including variable soil heterogeneity, microbial dynamics and environmental factors such as rainfall and temperature (Qureshi et al., 2024). Consequently, results from controlled studies must be interpreted with caution and field validation is necessary to confirm long-term applicability. Nevertheless, pot studies provide an essential foundation for evaluating amendment-specific effects on Cr immobilization, plant physiology and growth responses.

In this context, the present study evaluates and compares the effectiveness of cow dung, poultry manure, FYM, biochar and lignite in mitigating Cr stress in mungbean. It is hypothesized that nutrient-rich animal manures will reduce exchangeable Cr and improve plant growth relative to carbon-rich amendments, owing to the combined effects of nutrient enrichment and microbial-mediated Cr (VI) reduction. The study reports trends as relative percent changes compared to Cr-stressed controls to accurately reflect treatment efficacy, avoiding misleading raw fold-changes. Overall, this research aims to identify the most effective organic amendment for sustainably managing Cr-contaminated soils in mungbean systems, supporting environmental protection, crop productivity and food safety. By integrating mechanistic insights with comparative evaluation, the study provides a foundation for future field-scale applications and contributes to the broader understanding of organic-amendment-mediated heavy metal remediation.

2. Materials and methods

2.1. Soil sampling, spiking and analysis

An experiment was conducted in pots within a wire house to evaluate the effects of different organic amendments on the physiology and growth of mung bean cultivated in chromium (Cr)-contaminated soil. Surface soil samples were collected from a field at ISES. Baseline soil properties (pH, EC, texture, organic matter, CEC, macro- and micronutrients) were recorded and are presented in Table 1. The soil was analyzed before and after Cr contamination to determine its physicochemical properties. Soil texture was measured using the hydrometer technique and soil pH was tested with a saturated paste. Electrical conductivity (EC) was determined using a soil solution extract. Soluble cations (Ca^{2+}, Mg^{2+}) and anions (CO_3^{2-}, HCO_3^-, Cl^-) were quantified using titration. Cation exchange capacity was calculated using the ammonium acetate displacement technique. The bioavailable Cr in the soil was quantified using the ammonium bicarbonate-diethylene triamine penta acetic acid

©PagePal. All Rights Reserved.

Table 1. Physicochemical properties of the soil used in the experiment before chromium spiking

Property	Value	Method/Unit
pH	7.8	Saturated paste
EC	0.45 dS m^{-1}	Soil solution
Organic matter	1.8%	Walkley-Black
CEC	12.5 cmol kg^{-1}	Ammonium acetate
Texture	Loam	Hydrometer
Exchangeale Ca^{+2}	5.2 cmol kg^{-1}	EDTA titration
Exchangeable Mg^{+2}	2.8 cmol kg^{-1}	EDTA titration
AB-DTPA extractable Cr	0.85 cmol kg^{-1}	AAS

(AB-DTPA) method and analyzed with an atomic absorption spectrophotometer (AAS). Soil pH was measured using a pH meter calibrated with buffer solutions of pH 4 and 10. Electrical conductivity (EC) was determined with an EC meter calibrated using 0.01 N KCl solution. Soluble Ca^{2+} and Mg^{2+} were calculated through titration with 0.01 N EDTA using Eriochrome Black T as an indicator. Soluble carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) were measured by titration with 0.01 N H_2SO_4 using phenolphthalein and methyl orange indicators, respectively. AB-DTPA extractable Cr was determined using the ammonium bicarbonate-DTPA method and analyzed by AAS. The soil was ground, sieved through a 2 mm mesh, and divided into four sections to ensure uniform Cr dispersion during spiking. For Cr spiking, potassium dichromate ($K_2Cr_2O_7$) was used as the chromium source. A stock solution of $K_2Cr_2O_7$ was prepared in deionized water and applied to the homogenized soil to attain a final concentration of 25 mg kg^{-1} (25 ppm) Cr. The solution was added evenly, and the soil was thoroughly mixed to ensure uniform distribution. The contaminated soil was then incubated for 30 days under moist conditions to allow equilibration and simulate field aging. Pot size was 8 kg soil per pot, arranged in a Completely Randomized Design (CRD) with three replications per treatment. After incubation, 8 kg of treated soil were placed in each pot for the experiment; each treatment was replicated three times.

2.2. Collection and preparation of organic amendments

Organic amendments including cow dung manure, poultry manure, farmyard manure, biochar and lignite were collected from local sources. Manures were air-dried, ground, and sieved through a 2 mm mesh before application. Biochar and lignite were obtained in powdered form and homogenized. These amendments were applied individually to contaminated soil at a rate of 2% (w/w) before sowing to assess their role in mitigating Cr toxicity (Qureshi et al., 2024).

2.3. Crop husbandry

Treatments were applied, including control and organic amendments such as cow dung manure, poultry manure, farmyard manure, biochar and lignite. The amendments were applied under a level of Cr contamination (25 mg/kg). Each treatment was replicated three times. Recommended doses of nitrogen (120 kg/ha), phosphorus pentoxide (90 kg/ha) and potassium oxide (60 kg/ha) were applied. Phosphorus, potassium and half of the nitrogen fertilizer was applied at sowing, with the remaining nitrogen split into two equal applications. Fourteen mungbean seeds were sown per pot and four plants were retained after germination. Seeds of mungbean (*Vigna radiata* var. NM-2011) were obtained from the National Seed Council, Pakistan. Removed plants were mixed into their respective pots. Tap water was used for irrigation based on soil moisture conditions. The wire-house maintained natural daylight with average day/night temperatures of 28/22°C and relative humidity of 60–70%. Pots were arranged randomly and repositioned weekly to minimize micro-environmental variation. Harvesting was conducted at physiological maturity. Seeds were sown at 14 per pot after germination four seedlings were retained per pot and excess plants were returned to the soil to maintain nutrient balance.

Germination data were recorded daily until a constant germination rate was reached. Stomatal conductance, photosynthesis rate, CO_2 emission and transpiration rate were measured 50 days after sowing using an Infrared Gas Analyzer (IRGA). Chlorophyll content was determined using a SPAD meter. After harvesting, root and shoot samples were collected for analysis of Cr, Fe, Zn, and Si levels using an atomic absorption spectrophotometer (AAS). Silicon content

©PagePal. All Rights Reserved.

was calculated as % SiO_2 using the hydrogen peroxide oxidation method and measured with a double beam spectrophotometer (UH5300). Plant height, root length, number of tillers, number of spikelets, total grain weight, straw weight, spike weight, root fresh weight, root dry weight, and shoot dry weight were measured at physiological maturity. Plant samples were oven-dried at 65°C until constant weight was achieved. Samples were ground, stored, and prepared for wet digestion using a di-acid mixture of $HClO_4$ and HNO_3 (2:1). Digested samples were filtered and analyzed for Cr concentration using AAS. Quality assurance and control included analysis of reagent blanks, standard reference materials, and triplicate measurements. Calibration curves for Cr were prepared using certified $K_2Cr_2O_7$ standards, with detection limits of 0.01 mg L^{-1} and correlation coefficients >0.995. All laboratory measurements included quality assurance procedures using blanks, standard references, and recovery checks following standard protocols (Qureshi et al., 2024).

2.4. Statistical analysis

Data were statistically analyzed using analysis of variance (ANOVA) with Tukey's HSD test at a 5% significance level. All treatment comparisons are expressed as percent change relative to the Cr-stressed control. ANOVA assumptions were checked, and Tukey's HSD test was applied at $p \leq 0.05$ using statistix 8.1 version (Steel et al., 1997).

3. Results

3.1. Agronomic and morphological attributes

Similar trends across parameters are presented concisely to avoid redundancy. The experimental results (Figure 1) demonstrate the significant impact of various organic amendments on mung bean growth under chromium stress (25 ppm). Cow dung manure showed the strongest positive effects on all growth parameters. Relative to the Cr-stressed control, cow dung increased shoot length by 45.7% ($p < 0.05$) followed by poultry manure (+34.3%) and farmyard manure (+24.9%). Biochar showed a modest improvement (+15.4%) whereas lignite reduced shoot length by 34.2% compared to the control. Shoot fresh weight was maximized by cow dung, which improved values by 315.4% relative to the control ($p < 0.05$). Poultry manure also enhanced shoot fresh weight (+255.4%), while FYM (+35.0%) and biochar (+45.0%) showed moderate effects. Lignite performed poorly, showing a 55.0% decrease relative to control. Shoot dry weight increased by 243.2% under cow dung compared to control ($p < 0.05$), followed by poultry manure (+143.2%). FYM (+35.8%) and biochar (+42.9%) showed modest increases, while lignite reduced shoot dry weight by 57.1% relative to control.

Root length increased by 110.2% under cow dung relative to the Cr-stressed control ($p < 0.05$). Poultry manure (+90.1%) and FYM (+70.0%) also improved root length, while biochar showed a modest gain (+20.1%). Lignite resulted in a 9.9% reduction compared to control (Figure 2). Root fresh weight measurements showed cow dung (5.67 g) > poultry manure (4.33 g) > farmyard manure (4 g) > biochar (2.67 g) > control (2 g) > lignite (1.33 g). For root dry weight, cow dung again showed superiority (2.43 g) compared to poultry manure (2.23 g), farmyard manure (2.02 g), biochar (1.66 g), control (1.33 g), and lignite (1.02 g). The amendments also significantly influenced reproductive parameters. Cow dung treatment produced the highest number of leaves (55.33), followed by poultry manure (42.67), farmyard manure (35.67), biochar (29.33), control (24.67), and lignite (20.67). Seed production was strongly enhanced by cow dung, which increased seed number by nearly 68-fold compared to the Cr-stressed control ($p < 0.05$). Poultry manure produced ~39-fold more seeds than control, and FYM ~31-fold more. Biochar gave an ~18-fold increase while lignite performed worst with seed numbers like control. These results highlight the superior efficacy of cow dung manure in mitigating chromium stress, likely due to its rich nutrient content, organic matter composition, and ability to improve soil structure and microbial activity. The performance hierarchy (cow dung > poultry manure > farmyard manure > biochar > control > lignite) suggests that nutrient-rich animal-derived amendments are more effective than carbon-rich amendments for chromium stress alleviation. Lignite's poor performance suggests nutrient-poor carbon materials are unsuitable for chromium-contaminated soils.

3.2. Chromium fractionation in soil under organic amendments

The study evaluated chromium distribution among different soil fractions under organic amendments in chromium-contaminated soil (25 ppm) (Figure 3). Relative to the Cr-stressed control, cow dung reduced the exchangeable chromium fraction by 43% ($p < 0.05$). Poultry manure achieved a 33% reduction, while FYM and biochar reduced it by 24% and 18%, respectively. Lignite showed negligible effect. The effectiveness sequence was: cow dung > poultry manure (37.73 mg/kg) > farmyard manure (32.81 mg/kg) > biochar (29.25 mg/kg) > control (29.02 mg/kg) > lignite. Compared with the control, cow dung increased the organic-bound fraction of chromium by 124% ($p < 0.05$), poultry manure by 43%, FYM by 42% and biochar by 22%, whereas lignite only increased it by 12%. The pattern was: cow dung > poultry manure (4.31 mg/kg) > farmyard manure (4.28 mg/kg) > biochar (3.66 mg/kg) > control (3.01 mg/kg) > lignite (1.73 mg/kg). Relative to control, cow dung increased residual chromium by 132% ($p < 0.05$), poultry manure by

©PagePal. All Rights Reserved.

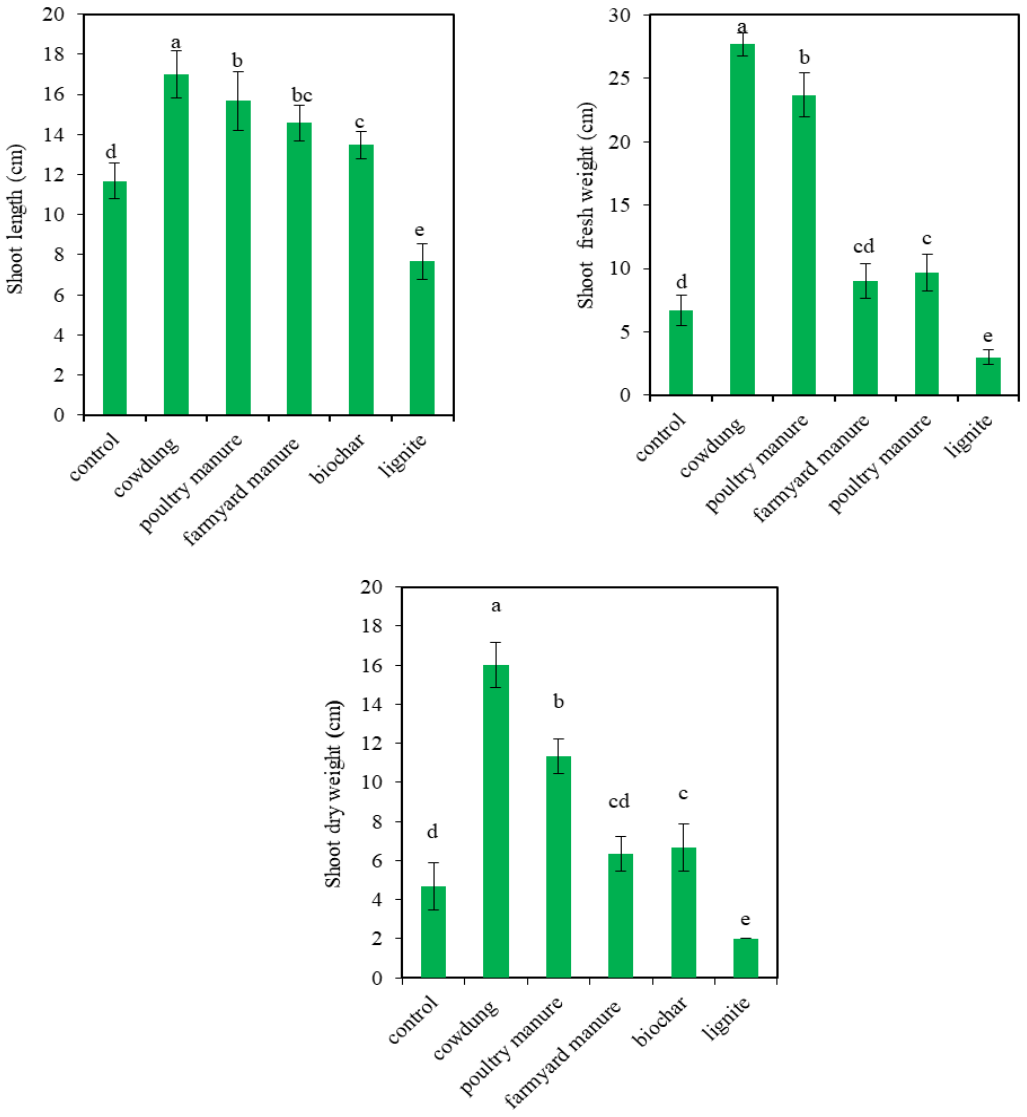


Figure 1. Effect of organic amendments on shoot growth attributes of mungbean under chromium stress. Values are expressed as mean ± SE (n = 3). Different letters above the bars indicate significant differences among treatments at $p \leq 0.05$.

107%, and FYM by 63%. Lignite showed the weakest effect, increasing residual Cr by only 10%. These results demonstrate cow dung's superior ability to transform chromium into less bioavailable forms, particularly in the residual fraction. The data suggests animal-derived amendments are more effective than carbon-rich materials for chromium immobilization, with cow dung showing the most consistent performance across all fractions. This highlights its potential for chromium-contaminated soil remediation.

3.3. Impact of organic amendments on total chromium distribution in mungbean systems

The study evaluated total chromium accumulation patterns under different organic amendments in chromium-contaminated soil (25 ppm) (Figure 4). Compared with the Cr control, cow dung reduced total soil chromium by 23.9% ($p < 0.05$) followed by poultry manure (15.1%) and FYM (11.5%). Biochar showed a minor reduction (7.0%), while lignite increased total soil chromium content. The effectiveness sequence was cow dung > poultry manure

©PagePal. All Rights Reserved.

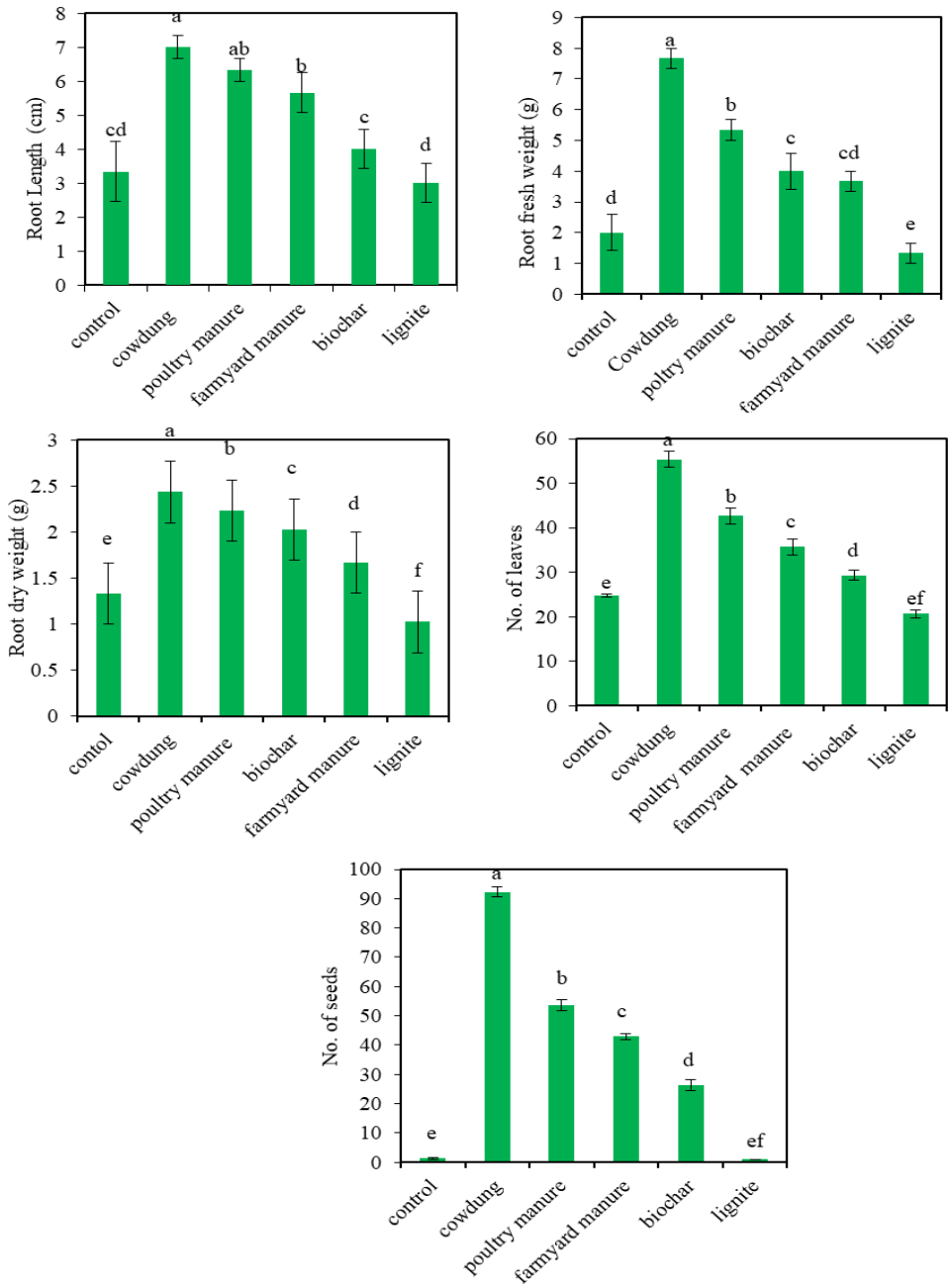


Figure 2. Effect of organic amendments on root and reproductive attributes of mungbean under chromium stress. Values are mean ± SE (n = 3). Different letters above bars indicate significant differences at $p \leq 0.05$.

(48.18 mg/kg) > farmyard manure (50.21 mg/kg) > biochar (52.7 mg/kg) > lignite. In roots, cow dung reduced chromium accumulation by 63.5% relative to control ($p < 0.05$). FYM lowered root chromium by 34.7%, poultry manure by 18.0% and biochar by 5.0%, whereas lignite increased root chromium by 48.2% compared to control. The treatment efficacy followed: cow dung > farmyard manure (428.63 mg/kg) > poultry manure (539.21 mg/kg) > biochar (623.63 mg/kg) > lignite. In shoots, cow dung reduced chromium translocation by 82.8% relative to the Cr-stressed control ($p < 0.05$). Poultry manure lowered shoot chromium by 56.9%, FYM by 49.9%, and biochar by 13.0% while lignite increased it by 67%. The treatment effectiveness ranked: cow dung > poultry manure (146.33 mg/kg) > farmyard manure (169.78

©PagePal. All Rights Reserved.

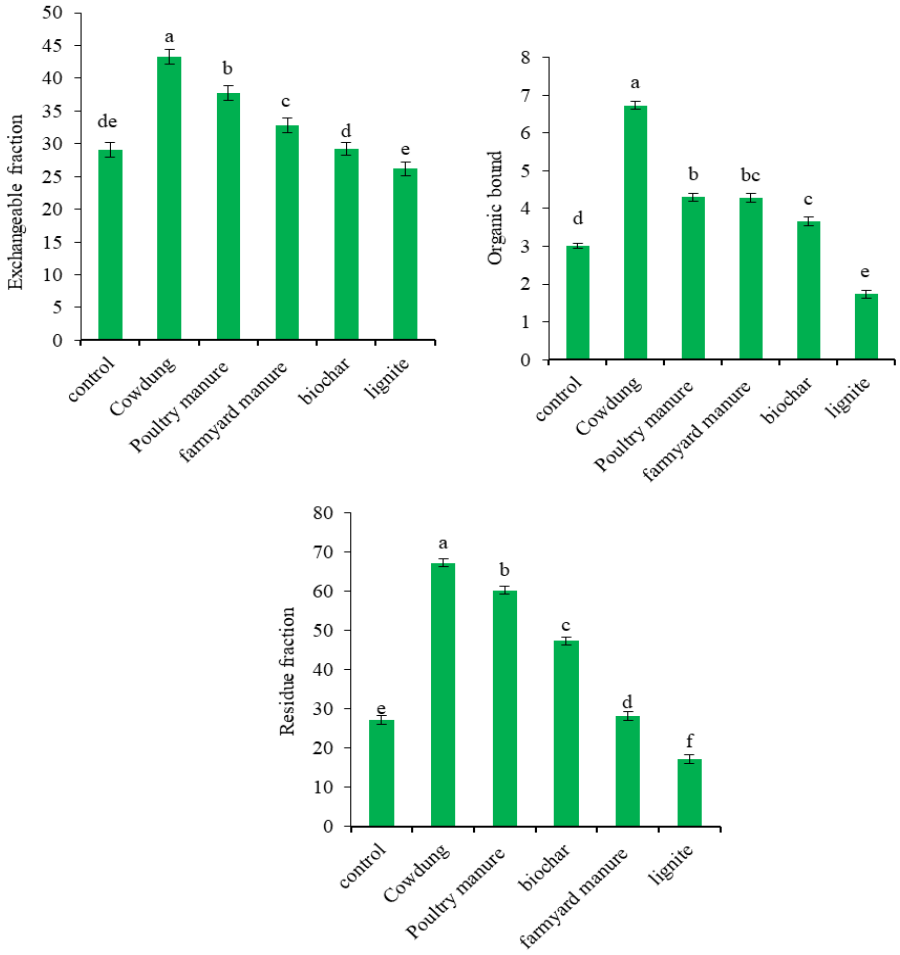


Figure 3. Effect of organic amendments on chromium fractions (exchangeable, organic-bound, residual) in soil under chromium stress. Values are mean ± SE (n = 3). Different letters above bars indicate significant differences at $p \leq 0.05$.

mg/kg) > biochar (294.91 mg/kg) > lignite (565.55 mg/kg). These results consistently demonstrate cow dung manure's superior performance in chromium immobilization and plant protection, likely due to its balanced nutrient composition and microbial stimulation properties. The findings suggest nutrient-rich animal manures are more effective than carbonaceous amendments for chromium-contaminated agricultural systems, particularly when prioritizing food safety through reduced metal translocation to edible plant parts.

3.4. Effects of organic amendments on hexavalent chromium distribution in soil and mungbean plants under chromium stress

The experimental results reveal distinct patterns of hexavalent chromium (Cr^{6+}) distribution across soil and plant tissues under different organic amendment treatments in chromium-contaminated soil (25 ppm) (Figure 5). Relative to control, cow dung reduced soil Cr^{6+} concentration by 42.4% ($p < 0.05$). Poultry manure decreased it by 35.8%, FYM by 28.9% and biochar by 19.9% while lignite only reduced it by 12.7%. The amendments followed this effectiveness sequence: cow dung > poultry manure (160.85 mg/kg) > farmyard manure (178.05 mg/kg) > biochar (200.83 mg/kg) > lignite (218.7 mg/kg). This gradient suggests that nutrient-rich organic amendments are more effective than carbon-dominant materials in immobilizing toxic Cr^{6+} in soil, likely through enhanced reduction to less mobile Cr^{3+} and organic complexation. In roots, cow dung reduced Cr^{6+} content by 42.2% compared to control ($p < 0.05$). Poultry manure and FYM each reduced it by about 21%, while biochar lowered it by 13%. Lignite showed little benefit, with only a 6% reduction. The treatment efficacy followed: cow dung > poultry manure (75.49 mg/kg) ≈ farmyard manure (75.76 mg/kg) > biochar (83.08 mg/kg) > lignite (90.11 mg/kg). The particularly strong effect of cow dung suggests this

©PagePal. All Rights Reserved.

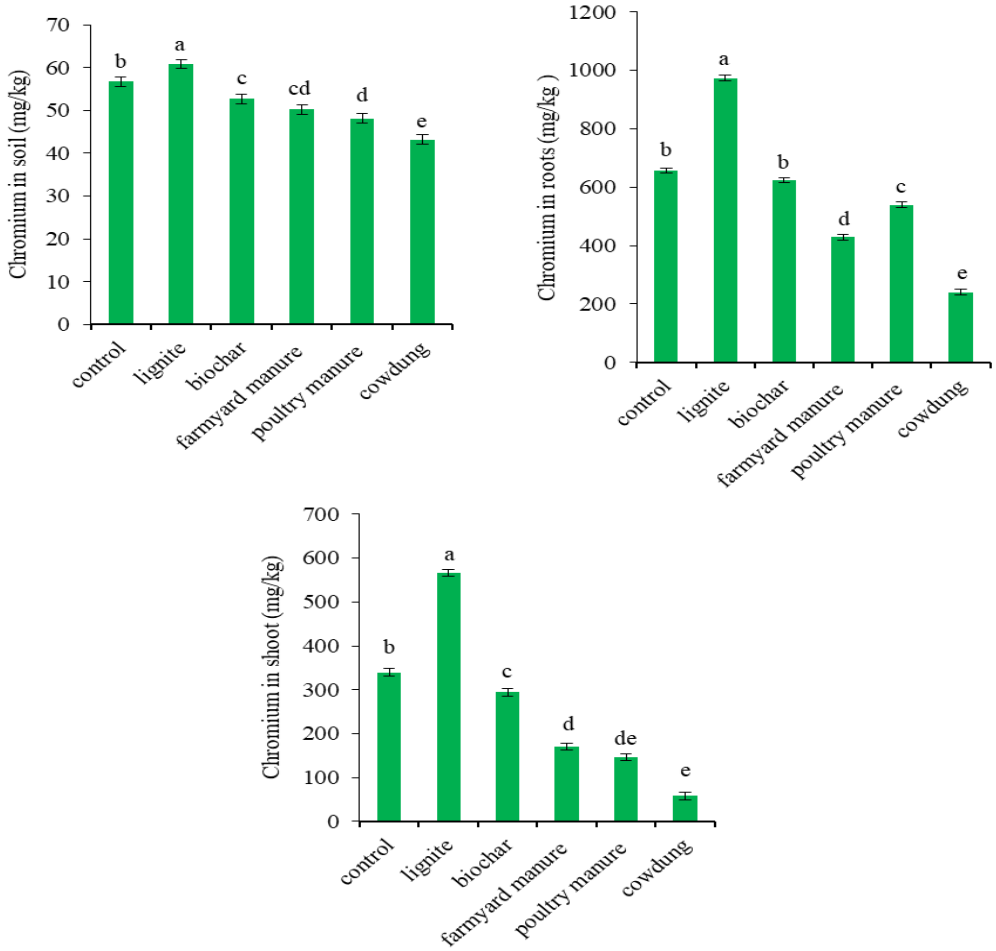


Figure 4. Effect of organic amendments on total chromium content in soil, roots, and shoots of mungbean under chromium stress. Values are expressed as mean ± SE (n = 3). Different letters above bars indicate significant differences among treatments at $p \leq 0.05$.

amendment may modify rhizosphere conditions to limit Cr^{6+} uptake through pH modification, competitive ion effects, or root membrane stabilization.

In shoots, cow dung reduced Cr^{6+} accumulation by 67.8% compared to the Cr control ($p < 0.05$). Poultry manure and FYM reduced it by about 14%, biochar by 8%, while lignite showed no reduction compared to control. The treatment effectiveness is ranked as: cow dung > poultry manure (9.64 mg/kg) ≈ farmyard manure (9.87 mg/kg) > biochar (10.31 mg/kg) > lignite ≈ control. These findings highlight that while all amendments showed some protective effect, animal-derived manures were substantially more effective at preventing Cr^{6+} translocation to edible plant parts compared to carbonaceous amendments. The consistent superiority of cow dung manure across all compartments suggests multiple beneficial mechanisms: (1) providing electron donors for microbial Cr^{6+} reduction, (2) supplying nutrients that promote plant health and metal exclusion mechanisms, and (3) creating favorable soil conditions for Cr^{6+} immobilization. The relatively poor performance of lignite and biochar, despite their high surface area and adsorption capacity, indicates that physical adsorption alone may be insufficient for effective Cr^{6+} management in agricultural systems. These results have critical implications for chromium-contaminated farmland remediation. The demonstrated effectiveness of cow dung manure - a widely available agricultural byproduct - offers a practical, low-cost solution for reducing chromium mobility and bioavailability. The findings particularly support using animal manures rather than pure carbon amendments when prioritizing food safety through reduced metal translocation to edible plant parts. Future research should investigate the longevity of

©PagePal. All Rights Reserved.

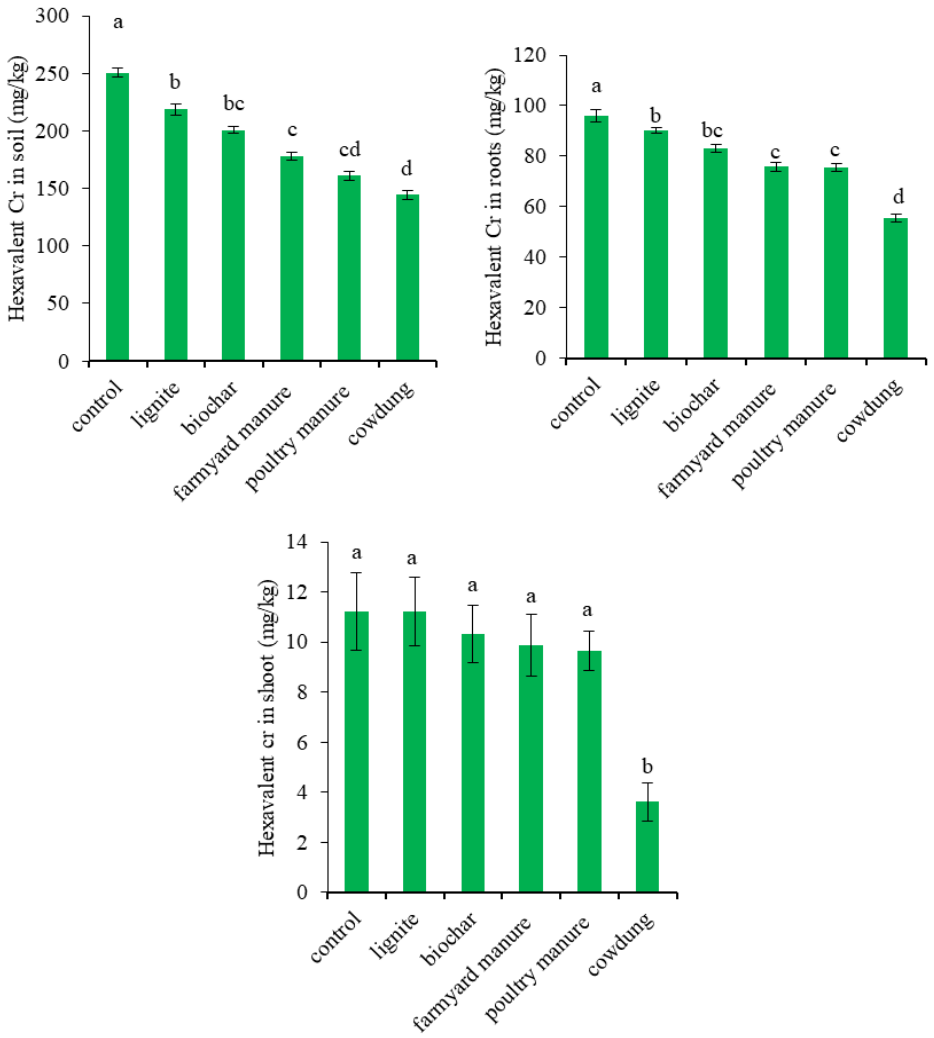


Figure 5. Effect of organic amendments on hexavalent chromium (Cr^{6+}) concentrations in soil, roots, and shoots of mungbean under chromium stress. Values are expressed as mean ± SE (n = 3). Different letters above bars indicate significant differences among treatments at $p \leq 0.05$.

these effects and the potential for combining different amendment types to optimize chromium immobilization while maintaining soil fertility.

3.5. Effects of organic amendments on cr^{3+} distribution in soil and mungbean plants under chromium stress

The experimental results demonstrate significant variations in trivalent chromium (Cr^{3+}) distribution patterns among different organic amendment treatments in chromium-contaminated soil (25 ppm) (Figure 6). Relative to control, cow dung reduced soil Cr^{3+} by 24.6% ($p < 0.05$). Poultry manure reduced it by 11.5%, FYM by 4.7%, biochar by 3.9%, and lignite by 2.5%. The amendments followed this effectiveness sequence: cow dung > poultry manure (364.13 mg/kg) > farmyard manure (392.01 mg/kg) > biochar (395.36 mg/kg) > lignite (401.29 mg/kg). This pattern suggests that nutrient-rich animal-derived amendments are more effective than carbon-rich materials in immobilizing Cr^{3+} in soil, likely through enhanced microbial activity and organic complexation. In roots, cow dung reduced Cr^{3+} accumulation by 56.8% compared to control ($p < 0.05$). Poultry manure lowered it by 53.3%, FYM by 51.6%, while biochar and lignite only reduced it by 5–3%. The treatment efficacy followed the order: cow dung > poultry manure (47.41 mg/kg) > farmyard manure (49.11 mg/kg) > biochar (95.55 mg/kg) > lignite (98.15 mg/kg). The substantial reduction in root Cr^{3+} accumulation with animal manure treatments suggests these amendments may alter rhizosphere chemistry

©PagePal. All Rights Reserved.

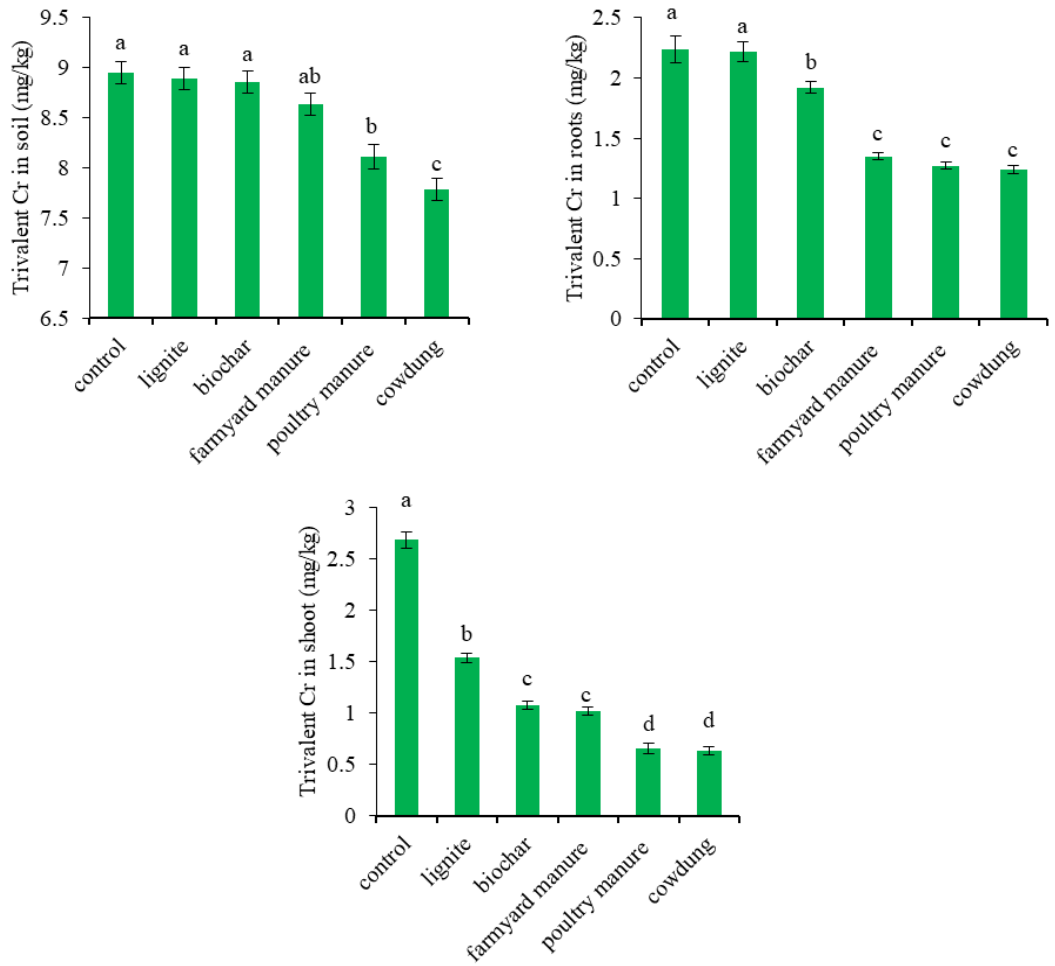


Figure 6. Effect of organic amendments on trivalent chromium (Cr^{3+}) concentrations in soil, roots, and shoots of mungbean under chromium stress. Values are expressed as mean ± SE (n = 3). Different letters above bars indicate significant differences

or promote root membrane integrity, limiting chromium uptake.

Animal manures (cow dung, poultry manure, FYM) reduced shoot Cr^{3+} content by 45–50% relative to control ($p < 0.05$). Biochar lowered it by 22%, while lignite had negligible effect. The treatment effectiveness ranked as: cow dung > poultry manure (54.71 mg/kg) ≈ farmyard manure (55.9 mg/kg) > biochar (78.92 mg/kg) > lignite ≈ control. These findings suggest that while carbon-rich amendments like lignite and biochar may immobilize Cr^{3+} in soil, they appear less effective at preventing plant uptake and translocation to shoots compared to nutrient-rich animal manures. The superior performance of cow dung manure across all compartments may be attributed to multiple mechanisms: (1) enhanced microbial activity promoting Cr^{3+} immobilization through reduction and complexation, (2) improved soil physicochemical properties that limit chromium bioavailability, and (3) potential stimulation of plant defense mechanisms against metal uptake. Notably, the similar performance patterns observed in soil, roots and shoots suggest that the amendments' effects on soil chromium chemistry directly influence plant accumulation patterns.

These results have important practical implications for chromium-contaminated agricultural systems. While all organic amendments showed some benefit compared to untreated control, animal-derived manures - particularly cow dung - appear most effective for comprehensive chromium management. The poor performance of lignite, despite its high carbon content, suggests that amendment selection

©PagePal. All Rights Reserved.

should consider both organic matter quality and nutrient composition. Future research should investigate the long-

3.6. Correlation analysis between growth attributes and chromium fractions in mungbean under organic amendment treatments

The correlation matrix for *Vigna radiata* grown under chromium contamination and treated with various organic amendments reveals strong and consistent relationships between growth parameters and chromium fractions in soil and plant tissues (Figure 7). Most morphological traits such as shoot length, root length, number of leaves, seed count and both fresh and dry biomass of shoots and roots exhibited elevated chromium bioavailability is detrimental to plant development. Notably, trivalent chromium (Cr (III)) fractions, while still toxic at high levels, demonstrated relatively weaker negative correlations with growth, reflecting the lower mobility and bioavailability of Cr (III) compared to Cr (VI). The strong negative correlation between Cr (VI) in plant tissues and biomass indices underscores the effectiveness of organic amendments in immobilizing or reducing Cr (VI) to less toxic forms, thereby mitigating chromium-induced phytotoxicity. Overall, the results emphasize that amendments capable of reducing soil and tissue Cr (VI) concentrations are key drivers of growth recovery in chromium-stressed mungbean systems.

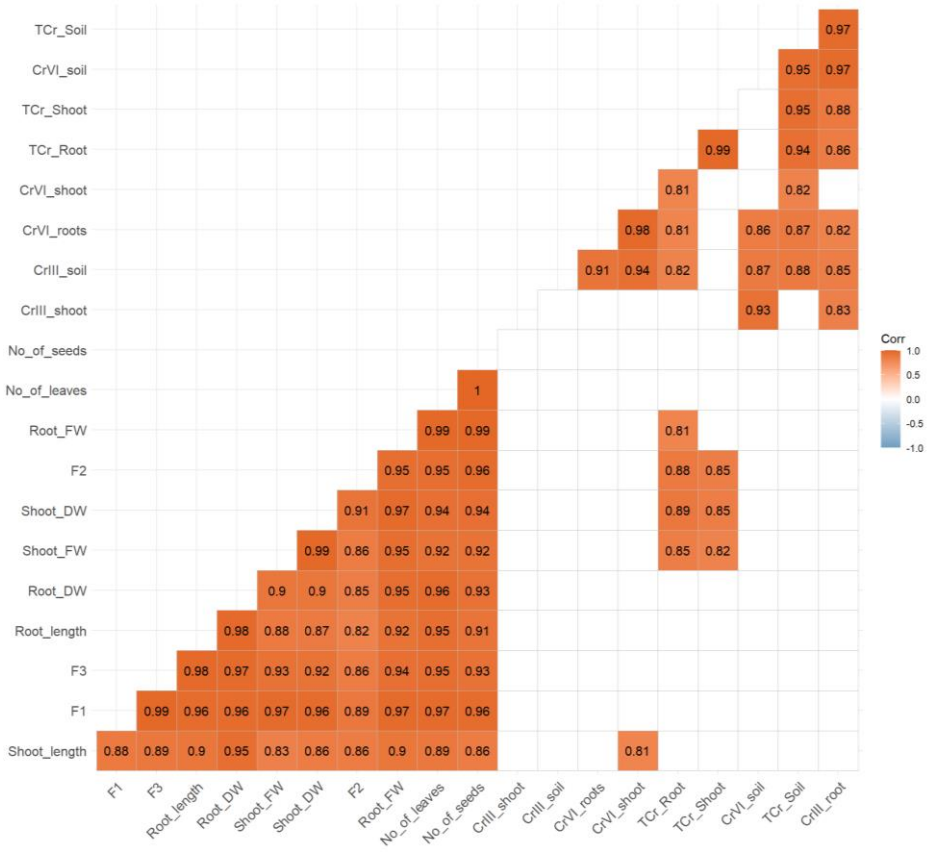


Figure 7. Correlation matrix showing relationships among growth traits and chromium fractions of mungbean under chromium stress and organic amendment treatments.

strong positive intercorrelations ($r > 0.85$), indicating that improvement in one growth metric was generally accompanied by proportional gains in others. This suggests that treatments enhancing plant vigor exert a broad, systemic effect rather than targeting isolated traits. Conversely, total chromium (TCr) and hexavalent chromium (Cr (VI)) concentrations in soil, shoots and roots showed negative associations with growth-related parameters, implying that

3.7. Heatmap analysis of growth traits and chromium fractions in mungbean under organic amendments

The heatmap provides a comparative visualization of how different organic amendments influence mungbean growth and chromium fractionation under chromium stress (Figure 8). Cow dung manure stands out as the most effective amendment, showing strong positive associations (deep red) with all growth parameters, including shoot and root length,

©PagePal. All Rights Reserved.

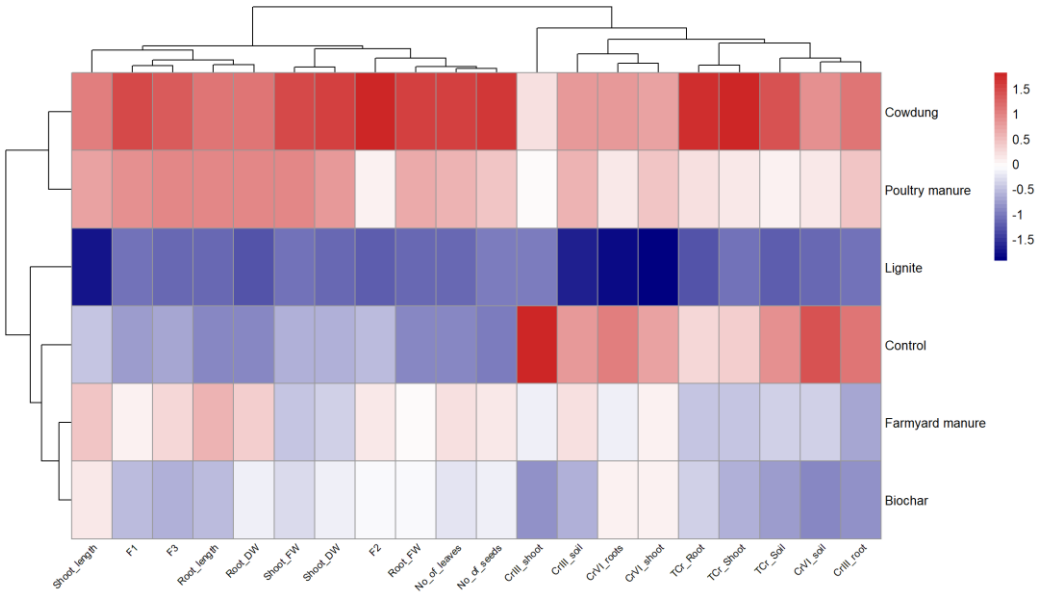


Figure 8. Heatmap illustrating the relationships between growth traits and chromium fractions of mungbean under chromium stress and different organic amendments.

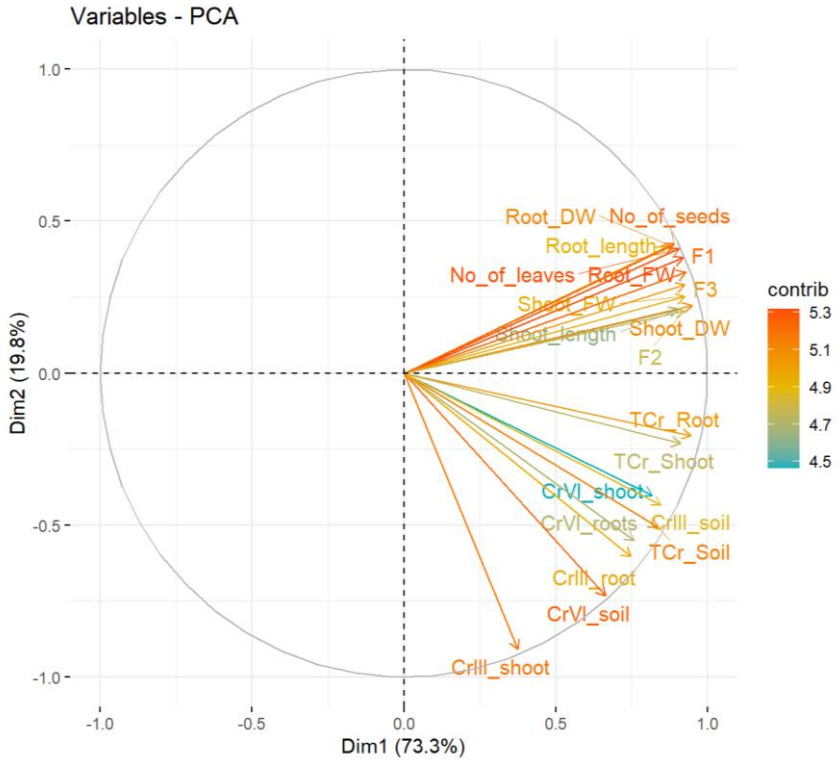


Figure 9. Principal component analysis (PCA) biplot showing associations between treatments, growth attributes, and chromium fractions of mungbean under chromium stress and organic amendments.

biomass (fresh and dry weight), number of leaves and seed production, while concurrently reducing toxic chromium fractions in plant tissues and soil. Poultry manure also displayed positive effects on growth traits, though slightly less pronounced, and moderate reductions in chromium fractions. In contrast, lignite exhibited the poorest

©PagePal. All Rights Reserved.

performance, marked by strong negative correlations (deep blue) with growth parameters and minimal reduction or even relative increases in toxic Cr(VI) concentrations in roots, shoots and soil, suggesting its unsuitability for remediation in such systems. The control treatment showed consistently low growth performance and higher chromium fractions compared to most amendments, reaffirming the detrimental effect of untreated chromium contamination. Farmyard manure and biochar showed moderate improvements in plant performance, with biochar notably reducing soil chromium fractions but with less effect on growth compared to nutrient-rich amendments. Overall, the clustering patterns indicate that amendments high in organic nutrients and with strong chromium-binding capacities, particularly cow dung and poultry manure are most effective for simultaneous growth recovery and chromium immobilization in mungbean under stress conditions.

3.8. Principal component analysis (PCA) of growth traits and chromium fractions in mungbean under organic amendment treatments

The PCA biplot illustrates the relationships between treatments, growth parameters, and chromium fractions, explaining 73.3% of the variation along the first principal component (Dim1) and 19.8% along the second (Dim2) (Figure 9). Cow dung manure is positioned far along the positive Dim1 axis, closely associated with all growth-related variables such as shoot and root length, biomass (fresh and dry weight), number of leaves and seed production, indicating its strong positive influence on plant performance under chromium stress. Poultry manure also clusters near growth traits but with a slightly smaller effect. In contrast, the control, lignite and to some extent biochar occupy the negative side of Dim1, aligning with higher total chromium (TCr), hexavalent chromium (Cr (VI)), and trivalent chromium (Cr (III)) concentrations in soil and plant tissues, reflecting their association with poor growth performance and elevated chromium bioavailability. Farmyard manure lies in an intermediate position, showing moderate improvements in growth and partial reduction of chromium fractions. The clear separation between nutrient-rich amendments (cow dung, poultry manure) and low-performing treatments (lignite, control) along Dim1 underscores the central role of amendment quality, particularly organic nutrient content and chromium-binding capacity in mitigating chromium toxicity. The clustering of chromium fractions opposite to growth traits further highlights the antagonistic relationship between chromium accumulation and mungbean productivity.

3.9. Data quality statement:

All treatments were replicated three times (n = 3). Percent changes are reported relative to the Cr-stressed control with mean ± SE values, and significance was tested using Tukey's HSD at $p \leq 0.05$. Effect sizes are expressed as percent differences with 95% confidence intervals, allowing assessment of both biological and statistical relevance.

4. Discussion

4.1. Agronomic and morphological attributes

Growth attributes showed clear trends across treatments: cow dung improved shoot and root growth, leaf number and seed production more strongly than poultry manure and FYM, while biochar had limited benefits and lignite produced neutral or negative effects. The variation in shoot length can be explained by the role of organic matter in improving soil fertility and promoting hormonal balance (Ahmed et al., 2023). Enhanced availability of nitrogen, potassium and micronutrients facilitates cell elongation, while better aeration and moisture conditions sustain root activity and nutrient uptake (Sajjad et al., 2025a; Rehman et al., 2025). Under chromium toxicity, oxidative stress suppresses auxin synthesis and restricts cell wall extensibility (Kazmi et al., 2025), but organic amendments improve nutrient status and reduce oxidative damage, maintaining normal cell division and elongation (Saud et al., 2022). Root elongation reflects improved soil structure and aeration (Ogorek et al., 2025), while higher root biomass indicates better hydration and carbon allocation (Sohaib et al., 2023). Similarly, enhanced leaf development is linked to nutrient availability, especially nitrogen and phosphorus (Sajjad et al., 2024), which support canopy persistence and photosynthesis. Improved seed set under manures indicates reduced oxidative stress during reproductive development (Nazeer et al., 2020). These mechanisms are consistent with recent microbial remediation studies, which highlight how animal manures sustain microbial activity and redox processes, thereby supporting plant growth under chromium stress.

4.2. Chromium fractionation in soil under organic amendments

Chromium fractions showed distinct patterns: cow dung most effectively reduced the exchangeable fraction and promoted conversion to organic-bound and residual pools, followed by poultry manure and FYM, whereas biochar had smaller effects and lignite minimal impact. The decline in the exchangeable fraction is attributed to sorption, precipitation, and complexation with organic matter (Sajjad et al., 2025b; Hao et al., 2022). Functional groups in humic and fulvic substances form stable complexes with chromium, reducing its mobility, while decomposition of organic inputs increases pH and promotes precipitation as hydroxides. The increase in the organic-bound fraction reflects incorporation into organo-metallic complexes resistant to leaching (Briffa et al., 2020; Kafle et al., 2022). The residual fraction rises due to co-

©PagePal. All Rights Reserved.

precipitation with Fe/Mn oxides and mineral occlusion (Saha et al., 2025). Cow dung's superiority is likely due to its balanced C:N ratio and strong stimulation of microbial communities, enhancing chromium immobilization. These findings align with recent reports on manure-driven microbial immobilization and long-term stabilization of chromium.

4.3. Impact of organic amendments on total chromium distribution in mungbean systems

Total chromium decreased in soil, roots, and shoots under cow dung, moderately under poultry manure and FYM, slightly under biochar, while lignite had little or even negative effects. The reduction in total chromium reflects transformation into stable forms that resist extraction (Jiang et al., 2023). Limited uptake results from apoplastic binding at the root surface, vacuolar sequestration, and chelation by organic ligands (Xing et al., 2025; Yin et al., 2024). Root cell walls provide primary binding sites, while phytochelatins and metallothioneins compartmentalize chromium in vacuoles (Qureshi et al., 2024). This reduces translocation to shoots, protecting the photosynthetic apparatus and minimizing accumulation in edible plant parts. Such mechanisms have also been reported in recent microbial remediation studies, confirming that manures reduce total chromium bioavailability and plant uptake.

4.4. Effects of organic amendments on hexavalent chromium distribution in soil and mungbean plants under chromium stress

Hexavalent chromium [Cr (VI)] decreased markedly under cow dung, moderately under poultry manure and FYM, slightly under biochar and minimally under lignite. The decline in Cr(VI) is driven by biological and chemical reduction processes. Metal-reducing bacteria utilize Cr(VI) as an electron acceptor, converting it into Cr(III), with organic amendments supplying sugars, phenolics, and amino acids as electron donors (Monga et al., 2022; Kapoor et al., 2022). Root exudates such as ascorbate and flavonoids further contribute to reduction. Once converted, Cr (III) precipitates or binds to humic substances, lowering its mobility (Pang et al., 2025). Reduced Cr (VI) uptake into roots is aided by selective transport, as chromate entry via sulfate transporters is limited (Ali et al., 2023). In shoots, reduced translocation reflects effective vacuolar sequestration in roots (Zulfiqar et al., 2023). These mechanisms explain why cow dung outperforms other amendments, consistent with microbial remediation literature emphasizing the role of organic inputs in driving Cr (VI) reduction.

4.5. Effects of organic amendments on cr^{3+} distribution in soil and mungbean plants under chromium stress

Trivalent chromium [Cr (III)] accumulation in bioavailable pools declined most under cow dung, followed by poultry manure and FYM, with little effect from biochar and lignite. Reduction of Cr (III) mobility occurs through binding organic matter and co-precipitation with Fe and Mn hydroxides (Xing et al., 2025). In roots, decreased Cr (III) is associated with restricted uptake and enhanced sequestration, supported by lignified cell walls and metal-binding peptides that trap chromium in the apoplast and vacuoles (Sharma et al., 2020; Agarwal et al., 2025). In shoots, lower accumulation reflects restricted xylem loading, preventing excessive chromium translocation (Srivastava et al., 2021). These mechanisms highlight the superiority of manure-based amendments, particularly cow dung, in reducing Cr (III) accumulation and ensuring lower risks of contamination in edible parts. The observed patterns confirm microbial remediation findings that organic manures promote immobilization and reduce heavy metal bioavailability in cropping systems.

The observed decreases in soil Cr (VI) and reduced Cr accumulation in plant tissues are likely due to sorption to organic matter, complexation with humic substances, microbial enzymatic reduction, and root-level sequestration, which limited Cr mobility and translocation to shoots and seeds. Simultaneously, growth recovery and improved biomass were supported by enhanced nutrient availability, increased antioxidant enzyme activity, and restoration of nodulation and nitrogen fixation, particularly in legumes, collectively mitigating Cr-induced stress (Zulfiqar, 2023; Gao et al., 2023).

5. Conclusion

This study demonstrates that organic amendments particularly cow dung manure are highly effective in mitigating chromium (Cr) toxicity in mungbean by reducing Cr bioavailability, improving soil health and enhancing plant growth and yield. Cow dung manure was most successful in lowering exchangeable Cr and increasing residual Cr, resulting in higher shoot biomass, seed production and plant vigor. Its effectiveness stems from its nutrient richness, organic matter content and stimulation of microbial Cr(VI) reduction to less toxic Cr (III). Poultry and farmyard manures also improved performance, though less effectively, while biochar and lignite showed limited benefits. Future work should focus on field-scale, multi-season trials and explore combined amendment use for synergistic effects. Policymakers, extension services and agricultural agencies should promote cow dung manure adoption in Cr-affected regions and provide farmer training, integrating this low-cost, locally available solution into soil health programs to restore productivity and ensure food safety in contaminated areas. Based on mechanistic interpretations, we recommend: (a)

©PagePal. All Rights Reserved.

conducting short-term microbial assays or quantifying redox-active microbial populations to validate microbially-mediated Cr(VI) reduction; (b) reporting soil pH, redox potential (Eh), and dissolved organic carbon to support sorption/reduction pathways; (c) moderating claims of field readiness and conducting multi-season trials, as pot studies may overestimate Cr immobilization; (d) exploring combined amendments (cow dung + biochar) for potential synergistic effects; and (e) performing a brief life-cycle or environmental-risk assessment to evaluate unintended consequences, such as trace element mobilization or nutrient runoff. These suggestions align with recent literature on organic amendments.

6. Funding

No funding was received for this study.

7. Acknowledgment

The authors want to acknowledge the Soil and Water Chemistry Laboratory, Institute of Soil and Environmental Science, University of Agriculture, Faisalabad, Pakistan.

8. Conflict of interest

The authors declare no conflict of interest.

9. Authors' contribution

Ayesha Shahid: Experimentation and illustration; Amina Rashid: Writing Original Draft and revision; Hamna Bashir: Proofreading and Writing Reviews; Muhammad Tahir Shehzad: Supervision, finding funds for experimentation, Proofreading and Writing Review

10. SDG's addressed

This article addressed the SDG2 (Zero hunger), SDG3 (Good health and well-being) SDG12 (Sustainable consumption and Production) and SDG14 (Life on land).

References

Agarwal, H., Chaudhary, D., Aggarwal, H., Karala, C., Purkait, N., Sharma, N., & Joshi, N. (2025). Molecular underpinning of heavy metal sequestration through advanced remediation strategies in higher plants. *Plant Stress*, *16*, 100881.

Ahmed, F., Waris, F., ibni Zamir, S., Sajjad, M., Nazeer, S., Khan, A., & Mustafa, F. (2023). Response of Different Organic and Inorganic Fertilizers on Alfalfa Yield Under Different Types of Irrigation Water. *Haya Saudi J Life Sci*, *8*(1), 1-8.

Ali, M. H., Sattar, M. T., Khan, M. I., Naveed, M., Rafique, M., Alamri, S., & Siddiqui, M. H. (2020). Enhanced growth of mungbean and remediation of petroleum hydrocarbons by Enterobacter sp. MN17 and biochar addition in diesel contaminated soil. *Applied Sciences*, *10*(23), 8548.

Ali, S., Mir, R. A., Tyagi, A., Manzar, N., Kashyap, A. S., Mushtaq, M., & Bae, H. (2023). Chromium toxicity in plants: signaling, mitigation, and future perspectives. *Plants*, *12*(7), 1502.

Amalina, F., Abd Razak, A. S., Krishnan, S., Sulaiman, H., Zularisam, A. W., & Nasrullah, M. (2022). Biochar production techniques utilizing biomass waste-derived materials and environmental applications–A review. *Journal of Hazardous Materials Advances*, *7*, 100134.

Amin, H., Habib, A., Asif, M., Hameed, M. U., Wassi, M., Manzoor, M., & Sajjad, M. (2023). Effect of Foliar Application of Boron, Zinc and Manganese on Growth, Yield and Oil Contents of Sunflower (*Helianthus annuus* L.). *Asian J. Soil Sci. Plant Nutri*, *9*(4), 86-94.

Angon, P. B., Islam, M. S., Das, A., Anjum, N., Poudel, A., & Suchi, S. A. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon*, *10*(7).

Briffa, J., Sinagra, E., & Blundell, R. (2020). Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon*, *6*(9).

Chafik, Y., Sena-Velez, M., Henaut, H., Missbah El Idrissi, M., Carpin, S., Bourgerie, S., & Morabito, D. (2025). Synergistic Effects of Compost and Biochar on Soil Health and Heavy Metal Stabilization in Contaminated Mine Soils. *Agronomy*, *15*(6), 1295.

Das, S., Sultana, K. W., Ndhlala, A. R., Mondal, M., & Chandra, I. (2023). Heavy metal pollution in the environment and its impact on health: exploring green technology for remediation. *Environmental health insights*, *17*, 11786302231201259.

Diatta, A. A., Abaye, O., Battaglia, M. L., Leme, J. F., Seleiman, M., Babur, E., & Thomason, W. E. (2024). Mungbean [*Vigna radiata* (L.) Wilczek] and its potential for crop diversification and sustainable food production in Sub-Saharan Africa: a review. *Technology in Agronomy*, *4*(1).

Enebe, M. C., & Erasmus, M. (2023). Mediators of biomass transformation–a focus on the enzyme composition of the vermicomposting process. *Environmental Challenges*, *12*, 100732.

Gao, J., Han, H., Gao, C., Wang, Y., Dong, B., & Xu, Z. (2023). Organic amendments for in situ immobilization of heavy metals in soil: A review. *Chemosphere*, *335*, 139088.

Hao, Y., Ma, H., Wang, Q., Zhu, C., & He, A. (2022). Complexation behaviour and removal of organic-Cr (III) complexes from the environment: A review.

©PagePal. All Rights Reserved.

Ecotoxicology and Environmental Safety, *240*, 113676.

Ijaz, B., Nazeer, S., Sajjad, M., Nadeem, M., Anwar, H., Idrees, M., ... & Khan, R. H. U. (2023a). Effect of various foliar applied micronutrients (Zn+ Fe+ Cu+ B) on growth and yield of wheat under Faisalabad condition. *Journal of Global Innovations in Agricultural Sciences*, *11*(2), 184-189.

Ijaz, B., Waraich, E. A., Shah, A., & Nazeer, S. (2023b). Morpho-physiological responses of wheat (*Triticum aestivum* L.) to foliar applied potassium under different planting geometry.

Jiang, X., Long, W., Xu, T., Liu, J., Tang, Y., & Zhang, W. (2023). Reductive transformation of Cr (VI) in contaminated soil by polyphenols: The role of gallic and tannic acid. *Ecotoxicology and Environmental Safety*, *255*, 114807.

Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., & Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. *Environmental Advances*, *8*, 100203.

Kapoor, N., Sharma, P., & Verma, S. (2022). Microbial remediation of hexavalent chromium from the contaminated soils. In *Microbes and Microbial Biotechnology for Green Remediation* (pp. 527-546). Elsevier.

Kazmi, A., Li, G., Yang, J., Zhao, X., Islam, M. F., Li, X., & Hou, H. (2025). Cadmium stress alters heterophylly, anatomy, and photosynthetic activity of Hygrophila difformis. *Ecotoxicology and Environmental Safety*, *302*, 118685.

Khaliq, A., Zafar, M., Sajjad, M., Hassan, M. U., Mudassar, M. A., Shakoor, M. A., & Niaz, S. (2023). Nitrogen use efficiency in sunflower (*Helianthus annuus* l.) influenced by various fertigation and bed planting techniques. *Pakistan Journal of Biotechnology*, *20*(02), 385-392.

Kierczak, J., Pietranik, A., & Pędziwiatr, A. (2021). Ultramafic geoecosystems as a natural source of Ni, Cr, and Co to the environment: A review. *Science of the Total Environment*, *755*, 142620.

Monga, A., Fulke, A. B., & Dasgupta, D. (2022). Recent developments in the essentiality of trivalent chromium and toxicity of hexavalent chromium: Implications on human health and remediation strategies. *Journal of Hazardous Materials Advances*, *7*, 100113.

Nazeer, S., Tahir, M., Sajjad, M., Idrees, M., Hameed, M. U., Saleem, M. A., & Shehzad, A. (2020). Response of Different Micronutrients (Zn, Cu, and Mn) Soil Application on Yield and Quality of Late Sown Wheat (*Triticum aestivum* L.) in Agro-Climatic Conditions of Faisalabad, Pakistan. *Pakistan Journal of Life & Social Sciences*, *18*(2).

Ogorek, L. L. P., Gao, Y., Farrar, E., & Pandey, B. K. (2025). Soil compaction sensing mechanisms and root responses. *Trends in Plant Science*, *30*(5), 565-575.

Pang, Z., Mo, L., Liu, Q., Huang, Q., Xiao, Y., & Yuan, Z. (2025). Soil acidification reduces flavonoids and key metabolites in sugarcane roots and rhizosphere leading to yield decline. *Rhizosphere*, *33*, 101028.

Qureshi, F. F., Ashraf, M. A., Rasheed, R., Hussain, I., Rizwan, M., Iqbal, M., & Yong, J. W. H. (2024). Microbial-assisted alleviation of chromium toxicity in plants: a critical review. *Plant stress*, *11*, 100394.

Rehman, A., Imran, M., Sajjad, M., Umair, R., Nawaz, S., & Ijaz, B. (2025). Evaluation of herbicide efficiency and their impact with reduced rates along with adjuvants at varying application time in maize (*Zea mays* L.). *Journal of Agricultural Research (JAR).*, *63*(1), 49-57.

Rupa, T. R., Rao, C. S., Rao, A. S., & Singh, M. (2003). Effects of farmyard manure and phosphorus on zinc transformations and phyto-availability in two alfisols of India. *Bioresource Technology*, *87*(3), 279-288.

Saha, N., Ren, C., Parry, D., & Huang, L. (2025). Geochemical factors governing Vanadium speciation and mobilisation in technosol eco-engineered from bauxite residue under field conditions. *Journal of Hazardous Materials*, 138920.

Sajjad, M., Hussain, K., Hakki, E. E., Ilyas, A., Gezgin, S., & Shakil, Q. (2025a). Impact of Irrigation Techniques on Water-Use Efficiency, Economic Returns, and Productivity of Rice. *Sustainability*, *17*(17), 7712.

Sajjad, M., Hussain, K., Wajid, S. A., & Saqib, Z. A. (2024). The impact of split nitrogen fertilizer applications on the productivity and nitrogen use efficiency of rice. *Nitrogen*, *6*(1), 1.

Sajjad, M., Ijaz, B., Khil, A., Ibtahaj, I., Hur, M., Azizi, N., ... & ur Rehman, H. (2025b). Influence of different organic mulches on growth, yield, and oil content of maize (*Zea mays* L.) hybrids and soil physical properties. *Journal of Ecological Engineering*, *26*(11), 410-427.

Saud, S., Wang, D., Fahad, S., Javed, T., Jaremko, M., Abdelsalam, N. R., & Ghareeb, R. Y. (2022). The impact of chromium ion stress on plant growth, developmental physiology, and molecular regulation. *Frontiers in Plant Science*, *13*, 994785.

Shakeel, A., Anjum, L., Ibni Zamir, S., Rizwan, M., Arshad, M., Mehmood, Q., ... & Waqas, A. (2021). Irrigation water quality effects on CO_2 emissions along with

©PagePal. All Rights Reserved.

crop and soil responses. *Pakistan Journal of Agricultural Sciences*, *58*(2), 637-642.

Sharma, A., Kapoor, D., Wang, J., Shahzad, B., Kumar, V., Bali, A. S., & Yan, D. (2020). Chromium bioaccumulation and its impacts on plants: an overview. *Plants*, *9*(1), 100.

Sohaib, N., Arif, M., Shah, M. N., Mahmood, S., Ali, H., Amjid, M., ... & Anwar, H. (2023). Exploring the Role of Anti-Oxidant on Growth and Yield of Cotton to Mitigate the Heat Stress.

Srivastava, D., Tiwari, M., Dutta, P., Singh, P., Chawda, K., Kumari, M., & Chakrabarty, D. (2021). Chromium stress in plants: toxicity, tolerance and phytoremediation. *Sustainability*, *13*(9), 4629.

Steel, R. G. D., Torrie, J., H. & Dickey, D. A. (1997). Principles and Procedures of Statistics, A Biometrical Approach, 3rd ed.; McGraw-Hill Book Company, Inc.: New York, NY, USA; Toronto, ON, Canada; London, UK, 352–358.

Xing, Y., Zheng, Y., & Wang, X. (2025). Integrated strategies for effective remediation of chromium-contaminated soils: advancements, challenges, and sustainability implications. *Environmental Advances*, 100614.

Yin, F., Li, J., Wang, Y., & Yang, Z. (2024). Biodegradable chelating agents for enhancing phytoremediation: mechanisms, market feasibility, and future studies. *Ecotoxicology and environmental safety*, *272*, 116113.

Zulfiqar, U., Haider, F. U., Ahmad, M., Hussain, S., Maqsood, M. F., Ishfaq, M., & Eldin, S. M. (2023). Chromium toxicity, speciation, and remediation strategies in soil-plant interface: A critical review. *Frontiers in Plant Science*, *13*, 1081624.

©PagePal. All Rights Reserved.

Disclaimer/Publisher's Note: The views, opinions, and data presented in all publications are exclusively those of the respective author(s) and contributor(s) and do not reflect the stance of Pagepal or its editorial team. Pagepal and the editor(s) disclaim any responsibility for harm to individuals or damage to property resulting from the use of any ideas, techniques, instructions, or products mentioned in the content.

©PagePal. All Rights Reserved.