



RESEARCH ARTICLE

Mitigating the Chromium Toxicity in *Zea mays* L. using Cr-resistant PGPR

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ABSTRACT

Heavy metal contamination, particularly with chromium (Cr) poses a serious threat to sustainable agriculture by impairing plant growth and productivity. The current study investigates the potential of plant growth promoting rhizobacteria (PGPR) to alleviate chromium induced stress using *Zea mays* under laboratory conditions. Seeds were inoculated using *Pseudomonas* spp. (AH3 and AH2) and *Pseudomonas qingdaonensis* (AR5) and were sown in pots under chromium stress. Morphological parameters like shoot and root length, number of leaves, fresh weight, as well as biochemical parameters like chlorophyll and protein content, were recorded under stressed and non-stressed plants. The results demonstrated that chromium toxicity significantly reduced plant growth. However, bacterial inoculation, under stressed conditions, enhanced plant growth as well as biochemical parameters. Hence, PGPR can be effectively employed as a sustainable bio-remediation strategy to restore heavy metal-contaminated soils and enhance crop productivity under stress conditions.

Key words: stress mitigation, oxidative stress, chromium remediation.

INTRODUCTION

Soil is under constant threat from contaminants introduced through various anthropogenic activities. Among these contaminants are heavy metals, fertilizers, household and industrial waste, undegradable plastic, pesticides, insecticides and synthetic chemicals, etc. which adversely affect soil health and its role as a medium for plant growth and development (Tayang & Songachan, 2021). Naturally occurring metals can become environmental pollutants when they exist in ecosystems at concentrations that are toxic or unnecessary (Zhuang *et al.*, 2024). These include chromium, zinc, lead, cadmium, selenium, mercury, silver, nickel, arsenic, and copper, all of which can disrupt ecological balance and pose significant risks to plant and human health. In soils, such metals are referred to as heavy metals due to their high atomic weight and density, often five times greater than that of water (Tafinta *et al.*, 2024). These metals enter the environment predominantly through industrial discharge, domestic waste, mining, agricultural runoff, and the overuse of metal-containing fertilizers and pesticides (Iqbal *et al.*, 2021).

Once heavy metals enter agricultural fields, they demonstrate toxic effects on plants, leading to inhibited growth and development (Qin *et al.*, 2024). Certain heavy

metals such as copper (Cu), zinc (Zn), iron (Fe), and manganese (Mn) exhibit dual functioning they are essential for plant growth in trace amounts but become harmful at higher concentrations (Jahan *et al.*, 2024). The entry of heavy metals into the food chain, even in trace amounts, presents a major threat to animal and human health. In plants, heavy metals are typically absorbed through the root membrane in ionic form (Soni *et al.*, 2014; Yang *et al.*, 2023). These ions enter the root cytoplasm, are stored in vacuoles, and then translocated through the xylem and phloem to reach aerial plant parts, where they cause deleterious physiological and morphological effects (Chen *et al.*, 2022; Hayyat *et al.*, 2025).

Chromium is a transition metal with the atomic number 24 and an atomic weight of about 52 g/mol. It naturally occurs in several forms, but the most common is Cr with atomic number 54 is most common which makes up about 83.78% of all chromium (Hurley *et al.*, 2017). Chromium is used in many industries, including the production of stainless steel, leather tanning, dyes, electroplating, and metal ceramics (Sadiq *et al.*, 2024; Dawar *et al.*, 2025). It is a hard, brittle metal with a silver-gray color. Some important physical properties include a density of 7.19 g/cm³, a melting point of 1907°C, and a boiling point of 2672°C. Chromium can be found in air, water, and soil,

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especially in areas close to industrial activity (Saleem *et al.*, 2023). In nature, it mainly exists in two forms: trivalent chromium (Cr(III)) and hexavalent chromium (Cr(VI)). Cr(III) is less harmful and does not dissolve well in water, while Cr(VI) is highly toxic, easily moves in the environment, and dissolves well in water. Cr(VI) can form harmful compounds like chromate (CrO_4^{2-}) and dichromate ($\text{Cr}_2\text{O}_7^{2-}$), which are strong oxidizers and known to cause cancer (Habib *et al.*, 2018; Adevumi *et al.*, 2024; Hanif *et al.*, 2024). Various methods have been developed to reduce the harmful impact of heavy metal contamination in the environment, including physical, chemical, and biological techniques (Islam *et al.*, 2016). Among these, biological remediation has gained increasing attention because it is environmentally friendly, cost-effective, and causes minimal disturbance to the natural condition of the soil (Ali *et al.*, 2020; Zahra *et al.*, 2025). Bioremediation is a sustainable and eco-safe approach that uses natural or introduced microorganisms to break down or remove dangerous pollutants like heavy metals, pesticides, hydrocarbons, and industrial waste from soil and water (Ali *et al.*, 2023). One of the major advantages of bioremediation is its safety for the environment, as it avoids the use of harmful chemicals and results in less ecological damage when compared to traditional physical or chemical methods (Khan *et al.*, 2020).

In agriculture, bioremediation plays an important role in improving soil health by decreasing the availability of toxic metals (Emenike *et al.*, 2022). It also helps to bring back microbial diversity and natural soil enzyme activity, which supports better plant growth and productivity. Furthermore, bioremediation supports sustainable land use by restoring polluted or damaged land, making it usable again for cultivation and ecological purposes (Faisal *et al.*, 2005). Another benefit is that microbial mixtures used in this process can often break down more than one type of pollutant at the same time, providing a wide range of detoxification abilities (Tayang *et al.*, 2021). This method also works effectively in various environmental conditions such as saline soil, industrial zones, mining areas, and farmlands, increasing its potential for use in different pollution situations (Kaur *et al.*, 2023). Bioremediation also aligns with global environmental and climate goals because it helps reduce secondary pollution, promotes the use of green technologies, and contributes to long-term ecosystem stability (Ahmed *et al.*, 2021). Phytoremediation is a green and affordable method that uses certain plant species to absorb, stabilize, or neutralize pollutants such as heavy metals, pesticides, and other harmful substances from the environment, including soil, water, and even air (Jahan *et al.*, 2024). This method relies on special plants that can take in or break down pollutants through several mechanisms like phytoextraction, phytostabilization, phytodegradation, and rhizofiltration (Ali *et al.*, 2020). Some plants such as sunflower, Indian mustard, poplar,

and vetiver grass have been proven to absorb significant amounts of toxic metals like cadmium, lead, arsenic, and chromium, which makes them suitable for use in clean-up projects (Jiang *et al.*, 2018). Phytoremediation not only improves the quality and fertility of soil but also enhances biodiversity and the visual appearance of polluted lands, making it part of sustainable land management efforts (Bux *et al.*, 2022). However, the success of phytoremediation depends on factors such as the type of plant used, the kind of pollutant present, and environmental conditions. Certain plants known as hyperaccumulators, such as *Solanum nigrum*, *Arabidopsis halleri*, *Phytolacca americana*, and *Pteris vittata*, can tolerate and collect high amounts of metals like cadmium, zinc, manganese, and chromium respectively (Ali *et al.*, 2020). Despite their abilities, the effectiveness of phytoremediation is sometimes limited due to the slow growth and low biomass of these plant species, which can reduce the speed of cleanup in large-scale contaminated areas (Ray *et al.*, 2009). Plant Growth-Promoting Rhizobacteria (PGPR) are a diverse group of naturally occurring bacteria that live in close association with plant roots, particularly in the soil surrounding them, known as the rhizosphere (Javed *et al.*, 2020). These bacteria originate from a variety of soil environments that support plant life, such as agricultural fields, organic-rich soils, forest floors, saline lands, compost-treated plots, and even areas polluted by industrial activities like mining and heavy metal discharge (Ahmed *et al.*, 2022). To mitigate the adverse effects of chromium (Cr) toxicity on crops, a controlled pot experiment was conducted with *Zea mays* and *Triticum aestivum*, two major cereal crops of global importance. The experiment evaluated the role of plant growth-promoting rhizobacteria (PGPR) *Pseudomonas* sp. Isolates (AH2 and AH3) and *Pseudomonas qingdaonensis* isolate AR5 in enhancing plant growth and stress tolerance under varying Cr levels 5, 10 and 15%. Plants were grown under controlled conditions, and physiological and biochemical parameters were observed.

The aim of the current study was to evaluate the potential of plant growth-promoting rhizobacteria (PGPR) in mitigating the adverse effects of chromium (Cr) toxicity on the growth and physiological performance of wheat and maize under controlled laboratory conditions. The study specifically focused on assessing the effectiveness of selected PGPR strains *Pseudomonas* sp. (AH2, AH3), and *Pseudomonas qingdaonensis* AR5 in enhancing plant growth parameters, chlorophyll content, protein content and stress tolerance when exposed to varying levels of chromium stress.

MATERIALS AND METHODS

The materials required for the experiment included beakers, petri plates, test tubes, test tube stand,

measuring cylinder, micropipette, pipette flask. Materials were washed, oven dried or autoclaved at 121°C 15 lb/in² before use.

A pot experiment was conducted to study how beneficial bacteria (PGPR) help maize (*Zea mays*) grow better under chromium (Cr) stress. The tested PGPR strains were *Pseudomonas* spp. isolates AH2 and AH3, and *Pseudomonas qingdaonensis* isolate AR5. Plants were exposed to chromium stress at 5%, 10%, and 15% levels. The study included proper seed sterilization, bacterial treatment, chromium application, and observation of plant growth and biochemical changes under controlled conditions. The experiment took place in the Microbial and Molecular Genetics Lab, Institute of Botany, University of the Punjab, Lahore. All steps, like seed inoculation, chromium treatment, and data collection, were done under controlled environmental conditions to ensure accuracy. 48 plastic pots were used, filled with sieved garden soil. Three replicates were used for each treatment group, including controls and stressed plants. Certified maize (SG 2002) seeds were obtained from Punjab Seed Corporation, Lahore. Seeds were carefully selected, sterilized with 0.1% HgCl₂ solution for one minute, and rinsed several times with sterile distilled water.

Three PGPR strains (AH2, AH3, AR5) were taken from the lab and grown in L Broth for 24 hours. Sterilized seeds were soaked in the bacterial culture for 30 minutes before sowing. Six maize seeds were planted in each pot. Chromium stress was applied in the form of potassium chromate (K₂CrO₄) dissolved in sterile deionized water. The chromium solutions were given through irrigation at concentrations of 5%, 10%, and 15%. Control plants were irrigated only with distilled water. Plants were harvested after 25 days to measure the growth measurements like shoot length, root length, number of leaves, and fresh weight were recorded.

Shoot length

Shoot lengths of plants were measured from base of shoot to tip of leaves using a scale.

Root length

Root lengths were measured from base of shoot to the tip of root with the help of a scale.

Number of leaves per plant:

The number of leaves were counted.

Fresh weights

Fresh weight of plants was measured using a weighing balance.

Chlorophyll estimation

The method described by Wellburn *et al.* (1994) was used for the estimation of chlorophyll content of both treated and non-treated plants. For each treatment, 1g of plant material was crushed and soaked in 10 ml of 80% acetone solution and then incubated in the dark for 24 hours as shown in table 2.6. After incubation, the

absorbance of each sample was examined at 663 and 645 nm using a spectrophotometer. Chlorophyll 'a', chlorophyll 'b', and total chlorophyll content were calculated using the following formulas:

$$\text{Chlorophyll 'a' } (\mu\text{g/g}) = (12.72 \times A_{663} - 2.59 \times A_{645}) \times V / (m \times 1000)$$

$$\text{Chlorophyll 'b' } (\mu\text{g/g}) = (22.88 \times A_{645} - 4.67 \times A_{663}) \times V / (m \times 1000)$$

$$\text{Total chlorophyll content} = \text{Chl 'a'} + \text{Chl 'b'}$$

Protein estimation

Soluble protein analysis of treated plants was accomplished by following Lowry *et al.* (1951) method. Plant material for each treatment was crushed in a pestle and mortar with 1N phosphate buffer Phosphate used, 4 ml of phosphate buffer for 1 g of plant material. Samples for each treatment were centrifuged at 10,000 rpm for 10 minutes at 4°C. Supernatant was used for soluble protein estimation. 0.4 ml of extract for each sample was taken in a test tube, and 2 ml of Folin's mixture was added carefully (Table 2.7-10). Then test tubes were placed at room temperature for 15 minutes. After that, 0.2 ml of Folin Ciocalteu's reagent was added to each test tube, mixed, and placed at room temperature for 45 minutes to develop the color. Absorbance for each sample was then taken at 750 nm using a spectrophotometer.

Statistical Analysis

Data on various agronomic and physiological traits of *Zea mays* L., recorded under different bacterial treatments and varying chromium stress concentrations, were statistically analyzed for mean comparisons using Microsoft Excel.

RESULTS

The symbiotic relationship between plants and bacteria greatly improved the growth and health of maize (*Zea mays*). Plant growth-promoting rhizobacteria (PGPR) proved to be a better option than chemical fertilizers by producing helpful substances like phytohormones, siderophores, and by solubilizing phosphate, all of which supported plant growth. Chromium-resistant PGPR helped plants survive and grow better in chromium-contaminated soil. In this study, a controlled pot experiment tested three PGPR strains (*Pseudomonas* spp. AH2, AH3, and AR5) to see how well they reduced chromium toxicity at 5%, 10%, and 15% levels in maize.

The application of *Pseudomonas* spp. isolates AH3, AH2, and *Pseudomonas qingdaonensis* AR5 increased shoot length in *Zea mays* by 14.4%, 17.3%, and 12.1%, respectively, compared to the control. Conversely, chromium stress at 5%, 10%, and 15% concentrations reduced shoot length by 14.3%, 25.2%, and 34.6%, respectively, indicating a dose-dependent inhibitory effect of chromium toxicity on plant growth. Co-application of PGPR strains with chromium mitigated this toxicity. Among the tested strains, AH2 was most

effective, improving shoot length by 15.5% under 5% Cr + AH2 treatment compared to 5% Cr alone. These findings suggest that PGPR strains promote shoot growth under both normal and stress conditions, likely by enhancing plant development and nutrient availability.

In *Zea mays*, application of strains AH3, AH2, and AR5 under non-stressed conditions increased the number of leaves by 10.7%, 21.43%, and 23.3%, respectively, compared to the control, indicating improved leaf development. Conversely, chromium stress at 5%, 10%, and 15% reduced leaf numbers by 7.1%, 28.5%, and 28.5%, respectively, showing a concentration-dependent inhibitory effect on leaf formation. When PGPR strains were applied along with chromium, they mitigated these negative effects. The best improvement was observed with strain AR5, which increased leaf number by 21.43% under 15% Cr + AR5 compared to 15% Cr

alone. These results indicate that PGPR strains promote leaf growth in both stressed and non-stressed conditions by enhancing plant development and nutrient utilization, as shown in Figure 1.

Application of *Pseudomonas* spp. isolates AH3 and AH2, and *Pseudomonas qingdaonensis* AR5 increased fresh weight in *Zea mays* by 18.5%, 21.4%, and 21.4%, respectively, compared to the control, indicating enhanced biomass production under normal conditions as mentioned in the figure 2.

In contrast, chromium stress at 5%, 10%, and 15% reduced fresh weight by 7.1%, 28.5%, and 28.57%, respectively, showing that higher chromium levels caused greater biomass reduction. PGPR application with chromium alleviated these negative effects. The best result was observed with isolate AH2, which increased fresh weight by 21.43% under 15% Cr + AH2 compared to 15% Cr alone.

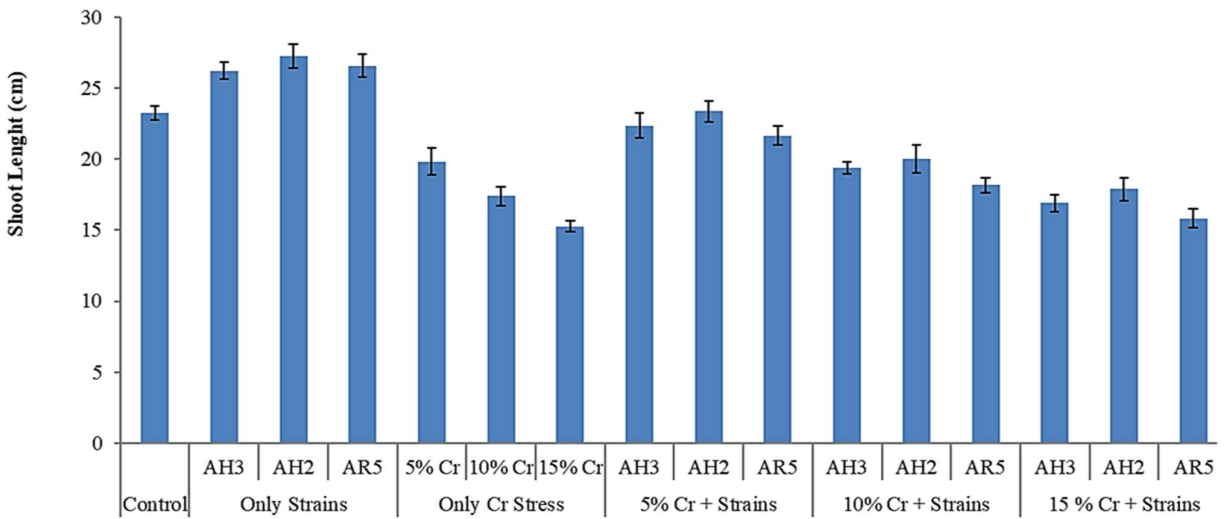


Fig. 1: Effect of bacterial treatments on shoot length of *Zea mays* L. under different Cr stress concentrations (5, 10 and 15 %). [Control, bacterial isolates *Pseudomonas* spp. (AH3 and AH2) and *Pseudomonas qingdaonensis* (AR5)].

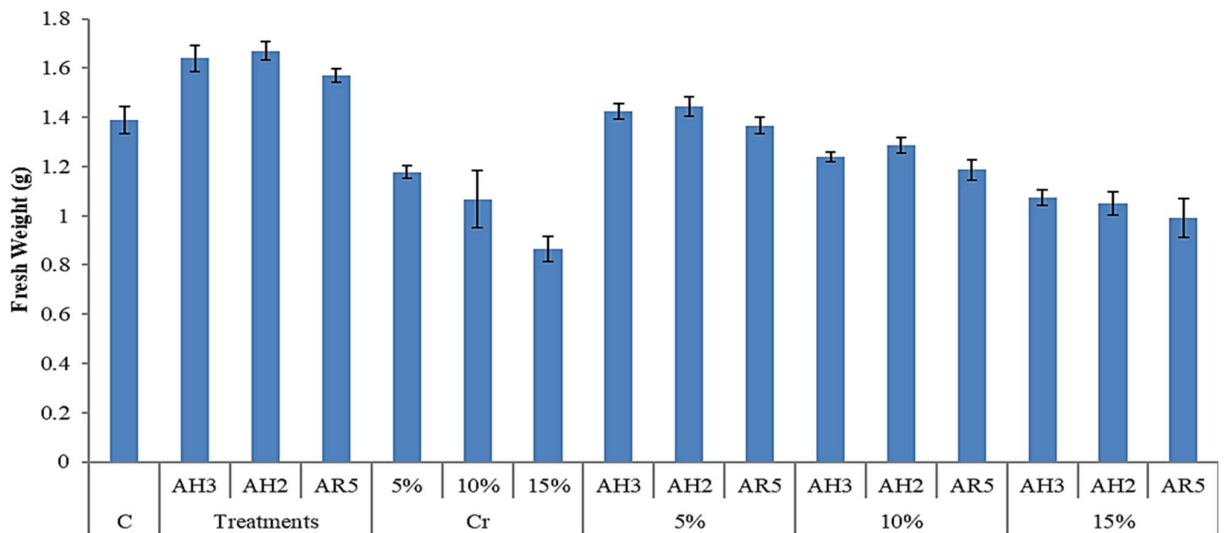


Fig. 2: Effect of bacterial treatments on fresh weight content of *Zea mays* L. under different Cr stress concentrations (5, 10 and 15 %). [Control, bacterial isolates *Pseudomonas* spp. (AH3 and AH2) and *Pseudomonas qingdaonensis* (AR5)].

Total chlorophyll content in *Zea mays* increased by 17.4%, 24.9%, and 18.2% with the application of *Pseudomonas* spp. isolates AH3, AH2, and AR5, respectively, compared to the control, indicating enhanced chlorophyll synthesis under normal conditions (figure1). In contrast, chromium stress at 5%, 10%, and 15% reduced total chlorophyll content by 9.7%, 20.5%, and 26.6%, respectively, showing a progressive decline with increasing Cr concentrations. PGPR co-application mitigated these negative effects. The highest improvement was observed with AH2, which increased total chlorophyll by 19.7% under 5% Cr + AH2 compared to 5% Cr alone as shown in figure 4.

In *Zea mays*, soluble protein content increased by 17.7%, 26.3%, and 17.7% with the application of *Pseudomonas* spp. isolates AH3, AH2, and *Pseudomonas qingdaonensis* AR5, respectively, compared to the control, indicating enhanced protein synthesis under normal conditions as shown in the figure 3. In contrast, chromium (Cr) stress at 5%, 10%, and 15% reduced protein content by 10.4%, 22%, and 29.2%, respectively, demonstrating a concentration-dependent decline in protein formation. Co-application of PGPR strains reduced these adverse effects. The best result was observed with AH2, which increased protein content by 5% under 5% Cr + AH2 treatment compared to 5% Cr alone.

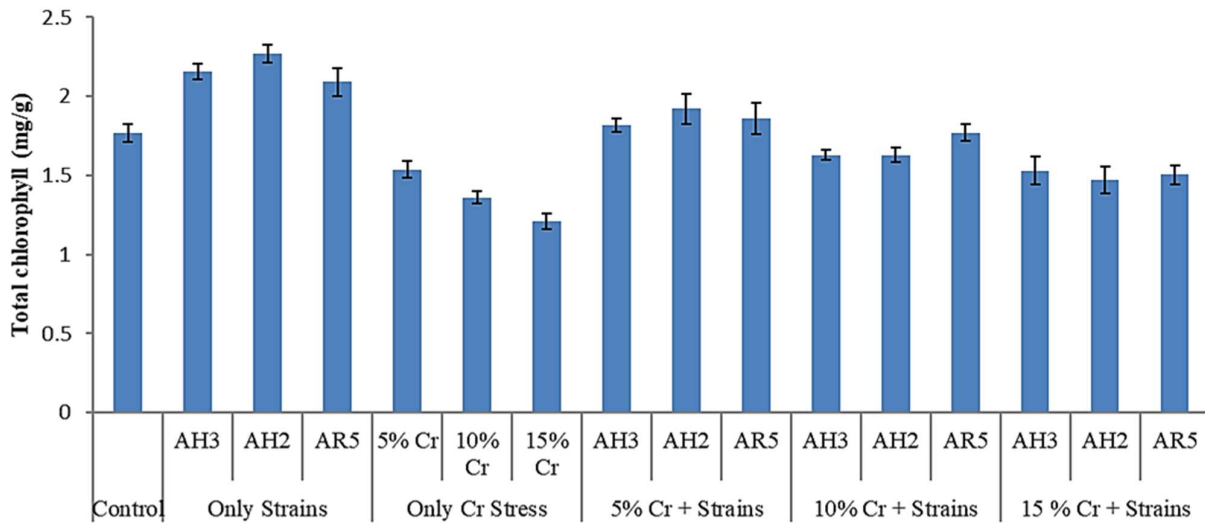


Fig. 3: Effect of bacterial treatments on Total chlorophyll contents of *Zea mays* L. under different Cr stress concentrations (5, 10 and 15 %). [Control, bacterial isolates *Pseudomonas* spp. (AH3 and AH2) and *Pseudomonas qingdaonensis* (AR5)].

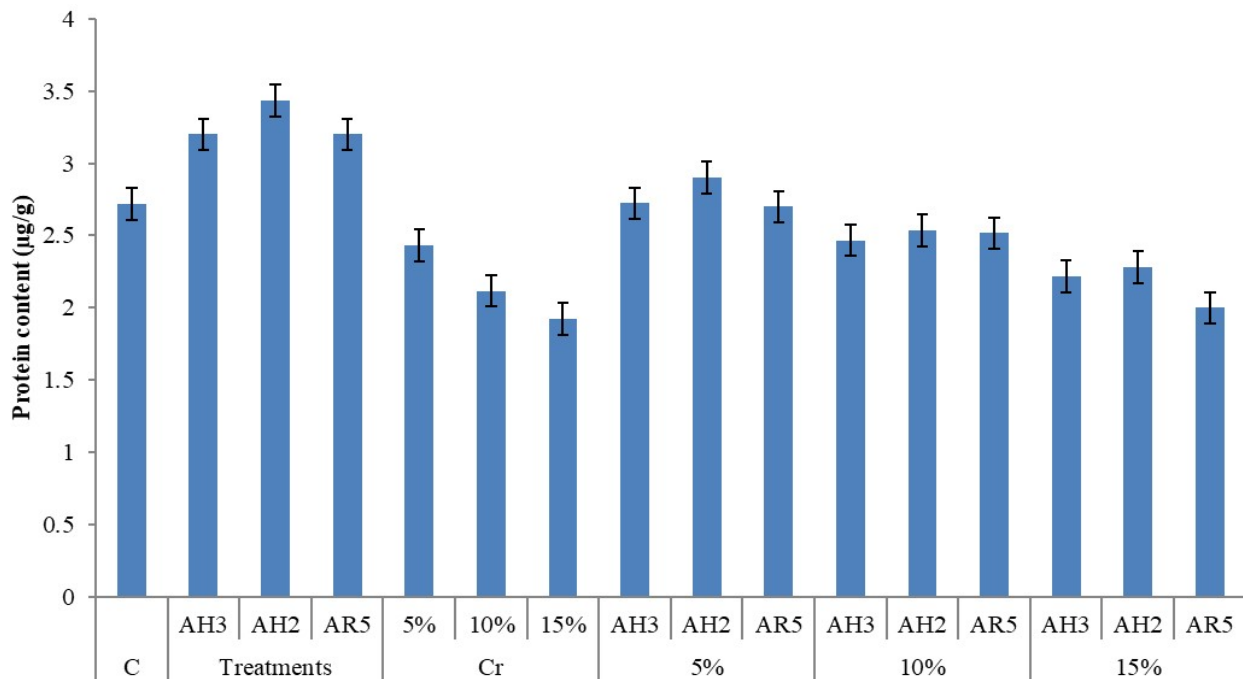


Fig. 4: Effect of bacterial treatments on protein content of *Zea mays* L. under different Cr stress concentrations (5, 10 and 15 %). [Control, bacterial isolates *Pseudomonas* spp. (AH3 and AH2) and *Pseudomonas qingdaonensis* (AR5)].

Application of *Pseudomonas* spp. isolates AH3 and AH2, and *Pseudomonas qingdaonensis* AR5 increased root length in *Zea mays* by 12.5%, 21.10%, and 13.9%, respectively, compared to the control, indicating enhanced root development under normal conditions as shown in the figure 5. In contrast, chromium stress at 5%, 10%, and 15% reduced root length by 9.3%, 20.6%, and 30.0%, respectively, demonstrating a concentration-dependent negative effect on the root system. Co-application of PGPR strains with chromium alleviated these toxic effects. Among all strains, AH2 was most effective, increasing root length by 15.2% under 5% Cr + AH2 treatment compared to 5% Cr alone.

In *Zea mays*, application of strains AH3, AH2, and AR5 under non-stressed conditions increased the

number of leaves by 10.7%, 21.43%, and 23.3%, respectively, compared to the control, indicating improved leaf development. Conversely, chromium stress at 5%, 10%, and 15% reduced leaf numbers by 7.1%, 28.5%, and 28.5%, respectively, showing a concentration-dependent inhibitory effect on leaf formation. When PGPR strains were applied along with chromium, they mitigated these negative effects. The best improvement was observed with strain AR5, which increased leaf number by 21.43% under 15% Cr + AR5 compared to 15% Cr alone. These results indicate that PGPR strains promote leaf growth in both stressed and non-stressed conditions by enhancing plant development and nutrient utilization, as shown in Figure 6.

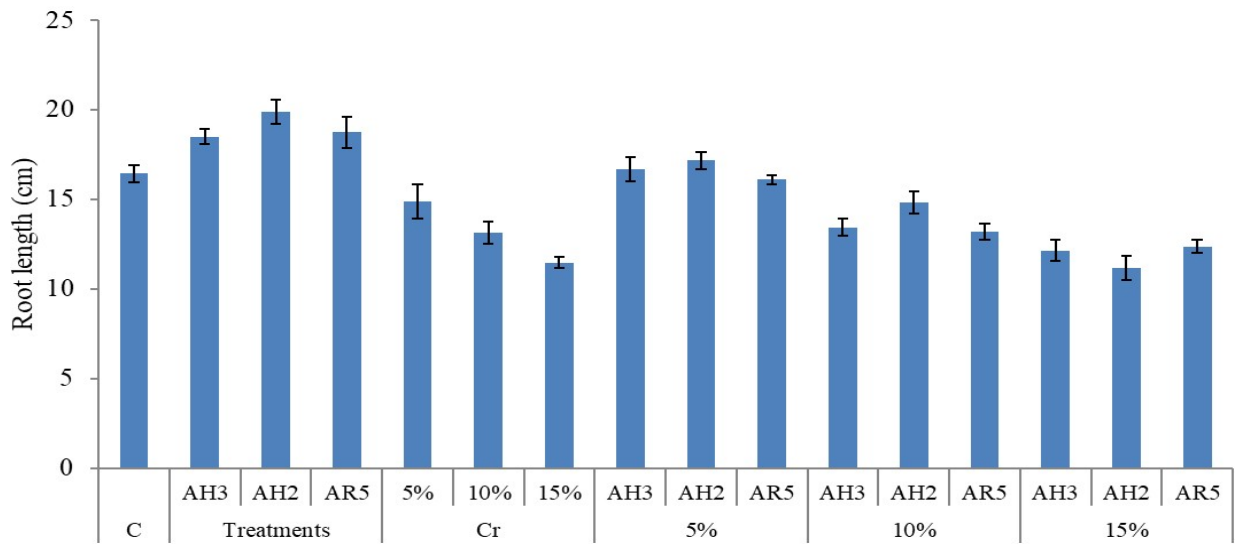


Fig. 5: Effect of bacterial treatments on root length of *Zea mays* L. under different Cr stress concentrations (5, 10 and 15%). [Control, bacterial isolates *Pseudomonas* spp. (AH3 and AH2) and *Pseudomonas qingdaonensis* (AR5)]

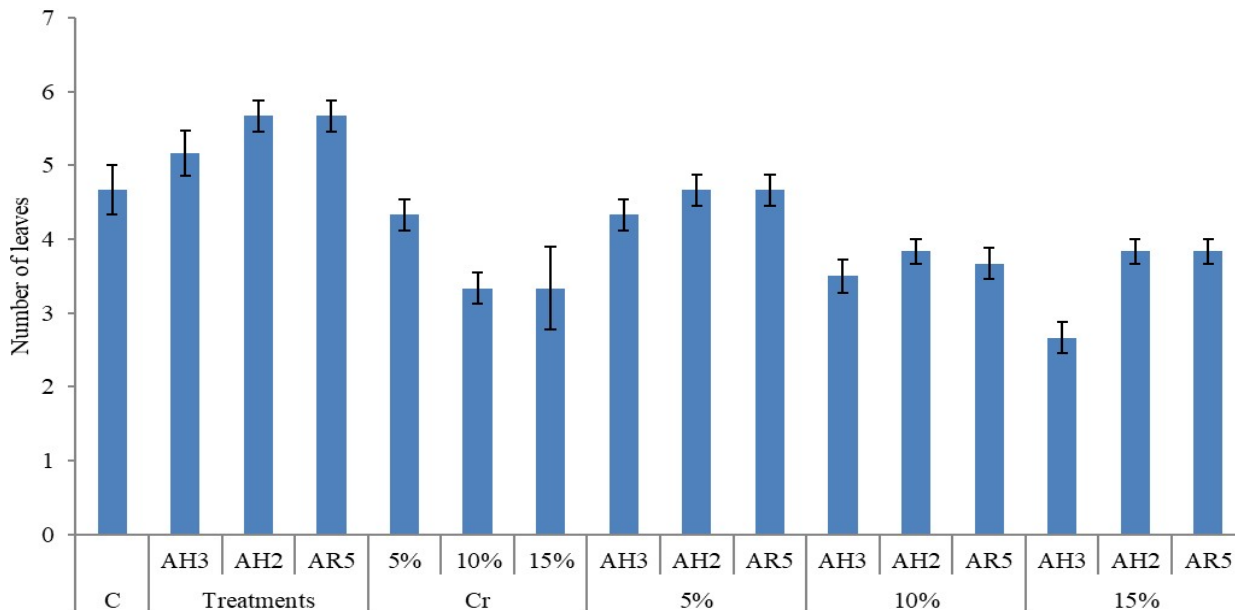


Fig. 6: Effect of bacterial treatments on number of leaves of *Zea mays* L. under different Cr stress concentrations (5, 10 and 15%). [C=control, bacterial isolates *Pseudomonas* spp. (AH3 and AH2) and *Pseudomonas qingdaonensis* (AR5)]

DISCUSSION

Heavy metal contamination caused by industrial discharge, mining operations, urbanization, and excessive application of agrochemicals has led to the accumulation of toxic elements such as chromium (Cr), cadmium (Cd), and lead (Pb) in agricultural soils and water bodies (Alloway, 2021; Rizwan *et al.*, 2020). These metals are highly persistent and can easily enter the food chain, posing serious health risks to humans and animals while simultaneously degrading soil fertility by altering soil microbial activity and nutrient cycling processes (Shahid *et al.*, 2021; Bashir *et al.*, 2022). Crop plants growing in contaminated soils often show reduced seed germination, inhibited root and shoot growth, chlorosis, and enhanced oxidative stress due to excessive generation of reactive oxygen species (Adrees *et al.*, 2021; Singh *et al.*, 2023). In recent years, sustainable and eco-friendly remediation approaches such as bioremediation and phytoremediation have gained increasing attention as effective alternatives to conventional remediation methods. In this context, plant growth-promoting rhizobacteria (PGPR) play a crucial role in mitigating heavy metal stress by enhancing plant growth, improving antioxidant defense systems, and immobilizing or transforming toxic metals into less harmful forms, thereby supporting plant productivity under contaminated conditions (Tirry *et al.*, 2021; Singh *et al.*, 2023).

The present study demonstrated a marked reduction in maize shoot length under increasing chromium stress, with decreases of 14.6, 25.2, and 34.26% at 5, 10, and 15% Cr levels, respectively. These findings are consistent with earlier studies reporting dose-dependent inhibition of shoot growth in maize under chromium toxicity, mainly due to disrupted nutrient uptake, hormonal imbalance, and restricted cell division (Adrees *et al.*, 2021). In contrast, inoculation with *Pseudomonas* isolates AH2 and AH3 significantly alleviated Cr-induced growth inhibition, resulting in a 15.5% increase in maize shoot length under 5% Cr stress, which agrees with earlier findings highlighting the role of PGPR in promoting plant growth under heavy metal stress through phytohormone production, siderophore secretion, and activation of antioxidant defense mechanisms (Albaqmi *et al.*, 2016; Batool *et al.*, 2020).

Chromium (Cr) stress reduces root growth, with roots becoming 9.3%, 20%, and 30.2% shorter at 5%, 10%, and 15% Cr, respectively, compared to normal plants. This happens because Cr stops root cells from dividing and makes it harder for roots to take up nutrients (Kartic *et al.*, 2017). However, PGPR increased maize root length by about 47% under Cr stress by producing growth hormones and molecules that help roots absorb nutrients better and cope with stress (Zahra *et al.*, 2025).

Chromium (Cr) stress reduced leaf numbers by 7.1, 28.5, and 28.5% at 5, 10, and 15% Cr, respectively, compared to non-stressed plants, as Cr disrupts hormones, inhibits cell division, and damages developing leaves (Sarwar *et al.*, 2023). Inoculation with plant growth-promoting rhizobacteria (PGPR), such as

Pseudomonas AH2, significantly improved leaf numbers under Cr stress; for example, AH2 increased maize leaf number by 21.4% at 15% Cr.

Chromium (Cr) stress significantly reduced fresh weight in *Zea mays* L. Compared with the control, maize plants exposed to 5% Cr showed a 7.14% reduction, while higher Cr levels (10 and 15%) caused 28.5 and 28.7% decreases, respectively, indicating that increasing Cr concentrations progressively impaired plant biomass and overall health. These reductions are consistent with reports that Cr disrupts physiological processes, lowers photosynthetic activity, and induces oxidative stress via reactive oxygen species (ROS) production, ultimately reducing plant growth (Ullah *et al.*, 2019; Mazhar *et al.*, 2020). However, PGPR (*Pseudomonas*) inoculation alleviated these adverse effects. Under 15% Cr stress, inoculation with strain AH2 increased maize fresh weight by 21.3% compared with the untreated Cr-stressed plants, demonstrating a protective role of PGPR against Cr toxicity.

Total chlorophyll content in *Zea mays* L. was significantly reduced under chromium (Cr) stress. Compared with the control, maize plants exposed to 5% Cr showed a 13.0% reduction, while higher Cr levels (10 and 15%) caused 22.9 and 31.5% decreases, respectively, indicating that increasing Cr concentrations progressively impaired photosynthetic capacity. These reductions are consistent with reports that Cr interferes with magnesium uptake, damages chloroplasts, and induces oxidative stress via reactive oxygen species (ROS), ultimately reducing chlorophyll content and photosynthetic efficiency (Kaymak *et al.*, 2017; Kamran *et al.*, 2017). However, PGPR (*Pseudomonas*) inoculation alleviated these adverse effects. Under 15% Cr stress, inoculation with strain AH2 increased maize chlorophyll content by 28.2% compared with untreated Cr-stressed plants, demonstrating a protective role of PGPR against Cr-induced photosynthetic inhibition.

Total protein content in *Zea mays* L. was significantly reduced under chromium stress. Compared with the control, maize plants exposed to 5% Cr showed a 10.4% reduction, while higher Cr levels (10 and 15%) caused 22.0 and 29.2% decreases, respectively, indicating that increasing Cr concentrations progressively impaired protein synthesis and overall plant health. These reductions are consistent with reports that Cr interferes with nitrogen metabolism, inhibits enzyme activity, and disrupts protein biosynthesis in plants (Javed *et al.*, 2017). However, PGPR inoculation mitigated these adverse effects. Under 5% Cr stress, inoculation with strain AH2 increased maize protein content by 19.22% compared with untreated Cr-stressed plants, demonstrating the protective role of PGPR against Cr-induced protein reduction.

Conclusions

The present study demonstrates that chromium (Cr) contamination severely hampers the growth and physiological performance of *Zea mays*, confirming the detrimental impact of heavy metal stress on sustainable

crop production. Chromium stress significantly reduced key morphological traits, including shoot and root length, number of leaves, and fresh biomass, along with essential biochemical parameters such as chlorophyll and protein content. However, inoculation with plant growth-promoting rhizobacteria (PGPR), specifically *Pseudomonas* spp. (AH3 and AH2) and *Pseudomonas qingdaonensis* (AR5), effectively mitigated the adverse effects of chromium toxicity. Under chromium-stressed conditions, PGPR-treated plants exhibited marked improvements in growth and biochemical attributes compared to non-inoculated stressed plants, indicating enhanced stress tolerance and metabolic activity. These beneficial effects can be attributed to the ability of PGPR to promote plant growth through improved nutrient uptake, enhanced chlorophyll synthesis, and stress alleviation mechanisms. Overall, the findings highlight the potential of PGPR as an eco-friendly and sustainable bio-remediation approach for restoring chromium-contaminated soils while improving crop productivity. The application of PGPR could therefore serve as a promising strategy for managing heavy metal stress in agricultural systems and supporting sustainable agricultural practices.

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Ethics Statement: No prior study was conducted on live animals/humans; thus, it did not require any ethical approval.

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REFERENCES

- Albaqmi, M., Alharbi, S. A., & Al-Ghamdi, A. A. (2016). Role of plant growth-promoting rhizobacteria in improving plant growth under abiotic stress conditions. *Journal of Plant Growth Regulation*, 35(3), 798–810. <https://doi.org/10.1007/s00344-016-9572-6>
- Ali, S., Mir, R. A., Tyagi, B. U., Mahmoudi, H., & Bae, H. (2023). Chromium toxicity in plants: Signaling, mitigation, and future perspectives. *Plants*, 12(7), 1502. <https://doi.org/10.3390/plants12071502>
- Batool, S., Khan, M. A., Shahzad, R., & Naeem, M. (2020). Plant growth-promoting rhizobacteria-induced oxidative stress tolerance in plants under heavy metal stress. *Ecotoxicology and Environmental Safety*, 202, 110914. <https://doi.org/10.1016/j.ecoenv.2020.110914>
- Dawar, K., Khan, A., Al-Mutairi, M., Alotaibi, M. O., Mian, I. A., Muhammad, A., Alam, S. S., Shoaib, S., & Ghoneim, A. M. (2025). Utilizing spent mushroom substrate biochar to improve *Zea mays* L. growth and biochemical resilience against cadmium and chromium toxicity. *Scientific Reports*, 15(1), 17511. <https://doi.org/10.1038/s41598-025-01617-8>
- Emenike, E. C., Iwuozor, K. O., & Anidiobi, S. U. (2022). Heavy metal pollution in aquaculture: Sources, impacts and mitigation techniques. *Biological Trace Element Research*. <https://doi.org/10.1007/s12011-021-03037-x>
- Faisal, M., Hameed, A., & Hasnain, S. (2005). Chromium-resistant bacteria and cyanobacteria: Impact on Cr(VI) reduction potential and plant growth. *Journal of Industrial Microbiology & Biotechnology*, 32(11–12), 615–621. <https://doi.org/10.1007/s10295-005-0241-2>
- Habib, S., Fatima, H.-e., & Ahmed, A. (2018). Comparative Analysis of Pre-Germination and Post-Germination Inoculation Treatments of *Zea mays* L. to Mitigate Chromium Toxicity in Cr-Contaminated Soils. *Polish Journal of Environmental Studies*, 28(2), 597–607. <https://doi.org/10.15244/pjoes/81570>
- Hanif, R., Ahmed, A., & Tariq, A. (2024). Chromium-stress alleviation study using plant growth promoting rhizobacteria for maize (*Zea mays* L.). *World Journal of Biology and Biotechnology*, 9(2), 25. <https://doi.org/10.33865/wjbb.009.02.01128>
- Hayyat, M. U., Iqbal, S., Khan, Q. F., Siddiq, Z., Sharif, F., Ali, S., Shahzad, L., Tahir, Z. u. R., Farhan, M., & Shah, T. A. (2025). Bioremediation of Metal(loid) toxicity in maize (*Zea mays* L.) by inoculating metal resistant bacterial strains. *International Journal of Environmental Science and Technology*, 22(12), 11689–11704. <https://doi.org/10.1007/s13762-025-06364-x>
- Javed, M. T., Hussain, S., & Malik, K. A. (2017). Chromium toxicity and protein synthesis inhibition in cereal crops. *Environmental Science and Pollution Research*, 24(15), 13725–13733. <https://doi.org/10.1007/s11356-017-8994-5>
- Kamran, M. A., Bibi, S., Xu, R. K., Hussain, S., Mehmood, K., & Chaudhary, H. J. (2017). Phyto-extraction of chromium and influence of plant growth-promoting bacteria to enhance plant growth. *Journal of Geochemical Exploration*, 182, 269–274. <https://doi.org/10.1016/j.gexplo.2016.09.005>
- Kamran, M., Ali, S., Khan, F., & Shahbaz, M. (2017). Chromium toxicity in maize: Effects on chlorophyll and photosynthesis. *Environmental Science and Pollution Research*, 24(15), 13675–13684. <https://doi.org/10.1007/s11356-017-9005-6>
- Kaur, S., & Roy, A. (2021). Bioremediation of heavy metals from wastewater using nanomaterials. *Environment, Development and Sustainability*, 23(7), 9617–9640. <https://doi.org/10.1007/s10668-020-01078-1>

- Kaymak, H. C. (2017). Potential of PGPR in agricultural innovations. In D. Egamberdieva & S. Ahmad (Eds.), *Plant growth and health promoting bacteria* (pp. 45–79). Springer. https://doi.org/10.1007/978-3-642-13612-2_3
- Kaymak, H., Turan, M., & Çakmak, İ. (2017). Impact of heavy metals on chlorophyll content and photosynthesis in crops. *Journal of Plant Nutrition*, 40(12), 1745–1755. <https://doi.org/10.1080/01904167.2016.1269344>
- Khan, M. S., Zaidi, A., Wani, P. A., & Oves, M. (2010). Role of plant growth-promoting rhizobacteria in the remediation of metal-contaminated soils. *Environmental Chemistry Letters*, 7(1), 1–19. <https://doi.org/10.1007/s10311-008-0155-0>
- Mazhar, M., Ali, S., Iqbal, N., & Khan, M. (2020). Chromium-induced stress in crops: Effects on growth and physiology. *Environmental Toxicology and Chemistry*, 39(10), 2051–2062. <https://doi.org/10.1002/etc.4821>
- Qin, H., Wang, Z., Sha, W., Song, S., Qin, F., & Zhang, W. (2024). Role of plant-growth-promoting rhizobacteria in plant machinery for soil heavy metal detoxification. *Microorganisms*, 12(4), 700. <https://doi.org/10.3390/microorganisms12040700>
- Ray, S., & Ray, M. K. (2009). Bioremediation of heavy metal toxicity with special reference to chromium. *Al Ameen Journal of Medical Sciences*, 2(2), 57–63.
- Sadiq, I., Laghari, A. H., & Kohli, H. (2024). Impact of plant growth-promoting rhizobacteria on spinach growth concerned with industrial effluents contaminated with chromium. *Lahore Garrison University Journal of Life Sciences*, 8(3). <https://doi.org/10.54692/lgujls.2024.0803360>
- Shahid, M., Dumat, C., Khalid, S., Schreck, E., Xiong, T., & Niazi, N. K. (2021). Foliar heavy metal uptake, toxicity and detoxification in plants: A comparison of foliar and root metal uptake. *Journal of Hazardous Materials*, 403, 123947. <https://doi.org/10.1016/j.jhazmat.2016.11.063>
- Tafinta, I. Y., Kutama, A. S., Abd Shakoar, M. Y., Musa, H., & Hayatu, N. G. (2024). Efficient removal of chromium (VI) ions from aqueous solutions using *Aspergillus flavus*. *UMYU Scientifica*, 3(2), 139–145. <https://doi.org/10.56919/usc.2432.015>
- Tirry, N., Kouchou, A., El Omari, B., Ferioun, M., & El Ghachtouli, N. (2021). Improved chromium tolerance of *Medicago sativa* by plant growth-promoting rhizobacteria (PGPR). *Journal of Genetic Engineering and Biotechnology*, 19, 1–14. <https://doi.org/10.1186/s43141-021-00254-8>
- Ullah, A., & Bano, A. (2019). Role of PGPR in the reclamation and revegetation of saline land. *Pakistan Journal of Botany*, 51(1), 27–35. [https://doi.org/10.30848/pjb2019-1\(43\)](https://doi.org/10.30848/pjb2019-1(43))
- Yang, X., Ren, J., Lin, X., Yang, Z., Deng, X., & Ke, Q. (2023). Melatonin Alleviates Chromium Toxicity in Maize by Modulation of Cell Wall Polysaccharides Biosynthesis, Glutathione Metabolism, and Antioxidant Capacity. *International Journal of Molecular Sciences*, 24(4), 3816. <https://doi.org/10.3390/ijms24043816>
- Zahra, F., Ahmed, A., Tariq, A., & Hanif, R. (2025). Investigation of PGPR's potential to promote growth in maize (*Zea mays* L.) under chromium and cadmium stress. *World Journal of Biology and Biotechnology*, 10(2), 1450. <https://doi.org/10.33865/wjb.10.2.1450>
- Zahra, F., Ahmed, A., Tariq, A., & Hanif, R. (2025). Investigation of PGPR's potential to promote growth in maize (*Zea mays* L.) under chromium and cadmium stress. *World Journal of Biology and Biotechnology*, 10(2), 1. <https://doi.org/10.33865/wjb.10.2.1450>
- Zhuang, P., McBride, M. B., Xia, H., Li, N., & Li, Z. (2024). Health risk from heavy metals via consumption of food crops grown on contaminated soils: A global review. *Science of the Total Environment*, 908, 168047. <https://doi.org/10.1016/j.scitotenv.2023.168047>