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Mahendar Kumar Sootahar

Soil Fertility Research Institute, Agriculture Research Center, Tando Jam

Abdul Ghafoor

aghafoor@kfu.edu.sa

water and Environmental Studies Center, King Faisal University, Al-Ahsa 31982, Saudi Arabia

Mukesh Kumar Soothar

College of Natural Resources and Environmental, Northwest A&F University, Yangling, Shaanxi, 712100

Muhammad Naeem Sattar

Central Laboratories Department of Chemistry, King Faisal University, Al-Ahsa, Saudi Arabia

Kashif Ali Kubar

Lasbela University of Agriculture Water and Marine Science

Babiker M. A Abdel-Banat

Date Palm Research Center of Excellence, King Faisal University, Al-Ahsa 31982

Research Article

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Morphological and Antioxidant Responses to Chromium-Induced and Metal Accumulation in Contrasting Tomato Cultivars

Mahendar Kumar Sootahar^a, Abdul Ghafoor^{b, *}, Mukesh Kumar Soothar^c, Muhammad Naeem Sattar^f, Kashif Ali Kubar^d, Babiker M.A Abdel-Banat^e

^a Soil Fertility Research Institute, Agriculture Research Center, Tando Jam, 70060, Pakistan. Mahender_935@yahoo.com

^b Water and Environmental Studies Center, King Faisal University, Al-Ahsa 31982, Saudi Arabia; kturk@kfu.edu.sa

^c College of Natural Resources and Environment, Northwest A&F University, Yangling, Shaanxi 712100, China. mukeshksoothar@gmail.com

^d Faculty of Agriculture, Lasbela University of Agriculture, Water and Marine Sciences, Uthal 90150, Balochistan, Pakistan. kashifkubar@luawms.edu.pk

^e Date Palm Research Center of Excellence, King Faisal University, Al-Ahsa 31982, Saudi Arabia bahmed@kfu.edu.sa

^f Central Laboratories, Department of Chemistry, King Faisal University, Al-Ahsa 31982, Saudi Arabia mnsattar@kfu.edu.sa

*Corresponding author; aghafoor@kfu.edu.sa; mahender_935@yahoo.com

Abstract: Chromium (Cr) in soil and water exceeding safe level has brought a series of problems to food safety and human health, and considered as major environmental concern that poorly affects plant physiology. Four Cr concentrations at (0, 25, 50 and 100 mg/kg) along with composite mix in soil were applied to determine the root morphological characters, fruit yield Cr antioxidant enzyme activity, accumulation, bioaccumulation and translocation in two Tomato (*Solanum lycopersicum* L.) (Red Pearl and Purple Beauty) screened cultivars. A randomized complete block design experiment was conducted in a controlled greenhouse with five replications. The results demonstrate that Red Pearl was significantly lower affected by Cr stress than Purple Beauty in some biochemical indicators, such as APX activity in leaf and shoot, MDA content in root, ASC content. However, Purple Beauty was significantly higher than Red Pearl in certain indicators such as CAT activity in leaf and shoot, indicating difference in their physiological mechanisms. The results also indicated that at 50 and 100 mg/kg Cr concentration Red Pearl accumulated significantly more Cr in its shoots and roots than Purple Beauty. The Cr absorbed by the entire plant was significantly higher in Red Pearl than in Purple Beauty under three Cr concentrations. Although bioaccumulation factor of Red Pearl was significantly higher than that of Purple Beauty, the translocation factors of the two cultivars differ but had not reached a significant level. Overall, the results of this experiment emphasized that Red Pearl showed more obvious Cr tolerance under experimental treatments, through enhanced antioxidant defense, efficient root sequestration of Cr and restricted translocation to aerial tissues. Therefore, it is concluded that Red Pearl can be a potential tomato cultivar for cultivation in moderately Cr contaminated soil, and provide genetic resources for breeding tomato cultivars, but further field experiment is worth studying

Keywords: Hexavalent Cr, *Solanum lycopersicum*; antioxidant enzymes; catalase; ascorbate peroxidase; malondialdehyde; ascorbic acid; bioaccumulation factor; translocation factor; heavy metal stress.

1. Introduction

Soil is the foundation of agricultural production, which contains a wide range of mineral elements, including essential trace elements and toxic elements (Wan et al. 2024). Among heavy metals, certain elements such as Zinc (Zn) and Copper (Cu) are essential micronutrients required for normal physiological functions in plants, animals, and humans when present at appropriate concentrations, however, excessive accumulation can become toxic. In contrast, metals such as cadmium (Cd), chromium (Cr), mercury (Hg) and arsenic (As) have no known biological function and are highly toxic even at relatively low concentrations (Tiecher et al. 2016; Rai et al. 2019). However, these toxic elements can be absorbed by plants roots due to the similarities of their physiochemical properties to essential elements (Zhao and Wang 2020). Over the last decades, due to rapid industrialization, mining, urbanization, development and overpopulation, large number of heavy metals discharge and entered into the soil through anthropogenic interference, and soil heavy metal pollution has become a global issue (Kumar et al. 2019). These heavy metals are non-biodegradable, they accumulate in agricultural soils, which adversely affecting soil fertility, nutrient availability and plant physiological processes (Kumar et al. 2019).

Among heavy metals, chromium (Cr) is a transitioning metal element present in all environments, and very poisonous element in the soil, in the recent decades, Cr contamination in soil has emerged as a significant concern particularly in areas with high levels of industrial applications and widespread contamination of agricultural soils and irrigation water (Malhi et al. 2026; Reale et al. 2016). Comparing with the other heavy metals the major anthropogenic source of Cr derives from leather tanning, electroplating, textile dyeing, and industrials waste disposal (Jena and Hembram 2024; Hassan et al. 2024). Cr exists in two most frequent forms in the environment trivalent [Cr(III)] and hexavalent [Cr(VI)] forms (Landrot et al. 2012), among them hexavalent [Cr (VI)] is highly oxidizing forms, including chromate, dichromate, and chromium trioxide, and is particularly hazardous to living beings (Gomes et al. 2017; Singh et al. 2025). Furthermore, soil properties strongly influence the availability of Cr and plant uptake, through pH, organic matter, redox potential, clay minerals and ionic interactions in rhizosphere (Jena and Hembram 2024; Hassan et al. 2024). The high Cr accumulation in plants extensively affects seed germination and reduces root and shoot growth rates and impact on the overall biomass and yield (Malhi et al. 2026;

Jobby et al. 2024; Hassan et al. 2024). Similarly, Cr toxicity interferes with membrane transport, cell division, leading to reduces nutrient acquisition and sensitive microorganisms' population (Bai et al. 2023). They physiological and metabolic disturbance ultimately suppress vegetative growth, reproductive development, and crop yield. The severity of Cr toxicity depends on the plant species, genotype. Cr concentration, exposure duration and environmental conditions, reflecting the complex nature of plant responses to Cr stress (Jobby et al. 2024; Qureshi et al. 2024).

Excessive Cr disrupts essential physiological and metabolic processes, including antioxidant defense, nitrogen uptake, enzyme function, mineral and water homeostasis, and normal cell division. Moreover, the Cr toxicity endorses excessive reactive oxygen species (ROS) productions, which causes oxidative damage (Ugwu and Agunwamba 2020; Kour et al. 2024). ROS accumulation causes membrane lipid peroxidation, which impairs membrane function and structure, as well as the oxidation of protein and nucleic acids, leading in cellular component damage and, finally, cell death (Wakeel et al. 2019; Jobby et al. 2024). However, elevated ROS hinders plants from responding biochemically, causing changes in morphology and architecture (Wakeel et al. 2020). Similarly oxidative injuries ultimately inhibit plant growth and reduce crop productivity under Cr stress (Batoool et al. 2024).

Plants counter Cr induced oxidative stress through an integrated antioxidant defense system consisting of enzymatic antioxidants such as catalase (CAT) and ascorbate peroxidase (APX), along with non-antioxidants detoxify reactive oxygen (ROS) and protect cellular structures from oxidative injury (Shah et al. 2024). Nevertheless, excessive Cr exposure can overwhelm this defense mechanism, leading to increased lipid peroxidation, membrane disruption and malondialdehyde (MDA) accumulation, a reliable indicator of oxidative stress (Kour et al. 2024). Besides physiological responses, the uptake and distribution of Cr among plan organs are critical determinants of crop safety and phytoremediation potential. Cr may be retained in roots or translocated to aerial tissues, influencing both plant tolerance and the risk of metal accumulation inedible parts (Shah et al. 2024; Batoool et al. 2024). Consequently, bioaccumulation factor (BAF) and translocation factor (TF), together with growth and biochemical traits, are widely used to evaluate Cr uptake, transport, and food safety risks in crop plants (Jena and Hembram 2024) (Singh et al. 2025).

Tomato (*Solanum lycopersicum* L.) considered as an important vegetable in the world (Sootahar et al. 2025; Naika et al., 2019), because of high economic value and rich in vitamins, antioxidants, broad dietary consumption, and some bioactive mechanisms that are very reliable and seem

preventative for some diseases (Sootahar et al. 2025; Aghaie et al. 2018), such as lung, breast and stomach cancers (Niamat et al. 2019; Choi et al. 2014). However, its production and cultivation increasingly exposed to environmental constraints, including salinity, drought, temperature extremes, nutrient imbalance and heavy-metal contamination (Malhi et al. 2026). Heavy metals are intrinsic components of the environment that cannot be biologically degraded, meanwhile Cr toxicity has been linked to a decrease in germination rates, stunted plant growth reduced flowering, lower enzyme activity and widespread chlorosis affecting the entire plant may create potential risks for consumers (Christou et al. 2021). Therefore, the evaluation of Cr responses in tomato should consider both crop productivity and the distribution of Cr within the plant.

Tomato varieties having diverse ability to absorb, retain, detoxify and translocate the Cr, which resulting in considerable variation in antioxidant responses biomass production and fruit yield (Shah et al. 2024). It was reported by different scientist that Cr tolerance in tomato is regulated through coordinated physiological, biochemical, and molecular mechanisms rather than a single defense pathway (Qureshi et al. 2024). Most of the studies have focused Cr and its impact on Seed germination rate, physiological, vegetative growth, while few have simultaneously evaluated fruit yield, CAT, APX, ascorbic acid, MDA, Cr accumulation, bioaccumulation factor and translocation factor (TF) under same experimental conditions.

Therefore, the present study was conducted to evaluate the enzymatic antioxidant responses of tomato cultivars subjected to chromium stress during seed germination. The study specifically investigated changes in catalase (CAT) and ascorbate peroxidase (APX) activities as biochemical indicators of oxidative stress tolerance. The findings are expected to improve our understanding of cultivar-dependent antioxidant defense mechanisms and provide valuable information for identifying chromium-tolerant tomato genotypes suitable for cultivation in chromium-contaminated environments.

2. Materials and Methods

2.1. Experimental Design for Chromium treatments

Two chromium (Cr) screened tomato cultivars were selected in a Pot experiment to examine the Cr tolerance at experimental greenhouse of university of southwest science and technology, China. The plant materials were collected from the local market Mianyang city and soil used in this experiment was collected from non-polluted area of Mianyang city, Sichuan province China (31°28' N, 104°45' E) (**Fig. 1**). The soil collected for this experiment was previously used by (Ram et al. 2019). The soil basic physiochemical properties are presented in (**Table 1**). The pots with 15

cm height and 20 cm upper diameter were selected around 25 pots were filled with 3 kg soil along with 1:1 compost. The pots were placed in a randomized complete block design (RCBD) in greenhouse to maintain the day and night temperature 24°C and 15°C, respectively. Two cherry tomato varieties, Red Pearl and Purple Beauty, which had received the highest and the lowest scores in comprehensive assessment of 14 varieties, were used as experimental plants (Malhi et al. 2026) and nominated to evaluate the growth under four CK/0, T₁/25, T₂/50 and T₃/100 mg/kg Cr treatment in the first two days before sowing the Cr treatments were obtained by dissolving 2.83 g K₂Cr₂O₇ was into 1000 mL of deionized water.

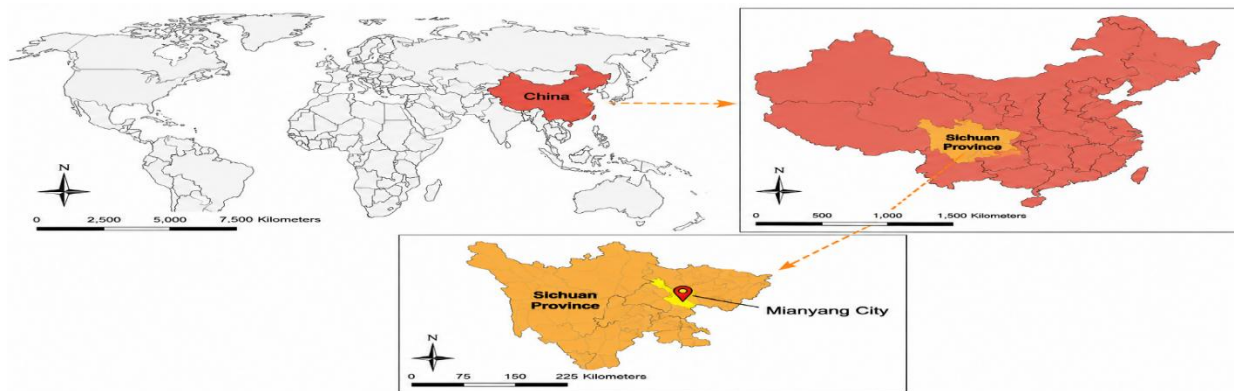


Fig. 1 Picture shows the sample collection from Mianyang City, Sichuan Province China.

Table 1. Physico-chemical properties of the background soil

Properties	Determined Value	Properties	Determined Value
Sand (%)			1.4 ± 0.052
Silt (%)			23.9 ± 0.56
Clay (%)			74.7 ± 0.84
pH			6.0 ± 0.06
Texture class			Silty Clay
Electrical Conductivity (mS m ⁻¹)			0.71± 0.28
Total Carbon (%)			0.132± 0.002
Nitrogen (%)			0.057 ±0.002
Sulfur (%)			0.003 ±0
Total Chromium (mg/kg)			0.0104±0

2.2. Determination of Growth Indicator (shoots, roots, leaves and Fruits)

Thirty sterilized seeds were sown 2~3 cm deep in each pot, with five replication per group. Ten uniform seedlings were selected and transplanted into plastic pots, with similar amount of water applied on each treatment and each pot 250 ml every day. To keep the same environmental condition the conventional water and fertilizer management was followed with different Cr concentrations solution with same volume to keep the plants growing. After the 90 days of sowing and 60 days of transplanting the tomato plants were separated into four parts, i.e. Leaves, shoots, roots and fruits, while roots were completely cleaned with water, and sucked the water out using

filter paper. Direct measurement indicators included the number of leaves and fruits, leaf area, length of shoots and roots, fresh weight of leaves, shoots, roots and fruits (Böhm 1979). Leaves from various places on the tomato plants were collected and leaf area was measured using a grip counting technique and represented in square centimeters (cm²) (Ram et al. 2019). Similarly, root morphological parameters including root surface area, root volume, root diameter, and the quantity of root tips were examined with EPSON scanner with WinRHIZO software by the method described by (Liu et al. 2016).

2.3. Determination of Catalyst (CAT), Ascorbate peroxidase (APX) activity and Malondialdehyde and Ascorbic acid content

After 70 days of sowing leaves, shoots were collected from the third or fourth branch from the top of the tomato plant downward, the enzyme activity, such as CAT activity was assessed in accordance with Hadwan's method (Hadwan and Abed 2016), and Ascorbate peroxidase (APX) activity were assessed using Nakano's method (Nakano and Asada 1981). Malondialdehyde (MDA) content of tissues (leaf, shoot and root) were determined using the method reported by. Singh et al. (2020). Fresh leaf, shoot, and root samples (about 0.3 g each) were used for determination. Ascorbic acid content was estimated referee to Mukherjee's method (Mukherjee and Choudhuri 1983).

2.4. Determination of Chromium Content, Bioaccumulation and Translocation Factor

In plant samples (leaves, shoot, and roots) Cr concentration were evaluated using acid digestion technique reported by Diwan et al. (2012). The Cr accumulation in the plant's roots, shoots, and leaves was determined using the method described by (Farid et al. 2017). The bioaccumulation (BAF) and translocation factor (TF) of the metal assessed to evaluate the phytoremediation abilities of the plant (Amin et al. 2019). Following calculation were used to calculate BAF and TF.

$$BAF = (Cr_{leaf} + Cr_{shoot}) / Cr_{soil}$$

$$TF = (Cr_{leaf} + Cr_{shoot}) / Cr_{soil}$$

2.5. Statistical Analysis

Data were analyzed using SPSS version 23 and GraphPad Prism version 9.0. Means $\pm$ standard deviation (SD) was calculated. One-way ANOVA was used to compare multiple treatment groups, with Tukey's LSD test for post-hoc analysis. Student's t-test was applied for comparisons between control and treatment groups, with significance set at $p < 0.05$.

3. Results

3.1. Cr concentration on Root surface area, volume, diameter and number of tips of Tomato cultivars

In the pot experiment, Cr treatments significantly decreased root growth parameters in both tomato varieties of Red Pearl and Purple Beauty. As Cr concentration increased with reductions in root surface area, root volume, root diameter, and numbers of root tip were observed in Red Pearl and Purple Beauty (**Fig. 2**). The root surface area of both tomato cultivars decreased progressively with increasing Cr concentration. At the control 0 mg/kg Cr, Red Pearl exhibited the highest (567.2 cm²) root surface area, while Purple Beauty showed a significantly lower (383.5 cm²). As Cr concentration increased, both varieties experienced a reduction in root surface area, with greatest reduction were observed at 100 mg/kg. Despite the decline, Red Pearl maintained a significantly larger root surface area than Purple Beauty at all Cr level, indicating better root development and greater tolerance to Cr stress (**Fig. 2a**).

Moreover, the (**Fig. 2b**) illustrates the effect of Cr concentration on the root volume of both tomato cultivars. Root volume of both Red Pearl and Purple Beauty decline with increasing Cr concentration. Under the control condition the highest root volume was recorded (6.4 cm³) in Red Pearl, whereas Purple Beauty showed a lower value (4.2 cm³). Increasing Cr stress gradually reduced the root volume, reaching the lowest values at 100 mg/kg. Although reduction was observed at both cultivars, Red Pearl consistently maintaining a higher root volume compare to Purple Beauty across all Cr concentrations, which suggest comparatively better preservation of root growth under Cr stress. The average root diameter of both tomato cultivars significantly decreased as increasing Cr concentration. The highest root diameter (54.8 mm) was observed at Red Pearl, while Purple Beauty had a diameter of about 53.9 mm under control condition. At the highest concentration (100 mg/kg), Red Pearl root diameter reduced to approximately 19.2 mm, while Purple Beauty showed an average diameter of 19.1 mm. The results indicated a concentration-dependent reduction in root diameter for both varieties, with Red Pearl consistently exhibiting a larger root diameter than Purple Beauty at all concentrations (**Fig. 2c**).

As shown in (**Fig. 2d**), at 0 mg/kg Cr, Red Pearl exhibited approximately 10100 root tips, while Purple Beauty had around 4904.7 root tips. As the Cr concentration increased, both varieties showed a marked significant reduction in the number of root tips, while the lowest numbers observed at 100 mg/kg in both cultivars. The results also showed that Red Pearl consistently showed more root tips than Purple Beauty at all Cr levels, indicating that its root branching ability was less affected by Cr toxicity and contributing to is greater tolerance.

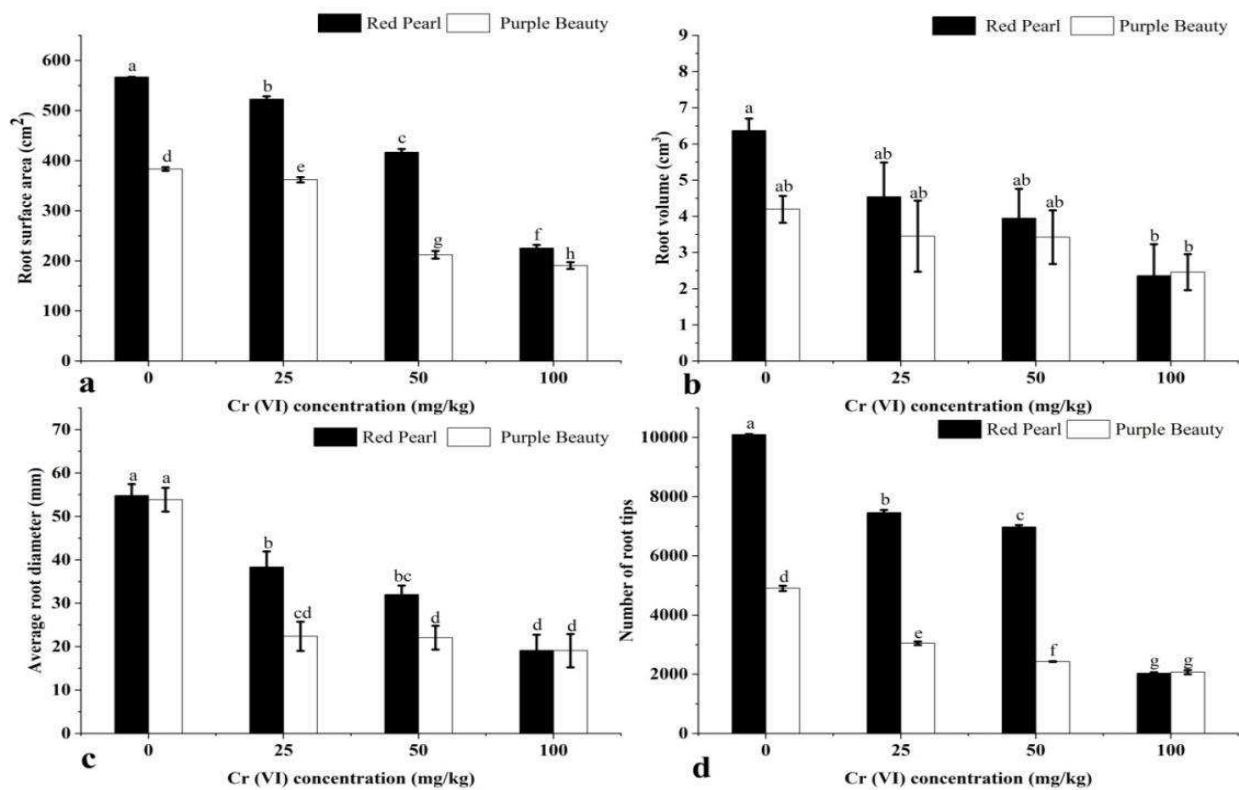


Fig. 2 Influence of Cr on root surface area (a), root volume (b), average root diameter (c), and number of root tips (d). Values are average $\pm$ SD (n=3); Bars with dissimilar letters among Cr treatments are significantly different at $p < 0.05$ from LSD test

3.2. Effect of Cr concentration on Number of Fruits, Fresh and Dry weight of Fruits of Tomato cultivars

As Cr concentrations increased, both tomato varieties exhibited a decline in the number of fruits, fresh and dry weight of fruit in Red Pearl and Purple Beauty as compare with control (**Fig. 3**). The effect of Cr on number of fruits significantly decreased with increasing of Cr in Red Pearl and Purple Beauty as compared with control (**Fig. 3a**). The highest number of fruits were recorded under control (36 fruits/plant) in Red Pearl, followed by Purple Beauty (28 fruits/plants). Increasing Cr concentration significantly reduced the number of fruits/plants of both tomato cultivars, while the lowest value was observed at 100 mg/kg Cr. Across all the treatment the Red Pearl consistently produced more fruits (13.7 fruits/plant) than Purple Beauty (9.3 fruits/plants). The fresh weight of fruits significantly decreased with increased Cr concentration in both tomato varieties to the compared with control, as showed in (**Fig. 3b**). At control, Red Pearl had the highest fruit fresh weight at 543.8 g, while Purple Beauty weight 420.7 g. As Cr levels increased, both varieties showed a decline in fresh weight. At 100 mg/kg, the lowest weights were recorded, with Red Pearl at 308.9 g and Purple Beauty at 218.8 g, indicating a concentration-dependent reduction

in fruit fresh weight. Similarly, in (Fig. 3c), the fruit dry weight showed a consistent decline. At control, Red Pearl had about 46.4 g, and Purple Beauty 43.8 g. At 100 mg/kg, Red Pearl was 23.5 g, and Purple Beauty had the lowest dry weight at 21.1 g. These results reveal a concentration-dependent decrease in both fresh and dry weights, with Red Pearl consistently outperforming Purple Beauty at all levels.

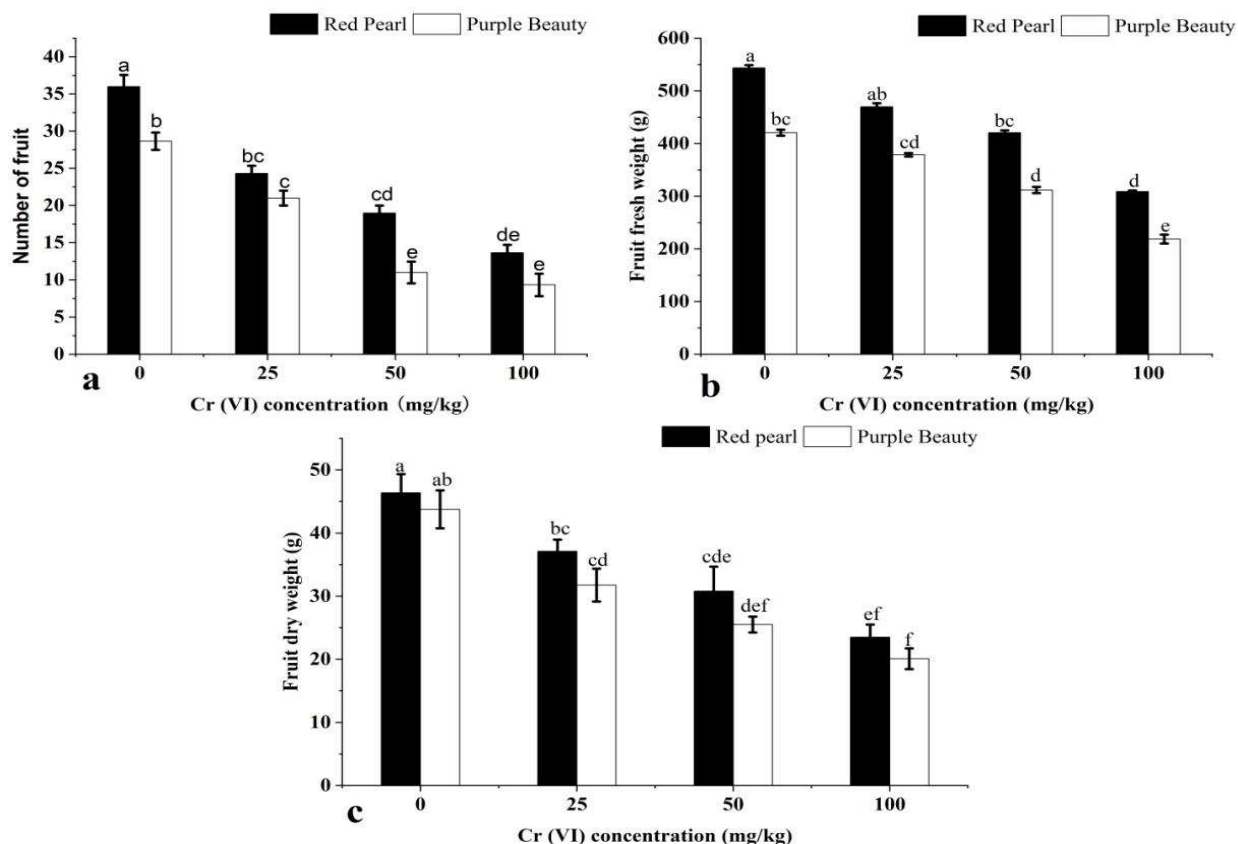


Fig. 3 Influence of Cr on number of fruit (a), fruit fresh weight (b), and fruit dry weight (c). Values are average $\pm$ SD (n=3); Bars with dissimilar letters among Cr treatments are significantly different at $p < 0.05$ from LSD test

3.3. Cr concentrations effect on Catalase (CAT) activity in Leaf, Shoot and Root of Tomato cultivars

The CAT activity of two tomatoes cultivars under Cr stress in pot experiment is shown in (Fig. 4). When tomato varieties were exposed to Cr, increased CAT activity in Red Pearl leaves, shoots and roots was observed in all Cr concentrations. Increasing Cr concentration up to 50 mg/kg the CAT activity in leaves increased, which highlight the antioxidant defense system activation in response to Cr induced oxidative stress. Under the control the CAT activity of leave in Red Pearl increased from 8 U/g to 48 U/g at 50 mg/kg, followed by piercing decline at 100 mg/kg. Whereas in Purple Beauty leave CAT activity showed a significant increased from 50.3% at 100 mg/kg as compared with control (Fig. 4a). In the shoot, CAT activity showed an increasing trend with increasing Cr

concentration up to 50 mg/kg in both tomato cultivars. Red Pearl showed the highest CAT activity in shoot up to 6.8 U/g at 50 mg/kg compare to control, followed by a sharp decreased around 31.6% at 100 mg/kg. On the other hand, Purple Beauty showed an increased throughout all the treatments, with highest CAT activity of shoot were observed (6.5 U/g) at 100 mg/kg (**Fig. 4b**). In root CAT activity showed a significant increased with increase Cr concentration in both tomato cultivars. The highest CAT activity in root was observed (13 U/g) in Red Pearl, followed by (10 U/g) in Purple Beauty at 100 mg/kg Cr, whereas the lowest were recorded at control, the results indicate that Red Pearl exhibited higher CAT activity than Purple Beauty, representing a stronger antioxidant response in roots under Cr stress (**Fig. 4c**).

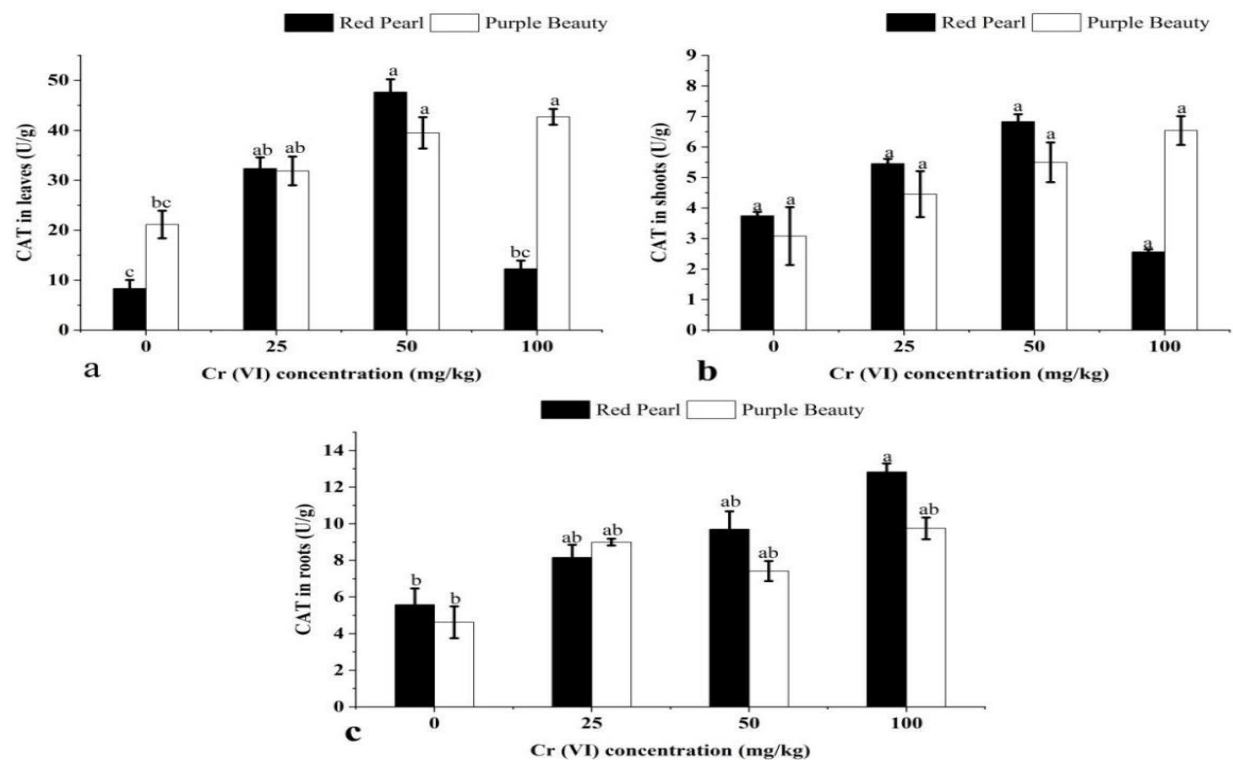


Fig. 4 Influence of Cr on CAT activity in leaf (a), shoot (b), and root (c). Values are average $\pm$ SD (n=3); Bars with dissimilar letters among Cr treatments are significantly different at $p < 0.05$ from LSD test

3.4. Effect of Cr concentration on Ascorbate peroxidase (APX) of Tomato cultivars

The APX activity in leaves, shoots and roots significantly increased in both tomato cultivars and recorded in (**Fig. 5**) after the effect of Cr stress. The APX activity in leaves of Red Pearl exhibited higher (43 U/g) than Purple Beauty (19 U/g) under the control condition. The Cr significantly increased the APX activity in leaf with highest (76 U/g and 35 U/g) were observed at 100 mg/kg in both Red Pearl and Purple Beauty respectively showed increase of around 42% compare with control (**Fig. 5a**). Similar, increase of APX activity in shoots were also observed in both tomato

cultivars. The highest APX activity in shoots were (27 U/g to 14 U/g) was recorded at 100 mg/kg in both Red Pearl and Purple Beauty respectively. Similarly, the lowest APX activity of shoots was (10 U/g and 8 U/g) were observed under the control condition the in both Red Pearl and Purple Beauty respectively (**Fig. 5b**). Increasing Cr concentration significantly increasing the APX activity root in both cultivars. Cr exposure caused a gradual increase in APX activity root, with highest (24 U/g in Red Pearl and 22 U/g Purple Beauty) values observed at 100 mg/kg. Although both cultivars exhibited enhanced APX activity under stress, Red Pearl generally maintained higher enzyme activity than Purple Beauty across the treatments (**Fig. 5c**).

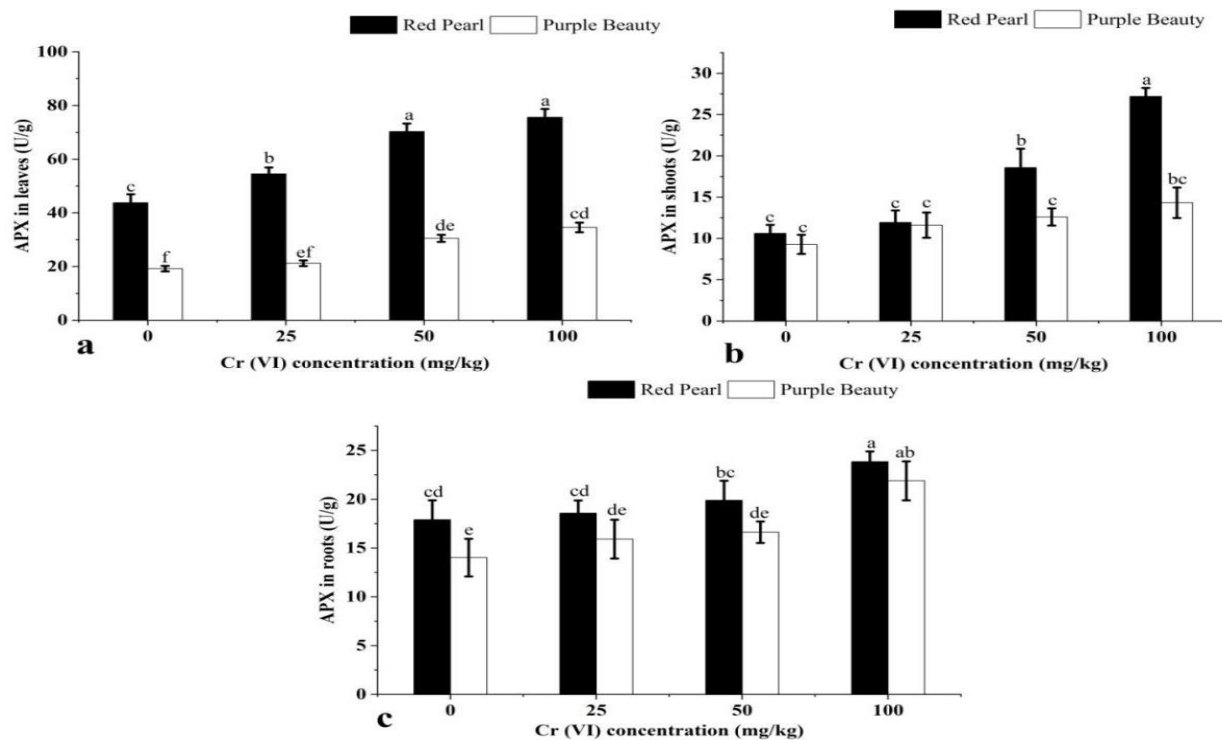


Fig. 5 Influence of Cr on APX activity in leaf (a), shoot (b), root (c). Values are average $\pm$ SD (n=3); Bars with dissimilar letters among Cr treatments are significantly different at $p < 0.05$ from LSD test

3.5. Effect of Cr concentration on Malondialdehyde (MDA) content in Leaves, Shoot and Root of Tomato cultivars

Increasing Cr concentration significantly increasing the MDA content of leaf, shoot and roots (**Fig. 6**). The Cr concentration significantly affected the MDA leaf content in both tomato cultivars; compare with control the MDA content were decline at 25 mg/kg in Red Pearl cultivar, and a gradual decreased (26.6%) was observed at 50 mg/kg and 100 mg/kg. Similarly, in Purple Beauty increasing Cr concentration progressively increasing the MDA content in leaves, the highest increase (47.4%) was recorded at 100 mg/kg (**Fig. 6a**). A similar, increased was also observed in

MDA content of shoots of both cultivars, where the highest value (26 $\mu\text{mol.mg}$) in Red Pearl and (22 $\mu\text{mol/mg}$) in Purple Beauty (**Fig. 6b**). Meanwhile, the root MDA content significantly increased, as the Cr concentration increased. The lowest MDA content was recorded under control and highest 100 mg/kg. Red Pearl consistently showed higher (20 to 40 $\mu\text{mol/mg}$) root MDA content than Purple Beauty (16 to 26 $\mu\text{mol/mg}$). The continues increase in root MDA reflects enhanced lipid peroxidation due to Cr accumulation in root tissues (**Fig. 6c**).

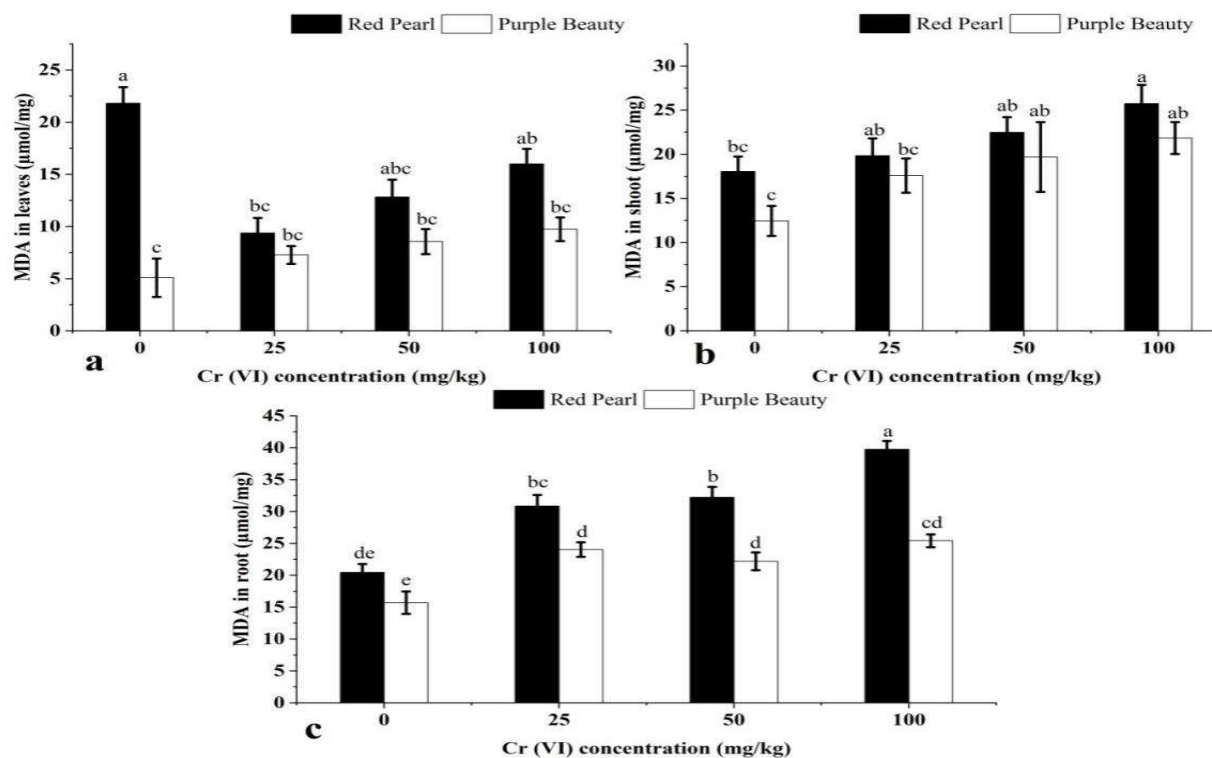


Fig. 6 Influence of Cr on MDA content in leaf (a), shoot (b), and root (c). Values are average $\pm$ SD (n=3); Bars with dissimilar letters among Cr treatments are significantly different at $p < 0.05$ from LSD test

3.6. Ascorbic Acid (ASC) content in Leaves, Shoot and Roots of Tomato cultivars

The analysis of ascorbic acid (ASC) content in leaves, shoots, and roots under varying Cr concentrations revealed significant differences between the two cultivars, Red Pearl and Purple Beauty, indicating variations in their response to Cr stress (**Fig. 7**). In the leaves, Red Pearl consistently exhibits significantly higher ASC content than Purple Beauty across all Cr concentrations. Whereas, Purple Beauty showed lower 15 mg/g throughout the Cr concentrations, Red Pearl consistently maintained significantly higher ASC content than Purple Beauty (**Fig. 7a**). The trend in shoot ASC content mirrored that of the leaves, with Red Pearl showing significantly higher ASC levels than Purple Beauty across all Cr concentrations, similarly, Red Pearl exhibited

higher ASC content than Purple Beauty, with highest values recorded at 100 mg/kg, indicating a stronger antioxidant response under Cr stress (**Fig. 7b**). In the roots, Red Pearl consistently exhibited much higher ASC content compared to Purple Beauty, particularly at higher Cr concentrations (50 and 100 mg/kg). The disparity in ASC levels between the two varieties became more marked as Cr concentration increases, with statistical significance at $p < 0.01$ for the higher concentrations and $p < 0.05$ for the lower ones. This pattern suggested that Red Pearl had a stronger root-based defense mechanism against Cr stress (**Fig. 7c**).

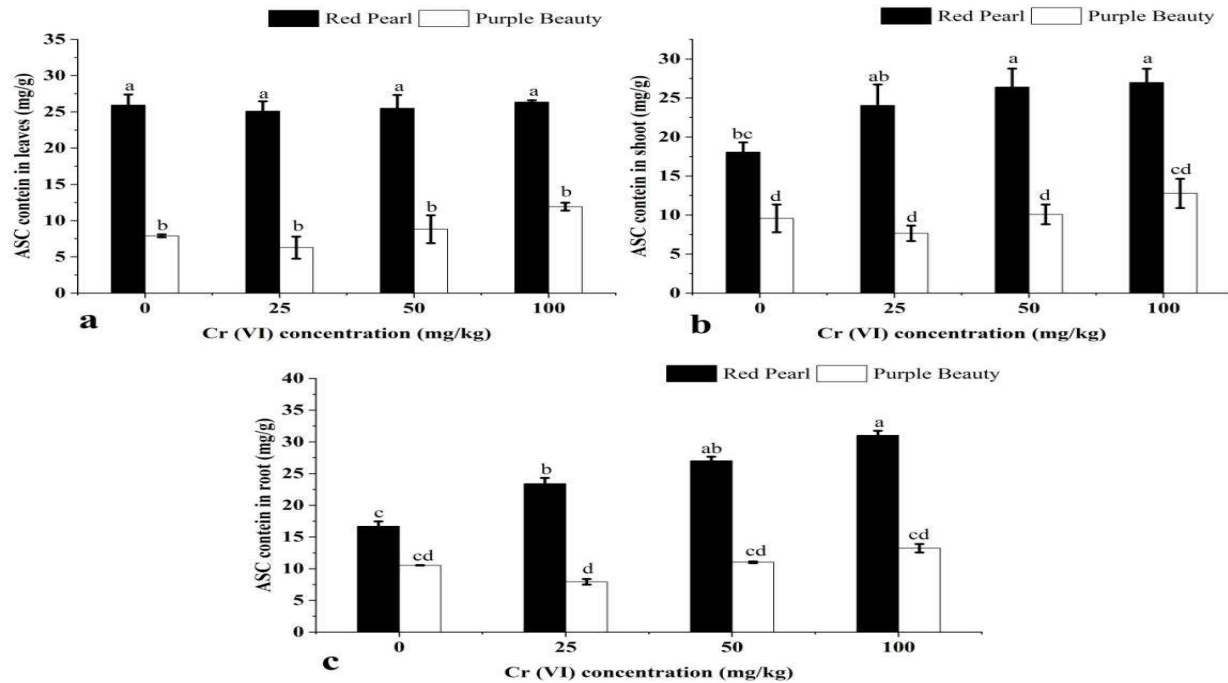


Fig. 7 Influence of Cr on ASC content in leaf (a), shoot (b), and root (c). Values are average $\pm$ SD ($n=3$); Bars with dissimilar letters among Cr treatments are significantly different at $p < 0.05$ from LSD test

3.7. Translocation Factor of Cr

The translocation factor (TF) was calculated for displaying the translocation Cr from roots to leaves and shoots of the plant (**Fig. 8**). The results showed that although there was a difference in the absolute value of the transfer factor, due to experimental errors, there was no significant difference between the two varieties in the control and three Cr concentration treatments.

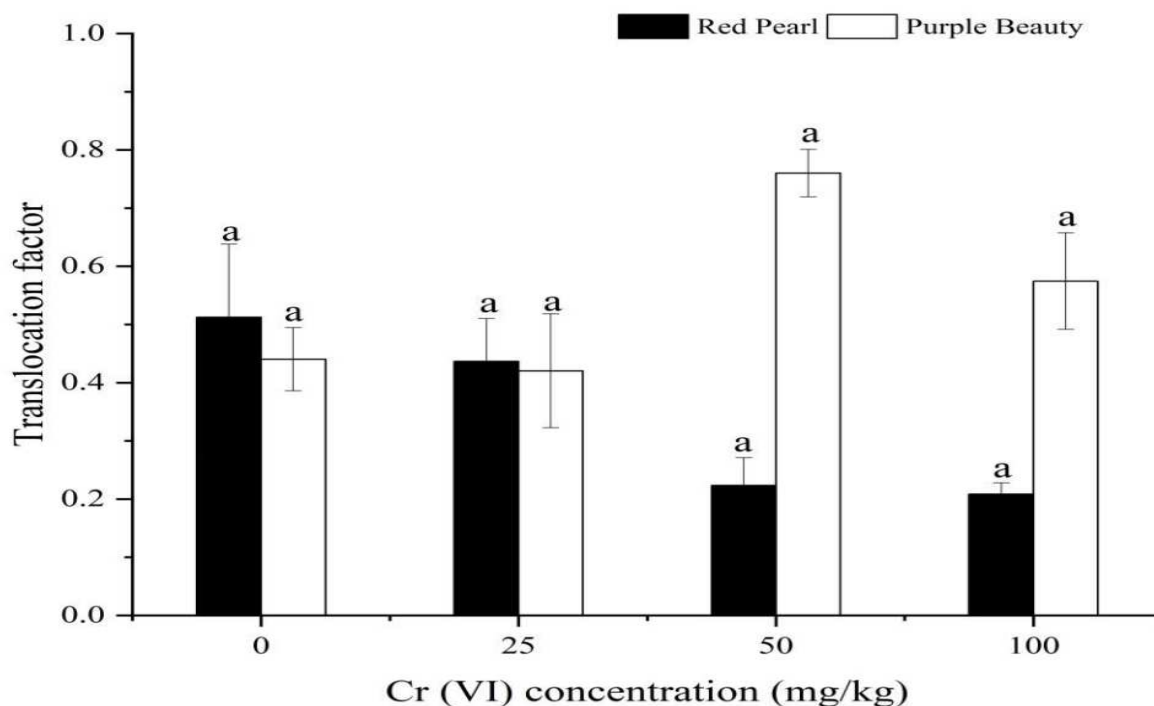


Fig. 8 Translocation factor of two tomatoes at different Cr concentration treatments. Values are average $\pm$ SD (n=3); Bars with different letters among Cr treatments are significantly different at $p < 0.05$ from LSD test

3.8. Bioaccumulation factor of Cr

The transfer of Cr from treated soil to the plant was estimated with the bioaccumulation factor (BAF) to evaluate the phytoremediation capability of tomato (**Fig. 9**). The BAF values of Red Pearl and Purple Beauty were > 1 , that indicated they all had good absorption capacity for Cr. Under three Cr concentration treatments of 25, 50 and 100 mg/g, the BAF of variety Red Pearl was 14.5, 40.9, and 30.5, respectively, all significantly higher than those of variety Purple Beauty at 8.6, 7.5, and 5.9.

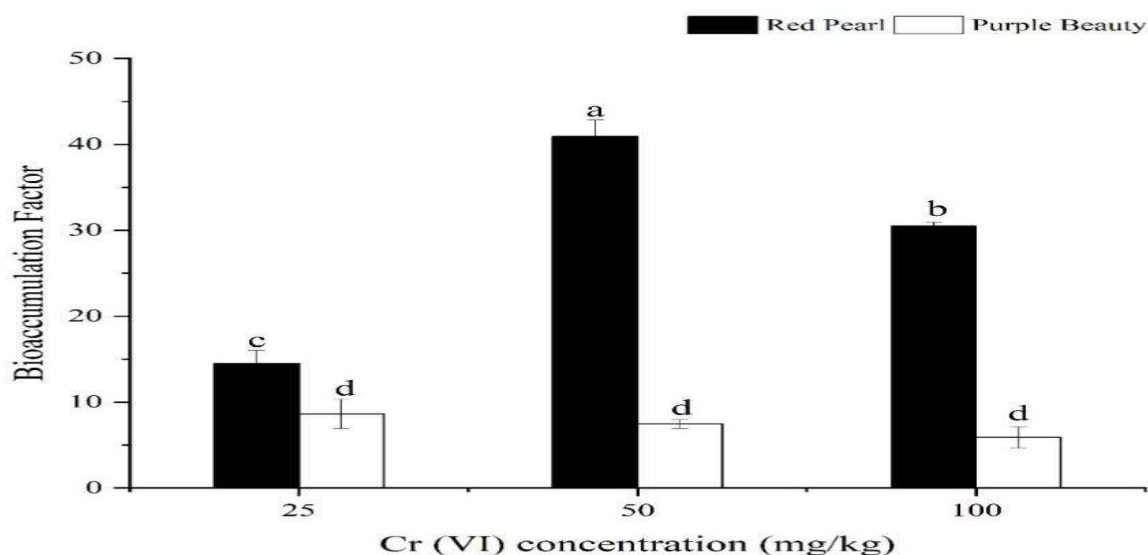


Fig. 9 Bioaccumulation factor of two tomatoes at three Cr concentration treatments. Values are average $\pm$ SD (n=3); Bars with different letters among Cr treatments are significantly different at $p < 0.05$ from LSD test

3.8. Accumulation of Cr in leave, roots and shoots of tomato cultivars

Cr accumulation in tomato plants leaves, roots and shoots was presented in (Table 2). Cr accumulation increased significantly with increasing soil Cr concentration in both tomato cultivars. Under control conditions, Cr concentrations were low in all tissues. At 25 mg/kg Cr accumulation increased slightly, whereas, a marked increase was observed at 50 and 100 mg/kg. The highest Cr concentration was recorded in the roots, particularly in Red Pearl (28.34 $\mu\text{g/g}$) at 50 mg/kg. Red Pearl consistently accumulated more Cr than Purple Beauty in most tissue. Overall, Cr accumulation followed the order roots>shoots>leaves, indicating that roots were the primary site of Cr sequestration.

Table 2. Accumulation of Cr in tomato leaves, shoots and roots

Soil Cr. Con mg/kg	Accumulated Cr Concentration ($\mu\text{g/g}$)			
	Tomato Cultivars	Leaves	Shoots	Roots
0	Red Pearl	1.09 $\pm$ 0.5c	2.03 $\pm$ 1.09c	1.31 $\pm$ 0.8c
	Purple Beauty	1.82 $\pm$ 1.0bc	1.32 $\pm$ 0.3c	3.80 $\pm$ 2.3c
25	Red Pearl	2.45 $\pm$ 0.7bc	2.54 $\pm$ 0.2bc	8.93 $\pm$ 2.3bc
	Purple Beauty	3.10 $\pm$ 0.7bc	2.65 $\pm$ 0.5c	7.51 $\pm$ 2.34bc
50	Red Pearl	6.21 $\pm$ 2.5abc	10.62 $\pm$ 5.1abc	28.34 $\pm$ 0.95a
	Purple Beauty	5.52 $\pm$ 3.21ab	3.45 $\pm$ 1.35abc	10.16 $\pm$ 4.5bc
100	Red Pearl	9.42 $\pm$ 7.8abc	10.60 $\pm$ 7.04ab	18.52 $\pm$ 2.5ab
	Purple Beauty	6.18 $\pm$ 1.02a	7.93 $\pm$ 6.7a	11.09 $\pm$ 2.5bc

Values are average $\pm$ (n=5); Data followed with different small letters indicate that the difference among treatments is significant ($p < 0.05$).

4. Discussion

Chromium (Cr) toxicity significantly impaired root development and fruit yield in both tomato cultivars, with the inhibitory effects becoming more severe as Cr concentration increased. Cr stress significantly inhibited root morphological traits, including root surface area, root volume, average root diameter, root tips formations, our results also demonstrate that Cr stress reduced the fruit number, fruit fresh weight, and fruit dry weight in both tomato cultivars in a concentration-dependent manner, the reduction become more pronounced as Cr concentration increased at 100 mg/kg. These adverse effects are mainly attributed to Cr-induced inhibition of cell division, interference with nutrient homeostasis, and reduced photosynthetic efficiency (Christou et al. 2021; Shahid et al., 2022). Similarly, Cr stress resulted in a significant decline in growth parameters for both tomato varieties. Similarly, Ali et al. (2011) reported reductions in root characteristics such as diameter, surface area, number of root tips, and volume in barley with increasing concentrations of aluminum and Cr in the nutrient solution. In a pot experiment, Mamta et al. (2012). found that various concentrations of Cr treatments significantly decreased root parameters, including root tips and root surface area, in rice, tomato, and brinjal seedlings. However, Red Pearl consistently maintained superior root architecture and fruit productivity compared with Purple Beauty, suggesting that this cultivar possesses more efficient physiological and biochemical mechanisms to withstand Cr stress (Christou et al. 2021).

Antioxidant enzyme activities are the most sensitive biochemical indicators for assessing the impact of stress on plants. Moreover, Cr exposure markedly enhanced the activities of CAT and Ascorbate peroxidase (APX), demonstrating activation of antioxidant defense system in response to oxidative stress. CAT activity increased under low to moderate Cr concentrations but declined at the highest Cr level in leaves, and shoots, indicating that excessive Cr may inhibit enzyme activity due to severe oxidative damage. Sheetal et al. (2015) also reported similar results in their study on antioxidant enzymes like CAT which showed significant increases with increasing metal concentration. The study by (Panda and Choudhury 2005) also provided an explanation for the increased production of these enzymes in plants under Cr stress. The previous study observed enzyme activity decrease at higher Cr concentrations, potentially due to severe oxidative stress (Ahmad et al. 2020). In contrast, APX activity increased progressively with increasing Cr concentration in all plant tissues, highlighting its central role in detoxifying hydrogen peroxide through the ascorbate-glutathione cycle. The significantly higher CAT and APX activities observed in Red Pearl compared with Purple Beauty suggest a more efficient enzymatic antioxidant system that effectively scavenges reactive oxygen species (ROS) and protects cellular structures under Cr

stress (Batoool et al. 2024; Ashraf et al., 2023). The reports by other researchers have shown that APX activity decreased with increased metal toxicity in *Brassica juncea* (Mobin and Khan 2007), *B. napus* (Ali et al. 2014), and wheat (*Triticum aestivum*) (Ali et al. 2015). Cr toxic levels in the soil also increased oxidative stress in the roots and leaves of *B. napus* plants, which were overcome by the activities of various antioxidant enzymes, such as CAT, and APX (Zaheer et al. 2020). The research by Patra et al. found that in lemongrass plants, the activity of oxidative inhibitor enzymes significantly increased in roots compared to shoots as Cr concentration in overburden soil rose. However, at higher soil Cr levels, enzyme activity was inhibited in both roots and shoots (Patra et al. 2019).

Malondialdehyde (MDA), an important indicator of membrane lipid peroxidation, generally increased with increasing Cr concentration, particularly in shoots and roots, confirming enhanced oxidative damage caused by Cr-induced ROS production (Shahid et al., 2022). The highest MDA accumulation in roots reflects the fact that roots are the primary site of Cr uptake and accumulation before its translocation to aerial tissues. Increased MDA levels indicate deterioration of membrane integrity, disruption of cellular metabolism, and enhanced lipid peroxidation under heavy metal stress (Shahid et al., 2022; Ashraf et al., 2023). Although Red Pearl exhibited relatively higher MDA levels in some tissues, it simultaneously maintained significant greater CAT and APX activities, suggesting that oxidative stress was accompanied by a stronger antioxidant defense capable of minimizing cellular damage (Batoool et al., 2024; Kour et al., 2024). Similarly, we have notified that a non-enzymatic antioxidant (ASC), enhanced under the Cr stress, mainly in the shoots, representing its connection in preserving cellular redox homeostasis. Red Pearl received the higher ASC content reliably which significantly reveals a above capacity to detoxify ROS and restore oxidized antioxidants through the ascorbate-glutathione cycle. Ascorbic acid functions synergistically with APX to convert hydrogen peroxide into water, thereby protecting membrane stability, chloroplast function, and metabolic processes during heavy metal stress (Al-Huqail et al. 2020). Enhanced ASC accumulation therefore represents an important adaptive mechanism contributing to Cr tolerance in tomato.

Overall, the superior performance of Red Pearl under Cr stress can be attributed its ability to maintain root growth and fruit while activating stronger enzymatic (CAT and APX) and non-enzymatic (ASC) antioxidant defenses. These coordinated responses reduced oxidative damage, preserved membrane integrity, and sustained physiological functions despite increasing Cr

concentrations. Similarly, mechanisms have been recognized as key determinants of Cr tolerance in tomato and other crop species exposed to heavy metal stress (Christou et al. 2021; Ashraf et al., 2023; Batool et al. 2024). Therefore, Red Pearl can be considered a promising Cr tolerant genotype for cultivation in moderately Cr contaminated soils and as valuable germplasm for future breeding programs.

5. Conclusion

The findings of our study prove that the Cr increasing concentrations significantly reduced tomato growth, root development, antioxidant metabolism, and fruit yield with the greatest adverse effects observed at 100 mg/kg. Reducing morphological traits, root development and fruit yield, indicating severe weakening of plant growth and productivity. Similarly, we have obtained that Cr inclusion significantly increased the oxidative stress, elevated malondialdehyde (MDA) accumulation, specifically in roots, confirming reactive force (ROS)-induced blood lipid peroxidation. The results also showed that equally increase in CAT, APX and ASC levels under Cr stress, proving their improvement role in detoxifying ROS and maintaining redox homeostasis in cells. With studying two cultivar Purple Beauty consistently receiving the lower tolerance to Cr than Red Purple. Red Pearl maintained better root morphology, higher fruit yield, stronger antioxidant enzyme activity, and higher ASC accumulation under Cr stress. In addition, Red Pearl accumulate supplementary Cr in the roots, simultaneously exhibiting a higher bioaccumulation rate (BAF) and lower translocation rate (TF), indicating an effective sequestration of Cr in roots tissues and restricted movement to aerial parts. These synchronized physiological and biochemical retorts lessened Cr toxicity and donated to improve growth and productivity under Cr stress. Overall, the findings identify Red Pearl as Cr tolerant cultivar with considerable potential for cultivation in moderately Cr contaminated soils and as valuable germplasm for breeding programs aimed at improving heavy metal tolerance. Future studies should investigate the molecular and genetic mechanisms underlying Cr tolerance and validate these findings under long-term field conditions.

Data Availability Statement: The datasets used in the current study are available from the corresponding author on reasonable request.

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Declaration The authors have declare that they have no conflict of interest.

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