



RESEARCH ARTICLE

Microbial assisted chromium mitigation: Impacts on germination, yield and quality of *Amaranthus*

S Sheeba^{1*}, K Niharika¹, S U Vikraman¹, P Sujatha², B Sivasankari³ & N Anitha¹

¹Department of Soils and Environment, Agricultural College and Research Institute, Madurai 625 104, Tamil Nadu, India

²Department of Economics, Dr. M. S. Swaminathan Agricultural College and Research Institute, Echangottai 613 009, Tamil Nadu, India

³Office of the Dean, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India

*Correspondence email - sheeba.s@tnau.ac.in

Received: 25 June 2025; Accepted: 10 August 2025; Available online: Version 1.0: 10 December 2025

Cite this article: Sheeba S, Niharika K, Vikraman SU, Sujatha P, Sivasankari B, Anitha N. Microbial assisted chromium mitigation: Impacts on germination, yield and quality of *Amaranthus*. Plant Science Today. 2025;12(sp3):01–08. <https://doi.org/10.14719/pst.10244>

Abstract

The disposal of chromium (Cr) rich tannery sludge onto agricultural lands possesses a significant environmental threat. Oxidation of Cr often resulted in yields hexavalent chromium (Cr⁶⁺), a component that is extremely dangerous and cancer-causing. On the other hand, trivalent chromium (Cr³⁺) is considered to be a crucial trace element in human nutrition and is the most stable form of Cr that can be found naturally making it less toxic than hexavalent form. This study employed a pot experiment to evaluate the effects of hexavalent (Cr⁶⁺) and trivalent chromium (Cr³⁺) with and without the influence of microorganisms, on the germination, growth, uptake, biochemical properties and yield of *Amaranthus gangeticus*. Nine chromium concentrations were tested: 0, 50, 100, 150 and 200 mg/kg of Cr⁶⁺ as K₂Cr₂O₇ and 50, 100, 150 and 200 mg/kg of Cr³⁺ as [KCr(SO₄)₂]. These treatments were combined with four microbial treatments: a control (no microbes), *Azospirillum*, phosphate-solubilizing bacteria (PSB) and potassium-releasing bacteria (KRB). The results showed that irrespective forms the increasing chromium concentrations led to a consistent decline in germination, growth and yield parameters. Hexavalent chromium caused a more pronounced reduction in germination percentages compared to Cr³⁺. However, treatments supplemented with KRB exhibited a mitigating effect on Cr toxicity and significantly improved growth and yield parameters.

Keywords: *Amaranthus*; chromium trivalent; phosphorous solubilizing bacteria; potassium releasing bacteria

Introduction

Chromium (Cr) is a non-essential heavy metal that exerts toxic effect on organisms even at low concentration. Due to its widespread industrial applications, Cr has become a major pollutant in various environmental settings. One of the primary sources of Cr contamination is the tanning industry, which significantly contributes to its release into the environment. The oxidation state and solubility of Cr have a significant impact on the risks associated with its environmental impacts. The oxidation states of Cr, which range from 0 to +6, determine its chemical reactivity and consequently, its impacts on environmental and human health.

In nature, chromium is commonly found in two oxidation states: trivalent (+3) and hexavalent (+6). The oxidation of Cr³⁺ can lead to the formation of Cr⁶⁺, which is highly toxic and recognized as a carcinogenic substance. In contrast, Cr³⁺ is regarded as an essential trace element in human nutrition and represents the most stable natural form of chromium, making it considerably less toxic than its hexavalent counterpart. Chromium has detrimental impacts on the physiological functions of the plants, viz. photosynthesis, germination, water relations and mineral nutrition. Chromium exposure has also been linked to metabolic changes in plants, either as a result of direct effects on enzymes or other metabolites or as a result of its capacity to produce reactive

oxygen species that may lead to oxidative stress (1). The selective absorption of certain heavy metals into seeds occurs in the embryo. This was originally implied by the observation that while seeds continued to germinate in the presence of high levels of heavy metals, later seedling development (after the seed coat had broken) was substantially impeded at considerably lower levels of these heavy metals. Compared to whole seeds, isolated embryos were substantially more vulnerable to heavy metals (2).

Metals may have a harmful impact on the embryonic radicle when they are absorbed by the tissues of the embryo, preventing root development after protrusion. The capacity of heavy metals to penetrate physiological barriers, namely seed coverings and enter embryo tissues is what determines how they affect seed germination. This capacity is directly influenced by the structure of the seed coat, which varies across a wide range of plant species, as well as by the physical and chemical characteristics of the metal ions themselves (3).

This investigation was undertaken to study the effects of forms of Cr on the germination process in *Amaranthus* seeds. Seedling roots exposed to Cr⁶⁺ tend to collapse and lose their ability to absorb water. Similarly, an excessive supply of Cr³⁺ can interfere with iron uptake, leading to iron deficiency and disrupting plant water relations. This disturbance ultimately reduces the physiological availability of water, negatively

impacting overall plant health. *Amaranthus* is one of the earliest varieties of food plants. The *Amaranthus* species is a superior source of calcium, potassium, iron, zinc, magnesium and a sizeable amount of carotenes and vitamin C (4). Pharmacological analysis of the seeds and leaf extracts of *Amaranthus* revealed the bioactive chemicals' potency in preventing serious ailments including diabetes, hyperlipidaemia and diarrhoea as well as their antioxidant, anthelmintic, antimalarial, anti-inflammatory and antifungal capabilities (5). *Amaranthus* employ the C4 photosynthetic pathway to provide for sustenance, making the plant easily tolerant of severe environmental circumstances. It is also included in the list of plants with heavy metal resistance and the capacity to clean the environment of dangerous heavy metals (6). The current study focuses on the effect of Cr and plant growth promoting microorganisms on the growth, uptake, yield and biochemical parameters of *Amaranthus*. The findings will contribute to develop eco-friendly strategies for managing Cr contamination in agricultural soils, promoting food safety and environmental sustainability.

Materials and Methods

A pot experiment was conducted using *Amaranthus* variety Thandukeerai CO-2 at the Agricultural College and Research Institute (AC & RI), Madurai during 2022. The experimental soil was sandy clay loam in texture with slightly acidic in pH (5.9) and low in electrical conductivity (EC= 0.24 dS m⁻¹). The Cation Exchange Capacity (CEC) of the soil was 8.64 cmol (p⁺) kg⁻¹. The soil was low in available nitrogen (172 kg ha⁻¹), medium in phosphorus (20 kg ha⁻¹) and medium in potassium (176 kg ha⁻¹) status. The DTPA extractable iron (Fe), manganese (Mn), zinc (Zn) and copper (Cu) contents were recorded as 5.28, 1.38, 5.46 and 1.24 mg kg⁻¹ respectively.

The Pot experiment was laid out in a Factorial Completely Randomized Design (FCRD) with two factors comprising nine treatments, each replicated three times, resulting in a total of 27

Table 1. Factor-1 (Chromium treatments)

T ₁	Control
T ₂	50 mg/L of Cr ⁶⁺ as K ₂ Cr ₂ O ₇
T ₃	100 mg/L of Cr ⁶⁺ as K ₂ Cr ₂ O ₇
T ₄	150 mg/L of Cr ⁶⁺ as K ₂ Cr ₂ O ₇
T ₅	200 mg/L of Cr ⁶⁺ as K ₂ Cr ₂ O ₇
T ₆	50 mg/L of Cr ³⁺ as KCr(SO ₄) ₂
T ₇	100 mg/L of Cr ³⁺ as KCr(SO ₄) ₂
T ₈	150 mg/L of Cr ³⁺ as KCr(SO ₄) ₂
T ₉	200 mg/L of Cr ³⁺ as KCr(SO ₄) ₂

Table 1. Factor-1 (Chromium treatments)

M ₁	Control
M ₂	<i>Azospirillum lipoferum</i>
M ₃	<i>Bacillus megaterium</i> (PSB)
M ₄	<i>Paenibacillus mucilaginosus</i> (KRB)

pots. The treatment details are shown in Table 1 & 2. Sowing was performed on January 2, 2022 and the crop was harvested on February 16, 2022.

Polybags (12" x 12") were used in the study. Each polybag was filled with 15 kg of homogenized red soil. The seeds were thoroughly mixed with sand in a ratio of 1:10 and sown in rows within each pot. Fertilizers were applied as per the recommended

dosage of N at 75 kg ha⁻¹ and K at 25 kg ha⁻¹ using Urea and Muriate of Potash as basal applications. Additionally, vermicompost was incorporated as organic manure at the recommended dose at 12.5 t ha⁻¹. Then irrigate the pot weekly thrice. Thinning was carried out when the plants reached a height of 15 cm, ensuring 10 plants per pot. Fresh leaves were harvested 45 days after sowing (DAS).

Germination percentage

Before the pot culture experiment, the germination test was conducted using a between-paper method. Twenty-five uniformly sized seeds were placed in Petri plates on moistened filter papers and treated with various concentrations (0, 50, 100, 150 and 200 mg L⁻¹) of Cr⁶⁺ and Cr³⁺ in solutions using potassium chromium sulfate [KCr(SO₄)₂] and potassium dichromate [K₂Cr₂O₇]. The plates were kept in a germination room at 25 ± 1 °C and 90 ± 1 % RH, with daily water applications to maintain moisture. After 14 days, normal seedlings were counted and germination percentage was calculated (7).

The number of normal seedlings was counted and germination percentage was computed using the following formula.

Germination percentage =

$$\frac{\text{Total seeds germinated}}{\text{Total number of seeds}} \times 100$$

Growth parameters

The plant height, root length, leaf length and leaf breadth of *Amaranthus* were measured at 15, 30 and 45 DAS.

Yield parameters

The leaf-to-stem ratio (L:S) was recorded from each pot wise are observed. The total yield was recorded as g pot⁻¹ at 45 DAS.

Nutrient content

The analytical methods used to determine various properties in the study are as follows: Nitrogen content was measured using the Kjeldahl digestion and distillation method (8). Phosphorus was determined using the vanadomolybdate yellow color method, which involves tri-acid digestion with a mixture of HNO₃, H₂SO₄ and HClO₄ in 9:2:1 ratio. Potassium levels were assessed using flame photometry with a tri-acid extract (9).

Quality parameters

Vitamin C content was estimated in the laboratory using the 2, 6-dichlorophenol indophenol visual titration method (10) and expressed in milligrams per hundred grams of plant sample.

Total carotenoid content was determined following the previously known method (11). The following equations were used to quantify carotenoids (mg 100 g⁻¹).

Carotenoid (mg 100 g⁻¹) =

$$\frac{\text{Optical density} \times 13.9 \times 10^4 \times 100}{\text{Weight of sample} \times 450 \times 1000}$$

Statistical analysis

The data were statistically analyzed using Agress software compared with the critical difference (CD) test at a 5 % probability level. Non-significant differences were indicated as “NS” (12).

Results

Growth and yield parameter

Germination percentage

The analysis of the data presented in Fig. 1 revealed significant variations in germination percentages across different Cr concentrations. The highest germination percentage, 77.2 % was recorded at 50 mg kg⁻¹ of Cr⁶⁺ (T6). In contrast, the lowest germination percentage, 56.75 % was observed at a concentration

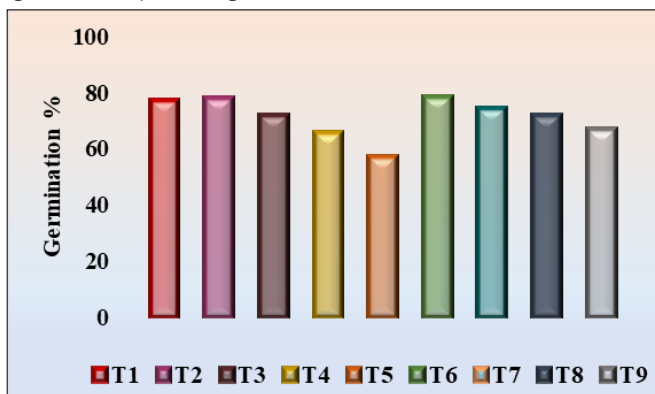


Fig. 1. Germination percentage of *Amaranthus* as influenced by Cr concentrations.

of 200 mg kg⁻¹ of Cr⁶⁺ (T6). The study showed a clear decline in germination percentage as Cr concentrations in the medium increased. Interestingly, the highest germination percentage was observed at 50 mg kg⁻¹ of Cr³⁺, indicating that at lower concentrations (up to 50 mg L⁻¹), Cr exhibited a stimulating effect on seed germination.

Plant height

The effect of Cr and microorganisms on shoot length (cm) of *Amaranthus* is presented in Table 3. The highest plant height was observed in the control (T1), with values of 27.33, 75.87 and 108.46 cm at 15, 30 and 45 DAS, followed by 50 mg kg⁻¹ Cr³⁺ (T6), which recorded 26.96, 74.93 and 108.13 cm. The lowest height (21.15,

Table 3. Effect of Cr and microorganisms on shoot length (cm) of *Amaranthus*

Cr Treatments	Microorganisms			
	Control (M ₁)	<i>Azospirillum</i> (M ₂)	PSB (M ₃)	KRB (M ₄)
T ₁ - Control	50.2	51.8	55.8	57.3
T ₂ - 50 mg/L Cr ⁶⁺	48.5	49.4	51.6	53.2
T ₃ - 100 mg/L Cr ⁶⁺	45.6	48.1	48.4	50.6
T ₄ - 150 mg/L Cr ⁶⁺	40.2	42.8	44.6	45.9
T ₅ - 200 mg/L Cr ⁶⁺	38.9	40.1	42.3	43.2
T ₆ - 50 mg/L Cr ³⁺	49.4	50.4	53.8	55.4
T ₇ - 100 mg/L Cr ³⁺	48.8	52.0	52.5	53.4
T ₈ - 150 mg/L Cr ³⁺	44.2	47.7	48.6	48.9
T ₉ - 200 mg/L Cr ³⁺	41.8	43.4	44.2	45.6
	T	M	TXM	
SE.d	0.485	0.323	0.971	
C.D (5 %)	0.967	0.856	2.568	

63.68 and 97.29 cm) was noted with 200 mg kg⁻¹ Cr⁶⁺ (T5). Among microbial treatments, KRB (M4) showed the maximum plant height (26.39, 72.15 and 105.52 cm), while un-inoculated treatments (M1) recorded the lowest values (23.11, 68.14 and 99.89 cm). In combined treatments, the highest plant height (28.63, 79.61 and 112.43 cm) was achieved with no Cr and *Azospirillum* inoculation (T1M2), whereas the lowest was observed with 200 mg kg⁻¹ Cr⁶⁺ without any microbial inoculation (T5M1).

Root length

A significant difference in the root length was observed due to both Cr as well as microbial inoculant applications (Table 4). The highest root length was recorded in the treatment with 50 mg kg⁻¹ Cr⁶⁺ (T2), measuring 8.07, 15.40 and 24.89 cm at 15, 30 and 45 DAS,

Table 4. Effect of Cr and microorganisms on root length (cm) of *Amaranthus*

Cr Treatments	Microorganisms			
	Control (M ₁)	<i>Azospirillum</i> (M ₂)	PSB (M ₃)	KRB (M ₄)
T ₁	13.5	12.4	14.7	15.3
T ₂	12.3	11.9	13.1	13.6
T ₃	10.8	12.4	12.2	13.4
T ₄	8.2	10.1	10.5	11.2
T ₅	7.6	9.2	10.1	11.3
T ₆	12.9	13.2	14.3	14.9
T ₇	13.1	12.9	14.1	14.1
T ₈	12.2	12.1	13.5	13.8
T ₉	10.6	11.7	11.2	12.7
	T	M	TXM	
SE.d	0.117	0.078	0.234	
C.D (5 %)	0.234	0.156	0.620	

followed by 50 mg kg⁻¹ Cr³⁺ (T6). The lowest root length (6.61, 10.45 and 18.14 cm) was observed in 200 mg kg⁻¹ Cr⁶⁺ (T5). Among microbial inoculants, KRB (M4) resulted in the maximum root length of 7.57, 14.55 and 23.46 cm, while the un-inoculated treatment (M1) showed the minimum. In combined treatments, the maximum root length (8.76, 15.83 and 25.83 cm) was observed with 50 mg kg⁻¹ Cr⁶⁺ and *Azospirillum* (T2M2), whereas the minimum (6.21, 8.52 and 15.24 cm) occurred with 200 mg kg⁻¹ Cr⁶⁺ and no microbial inoculation (T5M1).

Leaf length

The data concerned with leaf length is presented in Table 5. At 15 DAS, the highest leaf length (7.84 cm) was recorded in the control (T1), while the lowest (6.43 cm) was observed with 200 mg kg⁻¹ Cr⁶⁺ (T5). Among the microbial inoculants, KRB (M4) showed the maximum leaf length (7.89 cm). The interaction of Cr and microbial inoculants revealed the highest leaf length (8.56 cm) in *Azospirillum* without chromium (T1M2) and the lowest (5.59 cm) in 200 mg kg⁻¹ Cr⁶⁺ without inoculation (T5M1). At 30 DAS, the maximum leaf length (15.80 cm) was recorded with 50 mg kg⁻¹ Cr³⁺ (T6) and the minimum (14.08 cm) with 200 mg kg⁻¹ Cr⁶⁺ (T5). KRB (M4) resulted in the highest leaf length (15.69 cm), while un-inoculated treatments (M1) showed the lowest (14.29 cm). The combined effects of chromium and microbial inoculants were non-significant. At 45 DAS, the highest leaf length (18.39 cm) was found in the control (T1) and the lowest (16.63 cm) in 200 mg kg⁻¹ Cr⁶⁺ (T5). KRB (M4) had the maximum leaf length, while non-inoculated treatments (M1) recorded the least. Combined effects of chromium and microbial inoculants were non-significant.

Table 5. Effect of Cr and microorganisms on leaf length (cm) of *Amaranthus*

Cr Treatments	Microorganisms			
	M ₁	M ₂	M ₃	M ₄
T ₁	14.3	14.5	14.6	15.2
T ₂	13.7	14.6	14.0	14.5
T ₃	13.5	13.9	13.8	14.9
T ₄	12.9	13.5	13.8	14.3
T ₅	12.2	13.8	13.6	14.2
T ₆	14.5	14.3	14.8	15.3
T ₇	13.8	13.5	14.1	14.6
T ₈	13.1	13.6	13.5	14.9
T ₉	13.5	14.6	14.3	14.7
	T	M	TXM	
SE.d	0.136	0.091	0.273	
C.D (5 %)	0.272	0.181	0.544	

Table 6. Effect of Cr and microorganisms on leaf width (cm) of *Amaranthus*

Cr Treatments	Microorganisms			
	M ₁	M ₂	M ₃	M ₄
T ₁	6.8	7.0	6.9	7.2
T ₂	5.8	6.1	6.5	6.5
T ₃	5.5	5.9	6.2	6.1
T ₄	5.1	5.8	6.3	6.2
T ₅	4.8	5.5	5.7	5.9
T ₆	6.2	6.4	6.4	6.8
T ₇	5.9	6.1	6.4	6.6
T ₈	6.2	5.9	6.1	6.4
T ₉	5.8	5.9	6.0	6.2
	T	M	TXM	
SE.d	0.060	0.040	0.121	
C.D (5 %)	0.120	0.080	0.241	

Leaf breadth

The data related to the effect of Cr concentrations and microbial inoculations on leaf breadth of *Amaranthus* was furnished in Table 6. The highest values were observed in the control (T1) as 5.49, 6.97 and 8.40 cm at 15, 30 and 45 DAS respectively. The second highest values were recorded with 50 mg kg⁻¹ Cr³⁺ (T6), showing 5.45, 6.49 and 8.17 cm. The lowest leaf breadth (4.53, 5.50 and 6.92 cm) occurred with 200 mg kg⁻¹ Cr⁶⁺ (T5). Among microbial inoculations, KRB (M4) produced the highest leaf breadth at all stages, while un-inoculated treatments (M1) had the lowest (4.84, 5.82 and 7.26 cm).

Table 7. Effect of Cr (III) and Cr (VI) on chromium uptake in *Amaranthus*

Cr treatments	15 DAS					30 DAS					45 DAS				
	Microorganisms														
	M ₁	M ₂	M ₃	M ₄	Mean	M ₁	M ₂	M ₃	M ₄	Mean	M ₁	M ₂	M ₃	M ₄	Mean
T ₁	0.35	0.16	0.17	0.15	0.21	5.04	1.39	1.82	1.31	2.39	13.05	2.55	2.85	2.31	5.19
T ₂	10.92	10.02	7.73	9.17	9.46	96.62	88.25	80.11	75.53	85.13	236.03	235.45	245.77	257.55	243.70
T ₃	13.91	14.82	13.96	11.02	13.42	135.36	131.67	106.78	101.86	118.92	295.65	301.26	324.33	262.12	295.84
T ₄	15.66	17.20	17.53	15.84	16.73	146.71	133.08	121.40	106.39	126.89	343.01	314.66	332.31	269.46	314.86
T ₅	19.53	16.56	16.72	17.32	17.53	153.24	136.05	128.65	116.86	133.70	364.05	361.10	338.64	275.75	334.88
T ₆	6.47	6.52	4.89	3.72	5.40	56.05	53.20	48.88	47.84	51.49	124.86	116.10	100.51	97.96	109.85
T ₇	7.58	8.08	7.03	5.42	7.03	72.25	71.49	67.66	56.97	67.09	127.13	124.51	117.28	105.31	118.55
T ₈	8.07	8.13	8.12	7.49	7.95	81.48	79.76	73.73	67.49	75.61	135.26	128.52	121.48	108.73	123.50
T ₉	9.56	10.41	9.07	8.58	9.40	84.99	97.86	90.54	71.82	866.30	148.80	145.19	141.13	124.94	140.01
Mean	10.23	10.21	9.47	8.75	92.41	88.08	79.95	71.78	198.65	192.15	191.59	167.12			
	T	M	T x M		T	M	T x M		T	M	T x M				
SE.d	0.128	0.085	0.256		0.818	0.545	1.636		2.104	1.403	4.209				
C.D. (At 5 %)	0.255	0.170	0.511		1.631	1.087	3.261		4.195	2.797	8.390				

In combined treatments, the highest leaf breadth (5.67, 7.11 and 8.94 cm) was observed in T1M2 (*Azospirillum* inoculation without any Cr), while the lowest was found in T5M1 (200 mg kg⁻¹ Cr⁶⁺ without any microbial inoculation).

Chromium uptake

The data in Table 7 indicated that Cr uptake by *Amaranthus* was significantly influenced by both Cr application and microbial treatments. The highest Cr uptake was observed in plants grown with 200 mg kg⁻¹ Cr⁶⁺ (T5), with values of 17.53, 133.70 and 334.88 g/pot at 15, 30 and 45 DAS respectively. The second-highest uptake was recorded with 150 mg kg⁻¹ Cr⁶⁺ (T4). The control treatment (T1), with no Cr application, showed the lowest Cr uptake, measuring 0.21, 2.39 and 5.19 g/pot at 15, 30 and 45 DAS. Regarding microbial treatments, the un-inoculated treatment (M1) had the highest Cr uptake, with values of 10.23, 92.41 and 198.65 g/pot at 15, 30 and 45 DAS respectively. In contrast, the KRB inoculation (M4) resulted in the lowest Cr uptake, recording 8.75, 71.78 and 167.12 g/pot at these same intervals. The interaction between Cr treatments and microbial inoculations significantly affected Cr uptake. The combination of 200 mg kg⁻¹ as Cr⁶⁺ without any microbial inoculation (T5M1) led to the highest Cr uptake of 19.53, 153.24 and 364.05 g/pot at 15, 30 and 45 DAS respectively. The lowest Cr uptake occurred when KRB inoculation was applied without any Cr treatment (T1M4).

Yield

Leaf/stem ratio

The leaf-to-stem (L:S) ratio is a key yield parameter for leafy crops like *Amaranthus*. Significant differences were observed between Cr treatments, microbial inoculations and their interactions, as shown in Table 8. For Cr treatments, the highest L:S ratio of 0.43 was recorded with 50 mg kg⁻¹ Cr³⁺ (T6), followed by the control (T1) at 0.42. The lowest L:S ratio (0.24) was observed with 200 mg kg⁻¹ Cr⁶⁺ (T5). Among the microbial treatments, KRB inoculation (M4) resulted in the highest L:S ratio of 0.38, while the control (M1) had the lowest (0.32). In the interaction effect, the highest L:S ratio of 0.45 was seen with *Azospirillum* inoculation without chromium (T1M2), while the lowest ratio of 0.21 was recorded with 200 mg kg⁻¹ as Cr⁶⁺ without inoculation (T5M1).

Nutrient content

Nitrogen

The effect of Cr on N, P and K content in *Amaranthus* is presented in Table 9. The N content at harvest was significantly affected by

Table 8. Effect of Cr (III) and Cr (VI) on leaf to stem ratio and yield (g pot⁻¹) of *Amaranthus* as influenced by microorganisms

Cr treatments	Leaf to stem ratio				Yield					
					Microorganisms					
	M ₁	M ₂	M ₃	M ₄	Mean	M ₁	M ₂	M ₃	M ₄	Mean
T ₁	0.40	0.45	0.42	0.43	0.42	164.41	172.73	165.00	174.50	169.16
T ₂	0.34	0.37	0.39	0.42	0.38	116.30	121.70	127.28	132.25	124.38
T ₃	0.30	0.32	0.35	0.37	0.34	95.32	100.51	107.45	111.25	103.63
T ₄	0.25	0.27	0.29	0.31	0.28	79.63	86.25	92.24	97.52	88.91
T ₅	0.21	0.23	0.26	0.28	0.24	52.67	57.30	61.78	66.72	59.62
T ₆	0.41	0.42	0.44	0.45	0.43	151.21	157.21	164.48	168.22	160.28
T ₇	0.37	0.40	0.42	0.43	0.41	129.15	135.06	139.30	146.40	137.48
T ₈	0.32	0.34	0.37	0.39	0.35	110.60	116.50	123.54	127.26	119.47
T ₉	0.26	0.28	0.31	0.34	0.30	84.42	91.40	96.35	98.50	92.67
Mean	0.32	0.34	0.36	0.38		109.30	115.41	119.71	124.73	
	T	M		T x M		T	M		T x M	
SE.d	0.0039	0.0026		0.0079		0.727	0.481		1.433	
C.D. (At 5 %)	0.0079	0.0052		0.0157		1.433	0.956		2.867	

both Cr treatments and microbial inoculations, as well as their interaction. The highest N content (2.98 %) was observed in the control (T₁), followed by 50 mg kg⁻¹ as Cr³⁺ (T₆). The lowest N content (1.54 %) was found in 200 mg kg⁻¹ as Cr⁶⁺ (T₅). The microbial inoculation (KRB) (M₄) had the highest N content (2.54 %), while the lowest (2.02 %) was in the un-inoculated treatment (M₁). The highest N content (3.24 %) occurred with *Azospirillum* inoculation without Cr and the lowest (1.26 %) was with 200 mg kg⁻¹ as Cr⁶⁺ and no microbial inoculation.

Phosphorus

The P content (Table 9) was also significantly influenced by Cr treatments, microbial inoculations and their interaction. The highest P content (0.407 %) was observed in the control (T₁), followed by 50 mg kg⁻¹ as Cr³⁺ (T₆) at 0.384 %. The lowest P content (0.243 %) was in 200 mg kg⁻¹ as Cr⁶⁺ (T₅). KRB (M₄) inoculation resulted in the highest P content (0.361 %), while the un-inoculated treatment (M₁) had the lowest (0.286 %). The highest P content (0.432 %) was found in *Azospirillum* inoculation without Cr (T₁M₂), while the lowest (0.207 %) was in 200 mg kg⁻¹ as Cr⁶⁺ without any inoculation (T₅M₁).

Potassium

The Cr treatments and microbial inoculations had significant influence on K content (Table 9). The highest K content (2.91 %) was in the control (T₁), followed by 50 mg kg⁻¹ as Cr³⁺ (T₆). The lowest K content (1.22 %) was in 200 mg kg⁻¹ Cr⁶⁺ (T₅). The KRB

inoculation (M₄) resulted in the highest K content (2.37 %), while the un-inoculated treatment (M₁) had the lowest (1.79 %). The highest K content (3.15 %) was in *Azospirillum* inoculated treatments without Cr and the lowest (0.83 %) was in 200 mg kg⁻¹ Cr⁶⁺ without any microbial inoculations.

Vitamin C

The vitamin C content of harvested samples is presented in Table 10. The Cr treatments significantly influenced the Vitamin C levels, as it acts as an antioxidant, protecting plant tissues from damage caused by reactive oxygen species during heavy metal stress. Among the Cr treatments, the highest vitamin C content (89.41 mg/100 g) was found with 200 mg kg⁻¹ added as Cr⁶⁺ (T₅), followed by 150 mg kg⁻¹ as Cr⁶⁺ (T₄). The control (T₁) had the lowest vitamin C content of 72.12 mg/100 g. In microbial treatments, the control (M₁) showed the highest vitamin C content of 80.37 mg/100 g, while KRB inoculation (M₄) had the lowest at 78.14 mg/100 g. In the interaction effects, 200 mg kg⁻¹ Cr⁶⁺ without microbial inoculation (T₅M₁) showed the highest vitamin C content of 92.85 mg/100 g, while the lowest (64.38 mg/100 g) was found in the absolute control (T₁M₁).

Carotenoids

Significant differences were observed in carotenoid levels due to the Cr treatments, microbial inoculations and their interactions, as shown in Table 10. The highest carotenoid content (6.14 mg/100 g) was recorded in the control (T₁), followed by 50 mg kg⁻¹ as Cr³⁺ (T₆).

Table 9. Effect of Cr (III) and Cr (VI) on N, P and K content (%) of *Amaranthus* as influenced by microorganisms

Cr treatments	Nitrogen content					Phosphorus content					Potassium content				
						Microorganisms									
	M ₁	M ₂	M ₃	M ₄	Mean	M ₁	M ₂	M ₃	M ₄	Mean	M ₁	M ₂	M ₃	M ₄	Mean
T ₁	2.71	3.24	2.84	3.13	2.98	0.363	0.432	0.408	0.426	0.407	2.60	3.15	2.81	3.08	2.91
T ₂	2.48	2.53	2.70	2.80	2.63	0.315	0.334	0.357	0.384	0.348	2.37	2.50	2.64	2.72	2.56
T ₃	2.08	2.20	2.34	2.54	2.29	0.268	0.296	0.335	0.353	0.313	1.82	2.07	2.16	2.32	2.09
T ₄	1.50	1.62	1.82	2.15	1.77	0.229	0.258	0.286	0.317	0.272	1.30	1.40	1.51	2.05	1.56
T ₅	1.26	1.40	1.67	1.81	1.54	0.207	0.236	0.254	0.275	0.243	0.83	1.17	1.26	1.62	1.22
T ₆	2.51	2.60	2.74	2.90	2.69	0.345	0.395	0.386	0.410	0.384	2.40	2.54	2.66	2.80	2.60
T ₇	2.19	2.47	2.51	2.72	2.47	0.312	0.336	0.362	0.388	0.350	2.08	2.20	2.42	2.65	2.34
T ₈	1.86	2.18	2.20	2.53	2.19	0.285	0.302	0.341	0.364	0.323	1.51	1.70	2.18	2.20	1.90
T ₉	1.64	1.80	2.13	2.25	1.95	0.253	0.276	0.313	0.337	0.295	1.16	1.32	1.66	1.91	1.51
Mean	2.02	2.23	2.33	2.54		0.286	0.318	0.338	0.361		1.79	2.01	2.14	2.37	
	T	M		T x M		T	M		T x M		T	M		T x M	
SE.d	0.021	0.014		0.043		0.0038	0.0025		0.0076		0.020	0.014		0.041	
C.D. (At 5 %)	0.043	0.028		0.085		0.0076	0.0051		0.0152		0.041	0.027		0.082	

Table 10. Effect of Cr (III) and Cr (VI) on vitamin C and carotenoids (mg/100 g) of *Amaranthus* as influenced by microorganisms

Cr treatments	Vitamin C				Carotenoids					
	M ₁	M ₂	M ₃	M ₄	Mean	M ₁	M ₂	M ₃	M ₄	Mean
T ₁	64.38	74.52	73.25	76.32	72.12	5.72	6.41	6.14	6.31	6.14
T ₂	76.46	75.61	74.86	74.65	75.39	5.63	5.76	6.32	6.28	6.00
T ₃	82.35	81.14	80.27	78.67	80.61	4.42	4.94	5.33	5.67	5.09
T ₄	87.63	85.39	82.64	80.41	84.02	3.75	4.05	4.52	5.13	4.36
T ₅	92.85	89.51	88.53	86.76	89.41	3.27	3.73	4.11	4.45	3.89
T ₆	75.24	73.84	74.62	76.72	75.10	5.76	5.87	6.21	6.33	6.04
T ₇	77.74	76.86	76.13	75.58	76.58	5.32	5.51	5.72	6.12	5.67
T ₈	81.46	78.67	77.94	76.32	78.60	4.62	4.67	5.26	5.96	5.13
T ₉	85.10	80.54	79.45	77.87	80.74	4.12	4.53	5.07	5.42	4.79
Mean	80.37	79.56	78.633	78.14	4.73	5.05	5.41	5.74	5.74	5.74
	T	M		T x M	T	M		T x M		
SE.d	0.936	0.624		1.872	0.056	0.037		0.112		
C.D. (At 5 %)	1.866	1.244		3.732	0.112	0.074		0.223		

The lowest carotenoid content (3.89 mg/100 g) was found with 200 mg kg⁻¹ as Cr⁶⁺ (T5). Among microbial inoculations, KRB (M4) showed the highest carotenoid content of 5.74 mg/100 g, while the control (M1) had the lowest at 4.73 mg/100 g. Regarding the interaction effects, the highest carotenoid content (6.41 mg/100 g) was observed with *Azospirillum* inoculation without Cr (T1M2), while the lowest content (3.27 mg/100 g) was found with 200 mg kg⁻¹ as Cr⁶⁺ without any microbial inoculation (T5M1).

Discussion

Growth and yield parameters

The decline in germination percentage at higher chromium (Cr) concentrations can be attributed to the inhibitory effects of Cr species. Germination was higher in trivalent Cr treatments compared to hexavalent Cr, likely due to the rapid absorption of Cr⁶⁺ by the embryo, causing toxicity and inhibiting germination. Chromium exposure may suppress amylase activity, reducing sugar availability for the embryo and hindering germination (13). Additionally, increased protease activity under chromium stress lowered protein levels essential for germination, delaying or preventing it (14). Studies showed Cr³⁺ had minimal impact on germination, but radicle development was severely inhibited upon contact with chromium (15). It was observed that rising Cr levels progressively reduced germination and growth, with the highest Cr content (20 mg kg⁻¹) causing the greatest decline in sunflower seed germination (16).

Plant height

Plant height significantly declined with increasing Cr concentrations, with hexavalent chromium (Cr⁶⁺) exerting a stronger inhibitory effect compared to trivalent chromium (Cr³⁺). This reduction can be attributed to the excessive accumulation of reactive oxygen species (ROS), which disrupt cellular metabolism, impair root development and consequently restrict water and nutrient translocation to the shoots. Similar findings were reported earlier, i.e. suppressed plant height at elevated Cr levels (17-19). In contrast, microbial inoculation, particularly with KRB, alleviated the negative effects of chromium stress. The improvement in plant height under inoculated treatments may be explained by enhanced nutrient availability, improved antioxidant defense and the production of plant growth-promoting hormones, which collectively support shoot elongation (19).

Root length

Root length also declined with increasing Cr concentrations, mainly due to tissue damage and inhibition of lateral root initiation. However, at lower levels (e.g. 50 mg kg⁻¹ Cr⁶⁺), a slight stimulatory effect on root elongation was observed, suggesting a hormetic response of plants to mild stress. The application of beneficial microorganisms mitigated the adverse effects of Cr stress by facilitating the reduction of toxic Cr⁶⁺ to its less harmful form, Cr³⁺, thereby lowering toxicity in the rhizosphere. This microbial activity not only enhanced nutrient solubilization but also promoted root growth and branching. These results are consistent with the previous observations which highlighted the role of microbial inoculants in alleviating heavy metal stress and supporting root system development (20, 21).

Leaf length and breadth

Cr negatively affected leaf development, significantly reducing leaf length and breadth. This reduction was linked to decreased water availability, lower cell volume and nutrient imbalances caused by Cr stress. Other studies similarly reported decreases in leaf area, chlorophyll content and photosynthesis under elevated Cr levels (22, 23). Microbial inoculations alleviated these effects by improving nutrient uptake and mitigating Cr toxicity.

Yield parameters

Chromium significantly reduced the total yield of *Amaranthus*, with yield declining as Cr concentrations increased. It reduced biomass and yield to impaired physiological functions in plants exposed to wastewater (24). Excess Cr disrupted photosynthesis and nutrient absorption, further reducing biomass (25). Hexavalent Cr had a more pronounced effect due to its higher mobility, causing up to a 95 % reduction in biomass at the highest doses (26). Microbial inoculation, however, alleviated Cr toxicity, increasing plant biomass by enhancing nutrient availability and stress tolerance through beneficial plant-bacteria interactions (27).

Nutrient content and uptake

Chromium exposure significantly reduced the N, P and K content in *Amaranthus*, with Cr⁶⁺ showing a more severe impact than Cr³⁺. The highest nutrient levels were recorded in control plants, indicating that chromium toxicity interferes with nutrient uptake and physiological functions. Cr⁶⁺ toxicity arises from its structural similarity to phosphate and sulfate, leading to competitive inhibition of nutrient transport pathways, reduced translocation and impaired root function. Additionally, chromium disrupts metabolic processes, including enzyme activities, chlorophyll biosynthesis and photosynthesis, further limiting nutrient

assimilation. Oxidative stress caused by Cr-induced ROS aggravates these effects, damaging cellular integrity and nutrient transport systems (28-30).

Microbial inoculations counteracted chromium toxicity by enhancing N, P and K uptake and restoring physiological balance. Plant growth-promoting microorganisms (PGPMs) stimulated root growth through hormone secretion (IAA and ACC deaminase), increasing soil exploration and nutrient acquisition. They also solubilized nutrients like phosphorus, potassium and immobilized heavy metals, reducing their bioavailability. Furthermore, PGPMs mitigated oxidative stress by enhancing antioxidant enzyme activities, stabilizing cellular metabolism under Cr stress (31, 32).

These findings highlight the dual impact of chromium on nutrient content and metabolic health in *Amaranthus* and the potential of microbial inoculations to improve nutrient uptake, alleviate oxidative stress and support plant growth in chromium contaminated soils.

Chromium uptake

The study revealed that chromium uptake in *Amaranthus* increased with rising soil Cr concentrations, with hexavalent chromium (Cr^{6+}) being absorbed more efficiently than trivalent chromium (Cr^{3+}). The highest uptake was recorded at 200 mg kg⁻¹ Cr^{6+} . This difference can be explained by the uptake mechanisms: Cr^{6+} enters actively through phosphate and sulfate transporters, whereas Cr^{3+} is taken up passively and tends to become immobilized through electrostatic interactions.

Application of microbial inoculants, particularly KRB, significantly reduced Cr uptake by facilitating the conversion of bioavailable Cr^{6+} into its less mobile and less toxic form, Cr^{3+} . These results are consistent with the observations of [33, 34], who reported that microbial enzymes and extracellular reduction mechanisms play a central role in decreasing Cr bioavailability in soils.

Quality parameters

Vitamin C (ascorbic acid) content increased with higher Cr concentrations as plants respond to Cr-induced oxidative stress by producing antioxidants to mitigate ROS damage. Secondary metabolites like ascorbic acid, flavonoids and phenolics enhance metal toxicity resistance, prevent membrane deformation and aid in signal transmission (35). In *S. oleracea*, non-enzymatic antioxidants such as phenolics and anthocyanins increased at Cr levels up to 50 μM , but higher concentrations (100 μM) caused significant changes.

Carotenoid content in *Amaranthus* tissues decreased with rising Cr levels, likely due to ROS-induced chloroplast damage and disrupted electron transfer during redox reactions. Cr stress negatively impacts chlorophyll, carotenoids and photosynthetic processes like CO_2 fixation and enzyme activity (36). Reduced carotenoids, which protect chlorophyll from photooxidative degradation, are detrimental to plant health (37).

Conclusion

Chromium contamination severely affected the germination, growth, nutrient uptake, yield and quality of *Amaranthus gangeticus*, with hexavalent chromium (Cr^{6+}) proving more toxic than trivalent chromium (Cr^{3+}). Increasing concentrations of chromium consistently reduced germination percentage, plant

height, root length, leaf development and overall biomass production. The higher solubility and active absorption of Cr^{6+} through phosphate and sulfate transporters aggravated its harmful effects on plant metabolism. Microbial inoculations, particularly with KRB, effectively mitigated chromium toxicity by enhancing nutrient solubilization, promoting root growth and reducing Cr bioavailability. These microbes converted Cr^{6+} into the less toxic Cr^{3+} form, thereby lowering its uptake and accumulation in plant tissues. As a result, inoculated plants showed higher nitrogen, phosphorus and potassium content compared to uninoculated ones. Quality analysis revealed that vitamin C levels increased under chromium stress due to enhanced antioxidant defense, while carotenoid levels declined as a result of oxidative damage to chloroplasts. However, microbial inoculation helped maintain better carotenoid levels by alleviating oxidative stress. The combined influence of microbes and reduced chromium toxicity contributed to improved growth, nutrient status and yield performance. Overall, microbial-assisted chromium mitigation emerges as an eco-friendly approach to sustain crop productivity and nutritional quality in chromium-polluted soils.

Authors' contributions

SS write the manuscript, KN and SUV organise the data and tables. PS and BS coordinated the manuscript corrections and contributed to the statistical analysis. NA coordinated the correction of the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

- Shanker AK, Cervantes C, Loza-Tavera H, Avudainayagam S. Chromium toxicity in plants. *Environ Int.* 2005;31(5):739-53. <https://doi.org/10.1016/j.envint.2005.02.003>
- Li W, Khan MA, Yamaguchi S, Kamiya Y. Effects of heavy metals on seed germination and early seedling growth of *Arabidopsis thaliana*. *Plant growth Regul.* 2005;46(1):45-50. <https://doi.org/10.1007/s10725-005-6324-2>
- Seregin I, Kozhevnikova A. Distribution of cadmium, lead, nickel and strontium in imbibing maize caryopses. *Russ J Plant Physiol.* 2005;52(4):565-69. <https://doi.org/10.1007/s11183-005-0084-8>
- Steyn N, Olivier J, Winter P, Burger S, Nesamvuni C. A survey of wild, green, leafy vegetables and their potential in combating micronutrient deficiencies in rural populations: Research in action. *S Afr J Sci.* 2001;97(7):276-78. <https://hdl.handle.net/10520/EJC97355>
- Idris OA, Wintola OA, Afolayan AJ. Phytochemical and antioxidant activities of *Rumex crispus* L. in treatment of gastrointestinal helminths in Eastern Cape Province, South Africa. *Asian Pac J Trop Biomed.* 2017;7(12):1071-78. <https://doi.org/10.1016/j.apjtb.2017.10.008>
- Vara Prasad MN, de Oliveira Freitas HM. Metal hyperaccumulation in plants: biodiversity prospecting for phytoremediation technology. *Electron J biotechnol.* 2003;6(3):285-321. <https://doi.org/10.2225/vol6-issue3-fulltext-6>
- Qi Y, Li J, Fu G, Zhao C, Guan X, Yan B, et al. Effects of sublethal

- herbicides on offspring germination and seedling growth: Redroot pigweed (*Amaranthus retroflexus*) vs. velvetleaf (*Abutilon theophrasti*). *Sci Total Environ*. 2018;645:543-49.
8. Jackson WA, Flesher D, Hageman RH. Nitrate uptake by dark-grown corn seedlings: some characteristics of apparent induction. *Plant Physiol*. 1973;51(1):120-27. <https://doi.org/10.1104/pp.51.1.120>
 9. Piper J. Diffusion of hydrogen in copper-palladium alloys. *J Appl Phys*. 1966;37(2):715-21. <https://doi.org/10.1063/1.1708243>
 10. AOAC. Methods of analysis. Association of official Agricultural Chemists. Washington D. (USA). 1962.
 11. Ranganna S. Handbook of analysis and quality control for fruit and vegetable products. Tata McGraw-Hill Education. 1986.
 12. Gomez KA, Gomez AA. Statistical procedures for agricultural research. John Wiley & sons. New York. 1984. <https://tinyurl.com/2hmb5pb5>
 13. Shahid M, Shamshad S, Rafiq M, Khalid S, Bibi I, Niazi NK, et al. Chromium speciation, bioavailability, uptake, toxicity and detoxification in soil-plant system: A review. *Chemosphere*. 2017;178:513-33. <https://doi.org/10.1016/j.chemosphere.2017.03.074>
 14. Jahan S, Iqbal S, Jabeen K, Sadaf S. Ameliorating influence of sulfur on germination attributes of Canola (*Brassica napus* L.) under chromium stress. *Pak J Bot*. 2015;47(2):407-11. [http://www.pakbs.org/pjbot/PDFs/47\(2\)/03.pdf](http://www.pakbs.org/pjbot/PDFs/47(2)/03.pdf)
 15. Chow Y, Lee L, Zakaria N, Foo K. Phytotoxic effects of trivalent chromium-enriched water irrigation in *Vigna unguiculata* seedling. *J Clean Prod*. 2018;202:101-08. <https://doi.org/10.1016/j.jclepro.2018.07.144>
 16. Farid M, Ali S, Akram NA, Rizwan M, Abbas F, Bukhari SAH, et al. Phyto-management of Cr-contaminated soils by sunflower hybrids: physiological and biochemical response and metal extractability under Cr stress. *Environ Sci Pollut Res*. 2017;24(20):16845-59. <https://doi.org/10.1007/s11356-017-9247-3>
 17. Gupta K, Jain V, Bhardwaj S. Effect of chromium (VI) on growth and lipid components in developing seeds of *Brassica juncea*. *Indian J Plant Physiol*. 2005;10(3):241.
 18. Coelho LC, Bastos ARR, Pinho PJ, Souza GA, Carvalho JG, Coelho VA, et al. Marigold (*Tagetes erecta*): The potential value in the phytoremediation of chromium. *Pedosphere*. 2017;27(3):559-68. [https://doi.org/10.1016/S1002-0160\(17\)60351-5](https://doi.org/10.1016/S1002-0160(17)60351-5)
 19. Han H, Lee K. Phosphate and potassium solubilizing bacteria effect on mineral uptake, soil availability and growth of eggplant. *Res J Agric Biol Sci*. 2005;1(2):176-80. <https://tinyurl.com/5xb7ha8d>
 20. Zong H, Liu J, Wang F, Song N. Root morphological response of six peanut cultivars to chromium (VI) toxicity. *Environ Sci Pollut Res*. 2020;27(15):18403-11. <https://doi.org/10.1007/s11356-020-08188-3>
 21. Bahadur A, Afzal A, Ahmad R, Nasir F, Khan A, Suthar V, et al. Influence of metal-resistant Rhizobacteria on the growth of *Helianthus annuus* L. in Cr (VI)-contaminated soil. *Water Air Soil Pollut*. 2016;227(12):1-8. <https://doi.org/10.1007/s11270-016-3174-7>
 22. Hussain I, Saleem MH, Mumtaz S, Rasheed R, Ashraf MA, Maqsood F, et al. Choline chloride mediates chromium tolerance in spinach (*Spinacia oleracea* L.) by restricting its uptake in relation to morpho-physio-biochemical attributes. *J Plant Growth Regul*. 2022;41(4):1594-614. <https://doi.org/10.1007/s00344-021-10401-7>
 23. Devi P, Kumar P. Effect of bioremediation on internodal length and leaf area of maize plant cultivated in contaminated soil with chromium metal. *J Pharm Phytochem*. 2020;9(4):1408-13. <https://tinyurl.com/y3yt6rcj>
 24. Saeed-ur-Rehman K, Abdul W, Tareen RB, Kakar SA, Marriam T, Kayani SA. Impact of municipal waste water of Quetta city on biomass, physiology and yield of canola (*Brassica napus* L.). *Pak J Bot*. 2010;42(1):317-28. [http://www.pakbs.org/pjbot/PDFs/42\(1\)/PJB42\(1\)317.pdf](http://www.pakbs.org/pjbot/PDFs/42(1)/PJB42(1)317.pdf)
 25. Rendina A, Barros JM, Fabrizio de Iorio A. Changes in the speciation, partitioning and phytoavailability of chromium induced by organic soil amendments. *Chem Speciat Bioavail*. 2011;23(1):53-60. <https://doi.org/10.3184/095422911X12971977268431>
 26. Wyszowski M, Radziemska M. Effects of chromium (III and VI) on spring barley and maize biomass yield and content of nitrogenous compounds. *J Toxicol Environ Health A*. 2010;73(17-18):1274-82. <https://doi.org/10.1080/15287394.2010.492016>
 27. Babu AG, Shea PJ, Sudhakar D, Jung I-B, Oh B-T. Potential use of *Pseudomonas koreensis* AGB-1 in association with *Miscanthus sinensis* to remediate heavy metal (loid)-contaminated mining site soil. *J environ manage*. 2015;151:160-66. <https://doi.org/10.1016/j.jenvman.2014.12.045>
 28. Ghani A, Hussain M, Ikram M, Yaqoob M, Shaukat R, Munawar A, et al. Effect of chromium toxicity on the growth and mineral composition of brown mustard (*Brassica juncea* L.). *World Wide J Multidiscip Res Dev*. 2017;3(10):36-38.
 29. Yassen A, Nadia BM, Zaghloul M. Role of some organic residues as tools for reducing heavy metals hazards in plant. *World J Agric Sci*. 2007;3(2):204-07. <http://www.idosi.org/wjas/wjas.htm>
 30. Ali S, Zeng F, Qiu L, Zhang G. The effect of chromium and aluminum on growth, root morphology, photosynthetic parameters and transpiration of the two barley cultivars. *Biol Plant*. 2011;55(2):291-96. <https://doi.org/10.1007/s10535-011-0041-7>
 31. Etesami H, Alikhani HA. Co-inoculation with endophytic and rhizosphere bacteria allows reduced application rates of N-fertilizer for rice plant. *Rhizosphere*. 2016;2:5-12. <https://doi.org/10.1016/j.rhisph.2016.09.003>
 32. Khan MS, Zaidi A, Wani PA. Role of phosphate solubilizing microorganisms in sustainable agriculture-A review. *Sustain Agric*. 2009;551-70. https://doi.org/10.1007/978-90-481-2666-8_34
 33. Patra RC, Malik S, Beer M, Megharaj M, Naidu R. Molecular characterization of chromium (VI) reducing potential in Gram positive bacteria isolated from contaminated sites. *Soil Biol Biochem*. 2010;42(10):1857-63. <https://doi.org/10.1016/j.soilbio.2010.07.005>
 34. Thatoi H, Das S, Mishra J, Rath BP, Das N. Bacterial chromate reductase, a potential enzyme for bioremediation of hexavalent chromium: A review. *J Environ Manage*. 2014;146:383-99. <https://doi.org/10.1016/j.jenvman.2014.07.014>
 35. Javed MT, Saleem MH, Aslam S, Rehman M, Iqbal N, Begum R, et al. Elucidating silicon-mediated distinct morpho-physio-biochemical attributes and organic acid exudation patterns of cadmium stressed Ajwain (*Trachyspermum ammi* L.). *Plant Physiol Biochem*. 2020;157:23-37. <https://doi.org/10.1016/j.plaphy.2020.10.010>
 36. Ahmad R, Ali S, Rizwan M, Dawood M, Farid M, Hussain A, et al. Hydrogen sulfide alleviates chromium stress on cauliflower by restricting its uptake and enhancing antioxidative system. *Physiol Plant*. 2020;168(2):289-300. <https://doi.org/10.1111/ppl.13001>
 37. Gill RA, Zang L, Ali B, Farooq MA, Cui P, Yang S, et al. Chromium-induced physio-chemical and ultrastructural changes in four cultivars of *Brassica napus* L. *Chemosphere*. 2015;120:154-64. <https://doi.org/10.1016/j.chemosphere.2014.06.029>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited,