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RESEARCH ARTICLE

Toxicity of chromium to wheat (*Triticum aestivum* L.) in two soils: influence of soil properties and chromium form

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Abstract

The toxicity of Cr to plants depends on Cr form and soil properties. Currently, the phytotoxicity differences of Cr(VI) and Cr(III) in different soils are not clear. In this study, the toxicity of Cr(VI) and Cr(III) to root growth and root morphology of wheat (*Triticum aestivum* L.) were compared in Shandong fluvo-aquic soil (SD soil) and Jiangxi red soil (JX soil) that is differing in soil properties. The toxicity thresholds of Cr(VI) and Cr(III) on wheat root elongation were determined by fitting the dose-effect curves. Results showed that the 10% and 50% root length inhibitory concentrations (EC_{10} and EC_{50}) of Cr(III) were 53.1 and 125 times of Cr(VI) in SD soil and 8.11 and 1.36 times of Cr(VI) in JX soil, indicating that Cr(VI) was more toxic to wheat roots than Cr(III) in both soils and the toxicity discrepancy of the two forms of Cr was more prominent in SD soil. Cr(VI) exhibited higher toxicity in SD soil (alkaline) than in JX soil (acidic), whereas Cr(III) showed the opposite pattern. In addition, the ethylene diamine tetraacetic acid extractable Cr (EDTA-Cr) concentrations in soils were correlated well with the relative wheat root elongation (R^2=0.854, P<0.01), indicating that soil EDTA-Cr concentration can be used as a predictor of Cr phytotoxicity. Both Cr(VI) and Cr(III) showed significant biphasic dose effects on wheat root morphology (root length, root surface area, root volume, and root tip number) in JX soil. These findings are helpful for the risk evaluation of Cr contamination in agricultural soils.

Keywords Cr(VI) · Cr(III) · Toxicity threshold · Dose-effect curve · Root morphology

Introduction

Chromium (Cr) is one of the most common contaminants in the soil environment. Industries such as metallurgy, tannery, and electroplating are the major anthropogenic sources of Cr in soils (Kapoor et al. 2022). Cr has various oxidation states (+2–+6), among which Cr(VI) and Cr(III) are the most common and stable oxidation states in the natural environment (Wei et al. 2020). Compared with Cr(III), Cr(VI) is more mobile and toxic in soils (Kapoor et al. 2022). Excessive Cr in soil will destroy the normal metabolism and physiological functions of plants such as interfering with photosynthesis and plant absorption of nutrients, inhibition on seed germination, and root growth (Gao et al. 2021; Sardar et al. 2022).

Root is the first plant organ that senses soil Cr, typically responding to Cr-exposure by changing root growth and development (Wakeel et al. 2018). Depending on its concentration in the medium, plant species, duration of exposure, and so on, Cr may exhibit inhibition or stimulating effect on root growth (López-Bucio et al. 2022). High doses of Cr usually induce negative effects on root growth and development by inhibiting cell division, elongation, and differentiation (López-Bucio et al. 2022; Wakeel and Xu 2020), Whereas mild Cr stress may play a beneficial or stimulating role, increasing root meristem division, inducing the formation of adventitious root and twin roots (López-Bucio et al. 2022; Ruiz-Aguilar et al. 2020). This biphasic dose-response is called hormesis or hormetic response (Sonmez et al. 2023), which has been observed in several studies. For example, Ma et al. (2021) found that low concentrations of Cr(VI) (≤4 mg/kg) stimulated barley root elongation in brown soil and fluvo-aquic soil, with maximum relative root length of 130% and 123%, respectively; however, the roots hardly grew at Cr(VI) concentration of 64 mg/kg. Hormesis was also observed for Cr(III). Ding et al. (2014) found that

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carrot root length was significantly increased to 107–174% of the control at Cr(III) concentrations ≤150 mg/kg in paddy soil, red soil, and black soil, but was decreased at concentrations ≥ 200 mg/kg. In addition, the Cr-induced hormesis effect is also dependent on plant species. In the fluvo-aquic soil, the relative root elongation of monocotyledon (corn) was increased by 94% and 67%, respectively, at Cr(VI) concentrations of 5 mg/kg and 20 mg/kg, but was inhibited significantly at 50–300 mg/kg of Cr(VI), whereas no hormesis was observed for dicotyledonous plants (cucumber, cabbage, and lettuce) (Hou et al. 2014). López-Luna et al. (2009) found that hormesis effect was only observed for wheat among the three studied plant species (wheat, oat, and sorghum); the wheat shoot length was increased about 23% when treated with 50 mg/kg Cr(VI), but decreased by 60% at 500 mg/kg of Cr(VI).

The toxicity of Cr to plant roots is influenced by the combination of Cr form and soil physicochemical properties. The ability of plant roots to absorb Cr is primarily determined by the form of Cr in the soil, and the ways of Cr(VI) and Cr(III) uptake by plant root epidermal cells are different (Dazy et al. 2008). Cr(VI) is actively absorbed into plant roots by sulfate or phosphate carriers (De Oliveira et al. 2016), whereas Cr(III) enters plant via cation exchange sites on cell wall or is taken up by plant root cells via the same carriers or ion channels for Fe, Ca, Mg, and K (Singh et al. 2013; Xu et al. 2021). The phytotoxicity of Cr varies with its form. Dong et al. (2016) found that 25 mg/kg Cr(VI) treatment decreased the root vigor of ryegrass and petunia by 54.4% and 58.5%, respectively, whereas Cr(III) treatments at concentrations <250 mg/kg significantly increased the plant height, root length, and biomass ($P<0.05$). In addition, the phytotoxicity of Cr depends on soil physicochemical properties. Yang et al. (2022) found that Cr(VI) toxicity to wheat root growth was highly dependent on soil pH, organic matter, clay content, cation exchange capacity (CEC), and amorphous iron oxides. Similarly, Xiao et al. (2013a, 2013b) investigated Cr accumulation in rice and cabbage in three agricultural soils and discovered that the phytoavailability of Cr(VI) was strongly correlated with soil organic matter, ferrous iron content, and soil particle composition. Further, Ding et al. (2014) found that soil pH was one of the most significant variables affecting the toxicity of Cr(III) to carrot roots. As can be seen from the above description, many studies have been done on the phytotoxicity of both Cr(VI) and Cr(III). However, comparisons on the toxicity of Cr(VI) and Cr(III) to plant roots in different soils are scarcely conducted.

Wheat is a food crop widely grown globally, with an annual planted area of >220 million hectares (Shiferaw et al. 2013). China is one of the largest wheat producers in the world, accounting for about 18% of global wheat production (Zhang et al. 2022). Ensuring wheat safe production is of great significance for food security in China. Therefore, in this study wheat was selected as the test plant to conduct root elongation experiment with the objectives of (1) comparing the effects of Cr(VI) and Cr(III) to root length and root morphology in soils, (2) determining the 10% (EC_{10}) and 50% (EC_{50}) inhibitory effect concentrations of Cr(VI) and Cr(III) with root elongation and plant height as toxicity evaluation endpoints, and (3) examining the effects of soil properties on the toxicity of Cr(VI) and Cr(III) to wheat.

Materials and methods

Soil sampling and property determination

Soil samples, namely, Shandong fluvo-aquic soil (SD soil) and Jiangxi red soil (JX soil), were taken from the surface layer (0–20 cm) of agricultural fields in Shandong and Jiangxi provinces of China. The soil samples were air-dried, sieved (2 mm), and then stored at room temperature before use. Soil pH was determined in a suspension extracted using 0.01 mol/L $CaCl_2$ at a solid-liquid ratio of 1:2.5. Soil organic matter content was determined using the potassium dichromate volumetric method. Soil CEC was determined using the ammonium acetate exchange method (Yang et al. 2022). Soil textures were determined using Bouyoucos hydrometer (Bouyoucos 1962). Soil amorphous Fe and Al were extracted with ammonium oxalate solution and measured by an UV-Vis spectrophotometer (UV-6100, Shanghai Yuanxi Instrument Co. Ltd., China). Total Cr in soil was digested with nitric acid-perchloric acid-hydrofluoric acid mixture (15:2:2, v/v) (Lu 1999) and determined by an atomic absorption spectrophotometry (AAS-990, Shimazu, Japan). Cr(VI) in soil was extracted according to alkaline digestion procedure (USEPA method 3060A) and then determined using the above-mentioned atomic absorption spectrophotometry. The concentration of Cr(III) in soil was determined by the difference between total Cr and Cr(VI). Soil available Cr was extracted using 0.05 mol/L ethylenediaminetetraacetic acid disodium salt (EDTA-Na_2) and determined by an inductively coupled plasma-mass spectrometry (ICP-MS, ICAPAQ, Thermo Fisher Scientific, USA).

Soil spiking and aging

Cr(VI) was added to soils as K_2CrO_4 solution to obtain final concentrations of 0.5, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, and 1024 mg/kg. For Cr(III) treatments, $CrCl_3$ solution was added to soils to obtain the same concentrations as for Cr(VI). There are three replicates for each treatment, and the treatment without Cr(VI) and Cr(III) addition was used as control. For each treatment, soil was aged for 3 months with moisture maintained at 70% of field water holding capacity. Then the soils were air-dried, ground, passed through a 2

mm nylon sieve, and packed into culture tubes (4.5 cm in diameter and 15 cm in height), each containing 220 g of soil.

Wheat root elongation experiment

Wheat (*Triticum aestivum* L.) root elongation experiments were carried out according to ISO 11269-1 using Jimai 22 (seeds obtained from Shandong Academy of Agricultural Sciences) as the test wheat variety. Seeds with uniform size and fullness were selected, soaked in 2% hydrogen peroxide solution for sterilization, and then rinsed repeatedly with deionized water to remove the residual hydrogen peroxide solution on the surface. The sterilized seeds were placed in a Petri dish lined with a water-soaked filter paper and then placed in an artificial climate incubator (25±0.1°C) for 48 h for germination. Eight germinated seeds were planted in each culture tube and placed in an artificial climate incubator under controlled conditions (light intensity of 4000 lx for 14 h light/10 h dark, temperature 25/20°C at day/night, and a relative humidity of 70±5%). After 10 days of incubation, the wheat plants were removed from the culture tubes. The wheat roots were rinsed with deionized water, and the above-ground plant height and the length of the primary root of each wheat plant were measured and recorded separately.

Fresh root systems were scanned using an automated root scanner (Epson Expression 10000XL 1.0, Epson Electronics Inc., USA). The root imaging analysis software WinRhico™ 2000 was used to examine the wheat roots for morphological characteristics. Soil in each culture tube was mixed and sampled, freeze-dried, and ground through a 2 mm sieve. Then EDTA extractable Cr (EDTA-Cr) was determined.

Statistics and data analysis

The relative root elongation (Y, %) was calculated according to Equation 1.

$$Y = \frac{I}{I_0} \tag{1}$$

where I is the root length of Cr(VI)/Cr(III) treatments and I_0 is the root length of the control.

The log-logistic distribution model (Equation 2) was used to fit the wheat length and plant height data to obtain dose-effect relationship curves, from which EC_{10} and EC_{50} values were calculated.

$$Y = \frac{Y_0}{1 + e^{(b(X-M))}} \tag{2}$$

where X is $\log_{10}$ (added Cr concentration); Y_0, M, and b are fitting parameters; and M is $\log_{10}$ (EC_{50}). Since a value of 0 cannot be log-transformed, a relatively low level (0.01 mg/kg) was assigned for a soil Cr addition of 0.

Data processing and correlation analysis were performed using SPSS software (version 22.0). One-way ANOVA was used to test for significant differences ($P<0.05$) in EDTA-Cr concentrations and wheat root morphology data among different treatments.

Results

Soil physicochemical properties

The original physicochemical properties of the two test soils before Cr spiking and wheat planting were very different (Table 1). The pH of SD soil was 8.24, which was alkaline, while that of JX soil was 4.91, which was acidic. Compared with SD soil, the CEC and contents of clay, organic matter, amorphous iron, and amorphous aluminum were much higher in JX soil, being 2.59, 7.22, 1.26, 9.86, and 7.31 times those of SD soil, respectively. The total Cr contents were 49.35 mg/kg in SD soil and 83.07 mg/kg in JX soil, neither of which exceeded the Cr screening value specified in the Soil Contamination Risk Control Standards for Agricultural Land (GB15618-2018).

EDTA-Cr concentrations in soils

The EDTA-Cr concentrations in SD soil and JX soil are shown in Table 2. The EDTA-Cr concentrations in both soils increased with increasing Cr addition. In SD soil, the EDTA-Cr concentrations were significantly higher ($P<0.05$) than the control when treated with Cr(VI) and Cr(III) at concentrations greater than or equal to 16 mg/kg and 64 mg/kg, respectively, whereas in JX soil, the critical concentrations for Cr(VI) and Cr(III) treatments that resulted in significant

Table 1 Physiochemical properties of soils before Cr spiking and wheat planting

Soil properties	SD[a]	JX[b]
pH	8.24 ± 0.11	4.91 ± 0.03
Organic matter (g/kg)	8.04 ± 0.15	10.1 ± 0.15
CEC[c] (cmol/kg)	9.30 ± 0.35	24.1 ± 0.57
Sand (%)	62.8 ± 2.92	19.7 ± 0.68
Silt (%)	31.8 ± 2.48	41.7 ± 5.60
Clay (%)	5.34 ± 0.45	38.6 ± 4.92
Amorphous Fe (g/kg)	0.35 ± 0.16	3.45 ± 0.84
Amorphous Al (g/kg)	0.29 ± 0.01	2.12 ± 0.23
Total Cr (mg/kg)	49.4 ± 0.01	83.1 ± 0.02

[a]Shandong fluvo-aquic soil

[b]Jiangxi red soil

[c]Cation exchange capacity

Table 2 EDTA-Cr concentrations in soils

Added Cr(III)/Cr(VI) concentration (mg/kg)	SD soil		JX soil	
	Cr(III) treatment	Cr(VI) treatment	Cr(III) treatment	Cr(VI) treatment
0	0.15±0.01eA	0.15±0.02fA	1.32±0.01fA	1.01±0.24gB
0.5	0.14±0.01eB	0.20±0.02fA	1.87±0.06fA	1.08±0.02gB
1	0.14±0.00eB	0.29±0.02fA	1.58±0.02fA	1.24±0.08gB
2	0.11±0.08eB	0.62±0.08fA	1.87±0.19fA	1.48±0.03gB
4	0.20±0.02eB	0.65±0.02fA	1.97±0.10fA	1.58±0.03gB
8	0.14±0.10eB	3.26±0.27efA	2.14±0.23fB	2.52±0.24gA
16	0.24±0.04deB	7.19±0.72deA	2.53±0.12fA	2.40±0.3gA
32	0.52±0.01deB	7.76±1.91deA	2.56±0.10fB	4.45±0.13fA
64	0.75±0.05dB	9.62±0.34deA	5.73±0.49eB	6.46±0.18eA
128	1.31±0.09cB	13.55±0.04dA	8.80±0.41dA	8.30±0.43dB
256	1.39±0.09cB	65.01±3.20cA	12.89±0.63cA	11.56±0.57cB
512	2.66±0.08bB	148.17±5.81bA	24.89±0.18bB	26.57±0.78bA
1024	5.68±0.61aB	277.79±10.53aA	55.94±0.10aB	108.63±2.28aA

Different lowercase letters in the same column indicate significant difference in soil EDTA-Cr concentration among different concentrations of Cr(III)/Cr(VI) treatments ($P<0.05$). Different uppercase letters in the same line indicate significant difference in soil EDTA-Cr concentration between Cr(III) and Cr(VI) treatments for the same soil ($P<0.05$)

difference from the control were 32 mg/kg and 64 mg/kg, respectively ($P<0.05$).

At the same concentrations of Cr(VI) treatment, the EDTA-Cr concentrations in SD soil were 1.29–5.62 times those in JX soil, whereas for Cr(III) treatments, the EDTA-Cr concentrations in JX soil were 1.93–9.85 times those in SD soil. These results indicate that Cr(III) showed higher availability in JX soil than in SD soil, while Cr(VI) showed the opposite pattern.

The availability of Cr(VI) and Cr(III) differed greatly in both soils. The EDTA-Cr concentrations of Cr(VI) treatments were 1.42–55.7 and 1.1–2.1 times those of Cr(III) treatments in SD soil and JX soil, respectively. This indicates that Cr(VI) showed higher availability than Cr(III) in both soils, and the availability discrepancy between the two forms of Cr was much greater in SD soil than in JX soil.

Toxicity threshold of Cr to wheat root growth

The dose-effect curves based on the root length and plant height data of wheat are shown in Fig. 1. The relative root elongation of wheat decreased with increasing added concentrations of Cr(VI) and Cr(III). Significant inhibition ($P<0.05$) on wheat root elongation was observed at concentrations greater than or equal to 16 mg/kg and 256 mg/kg (with relative root elongation of 27.2% and 82.6%), respectively, for Cr(VI) and Cr(III) treatments in SD soil, whereas in JX soil, the critical concentrations for Cr(VI) and Cr(III) were 64 mg/kg and 512 mg/kg (with relative root elongation of 77.4% and 12.2%), respectively. This indicates that Cr(VI) inhibited wheat root growth at much lower concentrations than Cr(III).

Results showed that both Cr(VI) and Cr(III) stimulated wheat root elongation at low treated concentrations in JX soil (Fig. 1b). The relative root elongation reached 104%–107%. However, no similar stimulating effect was found in SD soil (Fig. 1a). The inhibitory effect of the same form of Cr on wheat root elongation was significantly different in different soils. At the same Cr(VI) addition concentration, the inhibitory effect on wheat root elongation was significantly higher in SD soil than in JX soil, whereas for Cr(III) treatments, the inhibitory effect on wheat root elongation was significantly higher in JX soil than in SD soil at concentrations greater than 256 mg/kg. Wheat plant height showed a similar pattern. This is consistent with the results of soil EDTA-Cr concentrations. As shown in Fig. 2, EDTA-Cr concentrations correlated well with the relative wheat root elongation ($P<0.01$), indicating that EDTA-Cr concentration could be used as an indicator of Cr phytotoxicity.

The toxicity thresholds of Cr(VI) and Cr(III) to wheat are shown in Table 3. For Cr(III) treatments, the EC_{50} and EC_{10} values based on wheat root elongation and plant height in SD soil were 1.24–6.51 and 3.37–6.14 times those in JX soil, indicating a higher wheat tolerance to Cr(III) in SD soil, whereas for Cr(VI) treatments, the EC_{50} and EC_{10} values based on root elongation and plant height of wheat in JX soil were 5.29–14.09 and 2.34–4.49 times those in SD soil, indicating a higher wheat tolerance to Cr(VI) in JX soil. In SD soil, the EC_{10} and EC_{50} values of Cr(III) based on wheat root elongation were 53.1 and 125.4 times those of Cr(VI); in JX soil, the corresponding values were 8.11

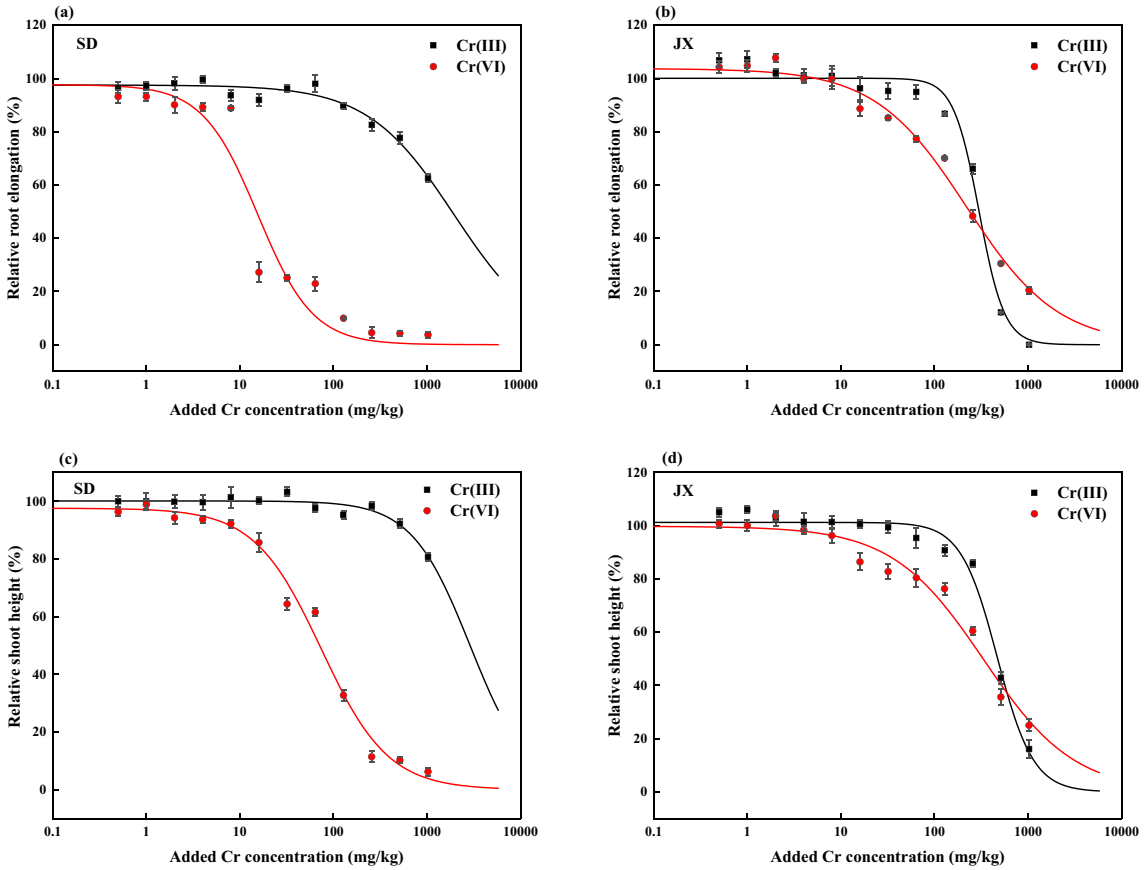

Fig. 1 Dose-effect curves based on (**a, b**) wheat root elongation and (**c, d**) plant height in Shandong fluvo-aquic soil (SD) and Jiangxi red soil (JX). All data are the mean ± standard deviation of three replicates

and 1.36 times, respectively. These results indicated that the toxicity of Cr(VI) was significantly higher than that of Cr(III) in both soils, and the toxicity discrepancy between Cr(III) and Cr(VI) was greater in SD soil. A similar pattern was observed for plant height. Although both root length and plant height of wheat indicated the toxicity of Cr, the EC_{10} and EC_{50} values based on wheat root elongation were significantly lower than those of plant height for the same form of Cr treatment in both soils. For example, in SD soil, the EC_{10} value based on plant height for Cr(VI) treatment was 3.74 times that of root elongation, indicating that wheat root length was more sensitive to Cr contamination than plant height.

Effect of Cr on wheat root morphology

As shown in Fig. 3, wheat root tips, root surface area, and root volume varied significantly between different concentrations of treatments. In SD soil, root tip number, root surface area, and root volume decreased with increasing Cr addition concentration, except for root diameter. Low concentrations of Cr(VI) (<2 mg/kg) and Cr(III) (<1 mg/kg) treatments in JX soil promoted wheat root growth and development, and root tip number, root surface area, as well as root volume increased accordingly, reaching a maximum at Cr(VI) concentration of 2 mg/kg and Cr(III) concentration of 1 mg/kg, respectively, showing significant differences ($P<0.05$) from the control. At Cr(VI) concentration greater than 2 mg/kg and Cr(III) concentration greater than 1 mg/kg, root growth and development was inhibited and thus decreased root tip number, root surface area, and root volume.

For Cr(VI) treatments, the root surface area, root volume, root tip number, and root mean diameter of wheat in JX soil were higher than those in SD soil, except for root tip number in soils treated with low concentrations of Cr (0–1 mg/kg) and root mean diameter in soils treated with medium concentrations of Cr (8–128 mg/kg). For Cr(III) treatments, except for low concentration groups (1–4 mg/kg), the root surface area, root volume, root tip number, and root mean diameter of wheat were higher in SD soil than in JX soil, which is different from the pattern of Cr(VI).

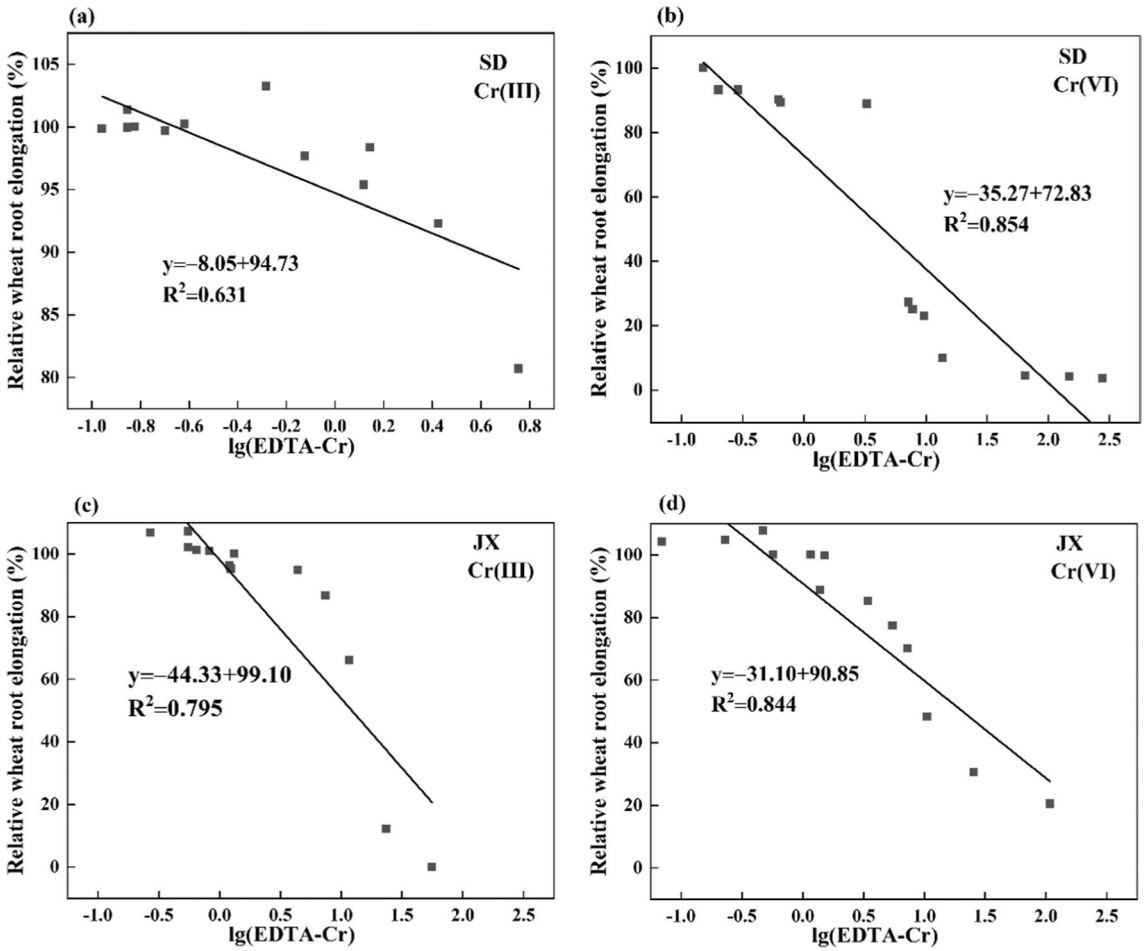

Fig. 2 Correlation relationship between soil EDTA-Cr concentrations and the relative wheat root elongation. **a, b** Cr(III) and Cr(VI) treatments in Shandong fluvo-aquic soil (SD); **c, d** Cr(III) and Cr(VI) treatments in Jiangxi red soil (JX)

Table 3 Toxicity thresholds of Cr(III) and Cr(VI) based on wheat root elongation and plant height

Evaluation endpoint	Soil	Cr form	EC_{10}	EC_{50}		
			Value (mg/kg)	95% CI[a]	Value (mg/kg)	95% CI
Root elongation	SD	III	187	107–327	1953	1276–2988
		VI	3.52	1.07–11.6	15.6	10.1–24.1
	JX	III	151	107–212	300	263–341
		VI	18.6	10.4–33.5	220	177–273
Plant height	SD	III	594	447–788	2878	1554–5331
		VI	12.1	7.06–20.9	74.1	59.3–92.6
	JX	III	176	132–237	469	419–525
		VI	28.4	12.2–66.0	333	253–437

[a]95% confidence interval

Discussion

Effect of soil properties on the toxicity of Cr(VI)/Cr(III) to wheat root

In this study, the differences in the effects of Cr(VI)/Cr(III) on wheat root elongation and root morphology in the two soils indicated that the toxicity of Cr was closely related to soil physicochemical properties. Cr(VI) showed greater

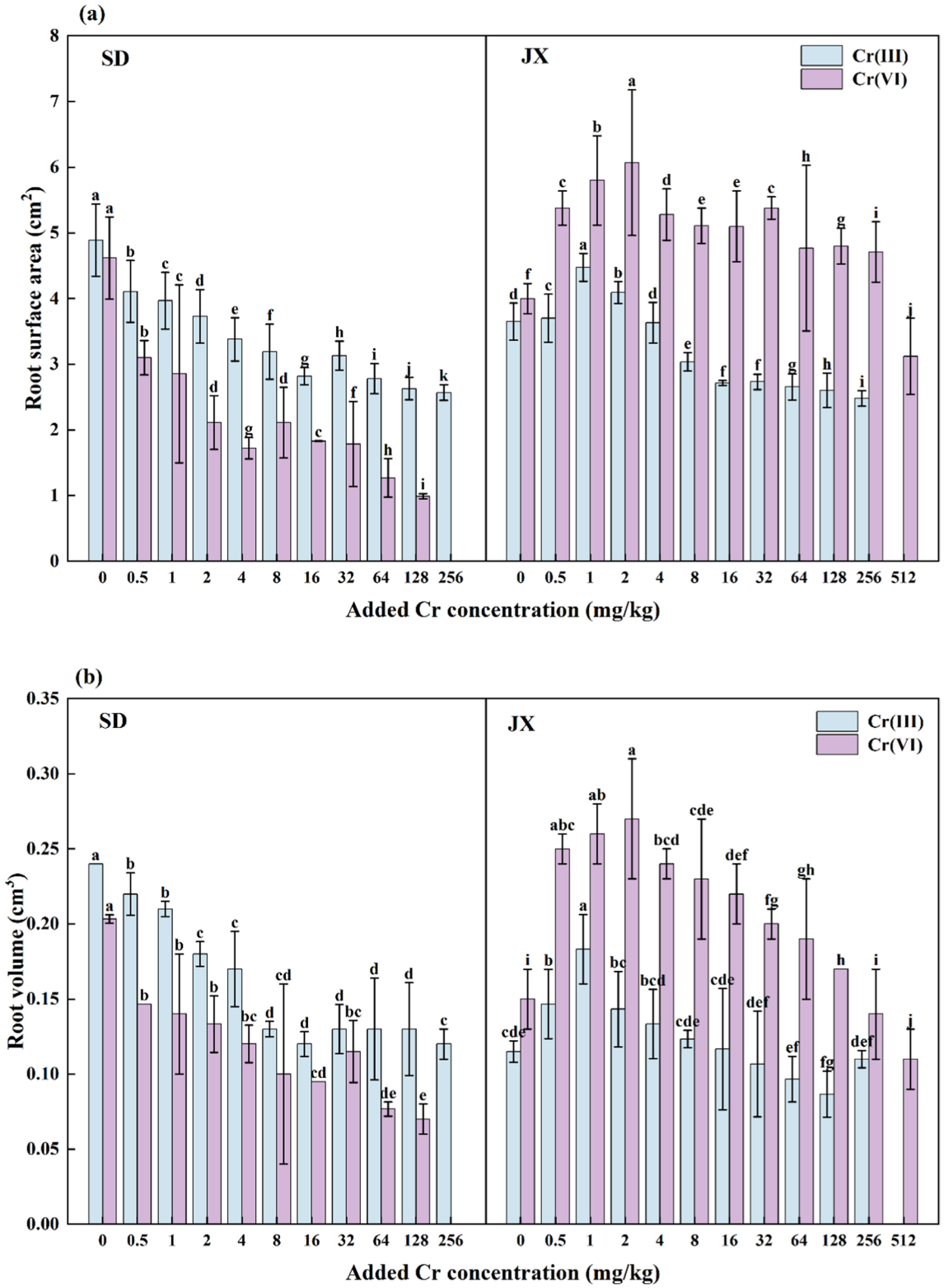

Fig. 3 Effects of Cr(VI) and Cr(III) on wheat root morphology in Shandong fluvo-aquic soil (SD) and Jiangxi red soil (JX). All data are the mean ± standard deviation of three replicates, and different lowercase letters indicate significant ($P<0.05$) difference among different concentrations of Cr treatment

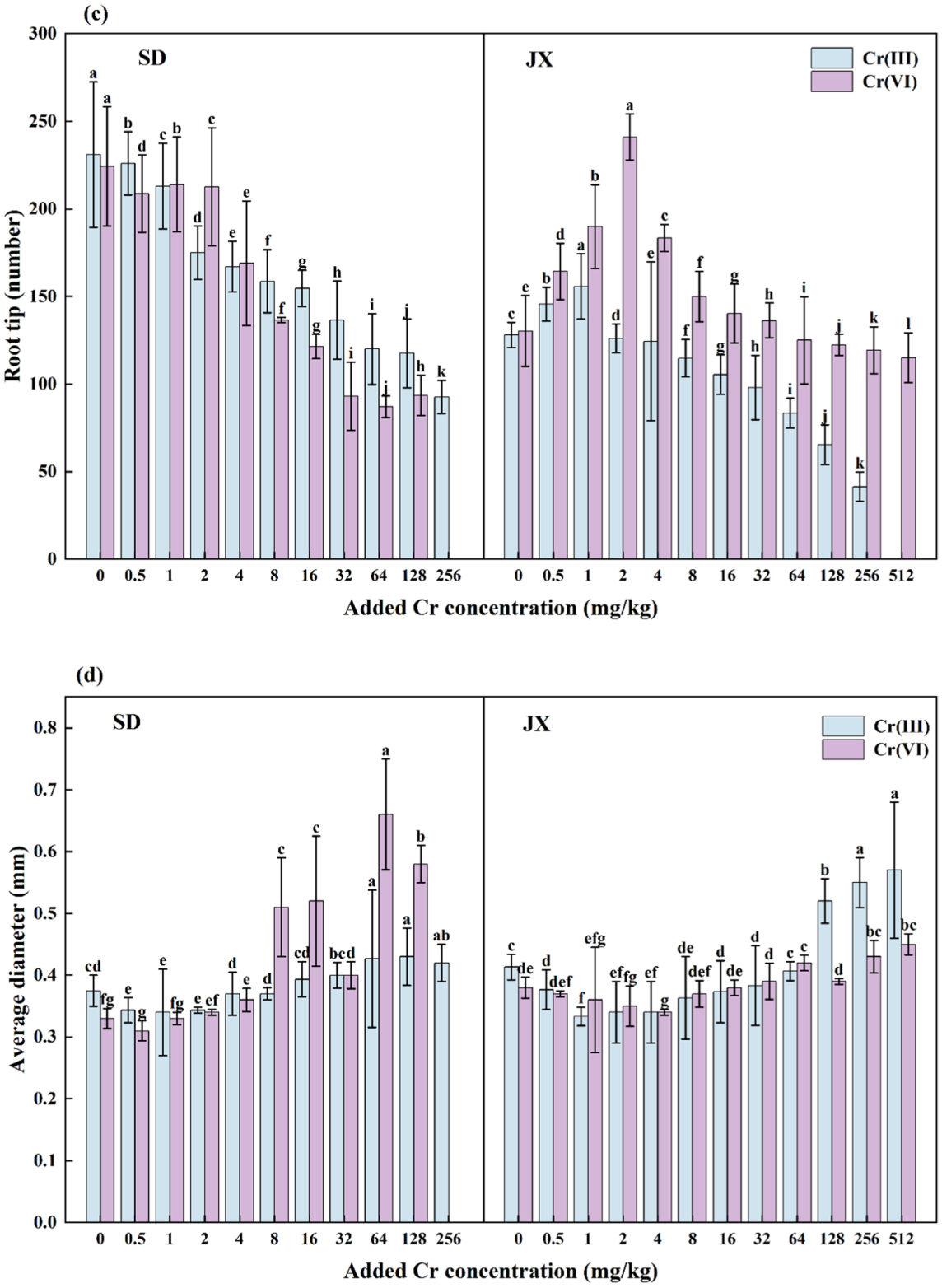

Fig. 3 (continued)

toxicity to wheat roots in SD soil than in JX soil, whereas Cr(III) showed the opposite pattern. This can be attributed to the different pH, CEC, as well as contents of organic matter and clay in the two soils.

In SD soil (alkaline), Cr(III) tended to be hydrolyzed into $CrOH^{2+}$, $Cr(OH)_2^{+}$, $Cr(OH)_3$, and $Cr(OH)_4^{-}$, which finally crystallizes into $Cr(OH)_3 \bullet H_2O$ and precipitated, reducing its bioavailability and thus the toxicity to the roots; whereas in JX soil (acidic), Cr(III) exists mainly as soluble Cr^{3+}, which is easily absorbed by wheat roots, inhibiting the uptake of nutrients and water by roots, preventing cell division and thus affecting the growth and development of roots. Similarly, Fu et al. (2020) found that the EC_{50} of Cr(III) on barley root elongation in Beijing soil (pH=8.1) was 2.3 times that in Hunan soil (pH=6). Cr(VI) existed in soils in anionic forms (CrO_4^{2-}, $HCrO_4^{-}$, and $Cr_2O_7^{2-}$). In SD soil, OH^- ions compete with CrO_4^{2-}, $HCrO_4^{-}$, and $Cr_2O_7^{2-}$ for sorption sites, eventually leading to a decrease in the sorption capacity of the soil for Cr(VI) (Qiu et al. 2020); more free Cr(VI) is taken up by plant roots and thus resulted in a higher toxicity. Similarly, Marti et al. (2013) discovered that the phytotoxicity of Cr(VI) was increased significantly in soils with higher pH. Furthermore, it was found that the EC_{50} and EC_{10} values of Cr(VI) based on plant root elongation were significantly ($P<0.01$) negatively correlated with soil pH (Fu et al. 2020; Sun et al. 2022).

Soil organic matter affects the behaviors of Cr(VI) and Cr(III) mainly through the processes of reduction and adsorption. The functional groups such as -COOH, R-OH, and C_6H_5OH on the surface of organic matter can directly reduce Cr(VI) to Cr(III) and can effectively adsorb both Cr(VI) and Cr(III) (Taghipour and Jalali 2016; Shahid et al. 2017). The higher organic matter content in JX soil facilitated the reduction and adsorption of Cr(VI) and thus decreased the phytotoxicity. It was found that soil organic matter content was significantly negatively correlated with the phytotoxicity of Cr(VI) (Sun et al. 2022; Yang et al. 2022).

JX soil is acidic with higher contents of iron and aluminum oxides, which are positively charged and favor the adsorption of Cr(VI). Moreover, Fe(II) in clay minerals can also reduce Cr(VI) to Cr(III) in soils (Kwak et al. 2018). Higher soil clay and CEC in JX soil alleviated the toxicity of Cr(VI) to wheat. Consistently, Sun et al. (2022) confirmed that the EC_{50} value of Cr(VI) on barley root elongation was significantly positively correlated with both soil clay content and CEC. Similarly, the results of principal component analysis between EC_{10} and soil properties showed that higher clay and CEC contents will increase the toxicity thresholds of Cr(VI) based on wheat root elongation (Yang et al. 2022).

The biphasic dose effect of Cr

In this study, we found that low concentrations of Cr(VI) and Cr(III) treatments increased wheat root length, root surface area, root volume, and root tip number in JX soil, whereas high doses of Cr(VI) and Cr(III) inhibited root growth and development (Figs. 1b and 3), which is known as biphasic dose effect. Mechanisms of the stimulating effect of Cr on plant roots might be explained from the following aspects. Firstly, low-dose Cr increased the cell viability by inducing the mitosis and differentiation of root cells, enhanced the cell wall thickness of root endoderm, and promoted the development of xylem tissue, thereby increasing root growth (Patnaik et al. 2013; Singh et al. 2015). Secondly, low doses of Cr led to the growth of apical meristem cells, inducing the high differentiation of meristems and stimulating the formation of lateral and adventitious roots, thereby increasing the surface area, root volume, and number of root tips (Hernández-Madrigal et al. 2018; Ruiz-Aguilar et al. 2020). Finally, the reactive oxygen species induced by low doses of Cr might play beneficial roles in regulating cell cycle, promoting cell differentiation, improving cell immune function, protecting genome integrity, and thus promoting root growth (Murali Achary and Panda 2010; Patnaik et al. 2013). However, high doses of Cr affect root growth by inhibiting mitosis and cell elongation after taken up by the root tip (Al-Huqail et al. 2020; Nie et al. 2021). High doses of Cr also affect root growth through interfering with nutrient uptake by root cells (nitrate, phosphate, and sulfate) leading to inadequate nutrient uptake (Singh et al. 2014). Moreover, Cr(VI) can seriously affect the process of plant sugar metabolism and thus the normal development of plant roots (Mahajan et al. 2013). The Cr-induced hormesis effect are related to soil properties. In this study, the hormesis effect was found to occur only in JX soil. Similarly, Sun et al. (2022) found that the hormesis occurred only in HY soils (red earth). The biphasic dose effect observed in this study furthered the understanding on the perception and adaption of chromium toxicity by wheat roots.

Toxicity differences between Cr(III) and Cr(VI)

In this study, we found that the EC_{10} values of Cr(III) based on wheat root elongation were 53.1 and 8.07 times those of Cr(VI) in SD soil and JX soil, respectively, indicating that Cr(VI) exhibited significantly higher phytotoxicity than Cr(III) in both soils. This is because Cr(III) tends to be adsorbed in acidic condition and forms $Cr(OH)_3$ precipitates in alkaline condition, which is more easily immobilized by the soil compared to Cr(VI) (Dai et al. 2009). In contrast, Cr(VI) exists as anions in soils which is highly bioavailable and harmful to plant growth and development (Dhal et al. 2013). Similar to the results of the present study, Su et al. (2005) observed by

electron microscopy that the number of leaf flesh cells and thin-walled tissue cells of Chinese brake fern (*Pteris vittata*) grown in Cr(VI) (500 mg/kg) contaminated soil was less than that of Cr(III) (1000 mg/kg) treatment. Yu et al. (2018) calculated the EC_{10} value of Cr(VI) to be 138 times that of Cr(III) based on ecotoxicological data of Cr(VI) and Cr(III) in soils of China.

Conclusions

In this study, we investigated the effects of different forms of Cr(VI) and Cr(III) on wheat (*Triticum aestivum* L.) root elongation and morphology in two soils with different properties and found that exogenous Cr significantly affected wheat root morphology, and wheat could be used as a biological indicator to evaluate soil Cr contamination. Compared with plant height, root length is more sensitive to indicate the toxicity of chromium in soils. EDTA-Cr is a good predictor of chromium toxicity in soil. Cr(VI) showed higher toxicity in SD soil (alkaline) than in JX soil (acidic), whereas Cr(III) showed the opposite pattern. Low concentrations of Cr(VI) and Cr(III) treatments stimulated the root growth and development in JX soil. The results of this study shed light on the different phytotoxicity of Cr(VI) and Cr(III) in soils with different properties.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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