*Research Article*

# Uptake of Chromium by *Portulaca Oleracea* from Soil: Effects of Organic Content, pH, and Sulphate Concentration

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Phytoextraction is an effective and environment-friendly approach for remediation of soil polluted with toxic metals. *Portulaca oleracea* is a potential hyperaccumulator of Cr(VI) from polluted soil. In this study, the effect of soil organic content, pH, and sulphate concentration on phytoextraction of Cr(VI) using *Portulaca oleracea* was investigated. Seedlings of *Portulaca oleracea* were grown in soils with (i) three organic content compositions, (ii) six levels of pH, and (iii) six concentrations of sulphate salts; all were irrigated with Cr(VI) solutions at 200 ppm concentration. Chromium concentration in different tissues of plants was monitored under the variant conditions. Results indicated that the uptake of Cr(VI) by *Portulaca oleracea* is favoured at (i) low organic content soil (0.42%), (ii) slightly alkaline pH range (~8), and (iii) with sulphate concentration in the range of 300–600 ppm.

## 1. Introduction

*Portulaca oleracea* is a succulent plant (family Portulacaceae) native to the Mediterranean area, but it grows in several parts of the world from India to Australia and North America. The plant is a self-compatible annual weed that grows fast and can reach up to 40 cm in height. Usually, it grows along the ground with smooth stems, alternate leaves, and taproots that enable it to tolerate poor soils and dry areas. *P. oleracea* is commonly known as purslane and it is used in food, where it is added to soups and salads, and in folk medicine remedies including antimicrobial, antidiabetic, anti-inflammatory, and anticancer properties [1, 2].

The process of phytoextraction requires the uptake of heavy metal pollutants from soil or water (by the roots) and then translocating them to the above-ground parts [3]. The process requires that the plant has the potential to accumulate a large amount of the heavy metal relative to its dry weight. Also, for the plant to be an effective candidate for the phytoextraction technique, it needs to accumulate more than

0.1% (1000 mg/kg) of its weight of chromium, cobalt, copper, or nickel metals and more than 1.0% of zinc or manganese metals [4]. *P. oleracea* has been shown to extract both organic pollutants and heavy metal ions. Okuhata et al. [5] have investigated its ability to remove bisphenol derivatives from aquatic solution and it was able to remove 97% of 4,4′-thiodiphenol from the culture within four days. Meanwhile, a significant number of studies focused on the ability of *P. oleracea* to extract heavy metals from contaminated soil or water [6–14]. These studies show that the plant has a high tolerance for many metals, including Cd (II), Cu(II), Cr(III), Cr(VI), Fe(III), Mn(II), Ni (II), Pb(II), and Zn(II) ions, and has the ability to extract them to its roots from either soil or aqueous solutions with variant capacities. It was, however, established that *P. oleracea* is a hyperaccumulator for Cr(VI); a hyperaccumulator plant can extract the metal at concentrations ten times (at least) higher than their concentrations in the soil or wastewater. We have previously reported that *P. oleracea* is tolerant to high concentrations of Cr(VI) in soil up to 400 mg/kg [6, 7]. The plant was able to

extract the metal (soil concentration of 200 mg/kg) into its roots with a total concentration exceeding 2000 mg/kg and a bioaccumulation factor (BAF) greater than 10. BAF is the ratio of the concentration of metal in dry roots (mg/kg dry weight) to the concentration of metal in dry soil or wastewater (mg/kg or ppm).

It is believed that *P. oleracea* is able to tolerate the stress of high Cr(VI) concentration in the growth medium through two pathways: (i) the production and accumulation of proline to maintain osmotic balance and (ii) the activation of anti-oxidant enzymes (such as the peroxidase) to combat the oxidative stress of the metals [12, 15]. It was shown that the plant is able to reduce more than 97% of Cr(VI) accumulated in its roots to the less toxic Cr(III) and then translocates it to the shoots and the leaves with a translocation factor (TF) of 0.4. TF is the ratio of the concentration of metal in dry shoots to its concentration in dry roots. Therefore, *P. oleracea* has great potential for remediation of chromium-contaminated environmental media and detoxification of the metal [7].

Cr(VI) is classified by the World Health Organization as a human carcinogen, and it is known to cause damage to respiratory tract tissues, kidneys, liver, and skin [16, 17]. The high toxicity of Cr(VI) is attributed to its strong oxidizing effect on the intracellular proteins and nucleic acids since hexavalent chromium compounds ($H_2CrO_4$, $HCrO_4^-$, $CrO_4^{2-}$, and $Cr_2O_7^{2-}$) have high solubility and permeability of cell membrane [18, 19]. The trivalent chromium, however, exists mainly as chromium oxide ($Cr_2O_3$) or chromium hydroxide ($Cr(OH)_3$); both species have low solubility and are biologically unavailable. Therefore, the ability of *P. oleracea* to extract the metal from the soil is dependent on the speciation of the metal and its bioavailability which, in turn, is dependent on several factors including (i) the organic content, (ii) the pH, and (iii) the presence of sulphate ions in the soil [18–21]. Herein, we report on the results of investigating these factors on the uptake of Cr(VI) by *P. oleracea* from contaminated UAE soil.

## 2. Results and Discussion

*2.1. Effect of Soil Organic Content.* The presence of organic matter in the soil affects the speciation and the mobility of chromium metal ions. The degradation of organic compounds in the soil leads to (i) the increase of dissolved organic carbon and (ii) the formation of the oxidized chelating ligands of metal ions, such as the carboxylic acids, which also lowers the pH of the soil [22–24]. The former enhances the reduction of Cr(VI) to Cr(III), which is less biologically available, while the latter increases the adsorption and the retention of the metal species to the soil (*vide infra*). Besides, the increase in the organic content of the soil helps in the bioreduction of Cr(VI) to Cr(III) by microorganisms that thrive in organic-rich soil. Due to these factors, the uptake of chromium by the plant is expected to decrease as the organic content of the soil increases [19, 25].

To investigate the effect of the organic content of soil on the uptake of Cr(VI) by *P. oleracea*, three sets of the plants (five pots in each set) were grown in soils with organic content of 0.42%, 17.5%, and 35.0%, respectively, and were irrigated with

Cr(VI) as sodium chromate. The plants were harvested and analysed for total chromium while the soils were sampled and analysed for Cr(VI) and total chromium concentrations. Figure 1 exhibits the concentrations of chromium in the plant tissues and Cr(VI) in the soil upon the change in the organic content of the soil. A significant decrease in the uptake of Cr(VI) by *P. oleracea* was observed in both roots and shoots as the organic matter content of soil increased ($p < 0.01$). In the dry roots, *P. oleracea* accumulated ~3,000 mg/kg of chromium in the presence of 0.42% of organic matter, but this concentration decreased to 530 mg/kg at 17.5% and to below 180 mg/kg at 35% organic matter. This change was also concomitant with a decrease in the bioaccumulation factor (Figure 1(c)) of Cr(VI) from 27 (at 0.42%) to 5.5 (at 35.0%) and a decrease of the concentration of Cr(VI) available in the soil (Figure 1(b)) from 107 mg/kg (at 0.42%) to 21 mg/kg (at 35.0%). BAF of total chromium (Figure 1(c)) followed a parallel trend to that of Cr(VI) but to a lower extent indicating that chromium uptake by the plant is mainly of Cr(VI). The concentration of total chromium (Figure 1(b)) in the soil shows that as the organic content increased, more chromium remained in the soil although the concentration of Cr(VI) decreased. This can be attributed mainly to the reduction of Cr(VI) to Cr(III) due to the oxidation of organic compounds. Yet, it is worth noting that the presence of other metals such as Mn ($370 \pm 40$ mg/Kg) and Fe ($4800 \pm 500$ mg/Kg) can contribute to the reduction of Cr(VI). However, although the concentration of these metals decreased as the organic content of the soil increased, the amount of total chromium, and hence Cr(III), in the soil increased. Thus, this indicates that the organic compounds are major contributors for reducing Cr(VI) to Cr(III).

These results indicate that the increase in the organic content of the soil has two major effects. First, it enhances the growth of the plant and thus it increases its dry weight (Figure 2) which in turn leads to a decrease in both the concentration of metal in the plant and the bioaccumulation factor. Second, the increase of organic content in the soil leads to the reduction of the soluble Cr(VI) to the less soluble Cr(III), which is less available to the plant especially at the pH range of the used soil (~7.9) (*vide infra*). At low organic content (0.42%), there was an insignificant increase in the dry weight of the plant (Figure 2) and in the reduction of the metal to Cr(III) in the soil. As the concentration of the organic matter increased to 17.5%, the dry weight of the plant increased significantly in the control sample but there was no significant increase in the weight of the plants irrigated with the metal solution. This is attributed to the negative effect of the metal uptake on plant growth. At this concentration of the organic content, the available Cr(VI) in the soil was at a moderate level of ~61 mg/kg for uptake by the plant. When the concentration of the organic matter increased to 35%, however, the dry weight of the plant increased significantly in both the control and the metal-irrigated samples while the available Cr(VI) in the soil was at very low levels of 21 mg/kg. Therefore, organic matter has an indirect impact on the chromium uptake by *P. oleracea* by reducing the concentration of the bioavailable Cr(VI) in the soil.

These results are in agreement with those of [9] which have shown that the uptake of chromium by *P. oleracea* from
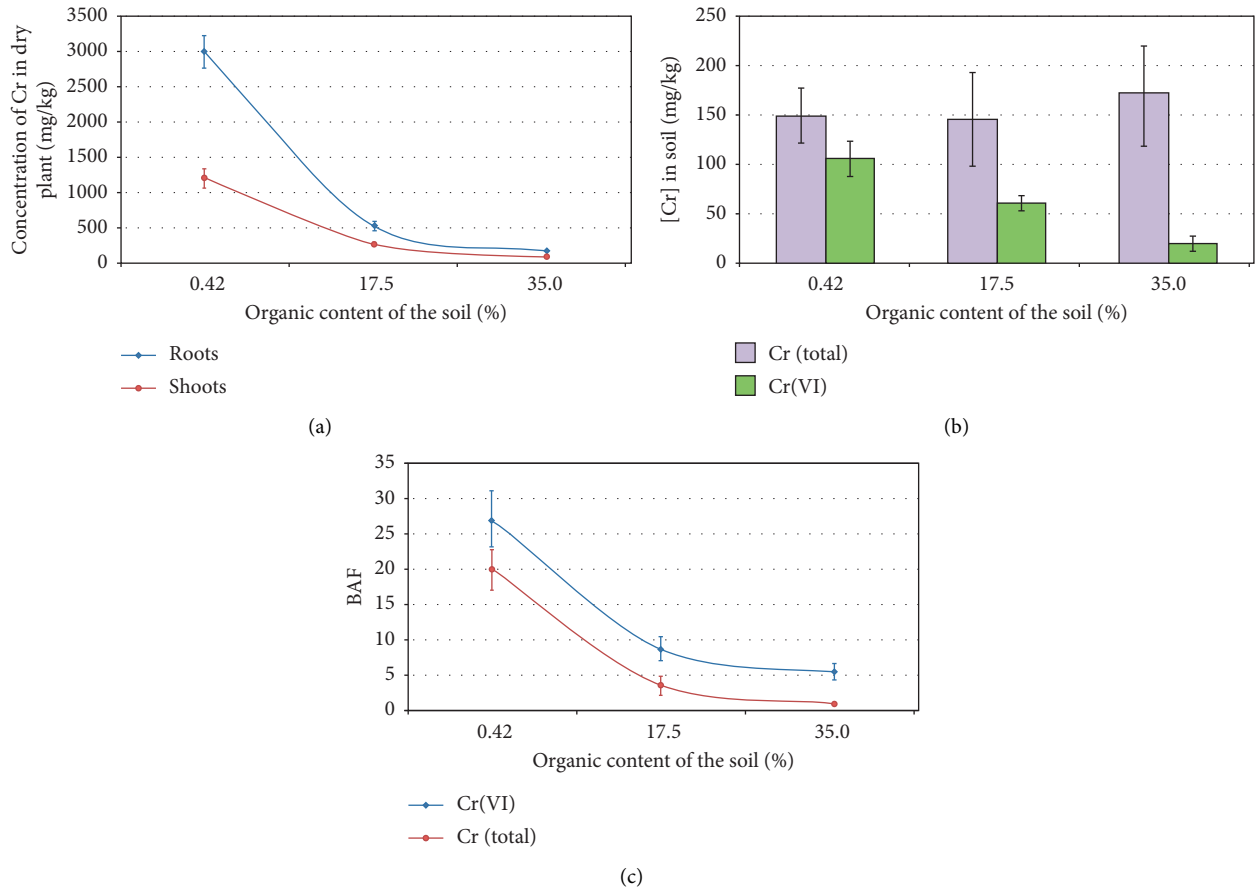
(a)



(b)



(c)

FIGURE 1: (a) Concentrations of total chromium in both shoots and roots of *Portulaca ole*racea, (b) concentrations of total chromium and Cr(VI) in the soil, and (c) change in bioaccumulation factors of total chromium and Cr(VI) at different levels of organic content in soil (mean of five replicates ± SE, 95% CLs).
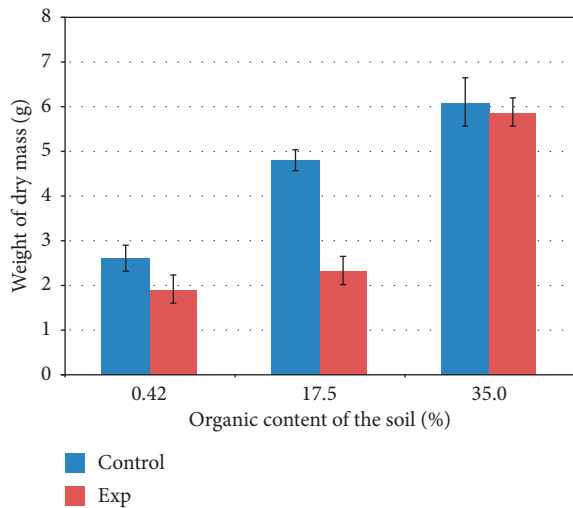


FIGURE 2: Weight of dry shoots of *P. oleracea* at different levels of organic matter in soil in both control and experimental samples (mean of five replicates ± SE, 95% CLs).

a sludge, with 51% organic matter content and 70 mg/kg Cr concentration, was at 45.1 mg/kg and a BAF of 0.89. Reports on the uptake of metals have shown that the increase in the organic content of soil had lowered the uptake of Cr by studied plants, as the addition of organic matter to soil increases the reduction of Cr(VI) to Cr (III) and, hence, lowers its bioavailability [22, 24, 26–28].

*2.2. Effect of Soil pH.* The pH of the soil has a major effect on the geochemical properties of chromium by affecting the chemical speciation of the metal and the adsorption ability of the soil. In acidic soils and solutions (pH < 4), Cr(III) mostly exists as $[Cr(H_2O)_6]^{3+}$, which is converted to $Cr(OH)_3$ as the pH increases. Cr(VI) may exist as soluble sodium chromate ($Na_2CrO_4$) or the sparingly soluble calcium chromate ($CaCrO_4$) in neutral-alkaline soils but in acidic conditions (pH < 5), $HCrO_4^-$ becomes the dominant form. As the concentration of Cr(VI) increases in highly acidic aqueous systems, $HCrO_4^-$ ion is converted to the dichromate ion ($Cr_2O_7^{2-}$) [19, 29–32].

The pH also affects the adsorbing ability of the soil for different metal species. At acidic pH (<4), the cation-exchange sites in the soil are saturated with the protons which leads to desorption and release of the metal ions into solution, which makes them more available to the plants. Meanwhile, the acidic soil has a higher adsorption affinity for anions such as $CrO_4^{2-}$ and $HCrO_4^-$, which will be less

available for plant uptake. At basic pHs, however, the metal-binding sites in the soil will be activated and the soil will have higher adsorption affinity for positive metal cations while the anions will be released. Therefore, the most suitable pH range for removal of Cr(VI) species from the soil is at the neutral-alkaline range where the dominant species for chromium, the chromate anion ($CrO_4^{2-}$), has the maximum mobility [19, 25].

Our previous studies on the uptake of chromium from UAE soil by *P. oleracea* showed that, at pH = $7.9 \pm 0.1$, the optimum concentration for the maximum uptake efficiency of the plant is at 200 mg/kg of chromium [7]. Thus, in the current study, the uptake of chromium by *P. oleracea* was monitored as the pH of the soil increased from 6.0 to 9.0 at a Cr(VI) loading of 200 mg/kg in the soil. The effect of the pH of the soil on the plant growth was also monitored in the presence and the absence of chromium metal. Therefore, six groups of pots were prepared at six pH levels (6.0, 7.0, 7.3, 7.6, 8.0, $9.0 \pm 0.1$) of the soil (10% organic content) and were irrigated with chromate solution (200 ppm) while another set of six groups at the same pH levels were irrigated with deionised water.

The observed results (exhibited in Figure 3) show that both chromium concentration in the roots and the BAF exhibited a sigmoidal relationship with the change in pH with significant increases between the mean values at pH 6.0, 7.3, and 9.0 ($p < 0.01$) while the concentration of total chromium in the soil remained relatively similar. Below pH 7.0, where the $HCr_2O_4^-$ is the dominant species, there were no significant changes ($p > 0.05$) in root chromium concentrations. A similar trend was observed when the pH exceeded pH 7.6 with no significant increase ($p > 0.05$) in root chromium content beyond this point and the amount of chromium in the roots exceeded 1300 mg/kg in dry biomass. Within this pH range (7.0–7.9), chromium primarily exists as the chromate species ($CrO_4^{2-}$); this implies that *P. oleracea* prefers to accumulate the metal in the form of $CrO_4^{2-}$ at neutral-to-alkaline pH rather than $HCr_2O_4^-$ which dominates at slightly acidic pHs (<7) [33, 34]. BAF of total chromium followed also a similar trend with the highest values (>8) at pH range 7.0–7.9. Yet, the concentration of chromium in the soil did not change significantly over the pH range (Figure 3(b)) which further supports that speciation of Cr(VI) to the chromate species enhances BAF at high pHs. On the other hand, the uptake of chromium did not have a significant impact ($p > 0.05$) on the growth of the plants as indicated by the recovered dry biomass between pH 6.0 and pH 8.0 (Figure 4). However, a significant decrease ($p < 0.05$) in the dry biomass was observed when the pH was raised to 9.0 in both the control and chromium-treated plants. This decrease suggests that the observed impact on growth was due to the basic pH, which affects the growth of the roots, rather than the accumulation of chromium.

The accumulation of chromium in the shoots of *P. oleracea*, on the other hand, exhibited a different response with increasing pH as compared to that in the roots (Figure 3(a)). In this case, the concentration increased linearly with the increase in the pH, unlike the sigmoidal change that was observed for the concentration of the metal in the roots (Figure 3(a)). This increase of chromium concentration in the shoots from 262 mg/kg at pH 6 to 813 mg/kg at pH 9 was accompanied with a TF (Figure 3(c)) ranging from 2.45 to 2.56, respectively, without being significantly affected by the change in the pH. These results suggest that the translocation of the metal from the roots to the shoots is not dependent on the speciation of chromium in the soil at different pHs. This is further supported by our previous findings [7] that more than 97% of Cr(VI) accumulated in roots is reduced to Cr(III) before its translocation to the shoots as a chelated cation [35].

These results are in agreement with previous studies that have shown that there is a significant effect of pH on the uptake of chromium by nutrient crop plants, fungi, and microorganisms [36–39]. Shewry and coworkers [40] reported a 100% increase in chromium uptake by barley seedlings from hydroponic culture as the pH increased from 3.0 to 6.7, where the chromate anion is the dominate species. These results seem inline also with a proposed mechanism for uptake of chromium by different plants using the same transport processes of the sulphate anion due to the structural similarity between the two anions in charge, shape, and size [12, 33, 34, 41–43].

*2.3. Effect of Sulphate Concentration in Soil.* In light of this proposed mechanism for the uptake of chromium by *P. oleracea*, we investigated the effect of sulphate concentration in soil on the uptake of chromium. Sulphate anion was introduced at five different concentrations (0, 300, 600, 1200, and 1800 ppm with Cr(VI) at 200 ppm in each solution) into five groups of identical soil (15% organic content) pots each containing four seedlings of *P. oleracea* (five replicates); a sixth group was irrigated with deionised water as a control.

The results exhibited in Figure 5(a) show that the concentration of chromium in roots increased significantly ($p < 0.01$) to over 1300 mg/kg as the concentration of sulphate increased from 0.0 ppm to 300 ppm. There was no further change in the uptake of Cr(VI) as the concertation of sulphate increased to 600 ppm ($p > 0.05$). However, when the concentration of sulphate exceeded 600 ppm, chromium concentration in roots decreased significantly ($p < 0.01$) to ~840 mg/kg. The change in the bioaccumulation factor (Figure 5(b)) of chromium followed a similar trend to that of metal concentration, reaching a maximum value of 7.2 at sulphate concentration of 300–600 ppm. However, there was no significant change in the concentrations of chromium in the shoots (Figure 5(a)) as the concentration of the sulphate in the irrigating solution changed from 0 to 1800 ppm ($p > 0.05$). A similar trend was also observed for the change in the TF of chromium (Figure 5(b)) from the roots to the shoots.

Previous studies reported similar results for the effect of sulphate concentration on the uptake of chromate. For example, studies on duckweeds (*Spirodela polyrhiza* and *Lemna minor*) showed even a better matching trend to our results where the uptake of chromium by the duckweed was enhanced at low concentration of sulphates (1.25 ppm) and diminished at high concentration (960 ppm). The observed
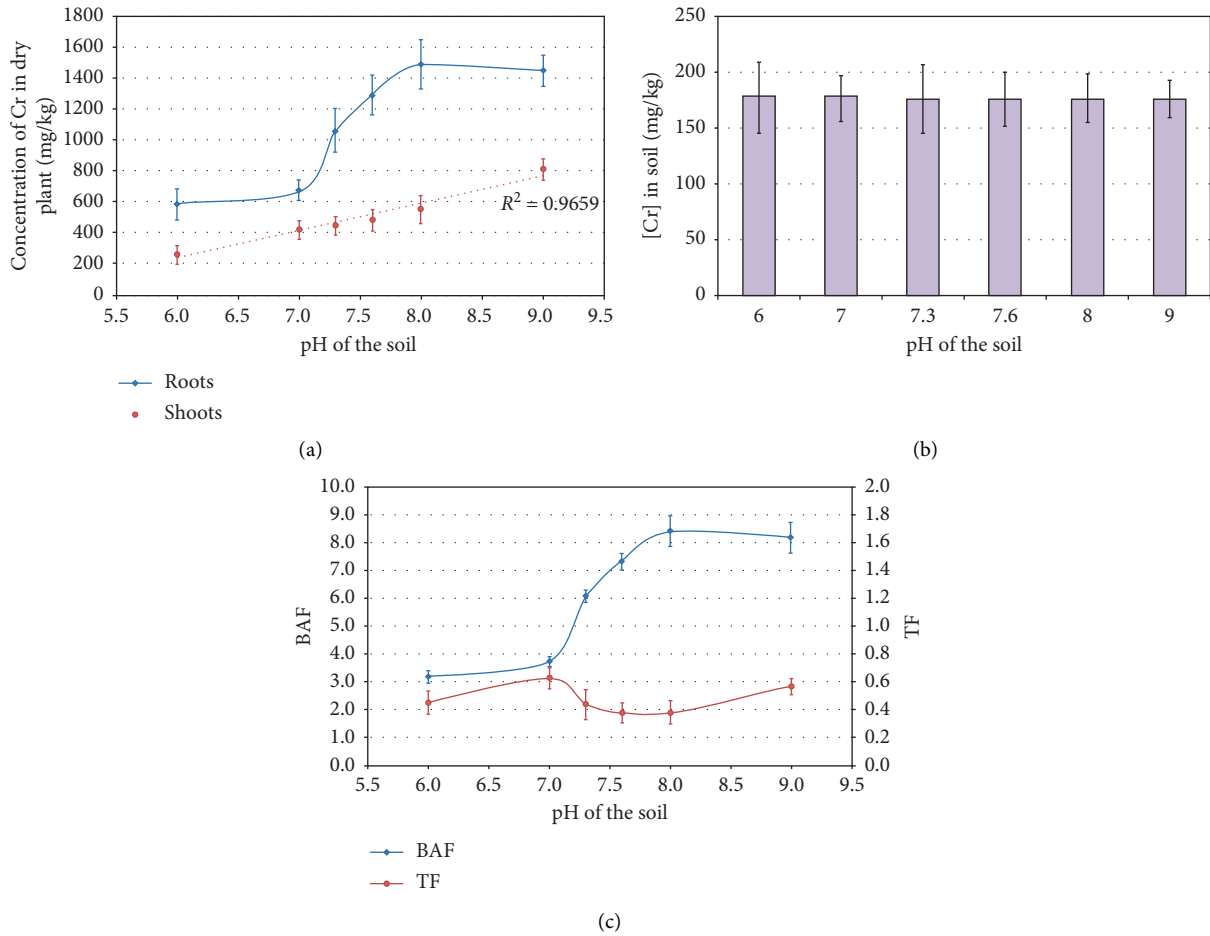
(a)

(b)



(c)

Figure 3: Change in concentration of total chromium (a) in the roots and shoots and (b) in the soil; (c) change in bioaccumulation and translocation factors of *P. oleracea* versus pH of the soil (mean of six replicates ± SE, 95% CLs).
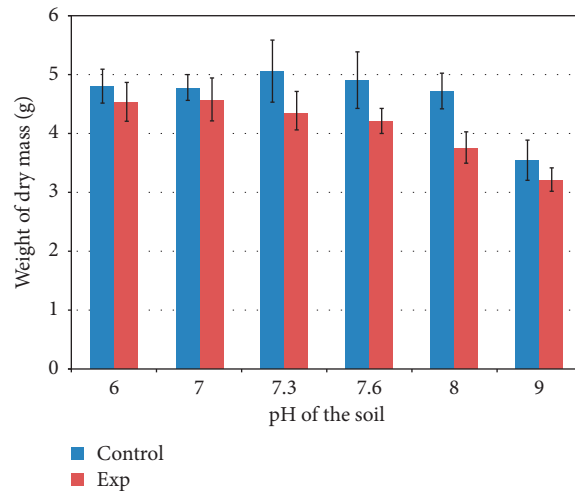


Figure 4: Change in the weight of dry biomass of *P. oleracea* in the absence (control) and presence (Exp) of chromium as the pH of soil increases (mean of six replicates ± SE, 95% CLs).

results were attributed to the uptake of chromate through the sulphate transporters but with a higher affinity to the chromate ions. The report concludes that the number of sulphate transporters on the roots is correlated with the sulphate concentration where, at high concentrations of the sulphate, the anion competes to bind to the transporters over the chromate [44]. Recent reports by de Oliveira et al. showed that the addition of sulphate at moderate
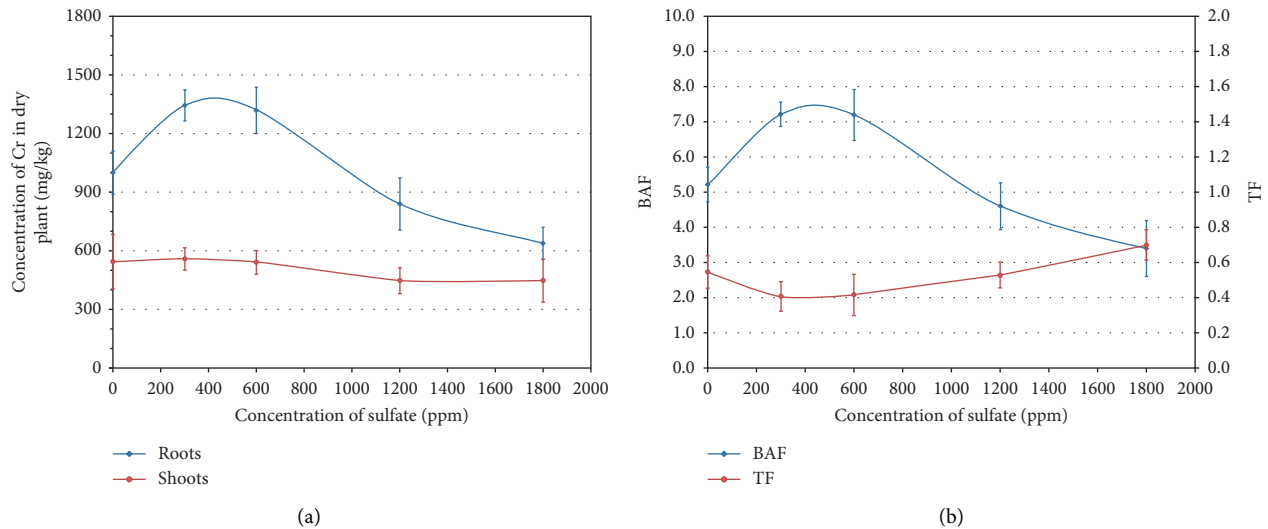
(a)



(b)

Figure 5: (a) Change in concentration of chromium in the roots and shoots and (b) change in bioaccumulation and translocation factors of *P. oleracea* at different concentrations of sulphate in the soil (mean of six replicates ± SE, 95% CLs).

concentrations (~125–250 ppm) to the hydroponic system of *Pteris vittata* enhanced its uptake of chromium by 1.3–7.8 folds. However, the translocation of the metal to the fronds was only slightly enhanced [33, 34].

Therefore, our results further support the hypothesis that the chromate anion is taken up by *P. oleracea* using the cellular carriers of sulphate in the plant cell membrane of the roots. At low concentration of the sulphate in the irrigating solution (300–600 ppm), the sulphate transporters in the plant's roots are activated or increased which facilitates the uptake of the chromate. However, at higher concentrations (>600 ppm), the sulphate carriers are saturated by the sulphate anion which competes for the plant transporters with the chromate anions and, hence, a decrease in the uptake of the metal is observed. Once in the roots, the translocation of chromium to the shoots is then limited by the concentration of the metal carrier ligands in the plant and/or the rate of the reduction process of Cr(VI) to Cr(III).

## 3. Materials and Methods

*3.1. Chemicals and Reagents.* Pure silica $SiO_2$ was purchased from Dubai Sand Purification Co. Jebel Ali, Dubai. Potting soil (70% organic content) was purchased from Blumen Erde from Syker Agrarberatungs, Skye, Germany. Ajman soil of 42% $CaCO_3$ was taken from sandy hills behind Ajman City Centre (near the coordinates 25°23′45.4″N 55°28′44.9″E). Standard chromium solutions (1000 ppm), hydrochloric acid (Conc. ≥37%, trace analysis grade), and nitric acid (ACS Reagent ≥ 90.0%) were purchased from Fluka Chemicals, Gillingham, UK. Reagent grade calcium oxide and sodium chromate were purchased from Panreac Química, Barcelona, Spain.

*3.2. Instruments and Equipment.* An ICP-OES instrument (Sequential Liberty AX, Varian, Mulgrave, Victoria, Australia) was used for measuring total chromium concentrations in soil and plant tissues, with the conditions recommended by the manufacturer [6, 7]. A UV-Visible spectrometer (HI 93723, Hanna Instruments, Leighton, Buzzard, Bedfordshire, UK) was used to determine Cr(VI) in plants and soils. A pH Meter (PerpHecT Basic Benchtop Model Orion 320, Thermo-Orion, Loughborough, UK) was used for measuring the pH of soil and irrigation solutions.

*3.3. Organic Content Effect: Growth Experiments.* Simulated test soil was prepared using normal clean soil from Ajman, which has no detectable Cr(VI) content, 370 ± 40 mg/kg of Mn, and 4800 ± 500 mg/kg of Fe, either pure or mixed with the potting soil as indicated in Table 1. Three groups of ten pots were filled with simulated test soil (1600 ± 100 g per pot) with different organic contents (%) (Table 1). Four seedlings of *P. oleracea* were grown in each pot and irrigated with deionised water for three weeks until considerable vegetation and rooting were achieved. Plants were grown at Ajman municipality nursery in partial shade (35% shaded nursery, 65% of light intensity to pass through the net).

A stock solution of 200 ppm Cr(VI) [7] was prepared by diluting a concentrated solution of sodium chromate (at 10,000 ppm of Cr(VI)). The pot sets of each soil with different organic contents were then divided into two subsets (5 pots each). One subset was irrigated with chromate solution ($8 \times 200$ mL per pot) over a period of ten days while the other subset was irrigated with the same quantity of deionised water as control groups.

The total organic content of the soil was determined using an adapted procedure [45]. In brief, a sample of the air-dried and sieved soil (0.5 g) was added to the $K_2Cr_2O_7$ standard solution (0.083 M, 10 mL) swirled at room temperature. Concentrated $H_2SO_4$ solution (15 mL) was then added to the mixture dropwise with gentle swirling and the mixture was heated under reflux for 1.0 hour. After cooling to room temperature, deionised water (100 mL) was added to the mixture with five drops of ferroin indicator

TABLE 1: Soil composition with different organic contents.

| Organic content (%) | Soil composition | |
| --- | --- | --- |
| | Potting soil (70% organic matter content) (%) | Ajman soil (contains 42% CaCO$_3$) (%) |
| $35 \pm 0.5$ | 50 | 50 |
| $17.5 \pm 0.5$ | 25 | 75 |
| $0.42 \pm 0.02$ | — | 100 |

(FeSO$_4$.7H$_2$O and 1,10-phenanthroline monohydrate in water). The mixture was titrated with ferrous ammonium sulphate (0.1 M) to reach an endpoint with the colour change from blue-green to violet-red. The same procedure was repeated for a blank solution (without the soil).

Organic carbon (mg/g) and organic content (%) of the soil were then calculated from the following equations:

$$\text{organic carbon (mg/g)} = 18 \times C \times V \times \frac{(1 - V_1/V_2)}{M},$$

$$\text{organic content (\%)} = \left(\frac{1}{5.8}\right) \times \text{organic carbon (mg/g)},$$

(1)

where $C$ (M) and $V$ (mL) are the molar concentration and the added volume of the K$_2$Cr$_2$O$_7$ solution, respectively, $V_1$ and $V_2$ (mL) are the added volumes of ferrous ammonium sulphate for the sample and the blank, respectively, and $M$ (g) is the sample weight [45].

### 3.4. pH Effect: Growth Experiments.

Six groups of twelve pots were filled with simulated test soil ($1200 \pm 100$ g per pot) at a range of pH values as indicated in Table 2. Four seedlings of *P. oleracea* were grown in each pot and irrigated with deionised water for three weeks at the same conditions of the first experiment.

A stock solution of 200 ppm Cr(VI) was prepared by diluting a concentrated solution of sodium chromate (at 10,000 ppm of Cr(VI)). Then, the stock solution was divided into six solutions and the pH of each was adjusted with either HCl or CaO to match the pH value of each set of the soil pots (6.0, 7.0, 7.3, 7.6, 8.0, and 9.0). Buffer solutions were not used in order not to add anions or cations which may alter the uptake of Cr(VI). During the experiment, periodic checks of soil pH were carried out in order to maintain consistency. When considerable vegetation and rooting growth were observed at each level of pH, the groups of twelve pots were divided into two sets of six-pot groups. The first six were irrigated with deionised water as a control and the other six were irrigated with 1200 mL of 200 ppm Cr(VI) with the matching pH at six doses over 12 days.

### 3.5. Sulphate Effect: Growth Experiments.

Six groups of five pots were filled with synthetic soil consisting of 15% v/v potting soil and 85% of Ajman normal soil ($1500 \pm 100$ g per pot). Four seedlings of *P. oleracea* were grown in each pot and irrigated with deionised water for three weeks at the same conditions of the previous experiments. When considerable vegetation and rooting growth were observed, each group of pots was irrigated with one of the solutions in

TABLE 2: Soil composition at different values of pH.

| pH of soil | Soil composition | | | |
| --- | --- | --- | --- | --- |
| | Pure silica (%) | Potting soil (70% organic matter content) (%) | Ajman soil (contains 42% CaCO$_3$) (%) | CaO (%) |
| $6.0 \pm 0.1$ | 90 | 10 | — | — |
| $7.0 \pm 0.1$ | 85 | 10 | 5 | — |
| $7.3 \pm 0.1$ | 80 | 10 | 10 | — |
| $7.6 \pm 0.1$ | 75 | 10 | 15 | — |
| $8.0 \pm 0.1$ | — | 10 | 90 | — |
| $9.0 \pm 0.1$ | — | 10 | 90 | ~0.1 |

Table 3 during a period of two weeks at six doses for a total of 1500 mL per pot. The plants were then harvested, separated into roots and shoots, washed, and dried.

### 3.6. Determination of Chromium Species.

After considerable plant growth, the plants were pulled out of the soil using a water stream to remove the wedged soil among the roots. The plants were rinsed with deionised water and the length of the roots was measured for each plant as an indicator of the growth of the plant. The plants were divided into leaves, stems, and roots, and samples were dried at 65°C for 48 hours up to a constant weight, then ground using mortar and pestle. The samples were analysed in either one of two methods: (i) nitric acid digestion to determine the total chromium using ICP-OES or (ii) alkaline digestion to determine Cr(VI) in the sample using EPA method 3060A [46]. The extracted Cr(VI) was reacted with 1,5-diphenylcarbazide (ACS Reagent, Sigma-Aldrich, Gillingham, UK) in the presence of sulphuric acid and analysed using a UV-visible spectrometer at a wavelength of 540 nm. Cr(III) was calculated by the subtraction of Cr(VI) from the total chromium in roots, leaves, and stems. Composite soil samples were taken from each pot, dried, sieved, and digested, and three replicates from each sample were analysed for Cr(VI) and total chromium.

### 3.7. Statistical Analysis.

SPSS software (Version 15, SPSS UK Ltd., Woking, Surrey) was used for statistical analysis. Microsoft Excel (Microsoft UK, Reading, Berkshire) was used for the preparation of the graphs and for simple statistical operations. Results are reported in tables and graphs as with 95% confidence intervals calculated using Student's *t*-test. Analysis of variance (ANOVA, post hoc Tukey's test) between the means is used to identify if there are significant differences between means.

TABLE 3: Concentrations of components of the irrigation solutions.

| Group # | # of pots | Cr(VI) as $Na_2CrO_4$ (ppm) | Sulphate as $Na_2SO_4$ (ppm) |
|---|---|---|---|
| 1 | 5 | 0 | 0 |
| 2 | 5 | 200 | 0 |
| 3 | 5 | 200 | 300 |
| 4 | 5 | 200 | 600 |
| 5 | 5 | 200 | 1200 |
| 6 | 5 | 200 | 1800 |

## 4. Conclusion

In this study, the effect of soil organic content, pH, and sulphate concentration on the uptake of Cr(VI) by *P. oleracea* was investigated. It was shown that as the organic matter content of the soil increases, the uptake of the chromium decreases due to the reduction of Cr(VI) to Cr(III) which has lower bioavailability. As for the pH effect, the results indicated that the uptake of chromium by *P. oleracea* is greatest at pH = 8, when the chromate anion is the dominant species. This speciation-dependent uptake suggested that the mechanism for the uptake of the chromate in *P. oleracea* resembles that of the sulphate anions. Hence, the effect of the sulphate concentration on the uptake of Cr(VI) by *P. oleracea* was investigated and it was shown that low concentrations (300–600 ppm) of the sulphate in the soil enhance the uptake of the metal by the plant while high concentrations (>600 ppm) inhibit it. In conclusion, this study further supports the hypothesis that *P. oleracea* is a suitable hyperaccumulator for remediation of chromium-polluted UAE soil, which has low organic content and an optimal pH at $7.9 \pm 0.1$ [7]. The process can be made more efficient by supplementing the soil with sulphate salts at low concentrations.

## Data Availability

All data used to support the findings of this study are included in the article.

## Disclosure

This paper represents the opinions of the authors and does not mean to represent the position or opinions of the American University of Sharjah.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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