



## Effects of cadmium uptake on growth and productivity of Chinese cabbage (*Brassica rapa* subsp. *pekinensis*) and pumpkin (*Cucurbita moschata* Duchesne) vegetables

Tumikia R. Sanga<sup>a,b,\*</sup>, Eliezer B. Mwakalapa<sup>c</sup>, Marco Mng'ong'o<sup>d</sup>, Kokusima Kalugendo<sup>b</sup>, Mohanadoss Ponraj<sup>a</sup>, Kenneth K. Maseka<sup>a</sup>

<sup>a</sup> Department of Biological Sciences, School of Mathematics and Natural Sciences, The Copperbelt University, P. O. Box 21692, Kitwe, Zambia

<sup>b</sup> Department of Applied Sciences, College of Science and Technical Education, Mbeya University of Science and Technology, P. O. Box 131, Mbeya, Tanzania

<sup>c</sup> Department of Natural Sciences, College of Science and Technical Education, Mbeya University of Science and Technology, P. O. Box 131, Mbeya, Tanzania

<sup>d</sup> Department of Crop Science and Horticulture, College of Agricultural Sciences and Technology, Mbeya University of Science and Technology, P.O. Box 131, Mbeya, Tanzania

### ARTICLE INFO

#### Keywords:

Cadmium  
Chinese cabbage  
Pumpkin leaves  
Growth effects  
Relative production

### ABSTRACT

Cadmium (Cd) is recognized as one of the most toxic elements to plants and humans when available in higher concentrations. In the present study, a pot experiment was carried out to investigate the effect of different Cd levels (0, 10, 20, 30, and 40 mg/kg) on the growth, production, and uptake of Cd using Chinese cabbage (*Brassica rapa* subsp. *pekinensis*) and pumpkin leaves (*Cucurbita moschata* Duchesne) vegetables. The study found significant differences ( $P < 0.05$ ) in all growth parameters in the studied vegetables. The Cd treatments resulted in decreasing number of leaves, shoot fresh weight, shoot dry weight, and total dry weight in both vegetables compared to the control. The total dry weight of Chinese cabbage was decreased by 6.79%, 48.42%, 5.88%, and 5.43%, at 10, 20, 30, and 40 mg/kg respectively compared to the control. In pumpkin leaves total dry weight was decreased by 28.95%, 28.95%, 18.42%, and 14.47% at 10, 20, 30, and 40 mg/kg respectively compared to the control. Increase and decrease effects on root length were observed for all the vegetables. Pumpkin leaves showed increased root length at 10 mg/kg (61.39%), 20 mg/kg (17.87%), and 30 mg/kg (70.03%) while at 40 mg/kg, there was a decrease in root length by 20.13% as compared to the control. The root length of Chinese cabbage decreased by 25.05%, 8.4%, and 7.26% at 20 mg/kg, 30 mg/kg, and 40 mg/kg compared to the control except at 10 mg/kg which was found to be higher by 0.6% compared to the control.

The Cd treatment in soil resulted in the increase of shoot Cd concentration in all the vegetables with maximum concentration observed at 20 mg/kg. Therefore, agricultural soil with elevated Cd levels will affect pumpkin and Chinese cabbage cultivation but also the consumption of such vegetables may result to toxic effects on human health.

### 1. Introduction

Potentially harmful elements (PHEs) are considered hazardous in the environment due to their persistence, bio-accumulative and toxicity nature [1]. Being persistent pollutants, PHEs accumulate in the environment and consequently contaminate the food chains [2]. Food crop contamination by PHEs is an issue of global concern due to the harmful health effects they pose to animals and humans through consumption [3].

Among various PHEs, cadmium (Cd) occupies the top position in terms of hazardous effects posed to plants and human health [4]. Cd is a non-essential trace metal, which is highly toxic to nearly all living organisms [5]. The toxicity of Cd is a serious threat to the global agricultural system [6]. This element has become an extremely serious concern for food safety, particularly in developing countries [7]. Also, it is recognized as one of the most toxic elements, which is easily taken up by plants even though it has no identified role in plant metabolism [8,9].

The natural sources of Cd are volcanic emissions, forest fires, rock

\* Corresponding author. Department of Biological Sciences, School of Mathematics and Natural Sciences, The Copperbelt University, P. O. Box 21692, Kitwe, Zambia.

E-mail address: [tumikiasanga@gmail.com](mailto:tumikiasanga@gmail.com) (T.R. Sanga).

<https://doi.org/10.1016/j.jafr.2023.100744>

Received 20 May 2023; Received in revised form 9 August 2023; Accepted 17 August 2023

Available online 19 August 2023

2666-1543/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

dust, and flooding [10,11]. The main anthropogenic sources of Cd are phosphate fertilizers, sewage sludge, solid municipal waste, mining and smelting, incineration fumes from cadmium-containing products, automobile emissions, coal burning, and metal manufacturing industries [7, 11–14].

Soil contamination by PHEs like Cd and their uptake and accumulation by plants interfere with the life cycle of plants and therefore reduce crop yields. Contamination of the food chain by Cd may pose a risk to human life [15,16]. It is well known that food is the main source of Cd intake in the non-smoking population [17] whereas foods from plants are generally considered to be the main source of Cd exposure in the population [18].

Vegetables are important source of food and nutrition [19]. Leafy vegetable consumption has been identified as a dominant exposure pathway of Cd in the human body [18]. The increasing concentration of Cd in the food chain is posing a threat to the growth of plants as well as human life [16,19]. According to Joint FAO/WHO, leafy vegetables with accumulated Cd concentrations >0.2 mg/kg (fresh weight) are harmful to humans [20]. The accumulation of Cd causes a wide range of deleterious effects on plants [18]. Different studies have reported that Cd affects plant growth, development, and biomass yield, and it can cause plant death due to its toxic effects on different metabolism and physiological processes [17,21–23].

In recent decades, the contamination of plants by Cd has gained much attention. Various studies have been conducted in different countries to determine Cd effect on plant growth. Several studies have reported the effect of Cd on the growth of medicinal plants [4,24,25]. Also, the effects of Cd on different food crops like sorghum [26], Chili [27], *Cucurbita pepo* [28], pea, wheat, and tomato [29], spinach, fenugreek and coriander [19] have been reported. Despite of an enormous number of studies conducted on Cd, limited studies have focused on pumpkin leaves and Chinese cabbage. Therefore, the present study aimed to determine the effect of different concentrations of Cd on growth, Cd accumulation in the shoot, and production of Chinese cabbage (*Brassica rapa* subsp. *pekinensis*) and pumpkin leaves (*Cucurbita moschata* Duchesne).

## 2. Material and methods

### 2.1. Soil sampling and analysis

The pot experiment was conducted in a screen house at Mbeya University of Science and Technology, Mbeya, Tanzania (latitude 8°56'36.8"S, longitude 33°25'4.0"E, and altitude 1638 m above the sea level) from September to November 2021. The topsoil (0–20 cm) was collected from Mount Rungwe Nature Forest Reserve, Mbeya (latitude 9°10.565'S, longitude 33°37.870'E, and altitude 1692 m above sea level). The collected soil sample was air dried and passed through a 3.5 mm sieve and utilized as a medium to grow the two selected vegetables: pumpkin leaves and Chinese cabbage. Before the pot experiment, the physical and chemical properties of the soil were determined. The pH of the soil was determined according to the method described by Okalebo et al. [30]. Electrical conductivity (EC), cation exchange capacity (CEC), soil texture, soil organic matter (SOM) and soil texture were determined by methods described by Estefan et al. [31]. Nutrients like nitrogen (N), phosphorus (P), and potassium (K) were determined following procedures described by Motsara and Roy [32]. The concentration of Cd was measured by Atomic Absorption Spectrometer (AAS) after the digestion of soil using hydrochloric acid (HCl) and nitric acid (HNO<sub>3</sub>) in ratio 3:1 as described by Sharma et al. [33].

### 2.2. Experimental design

The experiment was arranged in a randomized block design as described by Koller et al. [34]. In total 30 pots were observed (2 vegetables x 5 Cd treatments x 3 replicates). About 1 kg portions of the soil

were transferred to 2-L plastic pots (14.5 cm in diameter and 16 cm in height). The soils were then spiked with 5 Cd treatment levels (0 mg/kg (control), 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg) using CdCl<sub>2</sub>·H<sub>2</sub>O as a source in the form of a solution. The solution was poured evenly onto the soil surface in pots. The soils were irrigated with water for 2 days so that Cd can be mixed thoroughly in the soil. The solution that exuded from the pot was collected at the bottom of the pot using a plastic plate and poured back into the soil to avoid any potential loss.

Then four seeds of each vegetable were sown per pot. Good agronomic practices were carried out on the plants. All pots were regularly irrigated with tap water. In the second week from planting, the plants were thinned to two seedlings per pot. The number of leaves was recorded on a weekly basis. Plants were harvested after 42 days of growth. At the end of the experiment, the samples of each vegetable were collected from each treatment for plant growth, production, and cadmium determination. Plants were gently removed from the pots and the roots and shoots were further separated, rinsed with tap water, carefully washed with distilled water, and wiped with tissue paper.

### 2.3. Determination of plant growth parameters

Plant growth and yield parameters such as root length, stem length, shoot and root fresh weight were determined on the same day of harvesting. Shoots and roots were then dried in an oven at 65 °C to constant weight. The dry weight of shoots and roots was then measured.

### 2.4. Cadmium analysis

Analysis of Cd in the shoots of vegetables was carried out in the soil laboratory, at Sokoine University of Agriculture, Tanzania. The dried plant shoot samples were ground to a fine powder and passed through a 2 mm sieve. Samples were weighed, placed in flasks, and digested using nitric acid (HNO<sub>3</sub>) and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) in ratio 5:4 as described by Pequerul et al. [35]. HNO<sub>3</sub> (69%) was added and stirred until all the material was wet, followed by the addition of H<sub>2</sub>O<sub>2</sub> (30%). The mixture was heated on a hot plate at 100 °C for 8 min. The solution was then cooled and filtered into a 25 ml volumetric flask using (Whatman filter No.42) and diluted to a final volume of 25 ml using deionized water and stored in a plastic bottle and kept at 4 °C until further analysis. Cd concentration was measured by Atomic Absorption Spectrometer (AAS, Thermo SCIENTIFIC, iCE 3000, UK).

### 2.5. Relative production

The effect of Cd on dry matter production was obtained using the following equation as described by Cannata et al. [36].

$$RP (\%) = \frac{\text{dry matter produced using a given metal content}}{\text{dry matter produced with metal absent}} \times 100$$

### 2.6. Data management and statistical analysis

Data management and processing were carried out using Microsoft Excel 2016. Statistical analysis of the data was performed using Jamovi statistical software (1.2.5). Growth parameters between vegetables and Cd treatment levels were compared using a Two-Way Analysis of Variance (ANOVA). Tukey Post Hoc analysis was used to test the existence of significant differences ( $P < 0.05$ ). Plots were prepared using Minitab 14 and Origin Professional software (6.0).

## 3. Results and discussion

### 3.1. Physicochemical properties of the soil collected for pot experiment

The data on the physicochemical properties of soil collected for the pot experiment is shown in Table 1.

**Table 1**  
Physicochemical properties of soil collected for pot experiment.

Parameters	Values
Soil pH	5.46
OC (%)	9.85
EC (µs/cm)	235.00
CEC (Cmol/kg)	9.36
N (%)	0.99
P (mg/kg)	3.46
K (Cmol/kg)	1.04
Cd (mg/kg)	1.50
%clay	15.76
%silt	4.00
%sand	80.24
Texture class	Sandy loam

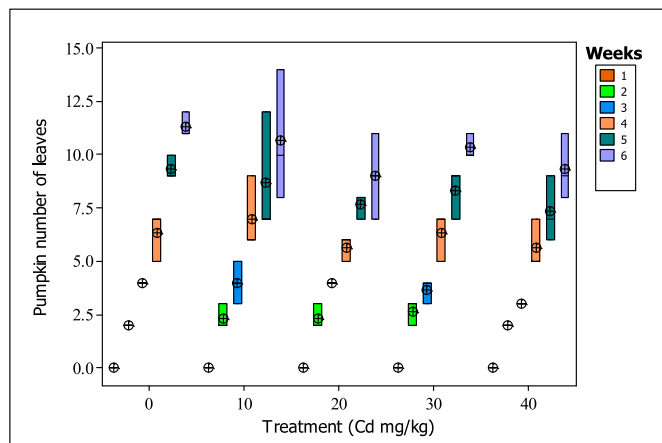
### 3.2. Effects of Cd on the growth of leafy vegetables

#### 3.2.1. Effects of Cd on the number of leaves

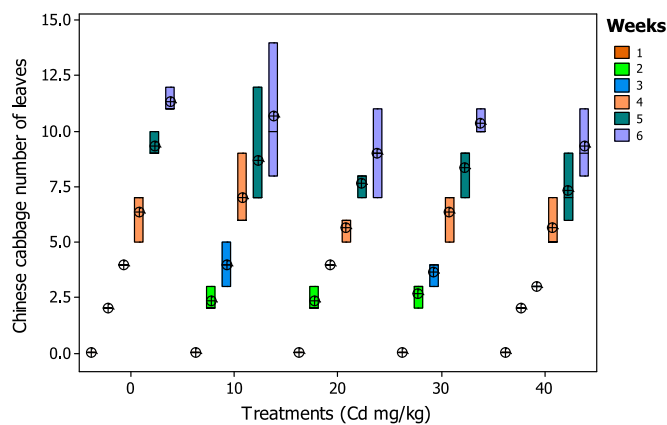
The average data obtained for the number of leaves at different weeks are shown in Figs. 1 and 2 for the pumpkin leaves and Chinese cabbage. At week 6, the number of pumpkin leaves at 20 mg/kg and 40 mg/kg of Cd treatment were equivalent to the control while they were reduced by 13.4% and 6.6% at 10 mg/kg and 30 mg/kg Cd treatment respectively compared to the control treatment. The number of leaves in Chinese cabbage declined under different treatments. They were decreased by 5.82% (10 mg/kg), 20.56% (20 mg/kg), 8.83% (30 mg/kg), and 9.33% (40 mg/kg) compared to that of control. Several studies have reported the decrease in the number of leaves in plants grown under Cd stress. For example, in blackberry nightshade and tomato [37], in Chili [27], and in rocket plants [38]. Cadmium is known to affect cell division in plants [38–40]. Cell division produces more cells in each leaf layer, which allows more leaves to be formed from the shoot apical meristem. Therefore, the reduced number of leaves in vegetables exposed to Cd may be attributed to the inhibition effect of Cd on cell division in the shoot tip.

#### 3.2.2. Effect of Cd on shoot fresh weight and shoot dry weight of vegetables

The growth parameters of vegetables are summarized in Table 2. Exposure of vegetables to Cd stress resulted in reduced shoot fresh weight in both Chinese cabbage and pumpkin leaves as shown in Table 2 and Fig. 3. Significant differences ( $P < 0.05$ ) were observed between the fresh weight of Chinese cabbage and pumpkin leaves grown in soils treated with different levels of Cd. A significant decrease ( $P < 0.05$ ) in shoot fresh weight of Chinese cabbage was observed at 20 mg/kg



**Fig. 1.** Effect of different treatment levels of Cd (0, 10, 20, 30, and 40 mg/kg) on the number of pumpkin leaves. Values are means of three replicates ± standard deviation.



**Fig. 2.** Effect of different treatment levels of Cd (0, 10, 20, 30, and 40 mg/kg) on the number of Chinese cabbage leaves. Values are means of three replicates ± standard deviation.

relative to the control. Shoot fresh weights of Chinese cabbage were decreased by 13.87%, 56.66%, 26.36%, and 22.08%, at 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg respectively compared to the control. Shoot fresh weight of pumpkin leaves decreased by 25.36%, 21.08%, and 18.14% at 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg respectively compared to the control. Shoot dry weights of leafy vegetables grown on soils treated with different levels of Cd are shown in Table 2 and Fig. 4. There was a significant difference ( $P < 0.001$ ) between shoot dry weight of Chinese cabbage and pumpkin leaves. In Chinese cabbage, decrease in shoot dry weights were observed by 7.58%, 48.82%, 7.58%, and 6.64% at 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg respectively compared to the control. Pumpkin leaves showed a decreased shoot dry weight by 30.66%, 32.85%, 23.36%, and 18.25% at 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg respectively compared to the control.

These findings are in line with some of the earlier studies. For example [28], observed the decrease in shoot fresh weight of *Curcubita pepo* plants and [41] reported the decrease in shoot fresh weight of rape cultivated in Cd contaminated growth media. Zhang et al. [42] found the decrease in shoot dry weight of muskmelon plants grown under Cd stress. Cadmium was also reported to decrease the shoot and total biomass of radish plants [43]. Physiological and biochemical processes are known to be inhibited by Cd toxicity resulting in a decline in crop yield [44]. Therefore, the decrease in the fresh weight of the shoot may be attributed to the effect of Cd on the transpiration and water content of the shoot [45]. The reduction in shoot dry weight of vegetables under Cd stress may be attributed to reduced growth of vegetables resulting from Cd effects on respiration, water and nutrient uptake, nitrogen and carbon assimilation, photosynthesis, and antioxidant activities [7,40, 45–47].

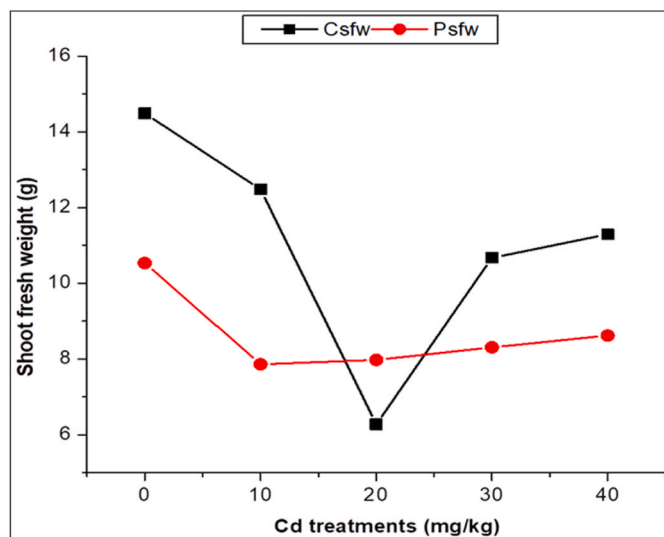
#### 3.2.3. Effect of Cd on the fresh and dry weight of root

The root fresh weights of leafy vegetables are shown in Table 2 and Fig. 5. Significant differences ( $P < 0.001$ ) were observed in root fresh weight between Chinese cabbage and pumpkin leaves grown in soil treated with different levels of Cd. Exposing leaf vegetables to different levels of Cd resulted in the decrease of root fresh weight of Chinese cabbage by 10.13%, 65.4%, 48.68%, and 44.34% at 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg respectively. Decreases in root fresh weight of pumpkin leaves were observed at 10 mg/kg and 20 mg/kg by 6.82% and 5.3% respectively and it was found to increase by 53.79% and 17.42% at 30 mg/kg and 40 mg/kg respectively in relation to the control. The decrease in root fresh weight of Chinese cabbage may be due to the decreased water content of the root due to the inhibition effect of Cd on transpiration. Transpiration plays an important role in maintaining the water content of the root [45,48].

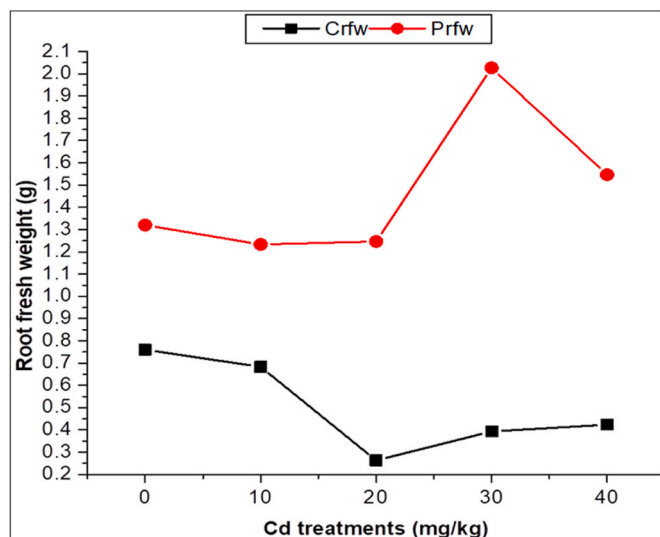
**Table 2**  
Effects of different Cd treatments on the growth of leafy vegetables.

Vegetable	Cd treatments (mg/kg)	sfw (g)	sdw (g)	r fw (g)	r dw (g)	rl (cm)	sl (cm)	tdw (g)
Chinese cabbage	0	14.49 ± 2.630 <sup>a</sup>	2.11 ± 0.412 <sup>a</sup>	0.76 ± 0.366 <sup>a</sup>	0.0967 ± 0.055 <sup>a</sup>	11.43 ± 3.371 <sup>a</sup>	1.17 ± 0.058 <sup>a</sup>	2.21 ± 0.448 <sup>a</sup>
	10	12.48 ± 5.368 <sup>ab</sup>	1.95 ± 0.895 <sup>a</sup>	0.683 ± 0.307 <sup>a</sup>	0.11 ± 0.04 <sup>a</sup>	11.5 ± 2.667 <sup>a</sup>	1.17 ± 0.115 <sup>a</sup>	2.06 ± 0.899 <sup>a</sup>
	20	6.28 ± 1.164 <sup>b</sup>	1.08 ± 0.167 <sup>a</sup>	0.263 ± 0.031 <sup>a</sup>	0.0667 ± 0.006 <sup>a</sup>	8.57 ± 3.415 <sup>a</sup>	1.03 ± 0.058 <sup>a</sup>	1.14 ± 0.170 <sup>a</sup>
	30	10.67 ± 0.901 <sup>ab</sup>	1.95 ± 0.087 <sup>a</sup>	0.39 ± 0.098 <sup>a</sup>	0.13 ± 0.006 <sup>a</sup>	10.47 ± 2.483 <sup>a</sup>	1.1 ± 0 <sup>a</sup>	2.08 ± 0.081 <sup>a</sup>
	40	11.29 ± 2.977 <sup>ab</sup>	1.97 ± 0.513 <sup>a</sup>	0.423 ± 0.065 <sup>a</sup>	0.12 ± 0.04 <sup>a</sup>	10.6 ± 2.879 <sup>a</sup>	1.1 ± 0.1 <sup>a</sup>	2.09 ± 0.552 <sup>a</sup>
Pumpkin leaves	0	10.53 ± 2.452 <sup>a</sup>	1.37 ± 0.289 <sup>a</sup>	1.32 ± 0.370 <sup>ab</sup>	0.15 ± 0.023 <sup>a</sup>	26.13 ± 8.909 <sup>bc</sup>	8.83 ± 1.021 <sup>ab</sup>	1.52 ± 0.297 <sup>a</sup>
	10	7.86 ± 0.696 <sup>a</sup>	0.95 ± 0.150 <sup>a</sup>	1.23 ± 0.151 <sup>b</sup>	0.13 ± 0.04 <sup>a</sup>	42.17 ± 14.585 <sup>ab</sup>	7.17 ± 0.252 <sup>bc</sup>	1.08 ± 0.185 <sup>a</sup>
	20	7.97 ± 2.423 <sup>a</sup>	0.92 ± 0.196 <sup>a</sup>	1.25 ± 0.329 <sup>b</sup>	0.16 ± 0.0153 <sup>a</sup>	30.8 ± 5.323 <sup>abc</sup>	7.97 ± 1.007 <sup>abc</sup>	1.08 ± 0.210 <sup>a</sup>
	30	8.31 ± 1.920 <sup>a</sup>	1.05 ± 0.197 <sup>a</sup>	2.03 ± 0.287 <sup>a</sup>	0.19 ± 0.023 <sup>a</sup>	44.43 ± 4.965 <sup>a</sup>	6.73 ± 0.321 <sup>c</sup>	1.24 ± 0.204 <sup>a</sup>
	40	8.62 ± 0.785 <sup>a</sup>	1.12 ± 0.145 <sup>a</sup>	1.55 ± 0.085 <sup>ab</sup>	0.18 ± 0.017 <sup>a</sup>	20.87 ± 1.484 <sup>c</sup>	9 ± 1.3 <sup>a</sup>	1.3 ± 0.153 <sup>a</sup>

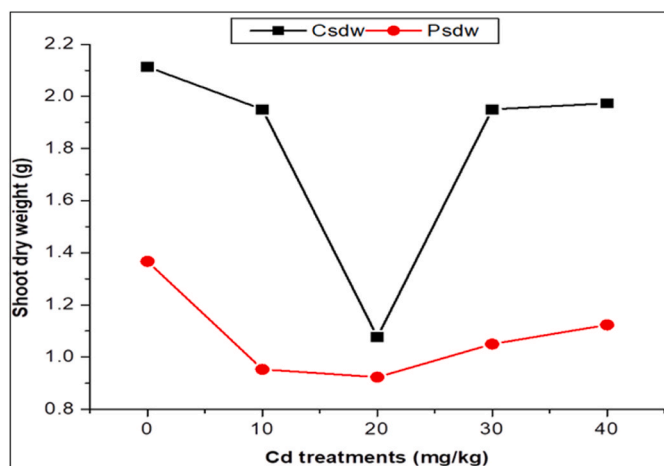
Note: sfw (shoot fresh weight), sdw (shoot dry weight), rfw (root fresh weight), rdw (root dry weight), rl (root length), sl (stem length), tdw (total dry weight). Values are means ± Standard deviation (n = 3). Mean values for the same vegetable in the same column sharing the same superscript letter(s) under different Cd treatments (0, 10, 20, 30, 40 mg/kg) do not differ significantly according to Tukey Post Hoc test at P < 0.05.



**Fig. 3.** Effects of different Cd treatments on shoot fresh weight of Chinese cabbage (Csfw) and pumpkin leaves (Psfw) exposed to different treatments of Cd (0, 10, 20, 30, and 40 mg/kg). Values are means of three replicates.



**Fig. 5.** Effects of different Cd treatments on root fresh weight of Chinese cabbage (Cr fw) and pumpkin leaves (Pr fw) exposed to different treatments of Cd (0, 10, 20, 30, and 40 mg/kg). Values are means of three replicates.



**Fig. 4.** Effects of different Cd treatments on shoot dry weight of Chinese cabbage (Csdw) and pumpkin leaves (Psdw) exposed to different treatments of Cd (0, 10, 20, 30, and 40 mg/kg). Values are means of three replicates.

Root dry weights of leafy vegetables are shown in Table 2 and Fig. 6. There were significant differences (P < 0.001) observed in root dry weight of Chinese cabbage and pumpkin leaves grown in soil treated with different levels of Cd. The root dry weight of Chinese cabbage increased at 10 mg/kg (13.75%), 30 mg/kg (61.86%), and 40 mg/kg (23.71%) and was found to be reduced at 20 mg/kg (31.24%) compared to the control. In pumpkin leaves, the root dry weight increased by 6.67%, 26.67%, and 20% at 20 mg/kg, 30 mg/kg, and 40 mg/kg treatments and reduced at 10 mg/kg by 13.33% relative to the control. An increase in root dry weight was observed in the study carried out by Xin et al. [43] in radish and by Zhang et al. [42] in muskmelon plants grown under Cd stress compared to the control. The increase in root dry weight experienced by vegetables in this study could be due to the indirect effect of essential trace elements in the dilution of Cd concentration by increasing plant biomass [7,49].

**3.2.4. Effect of Cd on total dry weight**

Exposure of vegetables to Cd stress resulted in reduced total dry weight in both Chinese cabbage and pumpkin leaves as shown in Table 2 and Fig. 7. Significant differences (P < 0.001) were observed between the total dry weight of Chinese cabbage and pumpkin leaves grown in soils treated with different levels of Cd. The total dry weight of Chinese cabbage was decreased by 6.79%, 48.42%, 5.88%, and 5.43%, at 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg respectively compared to the

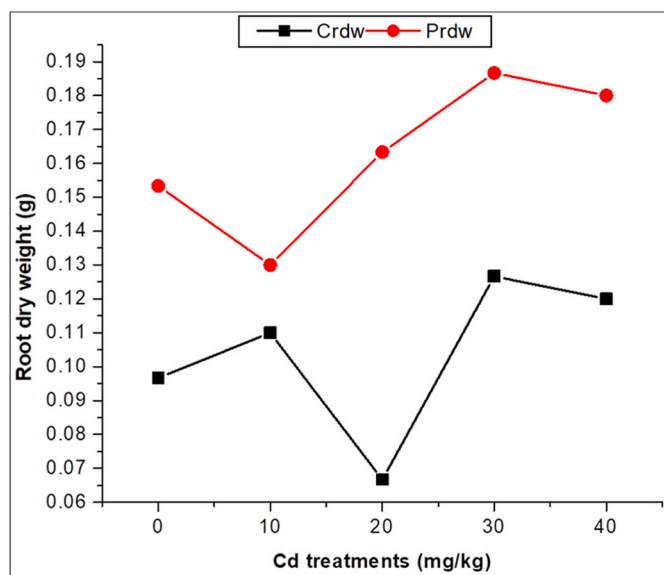


Fig. 6. Effects of different Cd treatments on root dry weight of Chinese cabbage (Crdw) and pumpkin leaves (Prdw) exposed to different treatments of Cd (0, 10, 20, 30, and 40 mg/kg). Values are means of three replicates.

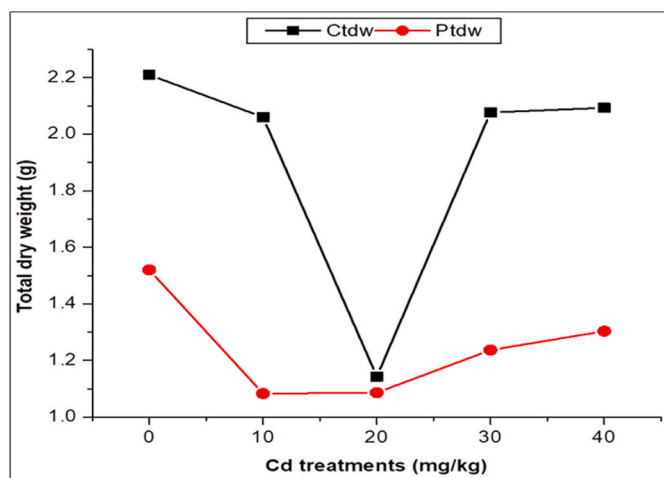


Fig. 7. Effects of different Cd treatments on total dry weight of Chinese cabbage (Ctdw) and pumpkin leaves (Ptdw) exposed to different treatments of Cd (0, 10, 20, 30, and 40 mg/kg). Values are means of three replicates.

control. Total dry weight of pumpkin leaves was decreased by 28.95%, 28.95%, 18.42%, and 14.47% at 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg respectively compared to the control. The reduction in total dry weight under Cd stress may be attributed to the reduced growth of vegetables resulting from Cd effects on respiration, water and nutrient uptake, nitrogen and carbon assimilation, photosynthesis, and antioxidant activities [7,40,45–47].

### 3.2.5. Effect of Cd on root and stem length

The effect of different Cd treatments on the root length of leafy vegetables is shown in Fig. 8 and Table 2. There was a significant difference ( $P < 0.001$ ) in root length between Chinese cabbage and pumpkin leaves. A significant increase ( $P < 0.05$ ) in the root length of pumpkin leaves was observed at 30 mg/kg relative to the control. Pumpkin leaves showed increased root length at 10 mg/kg (61.39%), 20 mg/kg (17.87%), and 30 mg/kg (70.03%) while at 40 mg/kg, there was a decrease in root length by 20.13% as compared to the control. The root length of Chinese cabbage decreased by 25.05%, 8.4%, and 7.26% at 20

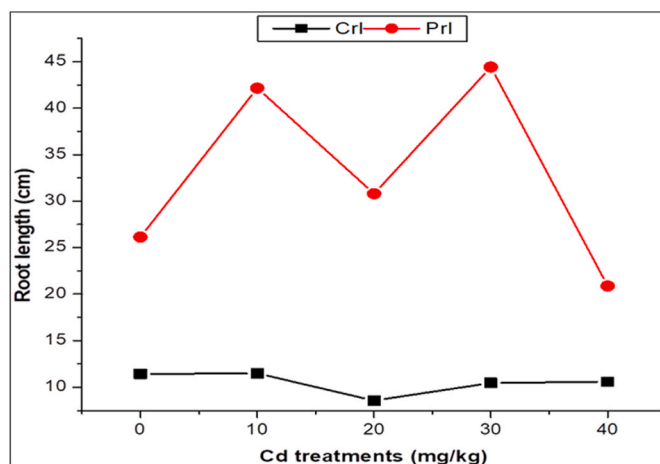


Fig. 8. Effects of different Cd treatments on root length of Chinese cabbage (Crl) and pumpkin leaves (Prl) exposed to different treatments of Cd (0, 10, 20, 30, and 40 mg/kg). Values are means of three replicates.

mg/kg, 30 mg/kg, and 40 mg/kg compared to the control except at 10 mg/kg which was found to be higher by 0.6% compared to the control.

The effect of different Cd treatments on stem length of leafy vegetables is shown in Table 2. Significant differences ( $P < 0.001$ ) were observed in stem length between Chinese cabbage and pumpkin leaves grown in soil treated with different levels of Cd. The reductions in stem length of Chinese cabbage plants because of treatment with Cd were observed at 20 mg/kg (11.97%), 30 mg/kg (3.42%), and 40 mg/kg (5.99%) compared to the control. Moreover, similar stem length was observed at 10 mg/kg and control treatment. The stem length of pumpkin leaves was reduced by 18.8%, 9.74%, and 23.78% at 10 mg/kg, 20 mg/kg, and 30 mg/kg respectively, and increased by 1.93% at 40 mg/kg compared to the control. A significant reduction ( $P < 0.05$ ) in stem length of pumpkin leaves was observed at 30 mg/kg by 23.78% compared to the control. Similar observation was reported by Hassan et al. [26] in stem length of sorghum and Piršelová et al. [50] observed an increase in the length of shoot of faba bean grown under Cd stress. Plants adapt to different types of stress conditions to ensure their existence through different tolerance mechanisms. One of the means by which plants respond to stress includes the synthesis of phytohormones. Therefore, the increase in root and shoot length observed in Cd exposed plants in this study may be due to the synthesis of Indole acetic acid (IAA) which increased root and stem growth to reduce the effect of Cd in vegetables [7,47,49]. IAA is a plant growth hormone that plays a significant role during different stress conditions [51]. The increase in the IAA level in shoot and roots were observed by Labidi et al. [28] following exposure of Cd to *Cucurbita pepo* which stimulated root growth compared to the control.

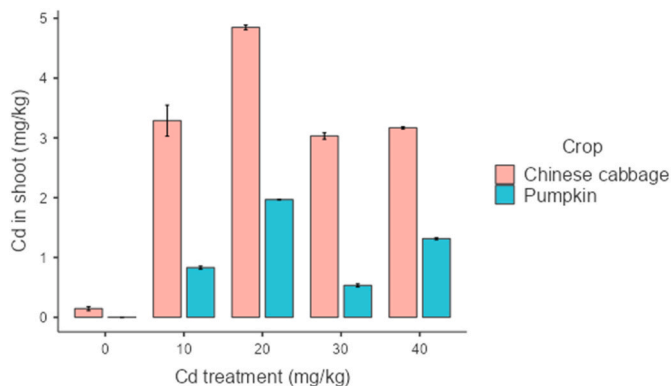
### 3.3. Effects of different Cd treatments on shoot Cd uptake

Plants grown in contaminated soil may not only uptake essential elements but also non-essential elements like Cd. The mean concentrations of Cd in shoots of pumpkin leaves and Chinese cabbage cultivated in different Cd soil treatments are shown in Table 3 and Fig. 9. The mean concentrations of Cd showed variation at different treatment levels. Treatment of Cd in the soil led to an increase in shoot Cd concentration of studied vegetables, however, the increase was not progressive. The uptake of Cd was significantly higher ( $P < 0.001$ ) in Chinese cabbage compared to pumpkin vegetables. The differences in shoot Cd concentrations between vegetables under different Cd treatment levels and the control were significant at ( $P < 0.05$ ). The maximum shoot Cd accumulations were 4.8471 mg/kg and 1.9688 mg/kg in Chinese cabbage and pumpkin vegetables respectively, both were observed at 20 mg/kg

**Table 3**  
Effect of different Cd treatments on shoot Cd accumulation of leafy vegetables.

Cd treatments (mg/kg)	Pumpkin leaves	Chinese cabbage
	Cd (mg/kg dw)	Cd (mg/kg dw)
0	ND	0.1453 ± 0.082 <sup>c</sup>
10	0.8306 ± 0.059 <sup>c</sup>	3.2882 ± 0.634 <sup>b</sup>
20	1.9688 ± 0.01 <sup>a</sup>	4.8471 ± 0.097 <sup>a</sup>
30	0.5342 ± 0.063 <sup>c</sup>	3.032 ± 0.131 <sup>b</sup>
40	1.3153 ± 0.042 <sup>b</sup>	3.1686 ± 0.042 <sup>b</sup>

Note: ND (not detected) and dw (dry weight). Mean values for the same vegetable in the same column sharing the same superscript letter(s) under different Cd treatments (0, 10, 20, 30, 40 mg/kg) do not differ significantly according to Tukey Post Hoc test at  $P < 0.05$ .



**Fig. 9.** Effect of different treatment levels of Cd (0, 10, 20, 30, and 40 mg/kg) on shoot Cd accumulation of leafy vegetables.

of Cd treatment. In general, the order of uptake was  $20 > 40 > 10 > 30 > 0$  for pumpkin leaves and  $20 > 10 > 40 > 10 > 0$  for Chinese cabbage as shown in Fig. 9. Chinese cabbage vegetables had 3.95, 2.46, 5.67, and 2.41-times higher shoots Cd concentration than pumpkin vegetable at 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg treatments respectively.

Metal uptake in plants can be affected by several factors. The accumulation of Cd by plants is closely related to the availability of Cd than to the total amount of Cd present in the soil [52]. In addition to the total amount of Cd present in the soil other factors that may have contributed to these results include different plant species used in this study and ionic pressure of the soil due to different Cd treatments. Haider et al. [7] explained that the lower the ionic pressure of the growth medium the higher the metal content of the plant. Also, different plant species have different accumulation patterns of Cd [52,53] as found in this study that Chinese cabbage accumulated Cd more than pumpkin leaves.

### 3.4. Relative production

The relative production of vegetables studied is shown in Table 4. The production of shoots in Chinese cabbage were decreased by 7.58%, 48.82%, 7.58%, and 6.64% at 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg treatment respectively compared to the control treatment. Increases in the production of root was observed at 10 mg/kg, 30 mg/kg,

**Table 4**  
Effect of different Cd treatments on the production of leafy vegetables.

Cd treatments (mg/kg)	Chinese cabbage				Pumpkin leaves			
	Sdw (g)	RP (%)	Rdw (g)	RP (%)	Sdw (g)	RP (%)	Rdw (g)	RP (%)
0	2.1133	100	0.0967	100	1.3667	100	0.1533	100
10	1.95	92.42	0.11	113.75	0.9533	69.75	0.13	84.8
20	1.0767	51.18	0.0667	68.98	0.9233	67.56	0.1633	106.52
30	1.95	92.42	0.1267	131.02	1.05	76.83	0.1867	121.79
40	1.9733	93.36	0.12	124.1	1.1233	82.19	0.18	117.42

and 40 mg/kg by 13.75%, 31.02%, and 24.1% while it was decreased at 20 mg/kg by 31.02% relative to the control. The observed shoot production in pumpkin leaves decreased by 30.25%, 32.44%, 23.17%, and 17.81% at 10 mg/kg, 20 mg/kg, 30 mg/kg, and 40 mg/kg treatment respectively compared to the control. The production of root increased at 20 mg/kg, 30 mg/kg, and 40 mg/kg by 6.52%, 21.79%, and 17.42% respectively while the decrease was found at 10 mg/kg by 15.2% relative to the control treatment. The decrease in the shoot production of vegetables under Cd stress relative to control may be attributed to reduced growth of vegetables resulting from Cd effects on respiration, water and nutrient uptake, nitrogen and carbon assimilation, photosynthesis, and antioxidant activities [7,40,45–47].

## 4. Conclusions and recommendation

The findings of this study have revealed that the growth and production of vegetables were affected by Cd treatments. It can be concluded that, the uptake of Cd in the studied vegetables affected their normal growth and production. This study revealed that Chinese cabbage accumulated more Cd as compared to pumpkin leaves, therefore it is suggested that any agricultural soil suspected to have high concentrations of Cd will not be suitable for their use in the cultivation of pumpkin leaves and Chinese cabbage for human consumption or animal feed due to accumulation in the shoots of both vegetables.

This study also revealed that all the studied parameters in Chinese cabbage vegetable were extremely reduced at 20 mg/kg treatment of Cd where the maximum Cd accumulation was observed in shoots. Therefore, this species might be a suitable candidate for Cd phytotoxicity and remediation studies. This is a pilot study with limitations such as; a few parameters were measured (growth, productivity, and shoot cadmium level), two plant species were used with limited growing period (42 days). An in-depth investigation of morphological, anatomical, physiological, biochemical, and molecular effects of Cd needs to be carried out to contribute to a better understanding of Cd toxicity in plants. Also, the tolerance mechanisms of vegetables under Cd stress need further studies. In addition, an extension of the growing period and continuous measurement of Cd levels and effects at different plant stages might help to identify the plant stage at which maximum uptake of Cd occurs. Furthermore, the determination of Cd in roots might help to determine the phytoremediation potential of the studied vegetable species.

## Funding

The present study was financially supported by The Copperbelt University Africa Centre of Excellence for Sustainable Mining (CBU-ACESM). The authors are grateful to the management of Mbeya University of Science and Technology (MUST), Mbeya, Tanzania for providing the necessary facilities to undertake the study.

## Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author upon request.

## Author contributions

T.R.S, E.B.M, M.P, and K.K.M; Conceptualization and methodology, T.R.S, E.B.M, M.M., K.K., M.P, and K.K.M; writing—original draft preparation, T.R.S, E.B.M, M.M., K.K., M.P, and K.K.M; writing—review and editing, E.B.M, M.P, and K.K.M. Supervision. All authors have read and agreed to the published version of the manuscript.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgments

The authors wish to thank all laboratory technicians at Sokoine University of Agriculture (SU)-Tanzania and Mbeya University of Science and Technology (MUST)-Tanzania, for their technical and guidance support during lab work of this study.

## References

- [1] H. Ali, E. Khan, Trophic transfer, bioaccumulation, and biomagnification of non-essential hazardous heavy metals and metalloids in food chains/webs—concepts and implications for wildlife and human health, *Hum. Ecol. Risk Assess.* (2018), <https://doi.org/10.1080/10807039.2018.1469398>.
- [2] H. Ali, E. Khan, I. Ilahi, Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation, *J. Chem.* (2019), <https://doi.org/10.1155/2019/6730305>.
- [3] M.M. Onakpa, A.A. Njan, O.C. Kalu, A review of heavy metal contamination of food crops in Nigeria, *Annals of Global Health* 84 (3) (2018) 488–494.
- [4] G. Zhu, H. Xiao, Q. Guo, Z. Zhang, J. Zhao, D. Yang, Effects of cadmium stress on growth and amino acid metabolism in two Compositae plants, *Ecotoxicol. Environ. Saf.* 158 (2018) 300–308, <https://doi.org/10.1016/j.ecoenv.2018.04.045>, 2018.
- [5] T. Sterckeman, S. Thomine, Mechanisms of cadmium accumulation in plants, *Crit. Rev. Plant Sci.* 39 (4) (2020) 322–359, <https://doi.org/10.1080/07352689.2020.1792179>.
- [6] M. Asgher, M.I.R. Khan, N.A. Anjum, N.A. Khan, Minimising toxicity of cadmium in plants—role of plant growth regulators, *Protoplasma* 252 (2) (2015) 399–413, <https://doi.org/10.1007/s00709-014-0710-4>.
- [7] F.U. Haider, C. Liqun, J.A. Coulter, S.A. Cheema, J. Wu, R. Zhang, M. Wenjun, M. Farooq, Cadmium toxicity in plants: impacts and remediation strategies, *Ecotoxicol. Environ. Saf.* 211 (2021) (2021), 111887, <https://doi.org/10.1016/j.ecoenv.2020.111887>.
- [8] Z. Huang, X. Pan, P. Wu, J. Han, Q. Chen, Heavy metals in vegetables and the health risk to population in Zhejiang, China, *Food Control* 36 (2014) 248–252, <https://doi.org/10.1016/j.foodcont.2013.08.036>, 2014.
- [9] R. Morgan, *Soil, Heavy metals and human health*, in: E. Brevic, L. Burgess (Eds.), *Soils and Human Health*, CRC Press, 2013, pp. 59–82.
- [10] S. Gunalan, K.R. Vijayalatha, T. Anitha, Heavy metals and its impact in vegetable crops, *Int. J. Chem. Stud.* 7 (1) (2018) 1612–1621, <http://www.chemjournal.com/archives/2019/vol7issue1/PartAB/7-1-229-742.pdf>.
- [11] M.J. McLaughlin, B.R. Singh, *Cadmium in Soils and Plants*, Springer, 1999, <https://doi.org/10.1007/978-94-011-4473-5.1>.
- [12] A. Kabata-Pendias, *Trace Elements in Soils and Plants (Fourth Ed)*, CRC Press, New York, 2011.
- [13] S. Kumar, S. Prasad, K.K. Yadav, M. Shrivastava, Hazardous heavy metals contamination of vegetables and food chain: role of sustainable remediation approaches—A review, *Environ. Res.* 179 (2019), 108792, <https://doi.org/10.1016/j.envres.2019.108792>, 2019.
- [14] K. Rehman, F. Fatima, I. Waheed, M.S.H. Akash, Prevalence of exposure of heavy metals and their impact on health consequences, *J. Cell. Biochem.* 119 (1) (2018) 157–184, <https://doi.org/10.1002/jcb.26234>.
- [15] T. Abedi, A. Mojiri, Cadmium uptake by wheat (*Triticum aestivum* L.): an overview, *Plants* 9 (4) (2020) 1–14, <https://doi.org/10.3390/plants9040500>.
- [16] Y. Huang, C. He, C. Shen, J. Guo, S. Mubeen, J. Yuan, Z. Yang, Toxicity of cadmium and its health risks from leafy vegetable consumption, *Food Funct.* (2017), <https://doi.org/10.1039/c6fo01580h>.
- [17] S. Qin, H. Liu, Z. Nie, Z. Rengel, W. Gao, C. Li, P. Zhao, Toxicity of cadmium and its competition with mineral nutrients for uptake by plants: a review, *Pedosphere* 30 (2) (2020) 168–180, [https://doi.org/10.1016/S1002-0160\(20\)60002-9](https://doi.org/10.1016/S1002-0160(20)60002-9).
- [18] X. Huang, S. Duan, Q. Wu, M. Yu, S. Shabala, Reducing cadmium accumulation in plants: structure–function relations and tissue-specific operation of transporters in the spotlight, *Plants* 9 (223) (2020) 1–17, <https://doi.org/10.3390/plants9020223>.
- [19] J. Latif, J. Akhtar, I. Ahmad, M. Mahmood, G. Mustafa, Unraveling the effects of cadmium on growth, physiology and associated health risks of leafy vegetables, *Braz. J. Bot.* 43 (4) (2020) 799–811, <https://doi.org/10.1007/s40415-020-00653-0>.
- [20] FAO/WHO, Joint FAO/WHO food standards programme, in: *CODEX Committee on Contaminants in Foods*, FAO/WHO, 2018. Cf/12 INF/1.
- [21] N. Garg, P. Bhandari, Cadmium toxicity in crop plants and its alleviation by arbuscular mycorrhizal (AM) fungi: an overview, *Plant Biosyst.* 148 (4) (2013) 609–621, <https://doi.org/10.1080/11263504.2013.788096>.
- [22] W. Noor, S. Umar, M.Y. Mir, D. Shah, Effect of cadmium on growth, photosynthesis and nitrogen metabolism of crop plants, *Journal of Research and Development* 18 (2018) 100–108, 2018.
- [23] M. Rizwan, S. Ali, M. Adrees, M. Ibrahim, D.C.W. Tsang, M. Zia-ur-Rehman, Z. A. Zahir, J. Rinklebe, F.M.G. Tack, Y.S. Ok, A critical review on effects, tolerance mechanisms and management of cadmium in vegetables, *Chemosphere* 182 (2017) 90–105, <https://doi.org/10.1016/j.chemosphere.2017.05.013>, 2017.
- [24] J.P.V. Oliveira, M.P. Pereira, V.P. Duarte, F.F. Corrêa, E.M. Castro, F.J. Pereira, Cadmium tolerance of *Typha domingensis* Pers. (typhaceae) as related to growth and leaf morphophysiology, *Braz. J. Biol.* 78 (3) (2018) 509–516, <https://doi.org/10.1590/1519-6984.171961>.
- [25] H. Zhao, J. Guan, Q. Liang, X. Zhang, H. Hu, J. Zhang, Effects of cadmium stress on growth and physiological characteristics of safflower seedlings, *Sci. Rep.* 11 (1) (2021), <https://doi.org/10.1038/s41598-021-89322-0>.
- [26] M.J. Hassan, M.A. Raza, S.U. Rehman, M. Ansar, H. Gitari, I. Khan, M. Wajid, M. Ahmed, G.A. Shah, Y. Peng, Z. Li, Effect of cadmium toxicity on growth, oxidative damage, antioxidant defense system and cadmium accumulation in two sorghum cultivars, *Plants* 9 (1575) (2020) 1–14, <https://doi.org/10.3390/plants9111575>.
- [27] A.K. Pal, A. Chakraborty, C. Sengupta, Differential effects of plant growth promoting rhizobacteria on chilli (*Capsicum annuum* L.) seedling under cadmium and lead stress, *Plant Science Today* 5 (4) (2018) 182–190, <https://doi.org/10.14719/pst.2018.5.4.419>.
- [28] O. Labidi, V.-P. Vicente, A. Gómez-Cadenas, R.M. Pérez-Clemente, N. Sleimi, Assessing of growth, antioxidant enzymes, and phytohormone regulation in *Cucurbita pepo* under cadmium stress, *Food Sci. Nutr.* 9 (2021) 2021–2031, <https://doi.org/10.1002/fsn3.2169>.
- [29] N. Baruah, S.C. Mondal, M. Farooq, N. Gogoi, Influence of heavy metals on seed germination and seedling growth of wheat, pea, and tomato, *Water Air Soil Pollut.* 230 (12) (2019), <https://doi.org/10.1007/s11270-019-4329-0>.
- [30] J.R. Okalebo, K.W. Gathua, P.L. Woomer, *Laboratory Methods of Soil and Plant Analysis: A Working Manual*, Second Ed, SACRED Africa, 2002.
- [31] G. Estefan, R. Sommer, J. Ryan, *Methods of Soil, Plant, and Water Analysis: A Manual for the West Asia and North (Third Edit)*, ICARDA, Beirut, Lebanon, 2013.
- [32] M.R. Motsara, R.N. Roy, *Guide to Laboratory Establishment for Plant Nutrient Analysis*, FAO, 2008.
- [33] S. Sharma, A.K. Nagpal, I. Kaur, Heavy metal contamination in soil, food crops and associated health risks for residents of Ropar wetland, Punjab, India and its environs, *Food Chem.* 255 (2018), <https://doi.org/10.1016/j.foodchem.2018.02.037>.
- [34] M. Koller, F. Rayns, S. Cubison, U. Schmutz, Guidelines for Experimental Practice in Organic Greenhouse Horticulture, vol. 1105, BioGreenhouse COST Action FA, 2016, <https://doi.org/10.18174/373581>.
- [35] A. Pequerul, C. Pérez, P. Madero, E.M. Pacheco, J. Val, A Rapid Wet Digestion Method for Plant Analysis, 1993, <https://doi.org/10.1007/978-94-017-2496-8>.
- [36] M.G. Cannata, A.C. Bertoli, R. Carvalho, A.S. Augusto, A.R.R. Bastos, M.P. Freitas, J.G. Carvalho, Stress induced by heavy metals Cd and Pb in bean (*Phaseolus vulgaris* L.) grown in nutrient solution, *J. Plant Nutr.* 38 (4) (2015) 497–508, <https://doi.org/10.1080/01904167.2014.934476>.
- [37] W. Al Khateeb, H. Al-qwasemeh, Cadmium, copper and zinc toxicity effects on growth, proline content and genetic stability of *Solanum nigrum* L., a crop wild relative for tomato; comparative study, *Physiol. Mol. Biol. Plants* 20 (1) (2014) 31–39, <https://doi.org/10.1007/s12298-013-0211-5>.
- [38] E. Yildirim, M. Ekinçi, Impact of cadmium and lead heavy metal stress on plant growth and physiology of rocket (*Eruca sativa* L.), *KSU Journal of Agriculture and Nature* 22 (6) (2019) 843–850, <https://doi.org/10.18016/ksutarimdogan.vi.548626>.
- [39] S. Jaiswal, R. Dey, A. Bag, Effect of heavy metal cadmium on cell proliferation and chromosomal integrity in *Allium cepa*, *Natl. Acad. Sci. Lett.* 45 (1) (2021) 35–37, <https://doi.org/10.1007/s40009-021-01072-9>.
- [40] T. El Rasafi, A. Ouakarroum, A. Haddioui, E.E. Kwon, N. Bolan, F.M.G. Tack, A. Sebastian, N.V. Prasad, J. Rinklebe, Cadmium stress in plants: a critical review of the effects, mechanisms, and tolerance strategies, *Crit. Rev. Environ. Sci. Technol.* (2020), <https://doi.org/10.1080/10643389.2020.1835435>.
- [41] H. Zong, S. Liu, R. Xing, X. Chen, P. Li, Protective effect of chitosan on photosynthesis and antioxidative defense system in edible rape (*Brassica rapa* L.) in the presence of cadmium, *Ecotoxicol. Environ. Saf.* 138 (2017) 271–278, <https://doi.org/10.1016/j.ecoenv.2017.01.009>, 2017.
- [42] J. Zhang, P. Wang, Q. Xiao, Cadmium (Cd) Chloride Affects the Nutrient Uptake and Cd-Resistant Bacterium Reduces the Adsorption of Cd in Muskmelon Plants, vol. 18, *De Gruyter*, 2020, pp. 711–719, <https://doi.org/10.1515/chem-2020-0500>, 2020.
- [43] J. Xin, X.H. Zhao, Q.L. Tan, X.C. Sun, Y.Y. Zhao, C.X. Hu, Effects of cadmium exposure on the growth, photosynthesis, and antioxidant defense system in two

- radish (*Raphanus sativus* L.) cultivars, *Photosynthetica* 57 (4) (2019) 967–973, <https://doi.org/10.32615/ps.2019.076>.
- [44] S. Mei, K. Lin, D.V. Williams, Y. Liu, H. Dai, F. Cao, Cadmium accumulation in cereal crops and tobacco: a review, *Agronomy* 12 (1952) (2022) 1–14, <https://doi.org/10.3390/agronomy12081952>.
- [45] F. Fodor, Physiological responses of vascular plants to heavy metals, in: M. V. Prasad, K. Strzalka (Eds.), *Physiology and Biochemistry of Metal Toxicity and Tolerance in Plants*, Springer Science+Business Media, 2002.
- [46] M.A. Ismael, M. Elyamine, M.G. Moussa, M. Cai, C. Hu, Cadmium in plants: uptake, toxicity, and its interactions with selenium fertilizers, *Metallomics* (2018), <https://doi.org/10.1039/c8mt00247a>.
- [47] U. Zulfiqar, W. Jiang, W. Xiukang, S. Hussain, M. Ahmad, M.F. Maqsood, N. Ali, M. Ishfaq, M. Kaleem, F.U. Haider, N. Farooq, M. Naveed, J. Kucerik, M. Brtnicky, A. Mustafa, Cadmium phytotoxicity, tolerance, and advanced remediation approaches in agricultural soils; A comprehensive review, *Front. Plant Sci.* 13 (2022), <https://doi.org/10.3389/fpls.2022.773815>.
- [48] R. Rucińska-Sobkowiak, Water relations in plants subjected to heavy metal stresses, *Acta Physiol. Plant.* 38 (257) (2016) 1–13, <https://doi.org/10.1007/s11738-016-2277-5>.
- [49] S. Singh, P. Parihar, R. Singh, V.P. Singh, S.M. Prasad, C. Antonio, Heavy metal tolerance in plants : role of transcriptomics , proteomics , metabolomics, and ionomics, *Front. Plant Sci.* 6 (1143) (2016) 1–36, <https://doi.org/10.3389/fpls.2015.01143>.
- [50] B. Píršelová, R. Kuna, P. Lukáč, M. Havrlentová, Effect of cadmium on growth, photosynthetic pigments, iron and cadmium accumulation of Faba Bean (*Vicia faba* cv. Aštar), *Agriculture* 62 (2) (2016) 72–79, <https://doi.org/10.1515/agri-2016-0008>.
- [51] Poonam, S. Ahmad, N. Kumar, C. Paromita, R. Kothari, Plant growth under stress conditions: boon or bane, in: V. Shukla, S. Kumar, N. Kumar (Eds.), *Plant Adaptation Strategies in Changing Environment*, Springer Nature, Singapore, 2017, pp. 291–314.
- [52] C.A. Grant, S.C. Sheppard, Fertilizer impacts on cadmium availability in agricultural soils and crops, *Human and Ecological Risk Assessment* 14 (2) (2008) 210–228, <https://doi.org/10.1080/10807030801934895>.
- [53] FAO/WHO, Development of a Code of Practice for the Prevention and Reduction of Cadmium Contamination in Cocoa, FAO/WHO, 2019. CX/CF 19/13/12.