HEAVY METALS ACCUMULATION AND DISTRIBUTION IN WHEAT (*TRITICUM AESTIVUM* L.) GENOTYPES GROWN IN CADMIUM-CONTAMINATED SOIL

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Abstract. A field investigation was carried out to study the uptake and distribution of copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) metals in ten wheat genotypes growing in cadmium (Cd) contaminated soil. Herein, the content of these metals was evaluated in the root, shoot, and grain of the ten wheat genotypes using atomic absorption spectrophotometry. The results revealed that wheat genotypes showed varied responses to Cd stress, which reflected in the uptake and translocation of Cu, Fe, Mn, and Zn. Cadmium stress reduced the translocation of Cu (0.54%), Fe (0.37%), and Mn (0.11%) to grains, while Zn content increased by 0.23%. The prominent effect of Cd was on the Fe content in all plant parts (0.10, 0.11, and 0.37%) for the root, shoot, and grain, respectively. Low Cd-accumulating genotypes such as Iraq, Al-Diar, and G-4 are recommended to minimize the translocation of pollutants to the grain. These findings indicate that Cd-contaminated soil can be exploited to grow wheat after applying essential elements, e.g., Cu, Fe, Mn, and Zn. Further investigations focusing on other types of heavy metals and micronutrients in a wide range of wheat genotypes are recommended in order to support food security and exploit polluted environments.

Keywords: *bioaccumulation, heavy metals, metal translocation, pollution, genotypic variation*

Introduction

Wheat (*Triticum sp*; Poaceae) is used in the nutrition of over half of the world's population as a source of carbohydrates, minerals, and vitamins. Therefore, it is planted and harvested every month of the year across the world (Curtis and Halford, 2014). Wheat (*Triticum aestivum* L.) is an agronomically essential crop in Iraq, a staple food for human nutrition and the most important source of carbohydrates (Ahmad et al., 2022; Khatlan et al., 2024). The popularity of wheat makes it vulnerable to all kinds of biotic and abiotic stresses, including pollution. Due to the industrial revolution at the end of the 19th century and the beginning of the 20th century, pollution risks started to be noticeable and classified as a global issue as a result of the mismanagement of environmental resources (Masindi et al., 2018). The pollution with heavy metals is markedly increased due to several reasons, including population growth, rapid industrial development, various transportation systems, fertilizers and pesticides, and sewage (Srivastava et al., 2017; Alengebawy et al., 2021). Heavy metals are dangerous due to their long life in the soil without chemical changes and their ability to form complex compounds with most organic and inorganic compounds in plant cells, thus making them immobile (Shahid et al., 2017). Therefore, heavy metals could be considered hazardous chemicals in the soil. The heavy metals pollution in Iraq is a significant environmental and public health problem due to the various sources, including remnants of wars, industrial activities, urbanizations, and inappropriate agricultural practices. Chemical weapons used in wars are considered one of the most important sources of heavy metals in the environment, followed by accumulated waste in cities, sludge places, dust, engine smoke, and waste and gas from factories. The overuse of phosphate fertilizers can also be a source of heavy metals. Conversely, it has been noted that sewerage, which is discarded in rivers, is one of the most dangerous sources of heavy metals (Magid and Al-Issawi, 2024).

It is essential to monitor heavy metal concentrations in human diets due to their toxicity and long-term health impact. Heavy metals pose a serious health hazard due to their potential bioaccumulation and biomagnification in organism cells (Ma et al., 2021). Therefore, an organism might have higher concentrations of those metals than the surrounding environments.

The potential transfer of heavy metals from polluted land and water to food chain become more concentrated in organisms, especially at higher trophic levels (Kumar Sharma et al., 2007). When heavy metals occur in the food chain, they might cumulatively cause severe problems to health over time, including neurological disorders, kidney damage, liver damage, developing abnormalities in children, and increased risks of cancers (Brunetti et al., 2012). Heavy metals in the food chain are a global concern due to the severe problems caused to human health and ecosystems worldwide. The heavy metals contamination should be monitored and mitigated in food production and environments. This is crucial for the integrity of public health and ecology (Guo et al., 2018). Wheat can be grown in a wide range of environments, making it vulnerable to being contaminated with pollutants such as heavy metals. Several heavy metals, such as Fe, Mn, Cu, Zn, etc., are essential for plant growth and development in small amounts, but they are very toxic in high concentrations. Conversely, there are other heavy metals not proven to have biological roles in plants, such as Cd, Pb, Ag, Hg, etc. (Mickovski Stefanović et al., 2023). For each heavy metal, there is a maximum allowable limit, whether it is essential or non-essential for plant growth and development. These limits were determined by the World Health Organization (WHO), Food, Agricultural Organization (FAO), and Codex Amlientarius. The concentration of the non-essential elements such as Cd and Pb should not exceed 0.2 mg kg^{-1} in the food, including wheat grain. The allowable limits of the essential elements, such as Cu and Zn, should not exceed 30 mg Kg^{-1} and 50 mg Kg^{-1}, respectively.

Previous studies have not comprehensively explained the interactions and distribution of heavy metals within plants. Recently, Ma et al. (2024) indicated that Cd uptake and transportation in plants are principally mediated through the transport channels of either Cu, Mn, Zn, or Fe, indicating a relationship between heavy metals in plants. It has been highlighted that genetic background is involved in the accumulation and distribution of metals in plants, providing evidence that genetic loci control those processes (Ma et al., 2024). The genetic disparities in the uptake of multiple heavy metals and their intrinsic associations, play vital roles in improving human nutrition by fortifying crop uptake to trace elements to reduce the accumulation of toxic elements (Zhang et al., 2024). Due to variations in genetic background, anatomy, and physiological responses, wheat genotypes can be varied in their content of heavy metals, Selecting the appropriate genotype for cultivation in heavy metal contaminated areas could reduce the risks that may occur to human health through reducing their accumulation in wheat grains (Huang et al., 2008; Rehman et al., 2015). Therefore, the present study aimed to elucidate the variations in the genetic constitution of bread wheat concerning the absorption and bioaccumulation of various heavy metals across different plant organs, in addition to exploring the interrelationship among these factors. Furthermore, this research was conducted in soils contaminated with cadmium in order to establish a scientific foundation for the safe agronomic utilization of cadmium-laden soils in the cultivation of bread wheat.

Materials and methods

Bread wheat genotypes

Ten bread wheat genotypes were used in the current investigation, eight of which were introduced by the Ministry of Science and Technology and suitable for planting in arid and semi-arid areas (G-3, G-4, G-9, G-24, G-28, G-29, G-39, and G-41), along with two local cultivars (Al-Diar and Iraq).

Experimental site and field soil

The experiment was conducted at Agriculture College, University of Anbar, Iraq, located at a longitude of 33.42.42 N and a Latitude of 43.33.31 E during the growing season of 2022-2023. The field experiment was prepared by digging the beds at a depth of 45 cm with dimensions of 100 cm in width and length of 600 cm in each main plot, separated by 50 cm. The beds were covered with plastic sheet to prevent Cd from leaching from the experiment soil, which was transferred to fill the main plots. Physical and chemical properties of the soil are presented in *Table 1* and the heavy metal concentrations in the experimental soil are presented in *Table 2*. The soil texture was sandy clay loam and two Cd treatments (0 and 75 mg Kg^{-1}) were applied. Cadmium was added at a rate of 75 mg kg^{-1} as $CdCl_2.H_2O$ (61% Cd) after dissolving in humic liquid, then spayed on the soil's surface. The experiment field was fertilized with 120 kg ha^{-1} from DAP fertilizer, and the nitrogen was brought up to 84 kg ha^{-1} according to the recommended amount (Al-Issawi et al., 2023; Khatlan et al., 2024; Khalid and Al-Issawi, 2024; Khatlan and Al-issawi, 2024). The amount of nitrogen was divided into three equal doses. The first dose was added after germination, the second dose was added one month following the first dose application, and the third was applied during the booting stage.

Experimental design and environmental conditions

A split arrangement was used in a randomized complete block design (RCBD with three replicates in each treatment. Cadmium treatments (0 and 75 mg Kg^{-1}) occupied the main plots, while bread wheat genotypes occupied the subplots. Three lines of each genotype were cultivated with a distance of 20 cm between each two lines (12 g per plot). The seeds were sown on 25 November 2022 and the crop was harvested on 15 June 2023. The experimental units were irrigated with river water (EC: 723 µSm/Cm; pH: 7.08; Cd concentration in the water: 0.08 mg L^{-1}). The climate conditions throughout the cultivation period of the experiment are shown in *Figure 1*.

Table 1. *Physical and chemical properties of the study soil (soil samples were analyzed in the central lab of Agriculture College at the University of Anbar)*

Characteristics	**Measurement Unit**	Value
pH (1:1)		7.14
Electrical conductivity (EC; 1:1)	Ds m^{-1}	1.62
Soil organic matter	g Kg^{-1}	5.40
CaCO$_3$	%	10.30
Bulk density	Mega gram Kg^{-3}	
Cation exchange capacity (CEC)	Centimole kg^{-1} soil	23.80
Soluble Ca^{+2}	Meq L^{-1}	6.23
Soluble Mg^{+2}	Meq L^{-1}	3.89
Soluble Na^{+1}	Meq L^{-1}	5.6
Soluble K^{+1}	Meq L^{-1}	1.39
Soluble SO$_4^{-2}$	Meq L^{-1}	7.52
Soluble HCO$_3^{-1}$	Meq L^{-1}	1.69
Soluble Cl^{-1}	Meq L^{-1}	6.7
Available N	Mg Kg^{-1} soil	12.2
Available P	Mg Kg^{-1} soil	10.3
Available K	Mg Kg^{-1} soil	130.4
Sand	Mg Kg^{-1} soil	684
Silt	Mg Kg^{-1} soil	112
Clay	Mg Kg^{-1} soil	204

Table 2. *Heavy metals concentrations in the experimental soil*

Heavy metal	**Value (mg Kg^{-1})**
Cd	0.138
Cu	5.55
Fe	138.5
Mn	60
Zn	88

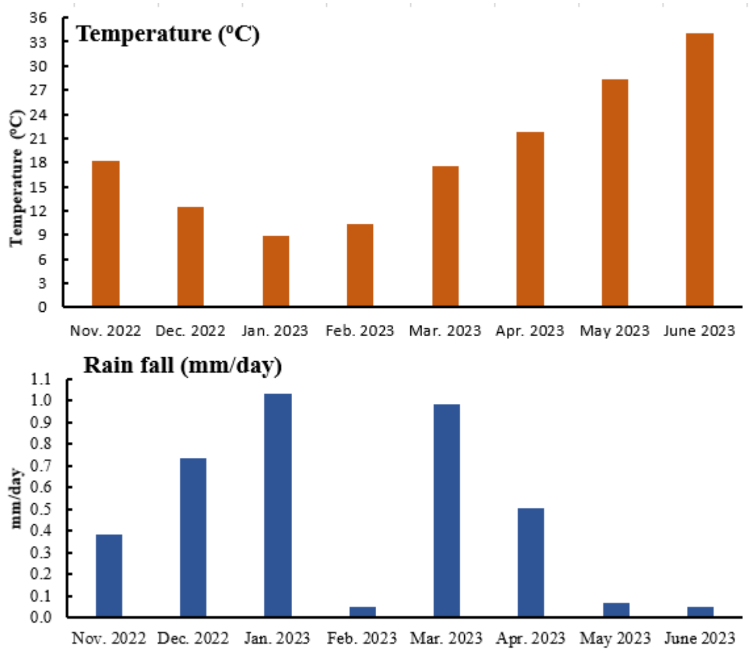

Figure 1. *Time course changes in air temperature and rain fall during the cultivation period*

Atomic absorption spectrophotometric analysis

Heavy metals, including Cd, Cu, Fe, Mn, and Zn, were estimated in the ten bread wheat genotypes' root, shoot, and grain according to the method described in Allen et al. (1986). Random plants from each plot were taken and finely ground, and then a sample (5 g) was taken from each part of the aforementioned parts from each genotype. Samples were then washed with distilled water and were kept in paper bags to be dried in an oven at 70°C for 72 h. Then, samples were ground and were passed through a sieve (1.6 mm). Each sample was digested with 15 ml of the tri-acid mixture (70% high purity HNO_3, 65% $HClO_4$, and 98% H_2SO_4 in a 5:1:1 ratio). The mix of each sample was then heated on a hot plate at 80°C until a transparent phase was obtained. Then, the obtained solution was filtered and diluted to 50 ml using deionized water. Finally, the concentration of each heavy metal was measured by using an atomic absorption spectrophotometer. The standard curve of each heavy metal was plotted using the standard concentrations versus the absorbance. The bioaccumulation factor of heavy metals was calculated by adding the amount of each heavy metal in the three plant parts to obtain the amount of heavy metal in the whole plant. Then, the following equation was applied to obtain each metal's bioconcentration factor (BCF) (Ma et al., 2024).

$$\mathrm{BCF} = \frac{Heavy\ metal\ conc\ in\ plant}{Heavy\ metal\ conc\ in\ siol} \qquad \text{(Eq.1)}$$

Statistical analysis

Collected data were analyzed for ANOVA according to the experimental design using MS Excel vs. 2019. Significant differences between means were measured using the LSD test at a probability level of 0.05 (Steel and Torrie, 1980).

Results

Heavy metals content in wheat genotype components

Wheat roots accumulated more heavy metals than the other plant parts (*Table 3*). The translocation of those heavy metals into other plant parts varied among genotypes. The genetic background considerably affected the accumulation and distribution of heavy metals in their components. Notably, the root Cd content in all genotypes included in this study exceeded the safeguard limits (0.2 mg kg^{-1}) according to Magid and Al-Issawi (2024) and Khatlan et al. (2024), except in genotypes such as G-28 and G-41. In contradiction, G-3 accumulated more Cd (4.38 mg kg^{-1}) than the other genotypes in the current investigation. The Fe and Mn contents were higher in the same genotype (G-3) as they recorded 35.24 and 3.595 mg kg^{-1}, respectively. Genotype G-39 was prominent in its Cu contents (0.343 mg kg^{-1}). The local cultivar had a higher Zn content (2.257 mg kg^{-1}) than the other studied genotypes.

Significant differences ($P<0.05$) were shown among genotypes in their shoot content of the heavy metals (*Table 3*). The translocation of Cd and Fe was higher in genotype G-3 as their content was higher (0.31 and 8.905 mg kg^{-1} for the two elements, respectively) in the shoot of wheat content of Mn differed between root and shoot as it was higher in the shoot of genotype G-41 and Iraq cultivar (0.668 and 0.640 mg kg^{-1}, respectively) indicating that those genotypes did not accumulate Mn in their roots. Genotype G-3 was prominent in accumulating Zn in its shoot (*Table 3*) while exhibiting a lower amount in the root. Grain cadmium content was significantly ($P<0.05$) high in G-3 and G-9 as they recorded amounts of 0.2 and 0.187 mg Kg^{-1}, respectively, as compared to Al-Diar and Iraq genotypes that recorded a significant amount ($P<0.05$) of Cd in their grains. The grain content of other heavy metals in this study varied among genotypes. The amount of Cu and Fe in G-24 grains was significantly higher ($P<0.05$) than in all genotype grains, 0.746 and 24.297 mg kg^{-1} for the two elements, respectively. Genotype G-24 was also superior in Mn content and G-3 and roots G-41. Genotype G-41 accumulated a higher amount of Zn than other genotypes. Overall, the results presented in table 3 suggest that roots accumulated more heavy metals than shoots, which accumulate more than grains of the various genotypes in this investigation. The higher content of certain heavy metals affects the content of other elements. Additionally, the results indicate a clear impact of genetic background on the accumulation and distribution of heavy metals.

Effects of Cd application on the accumulation of heavy metals in wheat components

Cd and Zn were accumulated in the root more than other components upon the application of Cd. The amounts of either Cd or Zn were 0.27, 0.66, and 0.97 mg Kg^{-1}, respectively, in the root of the control group (*Table 4*). Nevertheless, they were increased to 5.2, 0.86, and 1.03 mg Kg^{-1}, and the percentages of increase were 18.4, 0.30, and 0.06% for the three elements, respectively. A significant reduction ($P<0.05$) in the amount of Fe in the wheat root was recorded, while the content of Cu and Mn did not change upon the treatment with Cd. In wheat shoot, Cu and Mn, along with Cd, have significantly increased ($P<0.05$) following the application of Cd (75 mg kg^{-1}) in the experiment soil. Furthermore, a varied accumulation of heavy metals was observed in the wheat shoot (*Table 4*). However, Cd significantly accumulated ($P<0.05$) in wheat shoots upon treatment of Cd in comparison with Cu and Mn. Conversely, the content of Fe and Zn was reduced in the wheat shoot in response to Cd application and reduction percentages were -0.11, -0.44, and 0.51%, respectively. These findings highlight that Fe behavior was consistent in reduction among root and shoot while Zn behaved differently. The content of Cd and Zn in wheat grains were increased in comparison with Cu, Fe, and Mn, whose contents were declined upon treating the plant with 75 mg Kg^{-1} soil. The percentage of those elements in the shoot increased by 0.86, 0.12, and 0.23%, respectively. The content of Cu, Fe, and Mn in wheat shoot was decreased by -0.54, -0.37, and -0.11, respectively (*Table 4*). The results highlight an interaction of applied Cd with the available heavy metals in the experiment soil. Conversely, genetic background had a significant effect on the accumulation and distribution of heavy metals regardless of the presence or absence of Cd.

Bioaccumulation of heavy metals in wheat genotypes

Bioaccumulation is an indicator of a plant's ability to uptake and relocate heavy metals from soil to different plant components. According to the data presented in *Table 3*, the highest amount of heavy metals was accumulated in the root, followed by shoot and grain, respectively. This indicates that the relocation of heavy metals from one plant part to another differs from their accumulation from soil to plant. Collectively, the highest rate of accumulation was recorded for Cd, while the lowest rate was recorded for Mn, e.g., Cd>Zn>Cu>Fe>Mn. The results presented in *Table 5* show that bioaccumulation of heavy metals varies among wheat genotypes. Genotype G-28 recorded the lowest rate of Cd-accumulation (0.286), followed by genotype G-41, while genotype G-3 accumulated

Cd at a rate of 0.813, the highest among all genotypes included in this investigation. Cu, Fe, and Mn bioaccumulation in wheat plants followed different manners; hence, local genotypes Al-Diar and Iraq recorded the lowest accumulation rate; on the other hand, G-24 showed the highest rate of bioaccumulation of those heavy metals.

Table 3. *The content of heavy metals (mg kg^{-1}) in roots, shoots and grains of ten wheat genotypes*

Genotypes	Cd	Cu	Fe	Mn	Zn
The content of heavy metals in roots					
G-3	4.280 ±0.085 a	0.301 ±0.021 b	35.240 ±1.16 a	3.595 ±0.233 a	0.682 ±0.003 h
G-4	3.370 ±0.073 c	0.192 ±0.014 de	25.744 ±1.16 g	1.614 ±0.257 e	0.726 ±0.029 g
G-9	3.840 ±0.058 b	0.143 ±0.021 gh	25.896 ±1.16 f	2.828 ±0.231 b	1.429 ±0.017 b
G-24	2.640 ±0.089 f	0.203 ±0.018 cde	32.182 ±1.16 b	2.611 ±0.231 c	0.857 ±0.001 c
G-28	1.363 ±0.063 j	0.166 ±0.014 fg	19.969 ±1.16 i	2.508 ±0.174 c	0.819 ±0.014 de
G-29	2.220 ±0.082 h	0.221 ±0.021 c	31.622 ±1.17 c	1.942 ±0.231 d	0.790 ±0.015 e
G-39	2.790 ±0.083 e	0.343 ±0.023 a	30.270 ±1.16 d	1.870 ±0.231 d	0.856 ±0.022 c
G-41	1.830 ±0.037 i	0.183 ±0.022 ef	29.302 ±1.13 e	1.692 ±0.243 e	0.760 ±0.002 f
Al-Diar	3.010 ±0.058 d	0.213 ±0.045 cd	24.770 ±1.16 h	1.683 ±0.352 e	0.830 ± 0.021 cd
Iraq	2.400 ±0.186 g	0.132 ±0.013 h	18.785 ±1.15 j	1.113 ±0.230 f	2.257 ±0.019 a
LSD (0.05)	0.07	0.02	0.09	0.11	0.03
The content of heavy metals in shoots					
G-3	0.310 ±0.038 ab	0.250 ±0.270	8.905 ±0.560 a	0.472 ±0.023 c	0.814 ±0.057 a
G-4	0.250 ±0.036 d	0.227 ±0.270	7.750 ±0.280 b	0.320 ±0.006 f	0.398 ±0.034 c
G-9	0.200 ±0.038 e	0.205 ±0.300	5.745 ±0.280 e	0.392 ±0.030 e	0.347 ±0.058 de
G-24	0.330 ±0.056 a	0.237 ±0.270	6.108 ±0.290 d	0.591 ±0.010 b	0.345 ±0.035 de
G-28	0.249 ±0.038 d	0.283 ±0.260	6.358 ±0.290 c	0.459 ±0.016 cd	0.363 ±0.030 d
G-29	0.193 ±0.038 e	0.130 ±0.038	5.191 ±0.160 f	0.308 ±0.008 f	0.275±0.032 g
G-39	0.282 ±0.020 c	0.047 ±0.020	6.056±0.280 d	0.375 ±0.006 e	0.435 ±0.057 b
G-41	0.292 ±0.038 bc	0.214 ±0.016	7.654 ±0.270 b	0.668 ±0.033 a	0.409 ±0.036 c
Al-Diar	0.215 ±0.038 e	0.045 ±0.030	5.856 ±0.290 e	0.437±0.024 d	0.325 ±0.035 e
Iraq	0.240 ±0.038 d	0.077 ±0.018	5.350 ±0.290 f	0.640 ±0.026 a	0.300 ±0.039 f
LSD (0.05)	0.023	NS	0.162	0.031	0.024
The content of heavy metals in grains					
G-3	0.200 ±0.018 a	0.129 ±0.018 cd	10.995 ±0.20 b	1.037 ±0.027 a	1.004 ±0.008 c
G-4	0.185 ±0.033 ab	0.057 ±0.024 gh	3.493 ±0.35 g	0.515 ±0.032 f	1.093 ±0.022 b
G-9	0.187 ±0.012 ab	0.098±0.010 ef	4.378 ±0.35 e	0.727 ±0.010 c	0.712 ±0.008 f
G-24	0.174 ±0.012 bc	0.746 ±0.012 a	24.297 ±0.35 a	1.040 ±0.026 a	0.758 ±0.008 e
G-28	0.168 ±0.013bcd	0.273 ±0.009 b	9.319 ±0.32 c	0.808 ±0.020 b	0.762 ±0.006 e
G-29	0.165 ±0.008bcd	0.144 ±0.012 c	4.15 ±0.40 f	0.646 ±0.014 e	0.742 ±0.019 e
G-39	0.160 ±0.030 cd	0.136 ±0.012 cd	3.436 ±0.34 g	0.730 ±0.020 c	0.851 ±0.019 d
G-41	0.154 ±0.023cde	0.117 ±0.012 de	7.219 ±0.35 d	1.067 ±0.018 a	1.306 ±0.029 a
Al-Diar	0.148 ±0.011 de	0.077 ±0.012 fg	2.928 ±0.35 h	0.616 ±0.023 e	0.704 ±0.001 f
Iraq	0.133 ±0.032 e	0.040 ±0.005 h	2.977 ±0.35 h	0.684 ±0.019 d	0.840 ±0.016 d
LSD (0.05)	0.023	0.025	0.159	0.031	0.024

Values presented are means ± SE (n=3). Different letters refer to significantly different means at a probability level of 0.05

Table 4. *Effect of Cd application (75 mg Kg^{-1}) on heavy metals content (mg Kg^{-1}) and the increase/decrease (%) in wheat components*

Plant part	Cd Conc	Cd	Cu	Fe	Mn	Zn
Root	Cd0	0.27 b	0.26	28.75 a	2.20	0.97 b
	Cd75	5.28 a	0.16	26.01 b	2.09	1.03 a
LSD (0.05)		0.10	NS	0.13	NS	0.05
Shoot	Cd0	0.20 b	0.07	6.86 a	0.42	0.54 a
	Cd75	0.31a	0.27	6.13 b	0.52	0.26 b
LSD (0.05)		0.01	NS	0.15	NS	0.12
Grain	Cd0	0.12 b	0.25 a	8.98 a	0.84	0.79 b
	Cd75	0.22 a	0.12 b	5.66 b	0.74	0.97 a
LSD (0.05)		0.05	0.10	0.34	NS	0.11
The Increase/decrease (%) of heavy metals in response to Cd application						
Root		18.48	-0.36	-0.10	-0.05	0.06
Shoot		0.56	2.90	-0.11	0.24	-0.51
Grain		0.86	-0.54	-0.37	-0.11	0.23

Different letters refer to significantly different means at a probability level of 0.05

Table 5. *Bioaccumulation of heavy metals in wheat genotypes*

Genotypes (G)	Cd	Cu	Fe	Mn	Zn
G-3	0.813 a	0.132 bc	0.144 b	0.037 a	0.300 c
G-4	0.69 c	0.092 cd	0.098 f	0.015 g	0.278 d
G-9	0.76 b	0.086 de	0.095 g	0.019 f	0.306 c
G-24	0.544 e	0.233 a	0.163 a	0.024 d	0.237 e
G-28	0.285 i	0.141 b	0.092 h	0.019 f	0.23 ef
G-29	0.446 g	0.097 cd	0.107 d	0.030 b	0.224 f
G-39	0.555 e	0.103 bcd	0.104 e	0.027 c	0.281 d
G-41	0.383 h	0.099 cd	0.117 c	0.030 b	0.337 b
Al-Diar	0.604 d	0.065 de	0.088 i	0.020 e	0.233 e
IRAQ	0.478 f	0.048 e	0.072 j	0.020 e	0.492 a
LSD 0.05	0.013	0.040	0.001	0.001	0.008

Different letters refer to significantly different means at a probability level of 0.05

The rate of bioaccumulation of heavy metals in wheat plants upon treating the soil with 70 mg Cd Kg^{-1} soil is presented in *Table 6*. The bioaccumulation rate of Cd and Zn in wheat parts increased following Cd application. In contrast, the rate of Fe and Mn was decreased in the presence of Cd. Apart from Cd, which has been significantly accumulated ($P<0.05$) after applying Cd, it was found that the increase percentage of Zn was 153.33%. However, the reduction percentages of Fe and Mn were 8.85 and 50%, respectively. Additionally, it is worth mentioning that the Cd application did not affect the accumulation rate of Cu in wheat plants.

Table 6. *Bioaccumulation of heavy metals after Cd treatment*

Heavy Metals	Cd Treatment (mg Kg^{-1})	BCF	LSD (0.05)
Cd	0 75	0.003 b 1.108 a	0.0499
Cu	0 75	0.115 0.105	NS
Fe	0 75	0.113 a 0.103 b	0.0014
Mn	0 75	0.032 a 0.016 b	0.0051
Zn	0 75	0.165 b 0.418 a	0.0086

Different letters refer to significantly different means at a probability level of 0.05

Discussion

Heavy metal toxicity is a significant threat to the health of humans and food security; therefore, characterizing wheat genotypes of grains with low-safe content of the available heavy metals is crucial to ensure food safety. Besides the toxicity of the heavy metals to the plant, in the studies of plant-heavy metals interactions, the main focus most likely concerned the heavy metal uptake, distribution to the vegetative parts, and finally to the harvestable crop parts such as grain in case of wheat (Xiao et al., 2023). Due to the commonality of Cd in the environment through different sources, the current investigations focused on Cd uptake and distribution along with various other heavy metals such as Cu, Fe, Mn, and Zn. To our knowledge, the biological positive roles of Cd to the plant yet to be deciphered. Cd can be easily absorbed by plants, and could be translocated to other plant parts (Shahid et al., 2017; Zhang et al., 2019). There is a possibility that Cd could finally accumulated in the food chain. Some studies proved that Cd might be substituted with Zn (Cui et al., 2017), and it is evident that Cd has the potential to affect other metals' uptake and distribution in plant parts. Based on the results presented in *Table 4*, it appears that cadmium application affected the uptake and distribution of other heavy metals included in the current investigation. Cd reduced the amount of those metals in the root of wheat genotypes, proving that the transporters intervene with Cd transporters despite evidence available for only Zn and Fe. Also, it is worth mentioning that a small amount of these metals is translocated to the leaves and stems of all wheat genotypes despite the application of Cd. In grains, it is clear that the amount of the essential metals, e.g., Cu, Fe, Mn, and Zn, is significantly reduced ($P<0.05$), which might affect the nutritional value of wheat grains. The effect of Cd on the uptake and distribution of other elements can be attributed to the mechanisms of competition between those elements for the uptake pathways, which might reduce the absorbance of essential elements, e.g., Cu, Fe, Mn, and Zn (Rehman et al., 2015). Also, Cd can alter the way other metals translocation and redistribute to different plant parts, which reduces the transporting of essential elements to the grain and reduces their nutritional value (Li et al., 2020).

Generally, Cd affects the accumulation and translocation of other heavy metals in all wheat parts, including root, shoot, and grain. This explains the interaction of this metal with the rest of the metals in the plant. It affects the balance of minerals content in the plant in addition to affecting the nutritional value of edible parts of wheat. It has been reported that lower essential concentrations of Cu, Fe, Mn, and Zn in grains of wheat growing in Cd-contaminated soils, which are retained in the roots as a strategy used by plants to reduce the toxic effects in other plant parts (Brunetti et al., 2012). The ability of wheat to uptake heavy metals from soil can be assessed by calculating the bioaccumulation factor (BCF). BCF can also characterize the accumulation of heavy metals in grains. Based on the current investigation, the majority of Cd was retained in the roots in comparison with straw and grains (*Table 3*). These results were consistent with previous report by Vergine et al. (2017), who stated that wheat accumulated Cd mostly in the root in order to avoid the risks to other plant parts. For other heavy metals, it has been shown that they were absorbed and accumulated in plant parts in a different pattern to cadmium. This could be due to the variations in the mechanisms of absorption, pathways of transportation, and the capacity of storage of each metal (Sarwar et al., 2015; Li and Zhou, 2019; Zhou et al., 2020). Several factors might affect the uptake and distribution of heavy metals to the wheat plant and its parts, including the type of metal, genotype, soil characteristics, and environmental conditions (Liu et al., 2023). To sum up, the Cd application affected the uptake and distribution of other heavy metals by competing for the transporters, altering the distribution patterns, or increasing the oxidative stress, which affects the translocation of essential elements to the grains, ultimately affecting plant growth and development as well as grain quality, especially in Cd-contaminated environment.

Conclusions

Wheat genotypes exhibited a diverse array of responses to the application of cadmium and further demonstrated distinct behaviors regarding the absorption and distribution of metallic elements. The concentration of Cd within wheat grain remained below the critical threshold (0.2 mg kg^{-1}). Nevertheless, the minimal concentrations were observed in the local cultivars (Iraq and Al-Diar) alongside the introduced genotype (G-41), thereby rendering them advantageous for human consumption in Iraqi agricultural contexts. Conversely, other metallic elements are still considerably below the critical thresholds, which subsequently substantiates the notion that Cd adversely impacts the nutritional quality of wheat grain by modulating the levels of essential micronutrients, such as Cu, Fe, Mn, and Zn. Genotypes characterized by low grain content may be strategically utilized to rehabilitate contaminated soils.

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