Gaziosmanpaşa Üniversitesi Ziraat Fakültesi Dergisi
Journal of Agricultural Faculty of Gaziosmanpasa University
https://dergipark.org.tr/tr/pub/gopzfd

Araştırma Makalesi/*Research Article*

JAFAG
ISSN: 1300-2910
E-ISSN: 2147-8848
(2022) 39(2) 120-128
doi:10.55507/gopzfd.1088185

Determination of Grapevine Rootstocks Resistancy to Cadmium (Cd) Toxicity

Rüstem CANGİ[1*] Halil ERDEM[2] Banu KILIÇ[1]
[1]Gaziosmanpasa University, Faculty of Agriculture, Horticulture Department, 60240 Tokat
[2]Gaziosmanpasa University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, 60240 Tokat
***Corresponding author's email:** rcangi@hotmail.com

Alındığı tarih (Received): 15.03.2022 Kabul tarihi (Accepted): 18.08.2022

Abstract: In this study, response of 12 grapevine rootstock genotypes to cadmium (Cd) toxicity were investigated. The Cd application to the soil was made at the beginning of the experiment at 4 different (0, 5, 10 ve 20 mg Cd kg^{-1}) doses. Shoot, leaf and root dry matter yields, leaf Cd, N, P and Zn contents were determined to assess genotype tolerance of Cd toxicity. Present findings revealed that based on shoot, leaf and root dry weights, leaf Cd, N, P and Zn contents, there were Cd-sensitive and resistant genotypes among the present ones. At the greatest Cd dose (Cd20), the greatest Cd contents (µg plant^{-1}) were observed in 8B (6.13), 420A (5.35) and 1103P (4.69) rootstocks and the lowest Cd contents were observed in 99R (1.27) and SO4 (1.58) rootstocks. Among the grapevine rootstocks, SO4 with quite lower leaf Cd accumulation than the other genotypes and increasing shoot and leaf dry weights and leaf N, P and Zn content was identified as resistant against toxic Cd conditions. On the other hand, 8B, 420A, 1103P, 5BB, Harmony genotypes with decreasing shoot, leaf and root dry weights under Cd toxicity conditions, higher leaf Cd accumulations and significantly decreasing leaf N, P and Zn contents were considered as sensitive to Cd toxicity.

Key words: Grapevine rootstocks, cadmium, toxicity, heavy metal, nutrient uptake

Asma Anaçlarının Kadmiyum (Cd) Toksisitesine Karşı Dayanıklılıklarının Belirlenmesi

Öz: Bu çalışmada 12 asma anaçgenotipinin kadmiyum (Cd) toksisitesine tepkisi incelenmiştir. Toprağa Cd uygulaması deneme başlangıcında 4 farklı dozda (0, 5, 10 ve 20 mg Cd kg^{-1}) yapılmıştır. Sürgün, yaprak ve kök kuru madde verimi ile yaprak Cd, N, P ve Zn içerikleri belirlenmiştir. Elde edilen sonuçlar değerlendirildiğinde, asma anaçları arasında sürgün, yaprak ve kök kuru madde verimi ile yaprak Cd, N, P ve Zn içerikleri bakımından Cd toksisitesine karşı hassas ve dayanıklı anaçların olduğu ortaya çıkmıştır. Kadmiyum uygulamasının en yüksek olduğu Cd20 dozunda Cd içeriği en fazla en fazla 8B (6.13 µg plant^{-}1), 420A anacında (5.35 µg biki^{-}1) ve 1103P (4.69 µg plant^{-}1) anaçlarında olduğu buna karşın en düşük Cd içeriği ise 99R (1.27 µg plant^{-}1) ile SO4 (1.58 µg plant^{-}1) anaçlarında olduğu ortaya çıkmıştır. Asma anaçları arasında SO4 genotipinin diğer anaçlara göre yapraklarında çok daha az Cd birikimi yapması, sürgün ve yaprak kuru madde verimi ile N, P ve Zn içeriklerinde artışların olması bu anacın toksik Cd koşullarına karşı dayanıklı olabileceğini göstermiştir. Buna karşın toksik Cd koşullarında yapraklarında yüksek düzeyde Cd biriktiren ve kuru madde (gövde, yaprak, kök) verimlerinde önemli düzeyde azalma meydana gelen 8B, 420A, 1103P, 5BB, Harmony asma anaçlarının ise Cd toksisitesine karşı hassas olduğu ortaya çıkmıştır.

Anahtar Kelimeler: Asma anaçları, kadmiyum, toksisite, ağır metal, besin alımı

1. Introduction

Cadmium (Cd) is among the most dangerous heavy metals and pollutants in ecosystem and it has toxic impacts on living organisms (Alengebawy et al., 2021). Soils are contaminated by cadmium through parent material or industrial activities and phosphorus fertilizers-like anthropogenic activities. Of the Cd reached to soils through human activities, 56% comes from use of phosphorus-containing fertilizers, 40% comes from atmospheric and 2-5% comes from manure treatments (sludge-livestock) (Cheng et al., 2014; Suhani et al., 2021). Since cadmium has a more water solubility and the mobility than the other metals, it is more up taken by the plants. Therefore, it is the most dangerous metal accumulated in soils. Cadmium is not an essential element for plants, it is a heavy metal that makes it toxic to plants. Cadmium disrupts the root activity of plants, negatively affects plant nutrient uptake and use. At the same time, it negatively affects photosynthesis in plants, impairs carbohydrate metabolism and adversely affects plant yield and quality (Stachowiak et al., 2015; Yang et al., 2021).

Climatic conditions, soil properties and agricultural practices significantly affect the uptake of Cd by plants (Hart et al., 1998; Hussain et al., 2021). Cadmium causes in decelerated plant growth, low biomass, browning in root tips and ultimately plant die outs (Anjum et al., 2008; Erdem, 2021). Cadmium ions reduce root and shoot lengths. Inhibition of root growth is the most significant indicator of Cd^{+2} toxicity (Sgherri et al., 2001;2002; Xiao et al., 2022). Cadmium also negatively affects chlorophyll synthesis (Haider et al., 2021; Song et al., 2019). Cadmium ion especially influence photosynthesis, respiration and N metabolism of the plants (Cheng et al., 2014; Nascimento et al., 2021). Cadmium restrict uptake, transport and use of water and plant nutrients (Ca, Mg, P, K and Fe) (Haider et al., 2021). Cadmium uptake and transport largely vary with the plant species, thus plants have different tolerance levels to Cd toxicity (El Rasafi et al., 2021; Grant et al., 1998). Plant tolerance to Cd toxicity largely depend on Cd accumulation capacity and localization of the plants (Obata & Umebayashi, 1993; Shrivastava et al., 2019). Plant genetics also play a great role in Cd uptake and accumulation by the plants. Researchers reported that there are significant genetic variations in Cd tolerance of tobacco (Erdem et al., 2017; Lugon-Moulin et al., 2004), soybean (Zhi et al., 2020), maize (Rasool et al., 2020), wheat (Greger & Löfstedt, 2004; Zhou et al., 2020), and lettuce (Loi et al., 2018).

Grafting in grapevines could be increase the yield and quality of grapes and increase the resistance of plants to various stress factors such as extreme heat, cold stress, drought and heavy metals (He et al., 2020; Savvas et al., 2010; Yuan et al., 2019). Some vine rootstocks prevent Cd uptake and transport in xylem by plant roots by ion exclusion or retention mechanism. Plants are protected from heavy metal toxicity through these mechanisms. It has been reported that Cd accumulation in the leaves of the eggplant and tomato grafted to *Solanum torvum* rootstocks decreased (Yuan et al., 2019). In a study investigating the responses of grafted Malus plants to Cd toxicity, it was reported that applications varied according to rootstock, scion and rootstock-scion combinations (He et al., 2020).

In modern viticulture, grafted vine saplings must be used due to the phylloxera. Several different genotypes are used as rootstock in vine saplings. Grapevine rootstocks different macro and micronutrient uptake and grafted plants have different nutrient uptakes from the seed-propagated plants. Grapevine rootstocks may also differ in response to biotic and abiotic stress conditions (Bavaresco et al., 2003; Ibacache & Sierra, 2009; Lecourt et al., 2015; Zamboni et al., 2016).

In regions with industrial pollution, significant relationships were reported between grapevine roots and soil Cd concentrations of the vineyards located in regions with industrial pollution (Angelova et al., 1999). Al- Obeed et al., (2011) reported that fruit Cd contents of the different grape cultivars irrigated with treated domestic wastewater varied with the cultivars. Miklos & Erdei (1997) reported that high Cd concentrations adversely affected the development and nutrition of grape genotypes (Leányka and Ezerjó,), and plant roots had higher Cd concentrations than leaves.

In this study, the effects of increasing doses of toxic Cd on plant growth and leaf Cd, N, P and Zn content twelve different grapevine rootstocks on were investigated.

2. Material and Methods

2.1. Material

Plant Material: The research was carried out in the greenhouses of Tokat Gaziosmanpaşa University, Faculty of Agriculture, Department of Horticulture. Twelve different rootstocks (1103P, 1045P, 5BB, 8B, SO4, 420A, 99R, 110R, 140 Ru, Dogridge, Harmony, 41B) were used in the study. The rootstock saplings used in the study were grown in the greenhouse in 1-liter plastic bag with a 1:1 substrate mixture (peat-perlite).

Soil Material: The soil used for the pot experiment had the following chemical and physical properties: texture was clay, $CaCO_3$ content was %15.8, pH was 7.85, organic matter was 1.69 %, available P_2O_5 concentration was 5.60 kg da^{-1}, K_2O concentration was 16.4 kg da^{-1} and the DTPA extractable concentrations (ppm) of Zn, Fe and Cd were 0.52, 2.11, 0.005, respectively.

2.2 Method

The study was carried out in 5-liter plastic pots with 4 replications according to the randomized plots experimental design under open sections with 35% shading net conditions. Air-dried 4 mm sieved 4 kg soil, prior to filling the pots, was homogeneously mixed with a fertilizer solution containing 250 mg N kg^{-1} soil as $Ca(NO_3)_2.4H_2O$, 100 mg P kg^{-1} soil as KH_2PO_4, 2.0 mg Fe kg^{-1} soil as Fe-EDTA and 2.0 mg Zn kg^{-1} soil as $ZnSO_4.7H_2O$. The treatments were control (Cd0), 5.0 (Cd5), 10 (Cd10) and 20 (Cd20) mg Cd kg^{-1}, and Cd were applied to soil in the form of $(CdSO_4)_3.8H_2O$. Cd doses were given to the soil at the beginning of the experiment together with basic fertilizers and mixed with the soil in a homogeneously. After the fertilizer and Cd applications, one sapling was planted in each pot. The shoots on the seedlings were left 4-5 cm tall and only one shoot was allowed to grow according to the state of the dormant buds. In order to prevent water loss by evaporation in the soil, the top of the pot were dressed with 2-3 cm thick perlite and the plants were watered daily with distilled water.

Destructive harvest of the plant parts begun on the 134^{th} day according to the decrease in growth in the plants and the severity of Cd toxicity in the leaves. The plants were destructively harvested separately as roots, shoots and leaves. After the destructive harvest of the plant parts, they were washed with tap water, and dried at 65 ºC for 48 hours to obtain their dry weight. Dried leaf samples were then ground in agate mill, subjected to wet-digestion in HNO_3 – H_2O_2 in a microwave oven and Cd, P and Zn concentrations of the samples were determined in an ICP-OES (Varian Vista) device (Kacar and ? İnal, 2008). Total nitrogen analysis in leaf samples was made according to the Kjeldahl distillation method (Bremner, 1965). The Cd, N, P and Zn contents of the leaves were calculated by multiplying the leaf weights with Cd, N, P and Zn concentrations. It has been recommended to examine the effect of Cd on physiologically important micronutrients, particularly P (Wang, 1987) and Zn (Kim et al., 1988).

Statistical Analysis: The research was carried out in 4 replications, with one plant in each pot. Experimental data were subjected to variance analysis in accordance with randomized plots–factorial design. Duncan multiple range test was used to compare significant means.

Cluster analysis was performed to determine the relation between varieties. Cluster analysis was carried out using the Cd, N, P, Zn, shoot, leaf and root dry weight **v**alues of the control treatment. Since the units of the variables used in the analysis are not the homogeneous, the variables are standardized and then the Euclidean distance is calculated. The dendrogram showing the similarities and differences of rootstocks was obtained by cluster analysis according to Ward's method.

3. Result and Discussion

Toxic Cd negatively affects the nutrient uptake and transport of plants and causes physiological disorders in plants, resulting in reduced growth. Roots absorb Cd from the soil and transport it through xylem to upper section of the plants with the aid of transpiration stream (Salt et al., 1995; Zhang et al., 2022). Heavy metals absorbed by the roots initially combine with proteins, polysaccharides, and nucleic acids, then transported to shoots (Goyal et al., 2020). Therefore, generally a positive relationship is encountered between increasing Cd doses applied to soils and shoot Cd concentrations. Significant increases were observed in Cd contents of grapevine rootstocks with increasing Cd treatment doses. Rootstocks, Cd doses and rootstock x dose interactions were found to be significant at 5% level (Table 1). Average Cd content of grapevine rootstocks at Cd0 dose (0.66 µg plant^{-1}) increased to 1.96 µg plant^{-1} at Cd5 dose, to 2.34 µg plant^{-1} at Cd10 dose and to 3.15 µg plant^{-1} at Cd20 dose. Significant differences were observed in Cd contents of rootstock genotypes with increasing Cd doses. At the greatest Cd dose (Cd20), the greatest Cd contents were observed in 8B (6.13 µg plant^{-1}), 420A (5.35 µg plant^{-1}) and 1103P (4.69 µg plant^{-1}) rootstocks and the lowest Cd contents were observed in 99R (1.27 µg plant^{-1}) and SO4 (1.58 µg plant^{-1}) rootstocks (Table 1). Such findings on Cd contents indicated that rootstock response to Cd toxicity was different. Some rootstocks may prevent Cd uptake or transport through ion exclusion or retention, thus may mitigate heavy metal phytotoxicity. He et al. (2020) reported that Cd uptake of apple cultivars varied according to both rootstock and scion. Various plant species may have quite different Cd tolerance, uptake and transport (Chun et al., 2020; He et al., 2020; Yang et al., 2021; Zhou et al., 2017). Foliar Cd accumulations were reduced through grafting eggplant and tomato scions onto Solanum torvum rootstocks (Yuan et al., 2019).

Table 1. Effects of increasing Cd doses on leaf Cd and N contents of grapevine rootstocks
Çizelge 1. *Asma anaçlarında artan Cd dozlarının yaprak Cd ve N içerikleri üzerine etkileri*

Rootstock	Cd Content (µg plant^{-1})				N Content (mg plant^{-1})			
	0	5	10	20	0	5	10	20
5BB	0.90^{abC}	2.58^{abcAB}	1.89^{bB}	3.09^{cA}	83.8^{abA}	88.0^{aA}	52.6^{b-eB}	39.5^{cdB}
8 B	0.74^{abcC}	2.51^{abcB}	1.74^{bcBC}	6.13^{aA}	82.2^{abcA}	80.1^{abcA}	60.4^{b-eA}	65.5^{abcA}
SO4	0.60^{cdB}	A 2.75^{abA}	2.74^{abA}	1.58^{deAB}	58.2^{cdAB}	77.9^{abcA}	2.5^{deB}	71.4^{abB}
420A	0.85^{abC}	3.14^{aC}	2.47^{abB}	5.35^{abA}	82.5^{abcA}	59. 3^{abcAB}	71.5^{bcdAB}	53.1^{bcdB}
1613 C	0.65^{bcdB}	2.05^{a-dA}	2.04^{cbA}	3.14^{cA}	78.7^{abcA}	76.0^{abcA}	50.3^{cdeA}	731.7^{abA}
99 R	0.75^{abcC}	0.87^{eC}	2.55^{abA}	1.27^{eB}	91.3^{aA}	75.8^{bcAB}	67.7^{bcdBA}	47.0^{bcdC}
110 R	0.58^{cdC}	1.48^{cdeB}	2.36^{abA}	2.29^{cdeA}	64.5^{a-dB}	83.7^{abcA}	74.5^{abcAB}	60.4^{bcdB}
140 Ru	0.58^{cdB}	2.17 $^{a-dA}$	2.27^{bA}	2.25^{cdeA}	50.4^{dA}	65.7^{abcA}	52.5^{bcdeA}	40.9^{cdA}
1103P	0.57^{cdC}	1.93^{b-eB}	3.62^{aA}	4.69^{bA}	59.6^{bcdA}	62.2^{abcA}	82.1^{abA}	70.2^{abA}
1045 P	0.61^{cdB}	1.02^{eB}	2.27^{bA}	2.12^{cdeA}	63.0^{bcdAB}	50.9 ^{abcB}	67.8^{bcdAB}	90.9^{aA}
Dogridge	0.54^{cdB}	1.51^{cdAB}	0.82^{bcB}	2.21^{cdeA}	50.0^{dA}	65.9abA	29.8^{eA}	59.7^{bcdA}
Harmony	0.48^{dB}	0.89^{eB}	2.47^{abA}	2.27^{cdeA}	47.9^{dB}	43.9^{cBC}	102.4^{aA}	34.4^{dC}
41B	0.77^{abcA}	2.86^{abA}	3.06^{abA}	3.43^{cA}	70.5^{a-dA}	65.7^{abA}	67.6^{bcdA}	58.3^{bcdA}
Average	**0.66^{D}**	**1.96^{C}**	**2.34^{B}**	**3.15^{A}**	**68.2^{A}**	**67.4^{A}**	**62.1^{AB}**	**58.1^{B}**

Means shown with similar capital letters in the same row are not significant ($p<0.05$). Means shown with similar lowercase letters in the same column are not significant ($p<0.05$).

Considering the effects of increasing Cd doses on N contents of grapevine rootstocks, , Cd doses and rootstock x dose interactions were found to be significant at 5% level. The average N content of grapevine rootstocks in control treatment (68.2 mg plant^{-1}) decreased to 62.1 mg plant^{-1} in Cd10 and to 58.1 mg plant^{-1} in Cd20 treatments (Table 1). N content of the rootstocks either increased or decreased with increasing Cd doses, but generally a decrease was observed in majority of the rootstocks. For instance, N content of 420A genotype with a high Cd content in leaves with increasing Cd doses was measured as 82.5 mg plant^{-1} in Cd0 treatment and the value decreased to 53.1 mg plant^{-1} in Cd20 treatment. On the other hand, N content of SO4 genotype with a low Cd content in rootstocks was measured as 58.2 mg plant^{-1} in Cd0 treatment and the value increased to 71.4 mg plant^{-1} in Cd20 treatment (Table 1). Nitrogen deficiency in plants grown in soils with Cd toxicity was attributed to inhibition of nitrate reductase activity within the rootzone and about 70% reduction in nitrate absorption by Cd (Borchard et al., 2014; Genchi et al., 2020; Nascimento et al., 2021) reported that Cd toxicity induced metal bindings onto Sulphur hydride groups of proteins, resulted in replacement of macro nutrients, structural destructions or activity inhibition, thus ended up with nutrient deficiency. In previous studies conducted on tomato plants, significant decreases were reported in green herbage N concentrations with Cd treatments (Chaffei et al., 2004; Gouia et al., 2000).

In terms of the effects of increasing Cd doses on P contents of grapevine rootstocks, Cd doses, rootstocks and rootstock x dose interactions were found to be significant at 5% level (Table 2). While the average P content of grapevine rootstock was 4.80 mg plant^{-1} in Cd0 treatment, the value decreased to 2.68 mg plant^{-1} in Cd10 and to 2.74 mg plant^{-1} in Cd20 treatments (Table 2). P contents of the rootstocks either increased or decreased with increasing Cd doses, but generally a decrease was observed in majority of the rootstocks. For instance, P content of 420A genotype was 5.74 mg plant^{-1} in Cd0 treatment and the value decreased to 4.08 mg plant^{-1} in Cd20 treatment. On the hand, P content of SO4 genotype was 4.56 mg plant^{-1} in Cd0 treatment and the value increased to 5.90 mg plant^{-1} in Cd20 treatment (Table 2).

Rizwan et al. (2018) indicated that plants grown in contaminated sites might have different nutrient quantities since Cd accumulation largely depended on plant species and varieties. High Cd concentrations resulted in decreased P contents in tomato (Borges et al., 2019), strawberry (Muradoglu et al., 2015), maize (Anwar et al., 2017) and lettuce (Rizwan et al., 2017).

Table 2. Effects of increasing Cd doses on leaf P and Zn contents of grapevine rootstocks
Çizelge 2. *Asma anaçlarında artan Cd dozlarının yaprak P ve Zn içerikleri üzerine etkileri*

Rootstock	P Content (mg leaf^{-1})				Zn Content (µg leaf^{-1})			
	0	**5**	**10**	**20**	**0**	**5**	**10**	**20**
5BB	7.62^{aA}	5.99^{aA}	3.03^{cdeB}	2.65^{cB}	114.2^{aA}	75.6^{aB}	36.7^{cdC}	32.1^{gC}
8 B	6.35^{abA}	5.02^{abA}	4.33^{bcdA}	4.99^{abA}	64.8^{b-eA}	64.1^{abA}	56.8^{abcA}	54.9^{b-eA}
SO4	4.56^{b-eAB}	4.87^{abAB}	3.34^{cdeB}	5.90^{aA}	51.2^{deAB}	59.7^{abAB}	39.9^{cdB}	70.0^{abcA}
420A	5.74^{abcA}	4.32^{abA}	5.27^{abcA}	4.09^{bcA}	74.6^{bcA}	43.9^{bB}	70.9^{abA}	50.2^{c-fB}
1613 C	5.86^{abcA}	5.40^{abA}	4.16^{bcdeA}	5.05^{abA}	73.7^{bcdA}	59.0^{abA}	48.5^{bcA}	62.5^{a-dA}
99 R	5.83^{abcA}	5.93^{aA}	4.62^{bcdAB}	3.25^{bcB}	77.2^{bA}	57.7^{abB}	52.7^{bcB}	54.2^{b-eB}
110 R	5.73^{abcA}	5.68^{abA}	5.26^{abcA}	4.69^{abA}	57.4^{b-eB}	56.3^{abB}	54.7^{bcB}	77.0^{aA}
140 Ru	4.23^{bcA}	4.88^{abA}	3.81^{bcdeA}	3.28^{bcA}	56.3^{b-eA}	56.8^{abA}	43.3^{cdA}	39.6^{efgA}
1103P	5.03^{bcdAB}	4.89^{abAB}	6.05^{abA}	3.67^{bcB}	52.5^{cdeAB}	50.6^{abAB}	68.9^{abA}	39.4^{efgB}
1045 P	4.57^{b-eAB}	3.32^{bB}	5.09^{abcAB}	6.11^{aA}	64.8^{b-eAB}	40.3^{bB}	53.2^{bcAB}	70.9^{abA}
Dogridge	3.60^{deA}	5.02^{abA}	2.07^{eA}	3.53^{bcA}	49.1^{eA}	59.3^{abA}	22.7^{dA}	44.2^{d-gA}
Harmony	2.74^{eB}	3.25^{bB}	7.26^{aA}	2.82^{cB}	46.5^{eB}	38.1^{bC}	80.1^{aA}	28.0^{gD}
41B	5.26^{bcdA}	4.99^{abA}	4.37^{bcdA}	3.94^{bcA}	59.4^{b-eA}	49.6^{abA}	50.56^{bcA}	43.9^{defA}
Average	**4.80^{bcdA}**	**3.89^{abAB}**	**2.68^{deB}**	**2.74^{cB}**	**56.8^{b-eA}**	**3829^{bB}**	**37.3^{cdB}**	**37.7^{efgB}**

Means shown with similar capital letters in the same row are not significant (p<0.05). Means shown with similar lowercase letters in the same column are not significant (p<0.05).

Considering the Zn contents of the rootstocks under increasing Cd doses, rootstocks, Cd doses and rootstock x dose interactions were found to be significant at 5% level (Table 2). While the average Zn content of grapevine rootstocks was 56.8 µg plant^{-1} in Cd0 treatment, the value decreased to 37.3 µg plant^{-1} in Cd10 and 37.7 µg plant^{-1} in Cd20 treatments (Table 2). As it was in N and P contents, either decreasing or increasing Zn contents of the rootstocks were observed with increasing Cd doses, but generally a decrease was observed in majority of the rootstocks. For instance, while the Zn content of 5BB genotype was 114.2 µg plant^{-1} in Cd0 treatment, the value decreased to 32.1 µg plant^{-1} in Cd20 treatment; Zinc content of 420A genotype was 74.6 µg plant^{-1} in Cd0 treatment and the value decreased to 50.2 µg plant^{-1} in Cd20 treatment. On the other hand, Zn content of SO4 genotype was 51.2 µg plant^{-1} Cd0 treatment, the value increased to 70.0 µg plant^{-1} in Cd20 treatment (Table 2). Such decreases in Zn concentrations under increasing Cd conditions were attributed to antagonistic relationships between Cd – Zn. There are several other studies reporting decreased Zn uptakes with increasing Cd treatments (Erdem et al., 2012; Kinay et al., 2021; Tiecher et al., 2017). More Cd uptake of plants grown under Zn deficiency was attributed to competition of Zn and Cd with similar chemical characteristics for absorption points on membranes (Cakmak et al., 2000; Zhou et al., 2019) and increased membrane permeability under Zn deficiency (Cakmak & Marschner, 1988). Wu et al. (2003) applied increasing Cd doses (0, 0.1, 1.0 and 5.0 µM) to barley plants and determined green herbage Cd and Zn concentrations. It was observed that with Cd treatments to growth environment, not only the Zn concentration of plant tissues decreased, but also Zn transport from the roots to green herbage was inhibited.

Wu et al. (2004) applied increasing Cd doses (1 and 10 mM Cd) to cotton plants and reported decreasing Zn, Cu and Fe concentrations with increasing Cd doses. Hussain et al. (2016) also reported decreasing Zn contents of spinach with increasing Cd treatments. Such decreases were mainly attributed to similar transport and distribution mechanisms of Cd and Zn (Lin & Aarts, 2012). Cadmium toxicity symptoms are encountered in plants when the Cd accumulation reached to a certain threshold and such symptoms includes recessed growth and development, small plant size and browning (Genchi et al., 2020).

Reductions in photosynthesis, growth, and photosynthetic pigments are responses of higher plants to Cd toxicity (Kaya et al., 2019; Luo et al., 2016). For such decreases, rootstocks, Cd doses and rootstock x dose interactions were all found to be significant at 55 level (Table 3, 4 and 5). While the average shoot dry weight was 5.12 g plant^{-1} in Cd0 treatment, the value decreased to 4.27 g plant^{-1} in Cd20 treatment. The greatest decrease in shoot dry weights with Cd treatments were observed in Harmony, 110R and 5BB rootstocks and an increase was observed only in shoot dry weights of SO4 genotype (Table 3). In Harmony genotype with the greatest decrease in shoot dry weight, the value was measured as 5.00 g plant^{-1} in Cd0 treatment and 57% decrease was observed with Cd20 treatment and the value decreased to 2.13 g plant^{-1}. On the other hand, in SO4 genotype, shoot dry weight was measured as 4.44 g plant^{-1} in Cd0 treatment and the value increased to 4.92 g plant^{-1} with about 11% increase in Cd20 treatment (Table 3).

Table 3. Effects of increasing Cd doses on shoot dry weights of grapevine rootstocks

Çizelge 3. *Asma anaçlarında artan Cd dozlarının sürgün kuru ağırlıklarına etkisi*

Rootstock	**Shoot Dry Weight (g plant^{-1})**			
	0	**5**	**10**	**20**
5BB	5.25^{bcA}	4.78^{cA}	4.34^{bcAB}	2.91^{cdB}
8 B	5.49^{bcAB}	6.51^{abA}	5.43^{abAB}	4.41^{abcC}
SO4	4.44^{cB}	6.89^{aA}	3.43^{cdC}	4.92^{aB}
420A	6.88^{abA}	4.38^{cdAB}	6.27^{aB}	5.37^{aAB}
16163 C	4.32^{cA}	2.13^{efB}	1.94^{eB}	2.73^{cdAB}
99 R	5.14^{cA}	4.98^{cA}	4.49^{bcAB}	2.95^{cdB}
110 R	7.47^{aA}	5.00^{bcB}	4.39^{bcBC}	4.13^{abcC}
140 Ru	5.33^{bcA}	3.80^{cdeA}	3.46^{cdA}	3.45^{bcdA}
1103P	3.74^{cA}	2.82^{defB}	2.70^{deB}	3.05^{cdAB}
1045 P	3.96^{cA}	4.05^{cdA}	5.16^{abA}	3.45^{bcdA}
Dogridge	4.36^{cA}	2.95^{defA}	2.84^{deA}	3.79^{a-dA}
Harmony	5.00^{cA}	2.44^{egB}	5.75^{abA}	2.13^{dB}
41B	4.43^{cA}	4.31^{cdA}	3.58^{cdA}	4.15^{abcA}
Average	$\mathbf{5.12^{A}}$	$\mathbf{4.42^{B}}$	$\mathbf{4.31^{B}}$	$\mathbf{4{,}27^{B}}$

Means shown with similar capital letters in the same row are not significant ($p<0.05$). Means shown with similar lowercase letters in the same column are not significant ($p<0.05$).

Table 4. Effects of increasing Cd doses on leaf dry weights of grapevine rootstocks

Çizelge 4*. Asma anaçlarında artan Cd dozlarının yaprak kuru ağırlıklarına etkisi*

Rootstock	**Leaf Dry Weight (g plant^{-1})**			
	0	**5**	**10**	**20**
5BB	3.31^{a-dA}	3.73^{aA}	2.12^{b-eB}	1.71^{bcdB}
8 B	3.36^{abcA}	3.14^{abA}	2.50^{a-dA}	2.78^{abA}
SO4	2.39^{cdeAB}	3.05^{abA}	1.57^{deB}	2.95^{aA}
420A	3.79^{aA}	2.41^{abB}	3.11^{abcAB}	2.56^{abcB}
1613 C	$3.27^{abc\ A}$	$2.37^{ab\ B}$	$1.88^{d\ C}$	2.67^{abcB}
99 R	3.40^{abA}	2.97^{abAB}	2.55^{a-dB}	1.63^{cdC}
110 R	3.35^{abcA}	2.92^{abAB}	2.62^{a-dB}	2.59^{abcB}
140 Ru	2.37^{deA}	2.58^{abA}	2.11^{b-eA}	2.06^{a-dA}
1103P	2.52^{b-eA}	2.45^{abA}	3.18^{abA}	2.16^{a-dA}
1045 P	2.69^{b-eA}	2.09^{bA}	2.85^{abcA}	3.06^{aA}
Dogridge	2.15^{eA}	2.79^{abA}	1.22^{eA}	2.50^{abcA}
Harmony	$2{,}13^{eB}$	$1{,}86^{bB}$	$3{,}62^{aA}$	$1{,}27^{dC}$
41B	3.11^{a-dA}	2.62^{abaA}	2.40^{a-eA}	2.47^{abcA}
Average	$\mathbf{2.90^{A}}$	$\mathbf{2.73^{AB}}$	$\mathbf{2.49^{B}}$	$\mathbf{2.31^{C}}$

Means shown with similar capital letters in the same row are not significant ($p<0.05$). Means shown with similar lowercase letters in the same column are not significant ($p<0.05$).

Average leaf dry weight of the rootstocks was measured as 2.90 g plant^{-1} in Cd0 treatment and the value decreased to 2.31 g plant^{-1} in Cd20 treatment. The greatest decreases in leaf dry weights with increasing Cd treatments were observed in 99R, 5BB and Harmony genotypes and an increase was observed only in leaf dry weight of SO4 genotype (Table 4). In 99R genotype with the greatest decrease in leaf dry weight, the value was measured as 3.40 g plant^{-1} in Cd0 treatment and a

52% decrease was observed in Cd20 treatment and the value decreased to 1.63 g plant^{-1}. On the other hand, in SO4 genotype, leaf dry weight was measured as 2.39 g plant^{-1} in Cd0 treatment and the value increased to 2.95 g plant^{-1} with about 23% increase in Cd20 treatment (Table 4).

Significant changes were not observed in root dry weight of the rootstocks with increasing Cd doses. The average root dry weight of the rootstocks was measured as 5.97 g plant^{-1} in Cd0 treatment and the value increased to 6.00 g plant^{-1} in Cd20 treatment. The greatest decreases in root dry weights were observed in Harmony and 41B genotypes and an increase was observed in root dry weight of 420A genotype (Table 5). In Harmony genotype with the greatest decrease in root dry weight, the value was measured as 4.06 g plant^{-1} in Cd0 treatment and the value decreased to 2.63 g plant^{-1} with about 35% reduction in Cd20 treatment. On the other hand, in 420A genotype, root dry weight was measured as 5.37 g plant^{-1} in Cd0 treatment and the value increased to 8.18 g plant^{-1} with 52% increase in Cd20 treatment (Table 4).

Table 5. Effects of increasing Cd doses on root dry weights of grapevine rootstocks
Çizelge 5. *Asma anaçlarında artan Cd dozlarının kök kuru ağırlıklarına etkisi*

Rootstock	Root Dry Weight (g plant^{-1})			
	0	5	10	20
5BB	4.26^{dA}	5.49^{deA}	6.18^{abcA}	4.78^{c-fA}
8 B	8.45^{abA}	7.16^{cdA}	7.15^{abcA}	8.38^{aA}
SO4	8.81^{aA}	8.21^{bcA}	7.86^{abA}	8.58^{aA}
420A	5.37^{cdB}	3.98^{efB}	5.62^{cdeB}	8.18^{aA}
1613 C	7.26 ^{abcA}	7.08$^{cd A}$	5.48 ^{cdeB}	6.43 $^{a-dAB}$
99 R	5.90^{bcdA}	5.79^{cdeA}	4.92^{cdA}	5.46^{b-eA}
110 R	3.71^{dB}	5.68^{deA}	3.53^{deB}	3.41^{efB}
140 Ru	4.92^{cdA}	3.29^{efA}	4.98^{cdA}	4.44^{defA}
1103P	5.16^{cdA}	4.83^{defA}	5.29^{cdA}	6.65^{a-dA}
1045 P	7.74^{abcA}	10.08^{abA}	8.69^{aA}	7.04^{abcA}
Dogridge	4.10^{dA}	5.62^{deA}	4.76^{cdA}	4.95^{c-fA}
Harmony	4.06^{dA}	2.78^{fAB}	1.97^{eB}	2.63^{fAB}
41B	9.17^{aAB}	11.12^{aA}	7.97^{abAB}	7.51^{abB}
Average	**5,97^{A}**	**6.17^{A}**	**5.74^{A}**	**6.00^{A}**

Means shown with similar capital letters in the same row are not significant (p<0.05). Means shown with similar lowercase letters in the same column are not significant (p<0.05).

Chun et al. (2020) applied different Cd doses (0, 2.5, 10, 20, 50 and 100 mg Cd L^{-1}) to 9 different citrus rootstocks under aquaculture conditions and reported significant decreases in relative growth rates of the rootstocks with increasing Cd doses. As compared to the control, 12.2, 24.1, 57.8 and 94.4% decrease was observed respectively with Cd2.5, Cd10, Cd20 and Cd50 doses. Significant decreases were reported in dry matter content of maize plants with increasing Cd treatments to soils. About 11.9% yield reduction was reported with 10 mg kg^{-1} Cd treatment and 23.5% with 20 mg kg^{-1} Cd treatment (Khurana & Jhanji, 2014). Such decreases in dry matter yields were basically attributed to phytotoxic effect of Cd (El Rasafi et al., 2021; Pereira et al., 2011). Cd stress significantly inhibited plant growth in grafted apple combinations (He et al., 2020). It was reported in previous studies that Cd toxicity inhibited the efficiency of photosynthetic enzymes participating into Calvin cycle and chlorophyl biosynthesis, thus had negative impacts on photosynthesis and ultimately reduced plant yields (Zulfiqar et al., 2021).

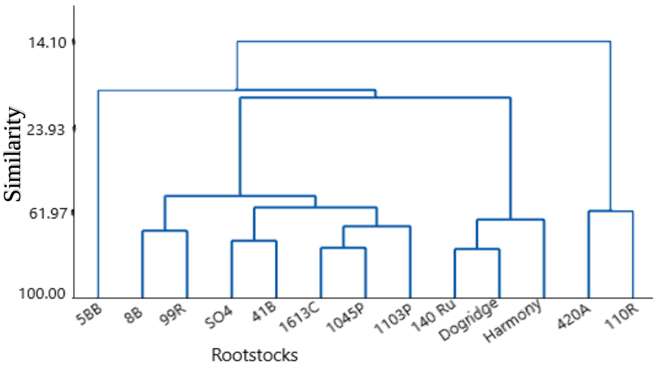

Figure 1. Genetic groupings of grapevine rootstock according to Cluster analysis
Şekil 1. *Kümeleme analizine göre asma anaçlarının genetik gruplamaları*

The dendogram obtained as a result of cluster analysis to determine the similarities between rootstocks in terms, shoot dry weight, leaf dry weight and root dry weight values, and N, P, Zn and Cd contents is given in Figure1. As a result of the analysis, rootstocks were divided into 6 groups according to their similarity. 140 Ru, Dogridge and Harmony have made up the first group. In this group, the similarity rate between 140Ru and Dogridge was 78%, and Harmony joined this group with a 64.9% similarity rate. This group can be characterized by its low nutrient content, and lower root and leaf dry weight. The second group has consisted of 1613, 1045P and 1103P rootstocks. The similarity rate between 1613C and 1045p was 77.4%. 1103P was 68% similar to these two rootstocks. The rootstocks in this group had lower shoot dry weight compared to the others. SO4 and 41B formed the third group with a similarity rate of 74.28%. The most distinctive feature of these two rootstocks was their high dry root weight. The rate of similarity between 8B and 99R, which make up the fourth group, was 69.8%. These two rootstocks were noted for their relatively high N content and high leaf dry weight. 420A and 110R have made up the fifth group with a 61.2% similarity rate between them. In addition to high shoot and leaf dry weight, low dry root weight emerged as the common feature of this group. The 5BB rootstock alone formed the sixth group. The most distinctive features of 5BB that made it different from other rootstocks were its high Cd, P and Zn content.

4. Conclusions

Cadmium pollution encountered in soils poses serious threats on sustainable agriculture and human health (Genchi et al., 2020). Present research revealed new information about the effects of toxic Cd doses on growth, leaf Cd, N, P and Zn contents of grapevine rootstocks. High soil Cd concentrations negatively influence photosynthesis, respiration and nitrogen processes, then recess plant growth and development and reduce plant yields. Recess in plant growth (shoot, leaf, root) under increasing Cd doses was attributed to Cd-induced disorders in plant metabolism and insufficient uptake of plant nutrients. Present findings revealed that based on shoot, leaf and root dry weights, leaf Cd, N, P and Zn contents, there were Cd-sensitive and resistant genotypes among the present ones. Quite lower leaf Cd accumulation than the other genotypes and increasing shoot and leaf dry weights and leaf N, P and Zn content revealed that SO4 genotype was more resistant against toxic Cd conditions. On the other hand, 8B, 420A, 1103P, 5BB, Harmony genotypes with decreasing shoot, leaf and root dry weights under Cd toxicity conditions, higher leaf Cd accumulations and significantly decreasing leaf N, P and Zn contents were considered as sensitive to Cd toxicity. It was determined that the responses of grafted vines to Cd toxicity were changed by rootstock-scion interaction. However, it should be evaluated for Cd accumulation and tolerance in different rootstock/scion combinations.

References

Al-Obeed, R., Kassem, H., & Ahmed, M. (2011). Leaf petiole mineral and fruit heavy metals content of different grape cultivars grown under arid environments and irrigated with treated domestic wastewater. *Advances in Agriculture & Botanics*, *3*(1), 5-14.

Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M.-Q. (2021). Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics*, *9*(3), 42. https://doi.org/10.3390/toxics9030042

Angelova, V. R., Ivanov, A. S., & Braikov, D. M. (1999). Heavy metals (Pb, Cu, Zn and Cd) in the system soil–grapevine–grape. *Journal of the Science of Food and Agriculture*, *79*(5), 713-721.

Anjum, N. A., Umar, S., Ahmad, A., & Iqbal, M. (2008). Responses of components of antioxidant system in moongbean genotypes to cadmium stress. *Communications in soil science and plant analysis*, *39*(15-16), 2469-2483. https://doi.org/10.1080/00103620802292871

Anwar, S., Khan, S., Ashraf, M. Y., Noman, A., Zafar, S., Liu, L., Ullah, S., & Fahad, S. (2017). Impact of chelator-induced phytoextraction of cadmium on yield and ionic uptake of maize. *International journal of phytoremediation*, *19*(6), 505-513. https://doi.org/10.1080/15226514.2016.1254153

Bavaresco, L., Giachino, E., & Pezzutto, S. (2003). Grapevine rootstock effects on lime-induced chlorosis, nutrient uptake, and source–sink relationships. *Journal of plant nutrition*, *26*(7), 1451-1465. Anwar, S., Khan, S., Ashraf, M. Y., Noman, A., Zafar, S., Liu, L., Ullah, S., & Fahad, S. (2017). Impact of chelator-induced phytoextraction of cadmium on yield and ionic uptake of maize. *International journal of phytoremediation*, *19*(6), 505-513. https://doi.org/10.1081/PLN-120021054

Borchard, N., Siemens, J., Ladd, B., Möller, A., & Amelung, W. (2014). Application of biochars to sandy and silty soil failed to increase maize yield under common agricultural practice. *Soil and Tillage Research*, *144*, 184-194. https://doi.org/10.1016/j.still.2014.07.016

Borges, K. L. R., Hippler, F. W. R., Carvalho, M. E. A., Nalin, R. S., Matias, F. I., & Azevedo, R. A. (2019). Nutritional status and root morphology of tomato under Cd-induced stress: comparing contrasting genotypes for metal-tolerance. *Scientia Horticulturae*, *246*, 518-527. https://doi.org/10.1016/j.scienta.2018.11.023

Bremner, J. (1965). Total nitrogen. *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*, *9*, 1149-1178.

Cakmak, I., & Marschner, H. (1988). Increase in membrane permeability and exudation in roots of zinc deficient plants. *Journal of Plant physiology*, *132*(3), 356-361. https://doi.org/10.1016/S0176-1617(88)80120-2

Cakmak, I., Welch, R., Erenoglu, B., Römheld, V., Norvell, W., & Kochian, L. (2000). Influence of varied zinc supply on re-translocation of cadmium (109Cd) and rubidium (86Rb) applied on mature leaf of durum wheat seedlings. *Plant and Soil*, *219*(1), 279-284. https://doi.org/10.1023/A:1004777631452

Chaffei, C., Pageau, K., Suzuki, A., Gouia, H., Ghorbel, M. H., & Masclaux-Daubresse, C. (2004). Cadmium toxicity induced changes in nitrogen management in Lycopersicon esculentum leading to a metabolic safeguard through an amino acid storage strategy. *Plant and cell physiology*, *45*(11), 1681-1693. https://doi.org/10.1093/pcp/pch192

Cheng, K., Tian, H., Zhao, D., Lu, L., Wang, Y., Chen, J., Liu, X., Jia, W., & Huang, Z. (2014). Atmospheric emission inventory of cadmium from anthropogenic sources. *International Journal of Environmental Science and Technology*, *11*(3), 605-616. https://doi.org/10.1007/s13762-013-0206-3

Chun, C.-P., Zhou, W., Ling, L.-L., Cao, L., Fu, X.-Z., Peng, L.-Z., & Li, Z.-G. (2020). Uptake of cadmium (Cd) by selected citrus rootstock cultivars. *Scientia Horticulturae*, *263*, 109061. https://doi.org/10.1016/j.scienta.2019.109061

El Rasafi, T., Oukarroum, A., Haddioui, A., Song, H., Kwon, E. E., Bolan, N., Tack, F. M., Sebastian, A., Prasad, M., & Rinklebe, J. (2021). Cadmium stress in plants: A critical review of the effects, mechanisms, and tolerance strategies. *Critical Reviews in Environmental Science and Technology*, 1-52. https://doi.org/10.1080/10643389.2020.1835435

Erdem, H., Kınay, A., Ozturk, M., & Tutus, Y. (2012). Effect of cadmium stress on growth and mineral composition of two tobacco cultivars. *Journal of Food, Agriculture & Environment*, *10*(1), 965-969.

Erdem, H., Kinay, A., Günal, E., Yaban, H., & Tutuş, Y. (2017). The effects of biochar application on cadmium uptake of tobacco. *Carpathian Journal of Earth and Environmental Sciences*, *12*(2).

Erdem, H. (2021). The effects of biochars produced in different pyrolsis temperatures from agricultural wastes on cadmium uptake of tobacco plant. *Saudi Journal of Biological Sciences*, *28*(7), 3965-3971. 10.1016/j.sjbs.2021.04.016

Genchi, G., Sinicropi, M. S., Lauria, G., Carocci, A., & Catalano, A. (2020). The effects of cadmium toxicity. *International journal of environmental research and public health*, *17*(11), 3782.

Gouia, H., Ghorbal, M. H., & Meyer, C. (2000). Effects of cadmium on activity of nitrate reductase and on other enzymes of the nitrate assimilation pathway in bean. *Plant Physiology and Biochemistry*, *38*(7-8), 629-638. https://doi.org/10.1016/S0981-9428(00)00775-0

Goyal, D., Yadav, A., Prasad, M., Singh, T. B., Shrivastav, P., Ali, A., Dantu, P. K., & Mishra, S. (2020). Effect of heavy metals on plant growth: an overview. *Contaminants in agriculture*, 79-101. https://doi.org/10.1007/978-3-030-41552-5_4

Grant, C. A., Buckley, W. T., Bailey, L. D., & Selles, F. (1998). Cadmium accumulation in crops. *Canadian Journal of Plant Science*, *78*(1), 1-17. https://doi.org/10.4141/p96-100

Greger, M., & Löfstedt, M. (2004). Comparison of uptake and distribution of cadmium in different cultivars of bread and durum wheat. *Crop Science*, *44*(2), 501-507. https://doi.org/10.2135/cropsci2004.5010

Haider, F. U., Coulter, J. A., Cheema, S. A., Farooq, M., Wu, J., Zhang, R., Shuaijie, G., & Liqun, C. (2021). Co-application of biochar and microorganisms improves soybean performance and remediate cadmium-contaminated soil. *Ecotoxicology and Environmental Safety*, *214*, 112112. https://doi.org/10.1016/j.ecoenv.2021.112112

Hart, J. J., Welch, R. M., Norvell, W. A., Sullivan, L. A., & Kochian, L. V. (1998). Characterization of cadmium binding, uptake, and translocation in intact seedlings of bread and durum wheat cultivars. *Plant physiology*, *116*(4), 1413-1420. https://doi.org/10.1104/pp.116.4.1413

He, J., Zhou, J., Wan, H., Zhuang, X., Li, H., Qin, S., & Lyu, D. (2020). Rootstock–scion interaction affects cadmium accumulation and tolerance of malus. *Frontiers in Plant Science*, *11*, 1264. https://doi.org/10.3389/fpls.2020.01264

Hussain, T., Murtaza, G., Ghafoor, A., & Cheema, M. A. (2016). The Cd: Zn ratio in a soil affects Cd toxicity in spinach (Spinacea oleracea L.). *Pak. J. Agri. Sci*, *53*(2), 419-424.

Hussain, B., Ashraf, M. N., Abbas, A., Li, J., & Farooq, M. (2021). Cadmium stress in paddy fields: effects of soil conditions and remediation strategies. *Science of The Total Environment*, *754*, 142188. https://doi.org/10.1016/j.scitotenv.2020.142188

Ibacache, A. G., & Sierra, C. B. (2009). Influence of rootstocks on nitrogen, phosphorus and potassium content in petioles of four table grape varieties. *Chilean Journal of Agricultural Research*, *69*(4), 503-508.

Kacar, B., & İnal, A. (2008). *Bitki analizleri* (Vol. No: 1241). Nobel Yayın.

Kaya, C., Okant, M., Ugurlar, F., Alyemeni, M. N., Ashraf, M., & Ahmad, P. (2019). Melatonin-mediated nitric oxide improves tolerance to cadmium toxicity by reducing oxidative stress in wheat plants. *Chemosphere*, *225*, 627-638. https://doi.org/10.1016/j.chemosphere.2019.03.026

Khurana, M., & Jhanji, S. (2014). Influence of cadmium on dry matter yield, micronutrient content and its uptake in some crops. *Journal of Environmental biology*, *35*(5), 865.

Kim, S., Chang, A., Page, A., & Warneke, J. (1988). *Relative concentrations of cadmium and zinc in tissue of selected food plants grown on sludge-treated soils* (0047-2425).

Kinay, A., Erdem, H., & Karakoç, E. (2021). Chemical Composition of Tobacco Genotypes in Response to Zinc Application Under Cadmium Toxicity. *Romanian Agricultural Research*, *38*, 301-310.

Lecourt, J., Lauvergeat, V., Ollat, N., Vivin, P., & Cookson, S. J. (2015). Shoot and root ionome responses to nitrate supply in grafted grapevines are rootstock genotype dependent. *Australian Journal of Grape and Wine Research*, *21*(2), 311-318. https://doi.org/10.1111/ajgw.12136

Lin, Y.-F., & Aarts, M. G. (2012). The molecular mechanism of zinc and cadmium stress response in plants. *Cellular and molecular life sciences*, *69*(19), 3187-3206. https://doi.org/10.1007/s00018-012-1089-z

Loi, N., Sanzharova, N., Shchagina, N., & Mironova, M. (2018). The effect of cadmium toxicity on the development of lettuce plants on contaminated sod-podzolic soil. *Russian Agricultural Sciences*, *44*(1), 49-52. https://doi.org/10.3103/S1068367418010111

Lugon-Moulin, N., Zhang, M., Gadani, F., Rossi, L., Koller, D., Krauss, M., & Wagner, G. (2004). Critical review of the science and options for reducing cadmium in tobacco (Nicotiana tabacum L.) and other plants. *Advances in agronomy*, *83*(1), 111-118.

Luo, Z.-B., He, J., Polle, A., & Rennenberg, H. (2016). Heavy metal accumulation and signal transduction in herbaceous and woody plants: paving the way for enhancing phytoremediation efficiency. *Biotechnology Advances*, *34*(6), 1131-1148. https://doi.org/10.1016/j.biotechadv.2016.07.003

Miklós, E., & Erdei, L. (1997). Effect of cadmium on growth and ion transport of grapevine. V International Symposium on Grapevine Physiology 526(P. 229-234).

Muradoglu, F., Gundogdu, M., Ercisli, S., Encu, T., Balta, F., Jaafar, H. Z., & Zia-Ul-Haq, M. (2015). Cadmium toxicity affects chlorophyll a and b content, antioxidant enzyme activities and mineral nutrient accumulation in strawberry. *Biological research*, *48*(1), 1-7. https://doi.org/10.1186/s40659-015-0001-3

Nascimento, V., Nogueira, G., Monteiro, G., Júnior, W., de Freitas, J. M. N., & Neto, C. (2021). Influence of Heavy Metals on the Nitrogen Metabolism in Plants. In *Nitrogen in Agriculture-Physiological, Agricultural and Ecological Aspects*. IntechOpen.

Obata, H., & Umebayashi, M. (1993). Production of SH compounds in higher plants of different tolerance to Cd. *Plant and Soil*, *155*(1), 533-536.

Pereira, B. F. F., Rozane, D. E., Araújo, S. R., Barth, G., Queiroz, R. J. B., Nogueira, T. A. R., Moraes, M. F., Cabral, C. P., Boaretto, A. E., & Malavolta, E. (2011). Cadmium availability and accumulation by lettuce and rice. *Revista Brasileira de Ciência do Solo*, *35*, 645-654.

Rasool, M., Anwar-ul-Haq, M., Jan, M., Akhtar, J., Ibrahim, M., & Iqbal, J. (2020). 27. Phytoremedial potential of maize (*Zea mays* L.) hybrids against cadmium (Cd) and lead (Pb) toxicity. *Pure and Applied Biology (PAB)*, *9*(3), 1932-1945. http://dx.doi.org/10.19045/bspab.2020.90206

Rizwan, M., Ali, S., Adrees, M., Ibrahim, M., Tsang, D. C., Zia-ur-Rehman, M., Zahir, Z. A., Rinklebe, J., Tack, F. M., & Ok, Y. S. (2017). A critical review on effects, tolerance mechanisms and management of cadmium in vegetables. *Chemosphere*, *182*, 90-105. https://doi.org/10.1016/j.chemosphere.2017.05.013

Rizwan, M., Ali, S., ur Rehman, M. Z., Rinklebe, J., Tsang, D. C., Bashir, A., Maqbool, A., Tack, F., & Ok, Y. S. (2018). Cadmium phytoremediation potential of Brassica crop species: a review. *Science of the Total Environment*, *631*, 1175-1191. https://doi.org/10.1016/j.scitotenv.2018.03.104

Salt, D. E., Prince, R. C., Pickering, I. J., & Raskin, I. (1995). Mechanisms of cadmium mobility and accumulation in Indian mustard. *Plant physiology*, *109*(4), 1427-1433. https://doi.org/10.1104/pp.109.4.1427

Savvas, D., Colla, G., Rouphael, Y., & Schwarz, D. (2010). Amelioration of heavy metal and nutrient stress in fruit vegetables by grafting. *Scientia Horticulturae*, *127*(2), 156-161. https://doi.org/10.1016/j.scienta.2010.09.011

Sgherri, C., Milone, M. T. A., Clijsters, H., & Navari-Izzo, F. (2001). Antioxidative enzymes in two wheat cultivars, differently sensitive to drought and subjected to subsymptomatic copper doses. *Journal of plant physiology*, *158*(11), 1439-1447. https://doi.org/10.1078/0176-1617-00543

Sgherri, C., Quartacci, M. F., Izzo, R., & Navari-Izzo, F. (2002). Relation between lipoic acid and cell redox status in wheat grown in excess copper. *Plant Physiology and Biochemistry*, *40*(6-8), 591-597. https://doi.org/10.1016/S0981-9428(02)01421-3

Shrivastava, M., Khandelwal, A., & Srivastava, S. (2019). Heavy metal hyperaccumulator plants: the resource to understand the extreme adaptations of plants towards heavy metals. In *Plant-metal interactions* (pp. 79-97). Springer. https://doi.org/10.1007/978-3-030-20732-8_5

Song, X., Yue, X., Chen, W., Jiang, H., Han, Y., & Li, X. (2019). Detection of cadmium risk to the photosynthetic performance of Hybrid Pennisetum. *Frontiers in plant science*, *10*, 798. https://doi.org/10.3389/fpls.2019.00798

Stachowiak, A., Bosiacki, M., Świerczyński, S., & Kolasiński, M. (2015). Influence of rootstocks on different sweet cherry cultivars and accumulation of heavy metals in leaves and fruit. *Horticultural Science*, *42*(4), 193-202. https://doi.org/10.17221/141/2014-HORTSCI

Suhani, I., Sahab, S., Srivastava, V., & Singh, R. P. (2021). Impact of cadmium pollution on food safety and human health. *Current Opinion in Toxicology*, *27*, 1-7.

Tiecher, T. L., Tiecher, T., Ceretta, C. A., Ferreira, P. A., Nicoloso, F. T., Soriani, H. H., De Conti, L., Kulmann, M. S., Schneider, R. O., & Brunetto, G. (2017). Tolerance and translocation of heavy metals in young grapevine (Vitis vinifera) grown in sandy acidic soil with interaction of high doses of copper and zinc. *Scientia Horticulturae*, *222*, 203-212. https://doi.org/10.1016/j.scienta.2017.05.026

Wang, W. (1987). Root elongation method for toxicity testing of organic and inorganic pollutants. *Environmental Toxicology and Chemistry: An International Journal*, *6*(5), 409-414. https://doi.org/10.1002/etc.5620060509

Wu, F., Zhang, G., & Dominy, P. (2003). Four barley genotypes respond differently to cadmium: lipid peroxidation and activities of antioxidant capacity. *Environmental and Experimental botany*, *50*(1), 67-78. https://doi.org/10.1016/S0098-8472(02)00113-2

Wu, F., Wu, H., Zhang, G., & Bachir, D. M. (2004). Differences in growth and yield in response to cadmium toxicity in cotton genotypes. *Journal of Plant Nutrition and Soil Science*, *167*(1), 85-90. https://doi.org/10.1002/jpln.200320320

Xiao, Y., Li, Y., Shi, Y., Li, Z., Zhang, X., Liu, T., Farooq, T. H., Pan, Y., Chen, X., & Yan, W. (2022). Combined toxicity of zinc oxide nanoparticles and cadmium inducing root damage in Phytolacca americana L. *Science of The Total Environment*, *806*, 151211. https://doi.org/10.1016/j.scitotenv.2021.151211

Yang, J., Bao, H., Wan, J., Ding, Y., Wang, F., & Zhu, C. (2021). Screening of tomato cultivars in cadmium-polluted areas and study on their antioxidant capacity. *Sheng wu Gong Cheng xue bao= Chinese Journal of Biotechnology*, *37*(1), 242-252. https://doi.org/10.13345/j.cjb.200242

Yuan, H., Sun, L., Tai, P., Liu, W., Li, X., & Hao, L. (2019). Effects of grafting on root-to-shoot cadmium translocation in plants of eggplant (Solanum melongena) and tomato (Solanum lycopersicum). *Science of The Total Environment*, *652*, 989-995. https://doi.org/10.1016/j.scitotenv.2018.10.129

Zamboni, M., Garavani, A., Gatti, M., Vercesi, A., Parisi, M. G., Bavaresco, L., & Poni, S. (2016). Vegetative, physiological and nutritional behavior of new grapevine rootstocks in response to different nitrogen supply. *Scientia Horticulturae*, *202*, 99-106. https://doi.org/10.1016/j.scienta.2016.02.032

Zhang, J., Zhu, Y., Yu, L., Yang, M., Zou, X., Yin, C., & Lin, Y. (2022). Research Advances in Cadmium Uptake, Transport and Resistance in Rice (Oryza sativa L.). *Cells*, *11*(3), 569. https://doi.org/10.3390/cells11030569

Zhi, Y., Sun, T., Zhou, Q., & Leng, X. (2020). Screening of safe soybean cultivars for cadmium contaminated fields. *Scientific Reports*, *10*(1), 1-12. https://doi.org/10.1038/s41598-020-69803-4

Zhou, J., Wan, H., He, J., Lyu, D., & Li, H. (2017). Integration of cadmium accumulation, subcellular distribution, and physiological responses to understand cadmium tolerance in apple rootstocks. *Frontiers in plant science*, *8*, 966. https://doi.org/10.3389/fpls.2017.00966

Zhou, Z., Zhang, B., Liu, H., Liang, X., Ma, W., Shi, Z., & Yang, S. (2019). Zinc effects on cadmium toxicity in two wheat varieties (Triticum aestivum L.) differing in grain cadmium accumulation. *Ecotoxicology and Environmental Safety*, *183*, 109562. https://doi.org/10.1016/j.ecoenv.2019.109562

Zhou, J., Zhang, C., Du, B., Cui, H., Fan, X., Zhou, D., & Zhou, J. (2020). Effects of zinc application on cadmium (Cd) accumulation and plant growth through modulation of the antioxidant system and translocation of Cd in low-and high-Cd wheat cultivars. *Environmental Pollution*, *265*, 115045. https://doi.org/10.1016/j.envpol.2020.115045

Zulfiqar, U., Ayub, A., Hussain, S., Waraich, E. A., El-Esawi, M. A., Ishfaq, M., Ahmad, M., Ali, N., & Maqsood, M. F. (2021). Cadmium Toxicity in Plants: Recent Progress on Morpho-physiological Effects and Remediation Strategies. *Journal of Soil Science and Plant Nutrition*, 1-58. https://doi.org/10.1007/s42729-021-00645-3