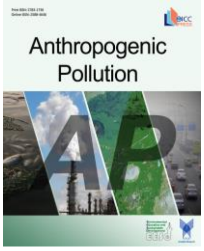

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Research Article

Assessing the Mitigation of Anthropogenic Cadmium Toxicity in Agricultural Soils: Selenium-Mediated Phytomanagement and Ecological Resilience Enhancement in the Wheat (Triticum Aestivum) Food Web

Hamid Adeli[1], Mehrdad Abdi [1,*], Ali Faramarzi[1], Jalil Ajali [1], Naser Mohebalipour [2]

[1] *Department of Agronomy and Plant Breeding, Mi.C., Islamic Azad University, Miyaneh, Iran*
[2] *Department of Genetic and Plant Breeding, Mi.C.,Islamic Azad University, Miyaneh, Iran*

***Corresponding author:** mehrdad.abdi@iau.ac.ir

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Abstract

Anthropogenic accumulation of cadmium (Cd) in agricultural soils heavily threatens ecological integrity and food web security through trophic transfer. To address this persistent challenge, the application of selenium (Se) has emerged as a novel approach in phytomanagement and bio-detoxification. This study aimed to evaluate the efficacy of Se as an eco-modulator to mitigate Cd dynamics and enhance the ecological resilience of agricultural ecosystems. A comprehensive field and greenhouse experiment was conducted during 2023–2024 to assess the morpho-physiological responses of three wheat cultivars to various Se treatments under Cd stress. The study employed a completely randomized block design (CRBD) with a three-factor factorial arrangement: Se source (sodium selenate vs. sodium selenite), Se application rate (0, 18, or 36g/ha), and wheat genotype. Morphological indices and photosynthetic pigment levels were quantified to assess the extent of heavy metal-induced damage and the corresponding remediation efficiency. The findings revealed that Cd stress—particularly at destructive concentrations of 350, and 700 µM —led to a significant reduction in wheat biomass and photosynthetic pigments, posing a direct threat to the health of the agricultural food web. However, eco-intervention through Se application effectively mitigated anthropogenic Cd toxicity. Among the evaluated genotypes, the Pishtaz cultivar exhibited the highest level of resilience against Cd toxicity when treated with selenate. Specifically, treating the Pishtaz cultivar with sodium selenate at an optimal concentration of 3 mg L^{-1} not only alleviated physiological damages induced by heavy metal pollution but also significantly promoted biomass stability. This Se-mediated phytomanagement approach offers a practical and effective ecological strategy for managing Cd-contaminated soils, detoxifying the food web, and safeguarding global food security against anthropogenic pollutants.

Keywords: Anthropogenic pollution; Phytomanagement; Bio-detoxification; Selenium biofortification; Cadmium toxicity; Ecological resilience; Triticum aestivum

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1. Introduction

The accumulation of heavy metals, particularly cadmium (Cd), in agricultural ecosystems has emerged as a formidable challenge to global environmental integrity and food security (Yuan et al., 2021). While the average Cd concentration in agricultural soils varies globally, the anthropogenic accumulation of this pollutant beyond plant tolerance thresholds—typically inducing growth inhibition at 3 mg kg^{-1}—is profoundly alarming. In Iranian soils, for example, this concentration generally ranges between 0.060 and 1.1 mg kg^{-1} (Atabaki & Lotfi, 2018). Wheat (Triticum aestivum), as a strategic staple crop, serves as the primary conduit for the trophic transfer of Cd from contaminated soils into the human food web (Zhou et al., 2022). Physiologically, Cd stress triggers the overproduction of reactive oxygen species (ROS), which precipitates the degradation of photosynthetic pigments and severely disrupts plant growth (Zhang et al., 2022). Consequently, the implementation of robust phytomanagement strategies is imperative to curtail Cd bioavailability and bolster the ecological resilience of crops (Zhang et al., 2024). Selenium (Se), recognized as a beneficial trace element and a potent antioxidant, holds substantial promise as an eco-modulator for the bio-detoxification of Cd. Therefore, this study was designed and executed to evaluate the interactive efficacy of various Se sources in mitigating anthropogenic Cd toxicity and enhancing the ecological resilience of rainfed wheat cultivars under both field and greenhouse conditions.

The cultivation of winter wheat (Triticum aestivum L.) represents a cornerstone of global agriculture, serving as a primary cereal staple and a significant source of nutrition for populations worldwide (He et al., 2018; Hein et al., 2020; FAO, 2023).Occupying approximately 17% of the world's cultivated land, wheat production contributes substantially to meeting global dietary requirements. Beyond its fundamental role in food security and economic systems, wheat is recognized as a key commodity within broader agricultural and trade frameworks (Ansari Ghojghar, 2022). The productivity of wheat systems is influenced by a range of agronomic and environmental factors. These can vary significantly across different regions and farming practices, and include variables related to climate, soil conditions, and plant health management (Rebouh et al., 2023; Temirbekova et al., 2022).

Therefore, all countries of the world seek policies to remove the need for importing this product and supply the main calorie and protein of the state population (Mollasadeghi et al., 2013; Deutsch et al., 2018; and Wang et al., 2022). Among these abiotic stresses, drought is the most complex global stress that affects plant growth and development (Olumi Somarin.et al., 2025).one of the most important limiting factors of wheat production is drought and water shortage (Dietz et al., 2021). Plants are permanently influenced by stressful factors and some stresses as drought stress, as one of the general stress, have very unpleasant effects on the agricultural plants' growth and production (Liu et al., 2024). Most heavy metals have been known as growth inhibitors of plants and have many hazardous effects on plants which make toxicity and reduce the yield and quality of the agricultural products.

Heavy metal (HM) contamination is not only a threat to living organisms but also a global environmental concern (Xu et al., 2022) and Heavy metal (HM) pollution is one of the significant obstructions in determining the productivity of crops at the worldwide level (Rather et al., 2020). The issue of HM stress has become a prominent concern in various soils and aquatic ecosystems worldwide (Alsafran et al., 2023). Cadmium (Cd) is classified as a heavy metal (Benzaoui et al., 2018) and is a non-essential element for biological systems (Xu et al., 2022). In environmental science, its characteristics, including mobility and persistence, have led to its identification as an element of significant concern within the broader category of trace metal contaminants (Abedi, 2020). The management of soil quality, particularly concerning trace elements, is a subject of ongoing global research. For instance, studies have investigated the distribution of heavy metals, with research indicating potential exposure in a notable portion of the world's agricultural land area (Yang et al., 2025). The movement of cadmium from soil into the food chain is a process governed by both plant physiology and soil chemistry. Research indicates that wheat (Triticum aestivum) may exhibit a higher potential for cadmium accumulation in its grains compared to some other cereal crops (Zhou and Li, 2020). This propensity is influenced by the crop's specific root architecture and nutrient transport mechanisms, as well as the bioavailability of the element in the cultivation environment.

The concentration of cadmium in mature wheat grains is the result of a multi-stage, genetically influenced pathway. This encompasses initial root uptake from the soil solution, subsequent translocation through the plant's vascular system to aerial tissues, and final remobilization into the developing grain (Sterckman and Thomine, 2020). Each of these stages interacts with the specific chemical conditions of the soil rhizosphere. In regions experiencing water scarcity, including some developing nations, the utilization of alternative water sources for agriculture is a practical consideration within irrigation management. When certain non-conventional water sources are used, such as in the cultivation of wheat, it can influence the soil's chemical profile, potentially affecting the uptake dynamics of elements like cadmium by the crop (Rehman et al., 2020). The pathway of cadmium within the wheat plant is a well-

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documented physiological process. Scientific consensus, supported by numerous studies, confirms that cadmium is primarily absorbed through the root system. Following uptake, systemic translocation occurs, whereby the element is moved through the plant's vascular tissues to aerial parts, including the stems, leaves, and ultimately the grains (Abedi and Mojiri, 2020). Cadmium (Cd) is a trace element whose presence in agricultural ecosystems is monitored due to its potential impact on environmental and human health. Unlike some other forms of soil alteration, changes in cadmium levels are not readily apparent, which underscores the importance of systematic soil testing and analysis as a component of sustainable crop production and food safety protocols (Niu et al., 2022). Cadmium influences the main processes of the plant such as photosynthesis, cell proliferation, and water absorption by plant roots (Das et al., 2016). Wheat is a staple food crop of global significance. Within the broader context of ensuring food quality and safety, the presence of trace elements, including cadmium, in wheat grains has been identified as a subject for ongoing scientific monitoring and agricultural management worldwide (Jamali et al., 2009). Most previous reports indicated that wheat can easily uptake Cd from the soil. Through Zaid et al (2018) collation, the local area produces at least 150,000 kg of wheat that Cd levels 1.7–12.8-fold that far exceeds the national food standards every year. Xing et al (2016) showed that grain concentrations of all 25 varieties for Cd exceeded the standard for consumption. While the wheat evolved tolerance mechanisms to alleviate the harmful effect of Cd stress, it was not enough for food safety (Rizwan et al., 2016). There need more measures to remediate contaminated soils to ensure the safe production of wheat grains (Zhou et al., 2022).

Selenium is a trace element found in diverse environments that exhibits a dual nature in biological systems, with its effects being highly concentration-dependent (Asgher et al., 2023). For plants, it is not considered a chief or essential element, but research suggests it can play a beneficial role. Studies indicate that at appropriate, low concentrations, selenium may support plant growth and development, including under conditions of environmental stress (Asgher et al., 2023). While selenium can play a beneficial role in plant systems, its effects are closely tied to concentration levels. Elevated accumulation of selenium in the soil or water environment can lead to phytotoxic effects. Consequently, a significant portion of scientific inquiry into plant-selenium dynamics focuses on its interaction with sulfur metabolic pathways, given their chemical similarities (Lu et al., 2020). Research suggests that selenium application can influence the bioavailability and movement of certain metallic elements within plants. This may involve mechanisms that modulate root uptake and subsequent translocation to aerial parts. These interactions are considered part of the plant's broader repertoire of physiological responses to environmental stimuli.

Studies indicate that at specific, low concentrations (typically below 1000 mg Se/kg dry weight), selenium can mitigate some of the physiological impacts associated with metallic elements on plants. This mitigation is thought to occur through the induction of various metabolic and protective pathways, thereby contributing to enhanced stress resilience (Yang et al., 2024). Selenium is recognized for its role in supporting biological defense systems. Research indicates it contributes to oxidative stress management, immune function, and may modulate the biological impact of certain heavy metals (Copat et al., 2018). The environmental presence and management of metalloids, a category that includes elements like selenium, are important considerations in environmental science due to their potential effects on ecosystems and human health (Asgher et al., 2022). In plant biology, selenium is categorized as a beneficial micronutrient. Studies suggest that at appropriate concentrations, it can support plant growth and development. Its physiological role is often associated with antioxidative properties, and it may interact in ways that influence plant responses to various metallic elements in the environment (Gui et al., 2022). The presence of cadmium in the growth environment can trigger abiotic stress in plants. This condition may be associated with an increase in reactive oxygen species (ROS), which can contribute to oxidative processes at the cellular level. To manage the physiological impact of cadmium and support plant resilience, various agronomic and biotechnological strategies are being explored, including phytoremediation techniques. Research has indicated that the application of certain nutrient elements can influence plant responses to heavy metals. For instance, calcium has been studied for its role in modulating plant reactions to metallic elements. Similarly, selenium has received significant scientific interest in recent decades for its observed potential in modifying plant interactions with cadmium. From a nutritional perspective, selenium is recognized as a beneficial element with antioxidant properties that contribute to human health. Concurrently, agronomic studies note that the selenium content in soils, and consequently in crops, varies geographically, with deficiencies identified in some agricultural regions. This duality makes selenium a relevant element in discussions concerning both crop nutrition and food quality.

According to the importance of wheat as a strategic product in the developing and low-water countries like Iran and selenium role to improve the plants tolerance in dry stress condition and state rainfed gardens, this research studies the probable role of selenium on agricultural and physiological characteristics, their improvement, and effect on increasing the plant tolerance against the caused damages by cadmium stresses in Maragheh rainfed conditions.

2. Materials and methods

This research was conducted to study the probable role of selenium on increasing the plant tolerance to damages induced by cadium stress under greenhouse and garden conditions. A test was conducted to study the agricultural characteristics of three wheat cultivars to spraying and various amounts of selenium experimentally as three-factor factorial design in completely randomized blocks design with three replications in a garden in 2023-2024.

2.1. Experimental site

The experiment was conducted on a farm located 10 km from the Maragheh-Hashrood road. An aerial map of the site is shown in Fig. 1. The site experiences a semi-arid, cold climate, at an elevation of 1,056 meters above sea level, with geographical coordinates of 37°26′ N, 46°39′ E. Upon collection and laboratory analysis of soil samples from a depth of 0-30 cm, the soil was characterized as having a clay loam texture. The analysis indicated medium levels of available potassium and phosphorus, while the nitrogen content was assessed to be in the lower range. Additional physical and chemical properties of the sampled soil are detailed in Table 1.

2.2. Garden part

The experiment was conducted using a factorial design with the following three factors:

a) Selenium Source: Sodium selenate and sodium selenite,b) Selenium Application Rate: 0, 18, and 36 g of elemental selenium per hectare. This corresponds to application rates of 0, 43.07, and 86.14 g/ha for sodium selenate, and 0, 59.94, and 119.88 g/ha for sodium selenite. c) Wheat Cultivar: Three cultivars were used: Azar 2, Pishtaz, and Sardari. General Agronomic Management: Prior to sowing, triple superphosphate fertilizer was uniformly incorporated into the soil at a rate of 1120 kg/ha. Sowing was performed manually. A planting density of 300 plants per square meter was maintained, with seeds sown in rows. Each experimental plot contained 12 rows, grouped into four rows per cultivar. A 50 cm border was maintained between cultivar groups within a plot, and individual rows were spaced 15 cm apart with a row length of 6 m. A uniform top-dressing of urea fertilizer was applied at the stem elongation stage to all plots at a rate of 2.5 kg per plot. Selenium Foliar Application: Selenium was applied as a foliar spray in two stages using a 20-liter sprayer. First Application: Coincided with the early stage of the fifth node becoming visible on the main stem, a period selected for optimal canopy development and foliar absorption. Second Application: Was timed to the stage when approximately 75% of the spikelets on the inflorescence had emerged (Sajedi and Nourozi, 2018). 1 m^2 area was sampled from each plot for the quantitative determination of grain yield and biological yield. Harvesting was as hand-weeding after three margin lines removal and half a meter from two ends of the plot. In this research, characteristics of fertile tiller number, plant height, spike without awn length, spike weight, grain weight in spike, weight of 1000 grains, straw yield, total dry matter weight, harvest index, biologic yield, and grain yield were evaluated in this research, and the Better cultivar was selected for greenhouse tests.

Table 1. Additional physicochemical properties of the soil are detailed

Soil depth (cm)	Texture	Sand%	Clay%	Silt%	PH of soil	Soil EC (mmhos/cm)
0-30	Sand-loam	38	24	38	7.99	1.95

Total N%	Organic C%	Absorbable phosphor P(ava)	Absorbable potassium K(ava)
0.08	0.95	14 (mg/kg)	255 (mg/kg)

Figure 1. Aerial view of the project implementation site in the farm section

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2.3. Greenhouse part

In this part of the test, 27 vases in medium size were used with 2:1 ratio of coarse aggregate to the soil. Concentrations were optimized and soil was analyzed before cultivation. Grains were soaked in water for 6 h then 10 grains were cultivated in each vase. Vases were kept in greenhouse condition (26-28 °C, 60% relative humidity, 12 h light, and 12 h darkness, 500 lux light density). Later, vases were irrigated every two days and fed with complete fertilizer solution and spraying Urea fertilizer solution every 15 days to supply the needed minerals. The test was conducted as the two-factor factorial test in completely randomized block designs with three replications. The experimental treatments include factor *a* of various cadmium concentrations (concentrations of 0, 350, and 700 µM), factor b of selenate sodium (concentrations of 0, 1.5, and 3 mg/lit), and prior evaluated cultivar based on the selection from the garden test. Selenate sodium spraying was repeated. The first step was spraying on 18-cm plants as the third-row leaves were grown in this step. The second step was spraying on the flowering spikes. First, the plantlets were sprayed on leaves by selenium treatment with 0, 1.5, and 3 mg/lit concentrations with ppm. After three days, $CdCl_2$ treatment was irrigated in 0, 350, and 700 µM in three permanent days by 120 ml every day. After two weeks, samples were taken for the physiological tests. In this part, characteristics of photosynthetic pigments, anthocyanin, ionic leakage, fresh weight, dry weight, spike weight, grain weight, stem height, and spike height were measured. Lichtenthaler method (1987) be used to measure the photosynthesis pigments, Wanger (1987) method be used to measure anthocyanin, and Ben-Hamed et al (2007) be used to measure the membrane damage.

2.4. Statistical analysis

The statistical analysis of the collected data was performed according to a randomized complete block design (RCBD) with a three-factor factorial arrangement of treatments, replicated three times. Data normality was verified prior to analysis. Analysis of variance (ANOVA) was conducted, and where significant effects were detected, treatment means were compared using Duncan's multiple range test at a significance level of $p \leq 0.05$. The statistical procedures were performed using SAS, SPSS-24, and MSTAT-C software. Data visualizations were subsequently created using Microsoft Excel.

3. Results

The analysis of variance for a three-factor factorial experiment in a randomized complete block design revealed statistically significant effects on yield and yield components in wheat (Table 2). Specifically, the selenium source (sodium selenate vs. selenite) significantly influenced most measured traits, with the exceptions of fertile tiller number, grain weight per spike, and harvest index. Different application rates of selenium also produced significant variations in the majority of characteristics, although the harvest index was not significantly affected. Furthermore, significant differences were observed among the three wheat cultivars (Azar 2, Pishtaz, and Sardari) for all evaluated traits.There was a significant difference in p-value in 5 and 1% based on reciprocal effect of a×b only for characteristics of plant height, total dry matter weight, biological yield, and HI and based on reciprocal effect of b×c for characteristics of fertile tiller number, plant height, straw yield, biological yield, HI, and grain yield.

There was a significant difference based on reciprocal effect only for plant height and biological yield. The aim of executing this part was selecting the prior resources of selenium, Better cultivar, and transferring it to the greenhouse for the complementary tests. Thus, only mean levels of factor *a* for various selenium resources (selenate and selenite sodium), levels of factor b for various selenium amounts (0, 18 and 36 g/ha), and levels of factor c for wheat three cultivars (Azar 2, Pishtaz, and Sardari) were compared and selected. Results of comparing mean levels of factor a about various selenium resources (selenate and selenite sodium) showed that all the evaluated characteristics of applying selenite sodium were prior than selenate sodium except for plant height (Table 3, 4 and 5). Therefore, selenite sodium treatment be examined more in the greenhouse part after selecting this treatment as the prior one and its higher effectiveness on the yield and yield components.

Their results showed that grain pre-treatment with 25 mg/kg as grain consuming while spraying 25 g/ha selenium from selenite sodium showed 4.5% increase in grain weight than the control treatment. However, this increase was 5.3% for wheat. Results of comparing mean levels of factor b for various selenium amounts (0, 18, and 36 g/ha) showed that various amounts of selenium were prior than it non-usage in all the measured characteristics except the fertile tiller number. Consuming 36 g/ha selenium was more prior than consuming 18 g/ha selenium in all the measured characteristics and was put in the prior class. Consuming 36 g/ha selenium increased the characteristics of plant height, spike with awn length, spike without awn length, grain weight in spike, weight of 1000 grains, straw yield, total dry matter weight, biological yield, and grain yield than the control treatment to 3.18, 1.96, 3.19, 3.9, 4.46, 0.16, 4.7, 3.15, and 3.54, respectively (Table 3, 4 and 5).

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Table 2. three-factor factorial variance analysis as completely randomized block design and yield components of wheat cultivars under the effect of selenium application

Change resources	Df	Mean squares					
		fertile tiller number	Plant height	Spike with awn length	Spike without awn length	Grain weight in spike	Weight of 1000 grains
Rep	2	0.104**	1.496**	0.5**	0.51**	0.00007 ns	5.565**
Factor a (selenium resources)	1	0.009 ns	2.77**	0.497**	0.428**	0.00004 ns	1.664 ns
Factor b (selenium amounts)	2	0.526**	36.803**	0.356**	0.26**	0.005**	18.879**
b×a	2	0.038 ns	1.076**	0.00014 ns	0.003 ns	0.00035 ns	1.395 ns
Factor c (cultivars)	2	1.389**	94.402**	1.102**	0.607**	0.03**	746.076**
c×a	2	0.093**	0.051 ns	0.362**	0.425**	0.0004 ns	0.16 ns
c×b	4	0.428**	8.163**	0.077 ns	0.037 ns	0.0005 ns	0.915 ns
c×b×a	4	0.013 ns	0.929*	0.017 ns	0.016 ns	0.0005 ns	0.449 ns
Error	34	0.012	0.278	0.038	0.028	0.00017	1.039
C.V (%)		11.44	12.61	11.38	12.27	12.29	14.33

NS = non-significant, * = significant at $p \leq 0.05$, ** = significant at $p \leq 0.01$

Table 3. three-factor factorial variance analysis as completely randomized block design and yield components of wheat cultivars under the effect of selenium application (Continued)

Change resources	Df	Mean squares				
		Straw yield	Total dry matter weight	Biological yield	Harvest index	Grain yield
Rep	2	21259**	665842**	6377.18*	0.084 ns	1091.341 ns
Factor a (selenium resources)	1	120227**	13420000**	116310**	0.578 ns	24155.001**
Factor b (selenium amounts)	2	16058*	2334205**	131022.36**	0.266 ns	17723.115**
b×a	2	1678.29ns	903222**	9228.73*	1.312*	1220.489 ns
Factor c (cultivars)	2	21426.8**	1755741.4**	39853.6**	20.563**	44290.61**
c×a	2	7124.963 ns	1363405**	19204.326**	1.837*	497.995 ns
c×b	4	7/12286.7*	63591.63 ns	8141.353**	2.276**	2704.617*
c×b×a	4	6516.241 ns	86927.611 ns	5501.87*	0.774 ns	459.569 ns
Error	34	3713.664	58033.4	1821.581	0.344	999.115
C.V (%)		10.73	8.61	14.82	11.91	10.82

Table 4. Analysis of Measured Characteristics in Response to Selenium Application Rate (0, 18, and 36 g/ha) and Wheat Cultivar in a Garden Plot Study

Various resources of selenium	Evaluated characteristics						
	PH (cm)	SWAL (cm)	SWOAL (cm)	SY (Kg/ha)	TDW (Kg/ha)	BY (Kg/ha)	GY (Kg/ha)
selenate	86.25	14.07	7.32	3479.15	14427.15	5168.94b	1718.08
selenite	85.79	14.27	7.5	3573.52	15424.15	5261.76	1760.38

PH: Plant height (cm), SWAL: Spike with awn length (cm), SWOAL: Spike without awn length (cm), SY: Straw yield (Kg/ha), TDW: Total dry matter weight (Kg/ha), BY: Biological yield (Kg/ha) and GY: Grain yield (Kg/ha)

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Table 5. Measured Plant Characteristics in a Garden Plot Study as a Function of Selenium Application Rate (0, 18, and 36 g/ha) and Wheat Cultivar

Various resources of selenium	Evaluated characteristics									
	FLN	PH (cm)	SWAL (cm)	SWOAL (cm)	GWS (gr)	WTG (gr)	SY (Kg/ha)	TDW (Kg/ha)	BY (Kg/ha)	GY (Kg/ha)
Control	7.68[a]	84.81[c]	14.02[c]	7.29[c]	0.561[b]	42.9[b]	3506.3[b]	14574.7[c]	5121.4[c]	1707.42[c]
18 g / hec	7.55[b]	85.65[b]	14.17[b]	7.41[b]	0.584[a]	43.59[b]	3560.6[a]	14907.8[b]	5236.6[b]	1739.4[b]
36 g / hec	7.35[c]	87.59[a]	14.31[a]	7.53[a]	0.592[a]	44.95[a]	3512[b]	15294.3[a]	5288.02[a]	1770.47[a]

Similar letters show the lack of significant difference in Duncan's test ($p \leq 0.05$)

fertile tiller number (FLN), PH: Plant height (cm), SWAL: Spike with awn length (cm), SWOAL: GWS: Grain weight in spike (gr), WTG: Weight of 1000 grains (gr), Spike without awn length (cm), SY: Straw yield (Kg/ha), TDW: Total dry matter weight (Kg/ha), BY: Biological yield (Kg/ha) and GY: Grain yield (Kg/ha)

Table 6. about various amounts of factor c of wheat for the measured characteristics in garden part

Cultivars	Evaluated characteristics										
	FLN	PH (cm)	SWAL (cm)	SWOAL (cm)	GWS (gr)	WTG (gr)	SY (Kg/ha)	TDW (Kg/ha)	BY (Kg/ha)	HI (%)	GY (Kg/ha)
Pishtaz	7.84[a]	88.4[a]	14.5[a]	7.6[a]	0.603[a]	41.2[b]	3542[a]	14870.8[b]	5269.5[a]	32.9[b]	1730.9[b]
Azar 2	7.3[c]	85.9[b]	14.1[b]	7.23[c]	0.603[a]	39.2[c]	3550[a]	15261.7[a]	5184.45[b]	34.6a	1792.4[a]
Sardari	7.45[b]	83.8[c]	13.9[b]	7.4[b]	0.532[b]	51.2[a]	3486.7[b]	14644.3[c]	5192.09[b]	32.6[b]	1694.3[c]

Similar letters show the lack of significant difference in Duncan's test ($p \leq 0.05$)

fertile tiller number (FLN), PH: Plant height (cm), SWAL: Spike with awn length (cm), SWOAL: GWS: Grain weight in spike (gr), WTG: Weight of 1000 grains (gr), Spike without awn length (cm), SY: Straw yield (Kg/ha), TDW: Total dry matter weight (Kg/ha), BY: Biological yield (Kg/ha), HI: Harvest index (%) and GY: Grain yield (Kg/ha)

Results of comparing mean levels of factor c about wheat three (Azar 2, Pishtaz, and Sardari) showed that Pishtaz cultivar had a significant priority than two other cultivars of Azar 2 and Sardari in all the measured characteristics except the weight of 1000 grains, dry material weight, and HI. In addition, the weight of 1000 grains, dry material weight, and HI are in the second rank (Table 6). The results indicated variations in grain yield among the studied genotypes under different treatment conditions. The Pishtaz and Sardari genotypes demonstrated their highest grain yield under the standard treatment regimen, which included the application of 18 and 36 g/ha of sodium selenite. Conversely, the lowest grain yield for these genotypes was recorded under conditions simulating water stress and in the absence of selenium application. Grain yield of Pishtaz cultivar was significantly higher than that for Azar 2 and Sardari cultivars in normal condition (18 and 36 g/ha selenite sodium), while it was indicated by executing water stress (absence of selenium application) that water stress has the lower effect on the grain yield of Azar 2 and Sardari cultivars. Under conditions of water stress without selenium application, a comparative analysis of grain yield revealed variation among cultivars. As shown in Table 6, the grain yield of the Azar 2 and Sardari cultivars was lower than that recorded for the Pishtaz cultivar under these specific conditions.

3.1. Greenhouse part

According to the obtained results from the garden part, Pishtaz was selected as the prior one and selenate sodium treatment as the prior treatment for the greenhouse step. To study more in the greenhouse part, the characteristics of photosynthesis pigments, anthocyanin, ionic leakage, fresh weight, dry weight, spike weight, grain weight, stem height, and spike height were evaluated. The obtained results from the variance analysis of the obtained data from measuring physiological characteristics of Pishtaz cultivar are shown in Table 7. Results of two-factor factorial variance analysis as a completely randomized block design of Pishtaz cultivar physiological characteristics of wheat under the effect of selenate sodium showed that (Table 7) a significant difference was observed in 1% sig. level in all the measured characteristics except anthocyanin based on cadmium levels of factor a (concentrations of 0, 350, and 700 μM). The significant difference was observed in 5 and 1 % sig. the level in all the measured characteristics based on factor b levels about various amounts of selenate sodium (0, 1.5, and 3 g/l). In addition, the significant difference was observed in 1% p-value based on the reciprocal effect of a×b except for chlorophyll b, carotenoids, grain weight, and spike height.

The obtained results from comparing the mean simple effects of factor a×b on the content of chlorophyll b, carotenoids, grain weight, and spike height are shown in Pishtaz cultivar in Table 8.

Results showed that the control treatment had the highest value based on cadmium levels in all the measured characteristics. In other words, cadmium stress significantly reduces the content of chlorophyll b, carotenoids, grain weight, and spike height in Pishtaz cultivar. Moreover, using selenate sodium has the incremental correlation with consumption of the content of chlorophyll b, carotenoids, grain weight, and spike height, and consuming 2 mg/lit selenate sodium had the significant difference than the control treatment. The obtained results from comparing the mean reciprocal effects (cadmium× selenate sodium) on the content of chlorophyll a, anthocyanin, and ionic leakage in Pishtaz cultivar respectively. The obtained data from this research showed about Pishtaz cultivar that both concentrations of 350 and 700 µM were significant in comparison to the control treatment. In non-stress condition, using selenate sodium significantly increases the content of chlorophyll a in comparison to the studied cultivar of cadmium treatment. Cadmium increases the content of anthocyanins in plants under treatment than the control treatment. This increase is significant in 700 µM concentration. In non-stress condition, using selenate sodium significantly increased the content of anthocyanins than the control treatment. The obtained results by measuring ionic leakage are shown in Table 8 and show that leakage index had higher values in plants under the cadmium stress than the control plants which was significant in both concentrations of 350 and 700 µM cadmium. In non-stress condition, using selenate sodium reduces the ionic leakage which is significant in 3 mg/lit selenate sodium. In this research, the obtained results from the photosynthesis pigments analysis showed that the caused stress by the tested cadmium reduces the content of the photosynthesized pigments. In addition, selenium increases the chlorophyll content in the evaluated cultivar. When the plants are exposed to the environmental stress, their chloroplasts were damaged and conducted the photosynthesis toward rupture. The obtained results from comparing the mean reciprocal effect of (selenate sodium × cadmium) were shown on morphological traits including the fresh and dry weight of aerial parts, spike weight, and stem weight in Pishtaz cultivar respectively. The obtained data from this research in Pishtaz cultivar showed that the characteristics of the fresh and dry weight of aerial parts, spike weight, and stem height reduced in the stress condition which is significant in the treatment of 700 µM cadmium (Table 8).

Moreover, using selenate, particularly in 3 mg/lit, significantly increased these characteristics in non-stress condition. Moreover, using selenate in stress condition could reduce the caused negative effects of cadmium treatment.

Table 7. A comparison of mean grain yield for the wheat cultivars was conducted between two distinct growing conditions: (i) standard cultivation with selenium application (at rates of 18 and 36 g/ha of sodium selenite) and (ii) a water stress condition without selenium application

Genotypes	Grain yield (kg/hec)		
	S	N1	N2
Pishtaz	1786.7 [a]	1813.8 [a]	1822.9 [a]
Azar 2	1733.2 [ab]	1739.5 [ab]	1797.2 [ab]
Sardari	1692.5 [b]	1705.2 [b]	1752.4 [b]

Similar letters show the lack of significant difference in Duncan's test ($p \leq 0.05$)

S: water stress (absence of selenium application), N1: normal condition (18 g/ha selenite), and N2: normal condition (36 g/ha selenite)

Table 8. variance analysis of two-factor factorial as completely randomized block design for physiological characteristics

Change resources	Df	Mean squares				
		Chlorophyll a	Chlorophyll b	Carotenoid	Anthocyanin	Ionic leakage
Rep	2	0.281**	2.275	0.314*	0.002	4.926*
Factor a	2	49.82**	11.48**	1.159**	0.002	743.8**
Factor b	2	5.26**	19.94**	0.237*	0.356**	216.04**
b × a	4	0.474**	0.844	0.055	0.023**	21.2**
error	16	0.014	1.058	0.064	0.001	0.801
C.V. (%)		1.46	10.78	15.4	5.53	2.4

NS = non-significant, * = significant at $p \leq 0.05$, ** = significant at $p \leq 0.01$

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Table 9. variance analysis of two-factor factorial as completely randomized block design for physiological characteristics(Continued)

Change resources	Df	Mean squares					
		Fresh weight of aerial parts	Dry weight of aerial parts	Spike weight	Grain weight	Stem height	Spike height
Rep	2	0.012	0.039**	0.024**	0.0001**	0.067	0.011
Factor a	2	4.64**	0.951**	0.033**	0.0001**	33.723**	1.21**
Factor b	2	1.8**	0.018**	0.004**	0.0002**	4.68**	0.533**
b × a	4	0.376**	0.001**	0.00011**	0.000001	0.441**	0.064
error	16	0.005	0.00001	0.00005	0.000001	0.08	0.03
C.V. (%)		4.39	2.05	2.67	3.31	6.62	4

NS = non-significant, * = significant at $p \leq 0.05$, ** = significant at $p \leq 0.01$

Table 10. means of cadmium and selenate sodium treatments about the measured characteristics

		Evaluated characteristics			
		Chlorophyll b content	Carotenoid content	Seed weight (gr)	Spike height (cm)
Cadmium levels	0 µm	10.83a	1.94a	0.045a	4.674a
	350 µm	8.7b	1.73b	0.037b	3.941c
	700 µm	9.10b	1.24c	0.032c	4.301b
		Evaluated characteristics			
		Chlorophyll content b	Carotenoid content	Seed weight (gr)	Spike height (cm)
Selenate levels	0 mg / lit Se	8.3c	1.51b	0.035c	4.03b
	1.5 mg / lit Se	9.13b	1.58ab	0.037b	4.39a
	3 mg / lit Se	11.19a	1.82a	0.042a	4.49a

Similar letters show the lack of significant difference in Duncan's test ($p \leq 0.05$)

4. Discussion

There was a significant difference in p-value in 5 and 1% based on reciprocal effect of a×b only for characteristics of plant height, total dry matter weight, biological yield, and HI and based on reciprocal effect of b×c for characteristics of fertile tiller number, plant height, straw yield, biological yield, HI, and grain yield. A study by Sajedi et al. (2018) investigated the response of wheat and barley agronomic characteristics to foliar application of different selenium sources and concentrations. Their analysis of variance reported several significant effects: a simple effect of selenium concentration, an interaction between selenium source and concentration, and an effect of selenium source on different genotypes, all at a significance level of $p \leq 0.05$. Furthermore, a significant effect of genotype on grain weight per spike was observed at $p \leq 0.01$.

According to the obtained results Consuming 36 g/ha selenium increased the characteristics of plant height, spike with awn length, spike without awn length, grain weight in spike, weight of 1000 grains, straw yield, total dry matter weight, biological yield, and grain yield than the control treatment to 3.18, 1.96, 3.19, 3.9, 4.46, 0.16, 4.7, 3.15, and 3.54, respectively. Selenium contributes to antioxidant processes in biological systems by serving as a key component of specific enzymes, such as glutathione peroxidase (GPx) and thioredoxin reductase, through its integration into selenoproteins (Lee et al., 2025). An analysis of grain yield under water stress conditions (without selenium application) showed variation among cultivars. The grain yield for the Azar 2 and Sardari cultivars was observed to be lower than that of the Pishtaz cultivar under these specific conditions.

Cd levels vary in different countries around the world due to geographic location, latitude and longitude, and environmental climate. Cd levels in soils are currently higher than the original environmental background values in all countries as a result of atmospheric deposition and overuse of phosphate fertilizers (Sall et al., 2020). For example, the average concentration of Cd in European soils is 0.33 mg kg^{-1} (Smolders et al., 2013), while in agricultural land in China, it is 0.19 mg kg^{-1} (Yuan et al., 2021), with an environmental background value of 0.097 mg kg^{-1}. In the United States agricultural soils, the average Cd concentration is 0.265 mg kg^{-1} (Sall et al., 2020). Cadmium (Cd) is the most mobile heavy element in Iranian soils, with a typical concentration of 0.06 to 1.1 mg/kg of soil. Plant tolerance to cadmium varies from 0.2 to 9 mg/kg of soil, but the presence of cadmium at a concentration of 3 mg/kg of soil inhibits the growth of many plants (Atabaki and Lotfi, 2018). According to the obtained results from the garden part, Pishtaz was selected as the prior one and selenate sodium treatment as the prior treatment for the greenhouse step. In this study, the results of the analysis of photosynthetic pigments showed that the stress caused by the tested cadmium caused a decrease in the content of photosynthetic pigments, while selenium caused an increase in the content of chlorophyll in the evaluated cultivar. Whenever plants are exposed to environmental stress, their chloroplasts are destroyed and photosynthesis is directed towards disruption. Increasing selenate at appropriate levels can partially reduce the destruction of chloroplasts and increase the content of chlorophylls (Xie et al., 2025). Liu et al. (2022) reported that the presence of selenate increased the plant's access to iron, which can be effective in maintaining the content of chlorophyll. The obtained data from this research in Pishtaz cultivar showed that the characteristics of the fresh and dry weight of aerial parts, spike weight, and stem height reduced in the stress condition which is significant in the treatment of 700 µM cadmium . Moreover, using selenate, particularly in 3 mg/lit, significantly increased these characteristics in non-stress condition. Moreover, using selenate in stress condition could reduce the caused negative effects of cadmium treatment. Cadmium (Cd) exerts a toxic influence on numerous crucial growth and development processes in plants, notably affecting seed germination rate, transpiration rate, chlorophyll content, and biomass. While considerable advances in Cd uptake and detoxification of plants have been made, the mechanisms by which plants adapt to and tolerate Cd toxicity remain elusive (Zhang et al., 2024).

5. Conclusion

Overall, the results suggest that selenium, particularly sodium selenate, at 3 mg L^{-1} can reduce cadmium toxicity in wheat (notably in the Pishtaz cultivar) and promote plant growth.

Ethics declarations

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Authors' Contribution
All authors have contributed equally to prepare the paper.

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare no competing interests.

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