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Response of Two Libyan Wheat Cultivars (*Triticum turgidum* L. and *Triticum aestivum* L.) to Cadmium Stress: Growth Parameters, Germination, and Seedling Vigor

Ashraf Soliman [1*], Awatef Shlibak [2], Souhaib ELfaraikh [3]
[1,3] Department of Botany, Faculty of Science, Derna University, Libya
[2] Department of Plant Tissue Culture, Libya Center for Biotechnology Research, Tripoli, Libya

استجابة صنفين من القمح الليبي (*Triticum turgidum* L. و*Triticum aestivum* L.) للإجهاد الناتج عن الكادميوم: معايير النمو، والإنبات، وقوة الشتلات

أشرف سليمان[1*]، عواطف شليبك [2]، صهيب الفريخ [3]
[3,1] قسم علم النبات، كلية العلوم، جامعة درنة، ليبيا
[2] قسم زراعة الأنسجة النباتية، المركز الليبي لبحوث التقنية الحيوية، طرابلس، ليبيا

[*]Corresponding author: ashraf.alfaidy@gmail.com

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Abstract:
Cadmium (Cd) toxicity is a major abiotic stress that significantly impedes wheat productivity across the globe. This study was designed to evaluate the relative tolerance of two indigenous Libyan wheat cultivars, 57LW (durum wheat, *Triticum turgidum* L.) and 29LW (bread wheat, *Triticum aestivum* L.), obtained from the Agricultural Research Centre (ARC) in Tripoli. The experiment utilized a completely randomized design (CRD) to test the effects of four distinct concentrations of $CdSO_4$: 0, 100, 250, and 500 µM. Six critical seedling traits were monitored over a 14-day period: germination percentage, shoot length, root length, root fresh weight, root dry weight, and the seedling vigor index (SIV). The findings revealed that cadmium stress significantly affected most growth parameters, though cultivars exhibited distinct levels of resistance. At the highest concentration (500 µM), the germination percentage for 29LW dropped by 27%, whereas 57LW showed a more resilient reduction of only 14%. Furthermore, shoot length in bread wheat (29LW) decreased by 46.8% at 500 µM, while durum wheat (57LW) maintained statistically stable shoot lengths across all treatments. Root system metrics, including length and biomass, declined in both cultivars as Cd levels increased, yet bread wheat consistently showed higher susceptibility. Specifically, at 500 µM, 29LW suffered reductions of 65.4% in root length and 72.1% in root dry weight, compared to 39.0% and 60.4% in 57LW, respectively. The seedling vigor index (SIV) emerged as the most comprehensive indicator of stress impact, decreasing by 65.7% in 29LW and 31.7% in 57LW at the

maximum dosage. Statistical analysis using Duncan’s test confirmed significant differences between the cultivars, particularly regarding root traits and overall vigor. These results demonstrate that the cultivar 57LW possesses superior cadmium tolerance mechanisms, making it an excellent candidate for cultivation in Cd-contaminated soils and for future breeding programs aimed at enhancing environmental stress resilience in Libya.

Keywords: Wheat, cadmium stress, germination percentage, seedling vigor, *Triticum turgidum*, *Triticum aestivum*, Libyan agriculture.

الملخص

تعد سمية الكادميوم (Cd) أحد أهم عوامل الإجهاد غير الحيوي التي تؤثر سلباً على إنتاج القمح في جميع أنحاء العالم. تناولت هذه الدراسة تقييم مدى تحمل صنفين من القمح الليبي هما LW57 (القمح الثنائي الحبة، *Triticum turgidum* L.) وLW29 (قمح الخبز، *Triticum aestivum* L.)، واللذين تم الحصول عليهما من مركز البحوث الزراعية (ARC) في طرابلس، لتراكيز مختلفة من كبريتات الكادميوم ($CdSO_4$) شملت (0، 100، 250، 500 ميكرو مول). اعتمدت الدراسة على تصميم عشوائي كامل (CRD) لفحص ستة معايير لنمو البادرات وهي: نسبة الإنبات، طول البرعم، طول الجذر، الوزن الرطب للجذر، الوزن الجاف للجذر، ومؤشر شدة البادرة (SIV). أظهرت النتائج أن إجهاد الكادميوم أثر بشكل كبير على معظم صفات الشتلات، مع تباين واضح في قدرة الأصناف على المقاومة. فعند تركيز 500 ميكرومول، انخفضت نسبة إنبات الصنف LW29 بمعدل 27% مقارنة بالشاهد، بينما انخفضت في الصنف LW57 بنسبة 14% فقط. كما تراجع طول البرعم في قمح الخبز بنسبة 46.8%، في حين ظلت أطوال البراعم في القمح الثنائي الحبة مستقرة إحصائياً عبر جميع التراكيز. وسجلت معايير الجذور (الطول والكتلة الحيوية) انخفاضاً مع زيادة التركيز في كلا الصنفين، إلا أن قمح الخبز كان أكثر حساسية؛ حيث بلغت نسبة الانخفاض في الصنف LW29 عند تركيز 500 ميكرومول حوالي 65.4% لطول الجذر و72.1% للوزن الجاف، مقابل 39.0% و60.4% للصنف LW57 على التوالي. وبرز مؤشر شدة البادرة (SIV) كأكثر المؤشرات التكاملية دقة، حيث انخفض بنسبة 65.7% في قمح الخبز و31.7% في القمح الثنائي الحبة عند أعلى تركيز. أكد اختبار دنكان وجود فروق معنوية بين الأصناف، خاصة في صفات الجذور وقيم SIV. تخلص الدراسة إلى أن الصنف LW57 يتمتع بتحمل استثنائي للكادميوم، مما يجعله طرازاً جينياً واعداً للزراعة في الأراضي الملوثة وفي برامج التربية لتحسين تحمل القمح للإجهاد في ليبيا.

الكلمات المفتاحية: القمح، إجهاد الكادميوم، نسبة الإنبات، قوة الشتلات، القمح الثنائي الحبة، قمح الخبز، الزراعة الليبية.

1. Introduction

Wheat stands as the most vital cereal crop globally, acting as a fundamental pillar for ensuring international food security. Within the realm of commercial and subsistence agriculture, two species predominate: bread wheat (*Triticum aestivum* L.) and durum wheat (*Triticum turgidum* L.). In Libya, the cultivation of these species is a cornerstone of the national agricultural sector; however, productivity is increasingly jeopardized by various environmental stressors. While conventional abiotic factors such as soil salinity and water scarcity have long been documented as yield-limiting constraints (Ehtaiwesh et al., 2024), the progressive deterioration of agricultural soil quality due to heavy metal pollution specifically cadmium (Cd) has emerged as a critical threat to local agricultural sustainability (Özkutlu et al., 2025; Zaari Jabri et al., 2024).

The gravity of heavy metal contamination in Libya extends beyond soil degradation to encompass the entire food chain, posing severe public health risks. Recent studies conducted in various Libyan regions, such as Bani Waleed, have highlighted an alarming presence of toxic elements like lead and cadmium in diverse food products, including pasteurized milk (Salem, Saeed et al., 2023), goat milk (Salem, 2023), and even baby formulas (Salem, Shouran et al., 2025). Furthermore, the accumulation of these metals has been detected in orange juices (Amheisen et al., 2025) and essential local fruit crops like date palms (Salem & Mohamed, 2025). This widespread environmental contamination underscores the urgent need for a "chemical safety" approach in agricultural production, as cadmium dynamics in the environment lead to its inevitable bioaccumulation in dairy and plant-based products (Salem, Khalil et al., 2025).

In response to these challenges, the Agricultural Research Centre (ARC) in Tripoli maintains a crucial repository of indigenous wheat varieties that are genetically adapted to the specific climatic and edaphic conditions of the Libyan environment (Agriculture Research Centre, 2023). Evaluating the resilience of these local cultivars to pollutants like cadmium is essential for identifying genotypes that can maintain productivity while potentially minimizing the translocation of toxic metals into the grain.

Cadmium is a highly mobile, non-essential heavy metal that is readily absorbed by plant roots and translocated to the aerial tissues, where it disrupts vital physiological processes. Exposure to Cd typically triggers significant oxidative damage through the excessive generation of reactive oxygen species (ROS), which results in the degradation of lipids, proteins, and nucleic acids within the plant cells (Cannea et al., 2025).

Since the seedling stage is the most vulnerable phase of the plant life cycle, early growth attributes including germination percentage, shoot and root length, biomass accumulation, and the seedling vigor index (SIV) are internationally recognized as reliable physiological markers for screening stress-resilient genotypes (Khatlan et al., 2024; Ehtaiwesh et al., 2024).

Consequently, the present investigation was designed to evaluate the morpho-physiological responses of two distinct Libyan wheat cultivars—57LW (*T. turgidum*) and 29LW (*T. aestivum*)—to varying cadmium concentrations (100, 250, and 500 µM). This study aims to elucidate the genotypic differences in cadmium tolerance at the seedling level, providing essential baseline data for the selection and breeding of resilient wheat varieties capable of thriving in Cd-affected soils, thereby contributing to the safety and security of the Libyan food supply.

2. Materials and Methods

2.1. Plant Material and Seed Source

The experimental study utilized two distinct Libyan wheat cultivars: 57LW (*Triticum turgidum* L., durum wheat) and 29LW (*Triticum aestivum* L., bread wheat). Uniform and healthy seeds were provided by the Agriculture Research Centre (ARC) located in Tripoli, Libya (Agriculture Research Centre, 2023).

2.2. Experimental Design and Treatments

The research was conducted under controlled laboratory conditions using a Completely Randomized Design (CRD) with three biological replicates per treatment (Khatlan et al., 2024). Each replicate consisted of 5 seeds sown in Petri dishes, totaling 15 seeds per treatment group (Özkutlu et al., 2025). The experiment tested four specific concentrations of cadmium (Cd) administered as cadmium sulfate ($CdSO_4$):

a. **Control:** 0 µM Cd
b. **Treatment 1:** 100 µM Cd
c. **Treatment 2:** 250 µM Cd
d. **Treatment 3:** 500 µM Cd

Treatment groups were systematically coded to differentiate between cultivars and exposure levels (57LW, control; 29LW, 500 µM) (Cannea et al., 2025).

2.3. Germination and Growth Conditions

To ensure aseptic conditions, seeds were surface sterilized in a 1% sodium hypochlorite (NaOCl) solution for 5 minutes, followed by a thorough rinsing with distilled water. The seeds were then imbibed for 24 hours prior to sowing (Cannea et al., 2025). Five seeds per replicate were placed in Petri dishes lined with Whatman No. 1 filter paper and moistened with 10 ml of the designated $CdSO_4$ solution (Wang et al., 2025b). Control groups were treated with distilled water.

The Petri dishes were maintained in a growth chamber at a constant temperature of 25 ± 2 °C with a regulated photoperiod of 16 hours of light and 8 hours of darkness (Zaari Jabri et al., 2024). Germination was monitored daily for a duration of 14 days. Seeds were officially considered germinated when the radicle length exceeded 2 mm (Cannea et al., 2025). The final germination percentage was calculated using the following formula:

$$Germintion = \left(\frac{Number\ of\ germinated\ seeds}{Total\ number\ of\ seeds}\right) \text{x}100$$

2.4. Growth and Biomass Measurements

Seedlings were harvested for morphological and biomass determination exactly 14 days after treatment initiation (Ali et al., 2025). The following measurements were recorded:

a. Shoot and Root Length: Determined using a high-precision digital caliper and expressed in millimeters (mm) (Özkutlu et al., 2025).
b. Root Fresh Weight (RFW): Measured immediately post-harvest using an analytical balance with an accuracy of 0.001 g, recorded in milligrams (mg) (Khatlan et al., 2024).
c. Root Dry Weight (RDW): Determined after the roots were oven-dried at 70 °C for 48 hours until a constant weight was reached, and recorded in milligrams (mg) (Cao et al., 2025).

2.5. Seedling Vigor Index (SIV)

The Seedling Vigor Index (SIV) was estimated as an integrative parameter to assess the overall impact of cadmium stress on seedling performance (Cao et al., 2025). The calculation followed the formula:

$$SIV = (Mean\ Shoot\ Length + Mean\ Root\ Langth) \text{ x } Germination\ Percentag\ (in\ decimal)$$

2.6. Statistical Analysis

The experimental data were subjected to a One-Way Analysis of Variance (ANOVA) using SPSS software (Version 26) to evaluate the significance of treatment effects. Treatment means were compared and separated using Duncan's Multiple Range Test (DMRT) at a significance level of $p < 0.05$ (Duncan, 1955). Different alphabetical letters were employed to indicate significant differences between treatments and to establish homogeneous subsets.

3. Results and Discussion

The findings of this study demonstrate that cadmium (Cd) stress exerts a profound impact on the majority of wheat seedling traits, particularly root length, fresh weight, dry weight, and overall seedling vigor. While shoot length and germination percentages showed fewer significant differences in certain comparisons, the cumulative data suggests a clear trend of physiological inhibition.

The observed high standard deviation in root and shoot measurements can be attributed to the natural biological variation among seedlings and potential heterogenic patterns in cadmium uptake (Özkutlu et al., 2025). This variance explains the lack of statistical significance in shoot elongation at moderate concentrations. Furthermore, inherent differences in seed viability might account for the non-significant influence on germination percentage observed at lower doses (Cannea et al., 2025).

Interestingly, the deleterious effects of Cd were significantly more pronounced in the root systems than in the shoots. This is primarily because roots serve as the primary site of exposure and the first point of entry for metal ions, leading to immediate cellular disruption (Ali et al., 2025). Consequently, seedling vigor was markedly inhibited due to the cumulative negative effects on both vegetative growth and biomass accumulation.

3.1. Germination Percentage Response

The percentage of germination exhibited a gradual decline as cadmium concentrations increased in both wheat cultivars (Table 1). The highest germination rate (100%) was recorded in the control group of the bread wheat cultivar 29LW, whereas the lowest values (73%) were observed at the maximum concentration of 500 µM Cd in both cultivars.

At 100 µM Cd, germination remained relatively high at 93% for bread wheat and 87% for durum wheat (57LW). At 250 µM Cd, both cultivars stabilized at an 80% germination rate. According to Duncan's Multiple Range Test, the majority of treatments did not differ significantly from one another (Khatlan et al., 2024). Only the bread wheat control was significantly distinct from the 500 µM treatments. This pattern suggests that germination is less sensitive to moderate cadmium levels than post-germinative growth traits, aligning with previous research indicating that cadmium toxicity often induces oxidative stress at trace levels without immediately halting the germination process (Cannea et al., 2025; Wang et al., 2025a).

Table 1. Effect of Different Cadmium Concentrations on Growth Parameters of Two Libyan Wheat Cultivars (57LW *Triticum turgidum* L. and 29LW *Triticum aestivum* L.)

Variety	Cd Treatments	Germination (%)	Shoot length (mm)	Root length (mm)
57LW	Control	87± 0.00 ^{ab}	13.20± 2.35 ^{b}	30.4±13.13 ^{ab}
	100µm	87± 12.00 ^{ab}	12.60± 5.74 ^{ab}	27.6±11.80 ^{ab}
	250µm	80± 20.00 ^{ab}	11.67± 6.20 ^{ab}	23.33±12.21 ^{bc}
	500µm	73± 12.00 ^{b}	11.27±6.20 ^{ab}	18.55±11.76 ^{cd}
29LW	Control	100± 0.00 ^{b}	15.40±2.35 ^{a}	31.8±6.66 ^{a}
	100µm	93± 12.00 ^{ab}	13.67±4.55 ^{a}	29.2±9.02 ^{ab}
	250µm	80± 20.00 ^{ab}	10.87±5.88 ^{ab}	17.8±9.50 ^{cd}
	500µm	73± 12.00 ^{b}	8.20±5.28 ^{b}	11.00±7.00 ^{d}

Values are presented as Mean ± SD. Germination values are shown as percentages. n = 15 for length traits (5 seeds × 3 replicates), n = 3 for germination, shoot and root length. Different letters in the same column indicate significant differences at p < 0.05 according to Duncan's Multiple Range Test.

3.2. Shoot Length Response

Statistical analysis revealed that shoot length was significantly affected by cadmium concentrations in bread wheat, but not in durum wheat (Table 1). Bread wheat (29LW) achieved its maximum shoot length (15.40 mm) in the control group, while exposure to 500 µM Cd resulted in a significant reduction to 8.20 mm—a 46.8% decrease.

In contrast, all concentrations were statistically comparable for durum wheat (57LW). Its shoot length varied from 13.20 mm (control) to 11.27 mm (500 µM Cd), representing a minor, non-significant decrease of only 14.6%. These results highlight that cultivar 57LW maintained its shoot architecture even at high toxicity levels, whereas bread wheat was significantly more vulnerable.

3.3. Root Length Response

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Root length showed a progressive and significant decrease ($p < 0.01$) in both cultivars as Cd concentrations rose (Table 1). Unlike shoot length, nearly all reductions in root length were statistically significant. Both cultivars peaked in their control groups (bread wheat: 31.8 mm; durum wheat: 30.4 mm).

The most severe reduction occurred in bread wheat at 500 µM Cd (11.0 mm, a 65.4% drop), while durum wheat at the same concentration maintained a length of 18.5 mm (a 39.0% drop). These findings are consistent with the work of Cao et al. (2025), who noted that tolerant wheat cultivars preserve better root architecture by sequestering Cd in root vacuoles. Furthermore, Özkutlu et al. (2025) confirmed species-level differences, noting that durum wheat often employs superior mechanisms to handle toxic elements compared to bread wheat.

Table 2. Effect of Different Cadmium Concentrations on Biomass of Two Libyan Wheat Cultivars (57LW *Triticum turgidum* L. and 29LW *Triticum aestivum* L.)

Variety	Cd Treatments	Seedling Vigor (SIV)	Root F.W (mg)	Root Dry weight (mg)
57LW	Control	190.27± 42.11 ^{ab}	105.67±5.132 ^{a}	16.000±1.00 ^{a}
	100µm	169.87± 20.57 ^{ab}	106.67±15.28 ^{a}	11.67±3.06 ^{abc}
	250µm	142.8± 69.72 ^{abc}	66.67±25.17 ^{c}	7.67±3.79 ^{bcd}
	500µm	129.87± 44.71 ^{bcd}	50±20.00000 ^{c}	6.33±1.53 ^{cd}
29LW	Control	207.67± 25.97 ^{a}	96.67±20.82 ^{ab}	14.33±2.09 ^{b}
	100µm	139.67± 30.44 ^{abc}	80±10.0000 ^{abc}	12.00±2.00 ^{ab}
	250µm	71.27±28.09 ^{cd}	70±10.0000 ^{bc}	7.00b±5.57 ^{cd}
	500µm	60.2± 28.09 ^{d}	50±10.0000 ^{c}	4.00±1.00 ^{d}

Values are presented as Mean ± SD. Germination values are shown as percentages. n = 15 for length traits (5 seeds × 3 replicates), n = 3 for fresh weight, dry weight, and SIV. Different letters in the same column indicate significant differences at p < 0.05 according to Duncan's Multiple Range Test.

3.4. Root Fresh and Dry Weight Responses

Root biomass parameters emerged as the most sensitive indicators of cadmium stress, showing drastic and significant declines (Table 2).

- **Root Fresh Weight (RFW):** Maximum values were found in the controls (durum: 105.67 mg; bread: 96.67 mg). At 500 µM Cd, both cultivars dropped to 50.00 mg, representing decreases of 52.7% and 48.3%, respectively.
- **Root Dry Weight (RDW):** This parameter showed even more substantial reductions. The minimum was recorded in bread wheat at 500 µM Cd (4.00 mg, a 72.1% reduction), while durum wheat at the same level recorded 6.33 mg (a 60.4% reduction).

Research by Ali et al. (2025) confirms that tolerant cultivars better preserve root cellular integrity under heavy metal stress. Our results align with Özkutlu et al. (2025), suggesting that Libyan durum wheat (57LW) possesses a higher capacity for biomass maintenance under toxic conditions than bread wheat (29LW).

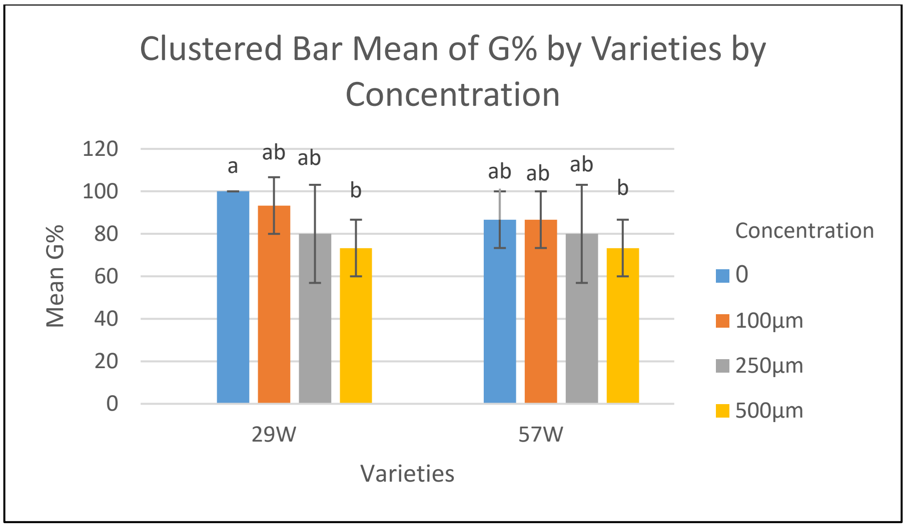

Figure 1: Impact of cadmium with different concentrations on germination percentage in wheat cultivars (57LW, 29LW).

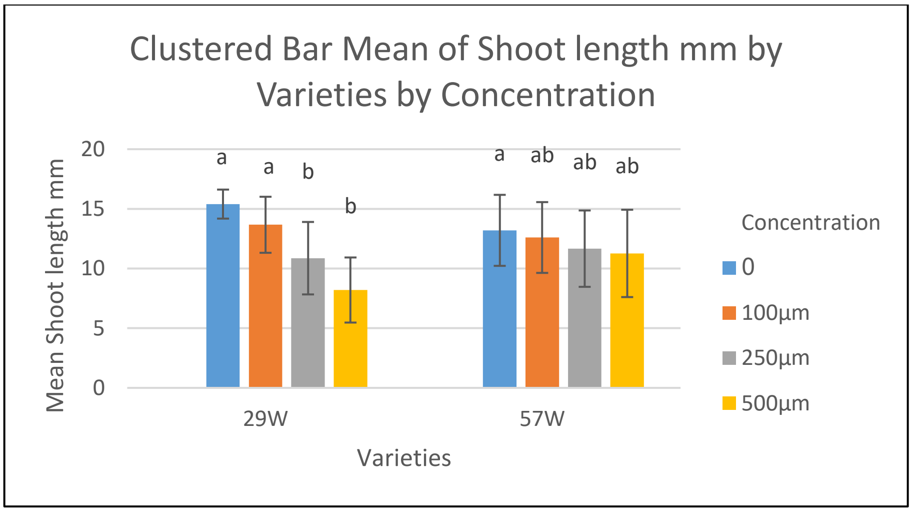

Figure 2: Impact of cadmium with different concentrations on shoot length (mm) in wheat cultivars (57LW, 29LW).

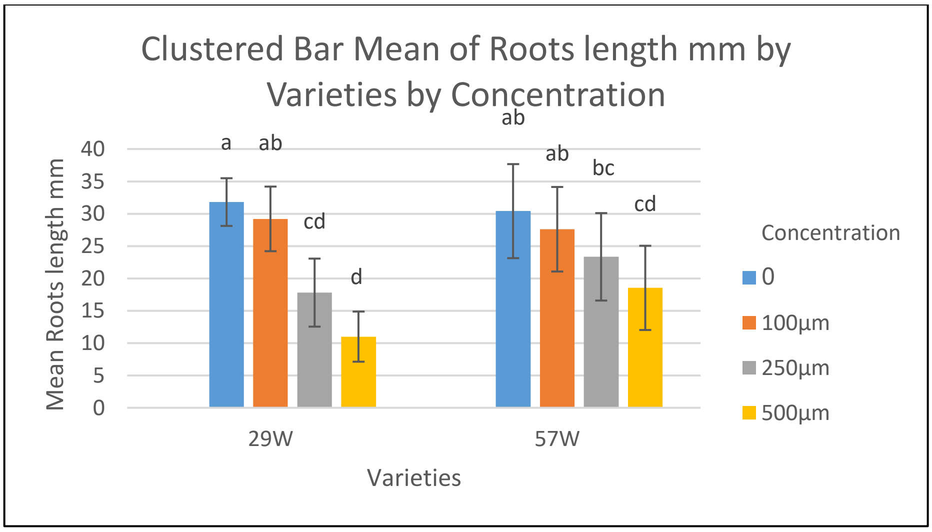

Figure 3: Impact of cadmium with different concentrations on root length (mm) in wheat cultivars (57LW, 29LW)

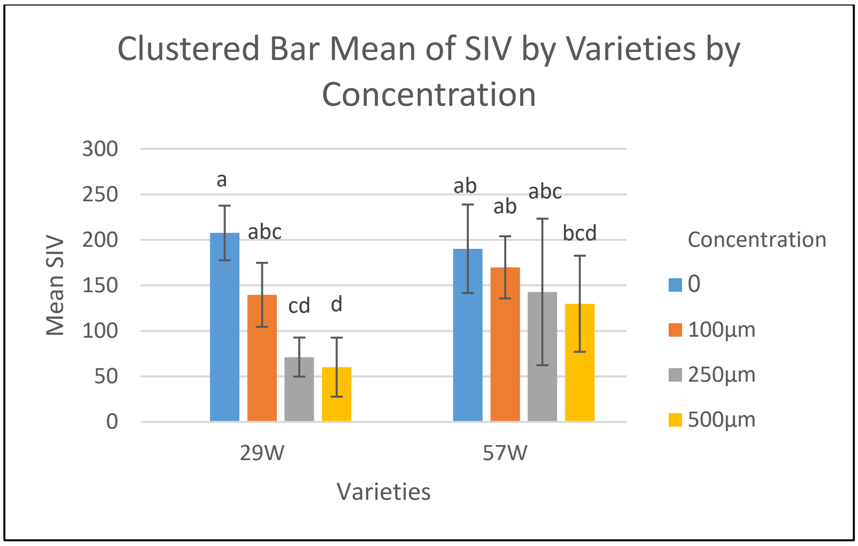

Figure 4: Impact of cadmium with different concentrations on seedling vigor (SIV) in wheat cultivars (57LW, 29LW)

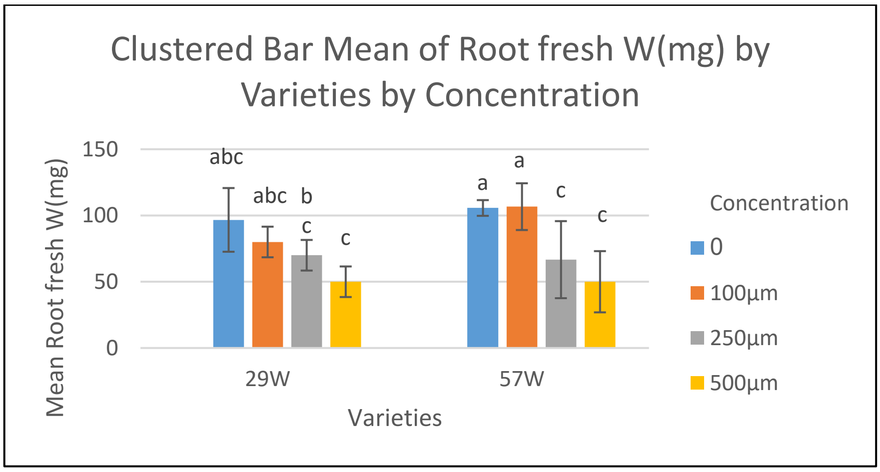

Figure 5: Impact of cadmium with different concentrations on root fresh weight (mg) in wheat cultivars (57LW, 29LW)

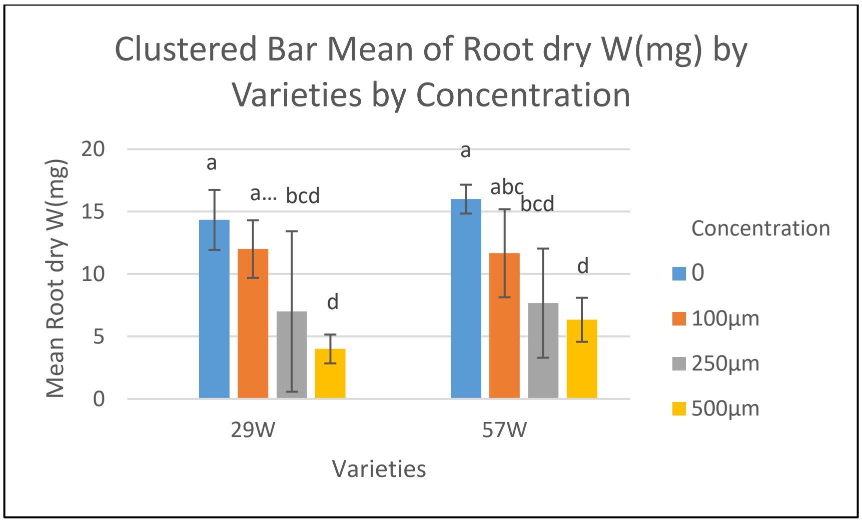

Figure 6: Impact of cadmium with different concentrations on root dry weight (mg) in wheat cultivars (57LW, 29LW)

3.5. Seedling Vigor Index (SIV) as a Summary Parameter

The Seedling Vigor Index (SIV) provides the most comprehensive and unambiguous differentiation between the two cultivars, as it integrates the cumulative effects of germination, shoot elongation, and root development (Table 2). In the absence of stress, the bread wheat control exhibited the highest vigor (207.67), followed closely by the durum wheat control (190.27). However, under cadmium exposure, the performance of the two cultivars diverged sharply.

The most substantial decline in SIV was recorded for bread wheat at 250 and 500 µM Cd, with values dropping to 71.27 and 60.20, respectively. These figures represent drastic reductions of 65.7% and 71.0% compared to its control. In contrast, durum wheat (57LW) maintained significantly higher vigor across all cadmium concentrations. Even at the maximum dosage of 500 µM Cd, durum wheat retained an SIV of 129.87, reflecting a manageable reduction of only 31.7%. This stark contrast clearly illustrates the superior physiological resilience of cultivar 57LW. As noted by Ali et al. (2025), SIV serves as an essential screening tool in breeding programs aimed at developing wheat with low cadmium accumulation. Furthermore, Wang et al. (2025b) suggested that cultivars with higher SIV stability, such as our durum wheat variety, are more effective at reallocating resources under chemical stress to maintain vital growth processes.

3.6. Overall Comparative Performance of Cultivars

The experimental data presented in Tables 1 and 2 indicate a consistent, cultivar-specific response to cadmium toxicity. Durum wheat (57LW) demonstrated superior performance across all measured parameters. It maintained stable germination rates (≥73%) and exhibited no statistically significant decrease in shoot length even at 500 µM Cd. Furthermore, it showed a much higher capacity for preserving root architecture (39.0% vs. 65.4% length reduction) and biomass (60.4% vs. 72.1% dry weight reduction) compared to bread wheat (29LW).

While bread wheat (29LW) showed slightly more robust growth under control conditions, it exhibited extreme sensitivity to cadmium stress, particularly in root-related traits and overall vigor. These findings confirm the species-specific variations reported in recent literature, which are often linked to complex internal mechanisms (Özkutlu et al., 2025; Ali et al., 2025). These mechanisms include enhanced vacuolar sequestration of metal ions (Cao et al., 2025), maintenance of nutrient homeostasis (Wang et al., 2025a), and a more efficient antioxidant defense system (Cannea et al., 2025).

The consistency of these results across all six growth parameters confirms that the Libyan durum wheat cultivar 57LW possesses inherent genetic traits for cadmium tolerance. This makes it an ideal candidate for cultivation in Cd-polluted soils and a valuable genetic resource for future breeding programs. The observed high standard deviations at elevated cadmium levels are expected, reflecting the natural biological variation and the threshold of physiological breakdown under severe toxicity (Cao et al., 2025; Wang et al., 2025b).

4. Conclusion

The present study confirms that the Libyan durum wheat variety 57LW exhibits a significantly higher degree of tolerance to cadmium (Cd) stress compared to the bread wheat variety 29LW. This resilience was consistently demonstrated through stable germination rates, sustained shoot elongation, and the preservation of higher root biomass and overall seedling vigor, even under elevated Cd concentrations. Among the parameters evaluated, the Seedling Vigor Index (SIV) and root morphological traits emerged as the most sensitive indicators of cadmium toxicity. These metrics provided the most definitive differentiation between the tolerant and sensitive cultivars, highlighting the pivotal role of root system architecture in heavy metal stress adaptation. These findings align with recent literature emphasizing that genotypic variation in wheat is a critical factor in determining the extent of physiological damage caused by non-essential heavy metals. The outstanding performance of cultivar 57LW under controlled toxicity levels provides essential insights for the future of Libyan agriculture. This cultivar stands out as a promising candidate for cultivation in areas affected by soil contamination and serves as a vital genetic resource for breeding programs focused on environmental resilience. Moving forward, it is recommended that these findings be validated through comprehensive field trials to account for complex soil-plant interactions. Furthermore, future research should aim to elucidate the underlying physiological and molecular mechanisms—specifically the expression of metal transporter genes and the efficiency of antioxidant defense systems. Such efforts will be instrumental in supporting the targeted breeding of stress-resilient wheat cultivars, ensuring food security in the face of increasing environmental challenges.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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