

Mitigating the Negative Effects of Moisture Stress by Adding Vermicompost and Spraying Boron on Mustard Plant Growth

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Abstract

A field experiment was conducted at the College of Agriculture, University of Diyala, at the Postgraduate Research Projects site during the spring season of 2023 to study the effect of adding vermicompost and spraying boron on the growth and yield of mustard plants affected by water stress. The experiment was implemented according to a randomized complete block design (RCBD) using a split-split plot design with three replications, consisting of 54 experimental units as a three-factor experiment. The three water stress treatments were placed in the main plots, while two concentrations of boron were placed in the subplots, and three levels of vermicompost were placed in the sub-subplots. The water stress treatments were irrigation every (3, 6, and 9) days, and the concentrations of boron were 0 mg L⁻¹ and 100 mg L⁻¹ in the form of boric acid (H₃BO₃). The levels of vermicompost added were 0, 1, and 2 mg ha⁻¹ as a soil amendment. The results were analyzed statistically, and the means were compared using Duncan's multiple range test at a probability level of 0.05. The results showed that the plant height, leaf area, dry weight, and relative chlorophyll content increased with the application of boron at a concentration of 100 mg L⁻¹, with averages of 8.99%, 7.54%, 16.57%, and 10.64%, respectively, compared to untreated plants. The soil application of vermicompost at a level of 2 mg ha⁻¹ led to a significant increase in the studied traits, achieving the highest averages for plant height, leaf area, dry weight, and relative chlorophyll content of 125.87 cm, 842.53 cm², 9.77 g, and 7.83 mg g⁻¹. The third irrigation period (W3) excelled in increasing plant height, leaf area, dry weight, and relative chlorophyll content in the leaves of the plants, with averages of 130.22 cm, 749.64 cm², 9.78 g, and 7.14 mg g⁻¹.

Introduction

Agriculture is the largest consumer of freshwater resources, with approximately 70% of freshwater being used for agricultural production. With the increase in global warming and variations in rainfall patterns, drought has become one of the most significant challenges facing both the environment and the agricultural sector, particularly in arid and semi-arid regions. The primary impact of drought (water stress) lies in damaging the cell membrane, proteins, and nucleic acids, which in turn negatively affects gas exchange and photosynthesis, ultimately reducing plant growth and, consequently, crop yield (1). Drought adversely affects various aspects of plant physiology,

particularly photosynthetic efficiency. If water stress persists for an extended period, it significantly impacts plant growth and productivity (2). Therefore, it is necessary to implement techniques and strategies to enhance water use efficiency, such as modern irrigation methods or the addition of certain compounds or organic materials that can reduce plant water demand and mitigate stress effects.

Boron is an essential element for plant growth, playing a crucial role in the biosynthesis of the cell wall, photosynthesis, enzymatic activities, and nucleic acid formation. Boron deficiency is widespread in crops and is among the most easily leached micronutrients in the soil compared to other trace elements.

Consequently, foliar spraying is considered one of the most effective methods to address boron deficiency in plants (3). Boron also regulates water balance within the plant and influences sugar transport to storage sites. It promotes the absorption of essential nutrients such as nitrogen (N), calcium (Ca), and potassium (K) and plays a vital role in hormone formation, cell division—particularly in meristematic tissues—and pollen grain formation. Boron deficiency leads to tissue necrosis, resulting in corky or decayed plant parts (4). Additionally, boron deficiency slows growth, reduces yield, and impairs root sugar supply, leading to reduced root development and limited nutrient uptake (5).

Vermicompost is an organic fertilizer rich in macro- and micronutrients essential for plant growth. It is highly absorbable by plants and enhances the activity of beneficial soil microorganisms, such as nitrogen-fixing bacteria and phosphate-solubilizing fungi. These microbes produce growth hormones like auxins and gibberellins (6). Vermicomposting is also an effective method for recycling food waste and plant and animal residues using earthworms (Edwards, 2010). Compared to conventional fertilizers, vermicompost is one of the most efficient organic fertilizers, offering optimal plant growth and higher crop yields (7).

Mustard (*Brassica* spp.) belongs to the Brassicaceae family and is a widely distributed herbaceous plant found in parts of Europe, North America, Asia, and Africa (8). and are widely utilized in the food and pharmaceutical industries. Mustard is valued for its oil and protein content, with its seeds commonly used in spice and oil production. Additionally, mustard exhibits a remarkable ability to adapt to different environmental conditions. Given its numerous benefits, mustard is considered a promising crop that warrants further research and development to optimize its cultivation techniques and expand its applications in

various fields, Objective of the Study This study aims to assess the response of mustard plants subjected to water stress when treated with boron foliar spraying and soil-applied vermicompost. Additionally, it seeks to determine the optimal combination of these factors and their effects on growth characteristics and yield.

Materials and Methods

A field experiment was conducted at the College of Agriculture, University of Diyala, at the Graduate Research Projects site during the spring season of 2024. The study aimed to investigate the effect of boron foliar spraying and soil application of vermicompost on mustard plants subjected to water stress. Soil samples were collected from different areas of the field before planting at a depth of 0–30 cm. These samples were air-dried, ground, and sieved using a 2 mm mesh sieve. The representative soil sample underwent several laboratory analyses in the postgraduate laboratories of the Department of Soil Sciences and Water Resources, College of Agriculture, University of Diyala.

The field was prepared for planting by plowing, leveling, and soil conditioning. It was divided into three blocks, each containing 18 experimental units, with three replications. Each experimental unit measured 2 meters in length and 0.5 meters in width, with 9 mustard seedlings planted per unit at a spacing of 20 cm between plants. A drip irrigation system (T-Tape) was used, with seedlings planted adjacent to the emitters distributed throughout the field.

The experiment followed a split-split plot design within a randomized complete block design (RCBD). The main plots were assigned to three water stress levels with irrigation intervals of (3, 6, and 9) days, designated as W1, W2, and W3, respectively. The subplots were allocated to two boron foliar spraying levels (0

and 100 mg L⁻¹) applied in the form of boric acid (H₃BO₃) and designated as B0 and B100. The sub-subplots included three levels of vermicompost soil application (0, 1, and 2 Mg ha⁻¹), represented as V0, V1, and V2. This setup resulted in a total of 54 experimental treatments (3 irrigation levels × 2 boron levels × 3 vermicompost levels × 3 replicates).

The results were statistically analyzed using the SAS software according to the experimental design, and means were compared using Duncan's multiple range test at a significance level of 0.05. Vermicompost was incorporated into the soil before planting and thoroughly mixed with the soil on February 18, 2024. The plants were fertilized with the chemical fertilizer NPK (20-20-20) in three applications according to the fertilization recommendation, and the pesticide (Actara)

Plant Height Measurement: The height of the plant was measured from the point of contact with the soil to the apex of the growing tip for five selected plants from each experimental unit, and the average was calculated.

Leaf Area Calculation: The leaf area of five randomly selected plants from each experimental unit was calculated using discs of

known area, according to the following equation:

$$\text{Leaf area} = (\text{Total dry weight of leaves} / \text{Dry weight of disks}) * \text{Disk area (9)}$$

Dry Weight Measurement: The dry weight of the plants was measured by selecting five fully grown plants, which were dried in the oven of the Soil Science and Water Resources Department at the College of Agriculture, University of Diyala, at a temperature of 70°C for 24 hours, and the average was calculated.

Relative Chlorophyll Content Measurement: The relative chlorophyll content was measured using a UV-Vis spectrophotometer at wavelengths of 645 nm and 663 nm (10).

Proline Estimation: Proline was estimated according to the method of (11) using a spectrophotometer at a wavelength of 520 nm, and proline content was calculated using the following equation:

$$\mu \text{ mole proline} / \text{g Fr.wt} = (\text{Reading} * 4 * 5 / \text{wt.in g}) 1.47$$

Table 1: Selected Chemical and Physical Properties of the Soil Before Planting

Soil Properties	Units	Value
pH (1:1)	-	7.73
Electrical Conductivity (EC1:1)	dS m ⁻¹	4.23
Available Nutrients		
Nitrogen (N)	mg kg ⁻¹	12.78
Phosphorus (P)	mg kg ⁻¹	8.28
Potassium (K)	mg kg ⁻¹	174.3
Boron (B)	mg kg ⁻¹	1.3
Organic Matter	g kg ⁻¹	1.6
Calcium Carbonate (CaCO ₃)	g kg ⁻¹	143.14
Soil Texture		
Sand	g kg ⁻¹	572

Clay	g kg ⁻¹	235
Silt	g kg ⁻¹	193
Soil Texture Class	-	Sandy Clay Loam

Results and Discussion

1- Plant Height (cm)

The results in Table 2 show that the second level of boron spraying (B100) significantly increased plant height compared to the first level, with a 8.99% increase. Similarly,

the third level of vermicompost application (V2) outperformed the first and second levels, with percentage increases of 30.39% and 16.42%, respectively. Additionally, the first moisture level

Table 2. Effect of Vermicompost Addition and Boron Spraying on the Growth and Yield of Mustard Under Water Stress Conditions (Plant Height in cm)

Boron interference And vermicompost	Water stress			Vermicompost Megagram 1-ha	Boron foliar spray (1-mg/L)
	9 W	6 W	3 W		
91.76 e	60.43 k	102.66 g	112.20 f	V0	B ₀
103.05 d	73.27 j	113.06 f	122.86 e	V1	
121.48 b	92.73 h	128.76 d	142.96 b	V2	
101.30 d	71.43 j	116.26 f	116. 20 f	V0	B ₁₀₀
113.17 c	83.50 i	123.50 e	132.53cd	V1	
130.24 a	101.80 g	134.33 c	154.60 a	V2	
Boron spray averages	Water stress			Interaction of water stress and borax spraying	
	9 W	6 W	3 W		
105.43 B	75.46 e	114.83 c	126.01 b	B ₀	
114.91 A	85.57 d	124.70 b	134.44 a	B ₁₀₀	
Vermicompost averages	Water stress			Interaction of water stress and vermicompost	
	9 W	6 W	3 W		
96.53 C	65.93 i	109.46 f	114.20 e	V0	
108.12 B	78.38 h	118.28 d	127.70 c	V1	
125.87 A	97.26 g	131.55 b	148.78 a	V2	
	80.52 C	119.76 B	130.22 A	Water stress averages	

The following letters refer to: B0 = No boron spraying, B100 = Boron spraying at a concentration of 100 mg B kg⁻¹ L⁻¹, V0 = No vermicompost addition, V1 = Vermicompost addition at a rate of 1 megagram hectare⁻¹, V2 = Vermicompost addition at a rate of 2 megagrams hectare⁻¹, W1 = Water added every 3 days, W2 = Water added every 6 days, W3 = Water added every 9 days., Numbers with identical letters and symbols do not differ significantly according to Duncan's test at a 5% probability level.

(W1) resulted in a greater plant height compared to the second and third levels, with

percentage increases of 8.73% and 61.72%, respectively.

Regarding the interaction between boron spraying and vermicompost application, a significant effect on plant height was observed. The highest average plant height (130.24 cm) was recorded in the (B100+V2) treatment, while the lowest average (91.76 cm) was found in the (B0+V0) treatment, representing a 41.93% increase.

The interaction between moisture levels and boron application also showed a significant effect, with the (W1+B100) treatment achieving the highest plant height (134.44 cm), whereas the lowest height (75.46 cm) was recorded in (W3+B0), with a 78.16% increase.

When comparing boron spraying levels within the third moisture level (W3), a significant difference was observed, with (W3+B100) outperforming (W3+B0) by 13.39%.

For the interaction between moisture levels and vermicompost application, the (W1+V2) treatment resulted in the highest plant height (148.78 cm), while the lowest height (65.93 cm) was recorded in (W3+V0), with a 125.66% increase. The (V2+W3) treatment

significantly outperformed (W3+V0) and (W3+V1) by 47.52% and 24.08%, respectively.

Effect of Triple Interaction Between Moisture Levels, Boron Spraying, and Vermicompost Addition, The treatment (W1+B100+V2) recorded the highest plant height (154.6 cm), while the lowest (60.43 cm) was observed in (W3+B0+V0), showing a significant increase of 155.83%. Additionally, the (B100+V2) treatment at the third moisture level (W3) outperformed other boron spraying and vermicompost application levels under the same moisture condition (W3).

2- Leaf Area (cm²)

The results in Table 3 indicate that the second level of boron spraying (B100) significantly increased leaf area by 7.54% compared to the first level.

Additionally, the third level of vermicompost application (V2) significantly enhanced leaf area compared to the first and second levels, with increases of 98.53% and 44.47%, respectively.

Table 3. Effect of Vermicompost Addition and Boron Spraying on the Growth and Yield of Mustard Under Water Stress Conditions (Leaf Area in cm²)

Boron interference And vermicompost	Water stress			Vermicompost Megagram 1-ha	Boron foliar spray (1-mg/L)
	9 W	6 W	3 W		
390.49 f	301.49 n	388.42 l	481.54 j	V0	B 0
539.26 d	417.59 k	523.37 i	676.83 f	V1	
790.57 b	622.39 h	759.71 d	989.63 b	V2	
458.26 e	369.03 m	477.21 j	528.54 i	V0	B 100
627.04 c	527.28 i	634.75 g	719.10 e	V1	
894.50 a	708.82 e	872.45c	1102.22a	V2	
Boron spray averages	Water stress			Interaction of water stress and borax spraying	
	9 W	6 W	3 W		
573.44 B	447.16 f	557.17 d	716.00 b	B 0	
616.69 A	535.04 e	661.47c	783.29 a	B 100	
Vermicompost	Water stress			Interaction of water stress	

averages	9 W	6 W	3 W	and vermicompost
424.37 C	335.26 i	432.18 h0	505.04 f	V0
583.15 B	472.43 g	579.06 e	697.96 c	V1
842.53 A	665.61 d	816.08 b	1045.92a	V2
	491.10C	609.32B	749.64A	Water stress averages

The following letters refer to: B0 = No boron spraying, B100 = Boron spraying at a concentration of 100 mg B kg⁻¹ L⁻¹, V0 = No vermicompost addition, V1 = Vermicompost addition at a rate of 1 megagram hectare⁻¹, V2 = Vermicompost addition at a rate of 2 megagrams hectare⁻¹, W1 = Water added every 3 days, W2 = Water added every 6 days, W3 = Water added every 9 days., Numbers with identical letters and symbols do not differ significantly according to Duncan's test at a 5% probability level.

The first moisture level (W1) also exceeded the second and third levels, increasing leaf area by 23.03% and 52.65%, respectively. The interaction between boron spraying and vermicompost addition significantly affected leaf area, with (B100+V2) achieving the highest average (894.5 cm²), while (B0+V0) recorded the lowest (390.49 cm²), reflecting a 129.07% increase..

Regarding the interaction between moisture levels and boron application, the (W1+B100) treatment resulted in the highest leaf area (783.29 cm²), whereas the lowest (447.16 cm²) was recorded in (W3+B0), with a 75.16% increase. Comparing boron spraying levels within the third moisture level (W3), (W3+B100) significantly outperformed (W3+B0) by 19.65%.

Effect of Interaction Between Moisture Levels and Vermicompost on Leaf Area Table 3 also illustrates the impact of the interaction between moisture levels and vermicompost application. The (W1+V2) treatment achieved the highest leaf area (1045.92 cm²), while the lowest (335.26 cm²) was recorded under (W3+V0), with a significant increase of 221.97%., Additionally, the (V2+W3) treatment

significantly outperformed (W3+V0) and (W3+V1) by 98.53% and 40.89%, respectively. For the triple interaction between moisture levels, boron spraying, and vermicompost application, (W1+B100+V2) exhibited the highest leaf area (1102.22 cm²), while (W3+B0+V0) recorded the lowest (301.49 cm²), with a 265.66% increase. Moreover, (B100+V2) at the third moisture level (W3) significantly surpassed other boron spraying and vermicompost treatments within the same moisture level (W3).

3- Dry Weight of the Plant (g)

The results in Table 4 indicate that the second level of boron spraying (B100) significantly increased plant dry weight by 16.57% compared to the first level.

Additionally, the third level of vermicompost application (V2) significantly enhanced dry weight compared to the first and second levels, with increases of 72.92% and 29.92%, respectively.

The first moisture level (W1) also exceeded the second and third levels, increasing dry weight by 28.18% and 77.17%, respectively.

Table 4. Effect of Vermicompost Addition and Boron Spraying on the Growth and Yield of Mustard Under Water Stress Conditions (Plant Dry Weight in g)

Boron interference And vermicompost	Water stress			Vermicompost Megagram 1-ha	Boron foliar spray (1-mg/L)
	9 W	6 W	3 W		
5.31 e	3.62 j	5.29 hi	7.03 fg	V0	B ₀
6.86 d	4.23 ij	7.23 efg	9.11 cd	V1	
9.02 b	6.64 fgh	8.68 cde	11.74 b	V2	
5.99 e	4.47 ij	6.12 gh	7.37 efg	V0	B ₁₀₀
8.19 c	6.46 fgh	8.57 cde	9.53 c	V1	
10.52 a	7.72 def	9.92 c	13.93 a	V2	
Boron spray averages	Water stress			Interaction of water stress and borax spraying	
	9 W	6 W	3 W		
7.06 B	4.83 f	7.06 d	9.29 b	B ₀	
8.23 A	6.21 e	8.20c	10.28 a	B ₁₀₀	
Vermicompost averages	Water stress			Interaction of water stress and vermicompost	
	9 W	6 W	3 W		
5.65 C	4.05 e	5.70 d	7.20 c	V0	
7.52 B	5.43 d	7.90 c	9.32 b	V1	
9.77 A	7.18 c	9.30 b	12.83 a	V2	
	5.52 C	7.63 B	9.78 A	Water stress averages	

The following letters refer to: B₀ = No boron spraying, B₁₀₀ = Boron spraying at a concentration of 100 mg B kg⁻¹ L⁻¹, V₀ = No vermicompost addition, V₁ = Vermicompost addition at a rate of 1 megagram hectare⁻¹, V₂ = Vermicompost addition at a rate of 2 megagrams hectare⁻¹, W₁ = Water added every 3 days, W₂ = Water added every 6 days, W₃ = Water added every 9 days., Numbers with identical letters and symbols do not differ significantly according to Duncan's test at a 5% probability level.

The interaction between boron spraying and vermicompost application significantly affected plant dry weight. The (B₁₀₀+V₂) treatment recorded the highest value (10.52 g),

while (B₀+V₀) recorded the lowest (5.31 g), reflecting a 98.11% increase.

Regarding the interaction between moisture levels and boron application, (W1+B100) resulted in the highest dry weight (10.28 g), while (W3+B0) had the lowest (4.83 g).

Effect of Triple Interaction on Plant Dry Weight A significant difference was observed with increasing boron spraying levels, as (W3+B100) surpassed (W3+B0) with a 28.60% increase. The interaction between moisture levels and vermicompost application also showed a significant effect, where (W1+V2) resulted in the highest plant dry weight (12.83 g), while (W3+V0) recorded the lowest (4.05 g), with an increase of 216.79%. Additionally, (V2+W3) significantly outperformed (W3+V0) and (W3+V1) by 77.28% and 32.22%, respectively. Regarding the triple interaction between moisture levels, boron spraying, and vermicompost application, (W1+B100+V2) achieved the highest plant dry weight (13.93 g), while (W3+B0+V0) recorded the lowest (3.62 g). Furthermore, (B100+V2) at the third moisture level (W3) surpassed all other boron and vermicompost treatments at the same moisture level (W3).

4- Chlorophyll Concentration in Leaves (mg g^{-1})

The results in Table 5 indicate that the second level of boron spraying (B100) significantly increased the relative chlorophyll content by 10.64% compared to the first level.

The third level of vermicompost application (V2) significantly enhanced chlorophyll concentration in plants, increasing by 109.91% and 38.82% compared to the first and second levels, respectively.

The first moisture level (W1) also surpassed the second and third levels, increasing chlorophyll concentration by 32.22% and 52.89%, respectively.

The interaction between boron spraying and vermicompost application significantly affected chlorophyll concentration, with the highest mean (8.01 mg g^{-1}) recorded at (B100+V2), while the lowest (3.42 mg g^{-1}) was recorded at (B0+V0), reflecting a 134.21% increase.

Table 5. Effect of Vermicompost Addition and Boron Spraying on the Growth and Yield of Mustard Under Water Stress Conditions (Chlorophyll Concentration in Leaves, mg g^{-1})

Boron interference And vermicompost	ater stressW			Vermicompost Megagram 1-ha	Boron foliar spray (1-mg/L)
	9 W	6 W	3 W		
3.42 f	2.78 n	3.56 m	4.09 j	V0	B ₀
5.27 d	4.15 j	5.16 g	6.49 e	V1	
7.66 b	6.44 e	6.77 d	9.76 b	V2	
4.04 e	3.56 l	3.77 k	4.80 h	V0	B ₁₀₀
6.02 c	4.67 i	5.84 f	7.55 c	V1	
8.01 a	6.41 e	7.46 c	10.15 a	V2	

Boron spray averages	Water stress			Interaction of water stress and borax spraying
	9 W	6 W	3 W	
5.45 B	4.46 f	5.11 d	6.78 b	B ₀
6.03 A	4.88 e	5.69 c	7.50 a	B ₁₀₀
Vermicompost averages	Water stress			stress and Interaction of water vermicompost
	9 W	6 W	3 W	
3.73 C	3.17 h	3.58 g	4.44 f	V ₀
5.64 B	4.41 f	5.50 e	7.02 c	V ₁
7.83 A	6.43 d	7.11 b	9.96 a	V ₂
	4.67 C	5.40 B	7.14 A	Water stress averages

The following letters refer to: B₀ = No boron spraying, B₁₀₀ = Boron spraying at a concentration of 100 mg B kg⁻¹ L⁻¹, V₀ = No vermicompost addition, V₁ = Vermicompost addition at a rate of 1 megagram hectare⁻¹, V₂ = Vermicompost addition at a rate of 2 megagrams hectare⁻¹, W₁ = Water added every 3 days, W₂ = Water added every 6 days, W₃ = Water added every 9 days., Numbers with identical letters and symbols do not differ significantly according to Duncan's test at a 5% probability level.

Effect of Interaction Between Moisture Levels and Boron Spraying on Chlorophyll Concentration The treatment (W₁+B₁₀₀) recorded the highest chlorophyll concentration (7.5 mg g⁻¹), while (W₃+B₀) had the lowest (4.46 mg g⁻¹), with a 68.16% increase. Comparing boron spraying levels at the third moisture level (W₃), a significant difference was noted, with (W₃+B₁₀₀) surpassing (W₃+B₀) by 9.41%. The interaction between moisture levels and vermicompost application showed that (W₁+V₂) resulted in the highest chlorophyll concentration (9.96 mg g⁻¹), while (W₃+V₀) recorded the lowest (3.17 mg g⁻¹), reflecting a 214.19% increase. Additionally, (V₂+W₃) significantly outperformed (W₃+V₀) and (W₃+V₁) by 102.83% and 45.80%, respectively. Regarding the triple interaction between moisture levels, boron spraying, and vermicompost application, (W₁+B₁₀₀+V₂) had

the highest chlorophyll concentration (10.15 mg g⁻¹), while (W₃+B₀+V₀) recorded the lowest (2.78 mg g⁻¹)

5-Proline Concentration in Plant Leaves (mg g⁻¹ Fresh Weight)

The results in Table 6 show that plants without vermicompost application (V₀) had the highest proline accumulation, surpassing the second and third levels by 29.72% and 81.86%, respectively.

The third moisture level (W₃) showed the highest proline concentration, exceeding the first and second moisture levels by 62.38% and 22.91%, respectively.

A significant interaction was observed between boron spraying and vermicompost application,

where (B100+V0) resulted in the highest proline concentration (3.71 mg g⁻¹ fresh weight), while (B100+V2) had the lowest (2.00 mg g⁻¹ fresh weight), reflecting an 80% increase.

The interaction between moisture levels and boron spraying showed that (W3+B0) had the highest proline concentration (3.57 mg g⁻¹ fresh weight), while (W1+B100) had the lowest (2.14

mg g⁻¹ fresh weight), reflecting a 66.8% increase.

Additionally, the interaction between moisture levels and vermicompost application showed that (W3+V0) had the highest proline concentration (4.56 mg g⁻¹ fresh weight), while (W1+V2) recorded the lowest (1.48 mg g⁻¹ fresh weight). (V0+W3) significantly outperformed (W3+V1) and (W3+V2).

Table 6. Effect of Vermicompost Addition and Boron Spraying on Proline Concentration in Mustard Plants Under Water Stress

interference Boron And vermicompost	Water stress			Vermicompost Megagram 1-ha	Boron foliar spray (1-mg/L)
	9 W	6 W	3 W		
3.70 a	4.57 a	3.72 b	2.82 d	V0	B 0
2.89 b	3.68 bc	2.71 d	2.27 f	V1	
2.07 c	2.47 e	2.16 f	1.58 g	V2	
3.71 a	4.54 a	3.78 b	2.80 d	V0	B 100
2.83 b	3.56 c	2.70 d	2.24 f	V1	
2.00 c	2.42 e	2.20 f	1.39 h	V2	
Boron spray averages	Water stress			Interaction of water stress and borax spraying	
	9 W	6 W	3 W		
2.89 A	3.57 a	2.86 b	2.22 c	B 0	
2.85 A	3.51 a	2.89 b	2.14 c	B 100	
Vermicompost averages	Water stress			Interaction of water stress and vermicompost	
	9 W	6 W	3 W		
3.71 A	4.56 a	3.75 b	2.81 d	V0	
2.86 B	3.62 c	2.70 e	2.26 g	V1	
2.04 C	2.45 f	2.18 g	1.48 h	V2	
	3.54 A	2.88 B	2.18 C	Water stress averages	

The following letters refer to: B0 = No boron spraying, B100 = Boron spraying at a concentration of 100 mg B kg⁻¹ L⁻¹, V0 = No vermicompost addition, V1 = Vermicompost addition at a rate of 1 megagram hectare⁻¹, V2 = Vermicompost addition at a rate of 2 megagrams hectare⁻¹, W1 = Water added every 3 days, W2 = Water added every 6 days, W3 = Water added every 9 days., Numbers with identical letters and symbols do not differ significantly according to Duncan's test at a 5% probability level.

Regarding the triple interaction between moisture levels, boron spraying, and vermicompost application, (W3+B0+V0) had the highest proline concentration (4.57 mg g⁻¹ fresh weight), while (W1+B100+V2) recorded the lowest (1.39 mg g⁻¹ fresh weight).

The data in Table 9 indicates that proline concentration increased with decreasing soil moisture, which aligns with previous findings. Research by Baqer suggested that drought stress increases proline accumulation due to the plant's inability to synthesize proteins, leading to a rise in free amino acids, including proline. Proline plays a crucial role in osmotic adjustment, membrane stabilization, and enhancing the plant's ability to absorb water and nutrients under drought stress conditions.

Effect of Vermicompost and Boron Spraying on the Growth and Production of Mustard Under Water Stress Conditions The above tables indicate that the second spraying level (100 mg L⁻¹) of boron significantly enhances the traits of plant height, leaf area, dry weight, chlorophyll concentration in leaves, number of leaves, and number of branches. This improvement is attributed to the role of boron in activating meristematic tissues and increasing cell division, which boosts the production and effectiveness of growth regulators, particularly auxins and cytokinins. This effect has positively influenced increased plant height and improved several physiological and biochemical processes during the growth stages of the plant, including cell elongation, membrane performance, nitrogen metabolism, and photosynthesis. These results align with the findings of (12), who highlighted the important role of boron in supporting vegetative growth in plants.

The results listed in the tables also demonstrate a direct and effective impact of vermicompost, which stimulated plant growth directly with increasing application levels from 0 to 2 mg ha⁻¹. Earthworms contribute to the increase of plant growth regulators such as auxins, cytokinins, and gibberellins (13), which in turn leads to increased cell division and elongation, positively reflecting on most vegetative traits of the plant, such as plant height, leaf area, and chlorophyll content.

Regarding the role of irrigation intervals, it negatively affected the growth of the vegetative mass, as shown in the tables above. The highest vegetative growth was achieved at the first level, followed by the second, and finally the third level. This indicates the negative impact of reduced water availability on vital and physiological activities, such as photosynthesis, nitrogen metabolism, and carbon assimilation in plants, along with an increase in the production of reactive oxygen species (ROS), which are a major source of damage to plant cells, causing their breakdown or alteration (14).

Based on the above findings, high levels of vermicompost application and the highest level of boron spraying achieved the best results in all vegetative mass traits of mustard, even with a reduced soil moisture content.

Table (6) indicates a significant increase with decreasing soil moisture content, where the third moisture level (the driest) showed superiority. It is believed that drought stress triggers proteolytic enzymes and the production of amino acids, including proline, which acts as an osmotic stabilizer. This acid plays a role in

the stability and integrity of cellular membranes and increases the cell's ability to absorb water and nutrients dissolved in the growth medium.

Regarding the interaction between moisture levels, boron spraying, and the addition of vermicompost, the treatment without boron spraying and without the addition of vermicompost at the third moisture level (W3) exhibited significant superiority. This indicates the individual effect of low moisture on increasing the concentration of this acid within the plant leaves. The high levels of amino acids observed in plants subjected to stress may result from either protein degradation or the accumulation due to decreased utilization of these acids in protoplasm formation. An increase in proline leads to increased osmotic pressure in the cell, subsequently promoting water uptake by the plant roots.

Additionally, proline is believed to play a role in energy production during drought stress, as the oxidation of one molecule of proline in the mitochondria yields one NADH_2 molecule and 30 ATP molecules. Its accumulation is thought to contribute to stress relief and maintaining cell turgor, ensuring a gradient favorable for water uptake by the plant. Moreover, proline is considered a protectant for photosynthetic enzymes against stress impacts (Enzyme Protectants) and mitigates the adverse effects of stress that lead to protein degradation and damage to chloroplast membranes (15).

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