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RESEARCH ARTICLE

The Effect of Biofertilizers, Organic Fertilizers, and Zeolite on the Growth, Yield, and Active Compounds of Two Broccoli Cultivars

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ABSTRACT

The field experiment was carried out in a personal farm in Abu Al-Jasim Village in the Al-Mussaib District (40 km north of Babylon) in the 2024-2025growing season. The research paper investigated the effects of organic fertilizers, bio fertilizers, and zeolite on the growth of two types of broccoli. The trial was organized using a randomized complete block design (RCBD) with three replicates. Three factors were included. The former was a cultivar with two hybrids, Convet-F1 and Jassmine-F1, denoted h1 and h2. The second was organic- bio fertilization, which was done using four treatments, namely no fertilizer (no fungi and no bacteria), 10 t ha^{-1} + bacterial inoculation, 10 t ha^{-1} + fungal inoculation, and 20 t ha^{-1} + both fungi and bacteria. These were the treatments B0, B1, B2, and B3. The third variable was zeolite at four levels: 0, 8, 16, and 24 t , which were coded as Z0, Z1, Z2, and Z3. The least significant difference test was used to compare the means of the treatments at the 0.05 probability level. The outcomes revealed that the hybrid Jassamine-F1 performed better on all measured traits than Convet-F1. It had increased averages of leaf area (103.01 dm^2), number of leaves per plant (21.92), head diameter (16.20 cm), number of heads per plant (5.83), vitamin C contents (92.29 mg 100 g^{-1} fresh weight), percent protein (3.92), and sulforaphane concentration. The fertilization treatment B3 (20 t ha^{-1} + fungi and bacteria) achieved the highest values for the same traits, reaching 106.63 dm^2 leaf area, 22.14 leaves $plant^{-1}$, 17.61 cm head diameter, 6.19 heads $plant^{-1}$, 93.56 mg 100 g^{-1} vitamin C, 4.07% protein, and 127.84 mg kg^{-1} sulforaphane. Zeolite alsohad a significant effect. The highest rate, 24 t ha^{-1} (Z3), produced the best results, with values of 108.43 dm^2 leaf area, 22.14 leaves $plant^{-1}$, 17.32 cm head diameter, 6.18 heads $plant^{-1}$, 93.42 mg 100 g^{-1} vitamin C, 4.17% protein, and 137.35 mg kg^{-1} sulforaphane. The two-way interactions B3 × Jassmine-F1, Z3 × Jassmine-F1, and Z3 × B3 yielded the highest means among the combinations. The three-way interaction Z3 × B3 × Jasmine-F1 surpassed all other treatments and recorded the highest overall averages for all studied traits.

Keywords: *Broccoli, Zeolite, Hybrid, Combination, Organic, Biofertilizer*

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INTRODUCTION

Broccoli (Brassica oleracea var. italica) is an herbaceous plant belonging to the Brassicaceae family. It resembles cauliflower in appearance. It has nutritional and medical importance because it contains vitamins, essential minerals such as calcium, magnesium, zinc, and iron, as well as protein and beta-carotene. Its leaves are rich in fiber, lipids, and polyphenols (Yaoishita *et al*., 2019).

Broccoli also contains sulforaphane, a compound that helps neutralize free radicals and limit the development of cancerous cells. It contains glucoraphanin, which supports the immune system, and indole-3-carbinol, which protects the body against liver inflammation and breast and colon cancers (Yaoishita *et al*., 2019). Broccoli is cultivated mainly for its edible florets, harvested at the floral bud stage along with their stalks (Abbas, 2022).

The global average yield is 22.71 t ha^{-1} (FAO, 2023), whereas the local average is 12.91 t ha^{-1} (Central Statistical Organization/Information Technology, 2023). This disparity indicates the low productivity per unit area in Iraq. The problem of local production is to increase, and several methods can be used, such as the use of organic and biofertilizers. Nitrogen and phosphorus are among the nutrients provided by organic fertilizers. Their decay produces organic acids that reduce soil pH, increase nutrient availability, promote root growth, and increase soil water retention (Ali, 2015).

Biofertilizers contain beneficial microorganisms that coexist with plant roots. They increase soil fertility and enhance physical characteristics such as porosity and structure (Al-Maamouri, 2020). The other strategy is the introduction of new cultivars and hybrids and their testing at research stations and universities to determine which are best adapted to local soil, water, and climatic conditions and can yield high yields.

On these grounds, the paper discusses variations in organic and biofertilization levels, coupled with zeolite rates, across different broccoli hybrids and their effects on plant growth, yield, and active compounds. The goal is to identify the optimal fertilization level, zeolite rate, and cultivar combination that perform best under local field conditions and deliver the greatest crop performance enhancement.

MATERIALS AND METHODS

Experimental Site

This was done in a farmer's field in Abu Al-Jasim Village, Al-Mussaib District, 35 km north of Babylon city. The experiment was conducted during the 2023-2024 autumn growing season to determine the effects of organic-bio fertilization and zeolite on the growth, harvest, and active compounds of two broccoli varieties.

Soil Analysis

Before the planting, they took five random soil samples at varying positions in the field at 0 30 cm depth. The samples were air-dried, ground, and passed through a 2-mm mesh. A physical and chemical analysis of a composite sample was then done at the Soil Laboratory of Al-Mussaib Technical Institute. The primary soil properties are shown in Table 1, which were measured before the commencement of the experiment.

Table 1. Selected physical and chemical properties of the field soil

Property	Value	Unit
Soil pH	7.1	–
Electrical Conductivity (EC)	3.8	dS m^{-1}
Organic Matter	1.27	%
Available Nitrogen (N)	15.01	mg kg^{-1}
Available Phosphorus (P)	4.3	mg kg^{-1}
Available Potassium (K)	167.20	mg kg^{-1}
Sand	170.33	g kg^{-1}
Silt	450.11	g kg^{-1}
Clay	379.36	g kg^{-1}
Texture	Silty-clay	–

Preparation and Planting of Fields.

The field was used in the experiment where the weeds had been piled out, plowed, leveled, and smoothed to provide uniformity. The environment was separated into three replications, each having 32 experimental units (4 × 4 × 2). In the experiment, total number of experimental units was 96 (3 x 32), and each unit had dimensions of 2 x 2 m. Each unit was applied with organic fertilizer at the specified levels before planting (5, 10, 15, and 20 t ha^{-1}). Treatment (fungal, bacterial, or both). Biofertilizers were applied at a rate of 10 g per seed at sowing.

Zeolite, acquired in Fadak Farm under the Holy Al-Hussain Shrine, was in large stones, crushed, and refined using an electric grinder. The material was added to the soil as per the planned levels (8, 16, and 24 t ha^{-1}) and applied proportionally within each unit at a depth of 30 cm. Planting was done in rows of four plants each within each unit. The distance between plants and rows, between experimental units, and between replications was 50 cm, 1 m, and 2 m, respectively.

On 10/10/2023, the seedlings were planted in the field after being transplanted from trays containing 100 cells; the plants were at the five-leaf stage. The practices of standard crop management such as irrigation, fertilization, and pest control, were used (Al-Sbayla and Al-Trawana, 2007). Drip irrigation was applied three times a week to young seedlings and then adjusted accordingly.

Experimental Design and Treatments

The experiment included three factors:

Cultivars: Two broccoli hybrids imported from Iran: Convet-F1 (h1) and Jassmine-F1 (h2).

Organic–Bio Fertilization: Four treatments: 0 t ha^{-1} with no biofertilizer (B0), 10 t ha^{-1} + bacterial inoculation (B1), 10 t ha^{-1} + fungal inoculation (B2), and 20 t ha^{-1} + both fungi and bacteria (B3).

Zeolite: Four rates: 0 t ha^{-1} (Z0), 8 t ha^{-1} (Z1), 16 t ha^{-1} (Z2), and 24 t ha^{-1} (Z3).

The experiment was laid out as a randomized complete block design (RCBD) with three replications (Al-Rawi & Khalaf Allah, 2000). Treatment means were compared using the least significant difference (LSD) test at $p \leq 0.05$. Statistical analysis was performed using GenStat software.

Measured Traits

Leaf Area: The fourth or fifth leaf below the growing tip was sampled and measured using the punch method described by Watson (1953). Thirty discs per leaf were taken, oven-dried at 75°C until constant weight, and leaf area per plant was calculated as:

Leaf area (dm^2) = Leaf discs area × Leaf dry weight / Dry weight of discs

Number of Leaves per Plant: Total leaves per randomly selected plant were counted at the flowering stage, and the mean was calculated.

Main Head Diameter (cm): The perimeter of the main inflorescence was measured with a measuring tape, and the diameter was calculated using:

Diameter (cm)= Perimeter/ 3.14

Number of Side Heads per Plant: Counted on the main stem until the end of the growth season.

Vitamin C Content (mg 100 g^{-1} fresh weight): Determined in the florets using the titration method with 2,6-dichlorophenol-indophenol (AOAC, 1970).

Leaf Protein Percentage (%): Calculated according to Dalali & Al-Hakim (1987):

%Protein=%N × 6.25

Zeolite Properties

Table 2. Selected physical and chemical properties of zeolite

Property	Value	Unit
pH	6.8	–
Electrical Conductivity	0.68	dS m^{-1}
Bulk Density	1.36	Mg m^{-3}
True Density	2.51	Mg m^{-3}
Cation Exchange Capacity (CEC)	260	cmol kg^{-1} zeolite

Table 3. Mineral composition of natural zeolite analyzed by the Geological Survey Laboratory, Ministry of Industry and Minerals, Baghdad (Al-Aradi, 2021)

Oxide	Value (%)
SiO_2	%45.25
Al_2O_3	%14.39
Fe_2O_3	%7.27
CaO	%8.84
MgO	%3.43
SO_3	%1.11
Li_2O	%5.2
Na_2O	%0.12
K_2O	%3.38
P_2O_5	%0.03

RESULTS AND DISCUSSION

Leaf Area (dm^2)

Table 4 shows that hybrid h1 outperformed h2 in leaf area, producing the highest mean value of 103.01 dm^2, while h2 had the lowest

mean of 97.98 dm². These results are consistent with Abbas (2022).

Regarding organic and biofertilization, treatment B3 (20 t ha^{-1} + fungal and bacterial inoculation) resulted in the highest leaf area mean (106.63 dm²), whereas B0 (0 t ha^{-1} + no biofertilizer) recorded the lowest mean (92.07 dm²), aligning with the findings of Al-Bermani (2017).

For zeolite, the highest leaf area was observed with Z3 (24 t ha^{-1}), averaging 108.43 dm², while the control Z0 (0 t ha^{-1}) gave the lowest mean of 89.73 dm².

Two-way interactions showed that:

Cultivar × Organic–Bio fertilizer: h1 × B3 gave the highest leaf area (109.06 dm²), while h2 × B0 had the lowest (89.44 dm²).

Cultivar × Zeolite: h1 × Z3 produced the highest mean (110.83 dm²), whereas h1 × Z0 had the lowest (87.60 dm²).

Zeolite × Organic–Bio fertilizer: Z3 × B3 resulted in the highest leaf area (113.17 dm²), and Z0 × B0 gave the lowest (77.32 dm²).

The three-way interaction among cultivar, zeolite, and organic–bio fertilizer showed that h1 × Z3 × B3 had the highest leaf area (115.57 dm²), while h1 × Z0 × B0 recorded the lowest (74.82 dm²).

The superiority of hybrid H1 can be attributed to its specific genetic makeup, which influences physiological and biological activity, including water and nutrient uptake, resulting in greater leaf area than other hybrids.

Zeolite enhances leaf area due to its high porosity and crystalline structure, which allow cation exchange, improve nutrient retention, mitigate soil toxins and pesticide residues, reduce the uptake of radioactive elements, and store water in its pores, benefiting plants under limited water conditions.

Organic and biofertilizers also positively affected leaf area. Biofertilizers introduce microorganisms

Table 4. Effect of organic–bio fertilizers and zeolite on leaf area of two broccoli hybrids (dm²)

Hybrid	Organic–Bio Fertilizer	Zeolite				Mean (Hybrid × Fertilizer)
		Z0	Z1	Z2	Z3	
H1	B0	79.76	90.40	102.45	106.22	94.70
	B1	93.32	105.64	108.52	111.71	103.79
	B2	94.62	102.87	106.72	109.82	106.50
	B3	99.73	107.29	113.66	115.57	109.06
H2	B0	74.88	85.68	94.33	102.87	89.44
	B1	98.82	100.96	104.75	106.82	101.33
	B2	86.81	96.40	100.98	103.70	96.97
	B3	95.92	103.69	106.42	110.77	104.20
LSD0.05		1.88				0.941
		Hybrid X Zeolite				Mean
H1		91.85	101.55	107.83	110.83	103.01
H2		87.60	96.68	101.62	106.04	97.98
LSD0.05		0.941				0.470
		Organic–Bio Fertilizer X Zeolite				Mean
B0		77.32	88.04	98.39	104.54	92.07
B1		93.07	103.30	106.63	109.26	103.06
B2		90.71	99.63	103.85	106.76	100.23
B3		97.82	105.49	110.04	113.17	106.63
LSD0.05		1.331				0.665
Average of Zeolite		89.73	99.11	104.72	108.43	
LSD0.05		0.665				

that release plant growth-promoting substances, including hormones, and fix atmospheric nitrogen in a form accessible to plants (nitrate and nitrite). Organic fertilizers, especially cow manure, release organic acids that solubilize phosphate rocks, increasing phosphorus availability and promoting vegetative growth, particularly leaf area (Salman, 2018).

Number of Leaves per Plant

Table 5 shows that hybrid h1 exceeded h2 in the number of leaves per plant, producing the highest mean of 21.92 leaves per plant, while h2 had the lowest mean of 20.83 leaves per plant. These results are consistent with those of Al-Sukmani (2020).

Regarding organic–bio fertilization, treatment B3 (20 t ha^{-1} + fungal and bacterial inoculation) produced the highest leaf number (22.14 leaves per plant), while the control B0 (0 t ha^{-1} + no biofertilizer) had the lowest (20.23 leaves per plant), consistent with Al-Azzawi (2020).

In the case of the zeolite, Z3 (24 t ha^{-1}) had the greatest number of leaves produced at 22.14 on average per plant, with the control Z0 providing 20.23 per plant, which is consistent with Al-Aradi (2021).

Bidirectional interactions indicated that:

Cultivar × Organic–Bio fertilizer: h1 × B3 registered the best mean (22.41 leaves per plant), and h2 × B0 was the lowest (19.32 leaves per plant).

Cultivar × Zeolite: The mean of the h1 × Z3 was the highest (22.51 leaves per plant), and the h2 × Z0 was the lowest (19.91 leaves per plant).

Zeolite × Organic–Bio fertilizer: Z3 × B3 had the highest number of leaves (22.69 leaves per plant), and Z0 × B0 had the lowest number (19.15 leaves per plant).

The three-way interaction between cultivar, zeolite, and organic- bio fertilizer revealed that h1× Z3× B3 had the highest mean number of leaves (22.88 leaves

Table 5. Effect of organic–bio fertilizers and zeolite on leaf number per plant of two broccoli hybrids (leaves $plant^{-1}$)

Hybrid	Organic–Bio Fertilizer	Zeolite				Mean (Hybrid × Fertilizer)
		Z0	Z1	Z2	Z3	
H1	B0	20.10	20.77	21.62	22.10	21.14
	B1	21.80	22.31	22.47	22.69	22.31
	B2	20.92	21.82	22.20	22.39	21.83
	B3	21.62	22.50	22.67	22.88	22.41
H2	B0	18.20	18.90	19.37	20.84	19.32
	B1	20.93	21.57	21.91	22.09	21.62
	B2	19.41	20.17	20.87	21.67	20.53
	B3	21.13	21.89	22.00	22.50	21.88
LSD0.05		2.129				1.064
		Hybrid X Zeolite				
H1		21.11	21.85	22.24	22.51	21.92
H2		19.91	20.63	21.03	21.27	20.83
LSD0.05		1.064				0.532
		Organic–Bio Fertilizer X Zeolite				
B0		19.15	19.83	20.49	21.47	20.23
B1		21.36	21.94	22.19	22.39	21.97
B2		20.16	20.99	21.53	22.03	21.17
B3		21.37	22.19	22.33	22.69	22.14
LSD0.05		1.505				0.753
Average of Zeolite		20.51	21.24	21.64	22.14	
LSD0.05						

per plant), whereas h2× Z0× B0 had the least number of leaves (18.20 leaves per plant).

Explanation:

The h1 is superior in terms of genetic composition, which has some influence on physiological and biological functions, including nutrient absorption, transpiration, photosynthesis, and growth, that cause an increase in the number of leaves.

Zeolite improves the vegetative growth because of its high porosity, cation exchange capacity, and water retention and capability to immobilize soil toxins, pesticides, and pathogens, thus increasing development on the leaf.

The effect of organic and biofertilizers was also positive on the number of leaves. Organic fertilizer provides the necessary nutrients and improves water retention in the soil, whereas biofertilizers add beneficial microorganisms to improve soil quality, promote root growth, and release growth-promoting agents, resulting in leaf production.

Main Head Diameter (cm)

Table 6 indicates that hybrid h1 was the best among h2, and it gave the highest mean head diameter of 16.30 cm, and the lowest of 14.75 cm at h2. The difference is an 8.95 percentage-point benefit for h1, which is consistent with the results of Saloon *et al.* (2019), Mohamed (2020), and Al-Khikani (2022).

In terms of the organic- bio fertilization, the B3 level (20 t ha $^{-1}$ + fungal and bacterial inoculation) gave the largest mean head diameter (17.61 cm), and B0 level (0 t ha $^{-1}$ + no biofertilizer) gave the smallest mean head diameter (13.95 cm); the difference between the two levels was 20.78%. These findings are consistent with Al-Asadi (2018) and Al-Khikani (2022).

In the case of Zeolite, the maximum mean head diameter was recorded in Z3 (24 t ha $^{-1}$), with the

Table 6. Effect of organic–bio fertilizers and zeolite on the main head diameter of two broccoli hybrids (cm)

Hybrid	Organic–Bio Fertilizer	Zeolite				Mean (Hybrid × Fertilizer)
		Z0	Z1	Z2	Z3	
H1	B0	13.10	13.74	14.66	15.25	14.18
	B1	14.83	15.90	17.33	18.81	10.71
	B2	13.89	14.36	15.90	17.76	15.45
	B3	15.80	17.57	19.35	21.22	18.48
H2	B0	12.87	13.21	13.88	14.91	13.71
	B1	13.37	13.89	14.79	15.89	14.48
	B2	13.10	13.68	14.22	15.09	14.02
	B3	14.28	15.80	17.32	19.74	16.78
LSD0.05		1.599				0.800
		Hybrid X Zeolite				
H1		14.40	15.39	16.81	18.23	16.20
H2		13.41	14.14	15.05	16.40	14.75
LSD0.05		0.800				0.400
		Organic–Bio Fertilizer X Zeolite				
B0		12.98	13.47	14.27	15.08	13.95
B1		14.10	14.89	16.06	17.35	15.60
B2		13.49	14.02	15.06	16.38	14.73
B3		15.04	16.68	18.33	20.42	17.61
LSD0.05		1.131				0.565
Average of Zeolite		13.91	14.76	15.93	17.32	
LSD0.05		0.566				

average of the diameter being 17.32 cm, and in the case of the control Z0, the average was 13.91 cm, which is an increase of 19.68 percent. This aligns with Al-Fatlawi (2023).

Two-way interactions showed that:

Cultivar × Organic–Bio fertilizer: h1 × B2 had the highest mean (18.84 cm), while h2 × B0 recorded the lowest (13.71 cm).

Cultivar × Zeolite: h1 × Z3 produced the highest mean (18.23 cm), whereas h2 × Z0 had the lowest (13.41 cm).

Organic–Bio fertilizer × Zeolite: B3 × Z3 gave the highest mean (20.42 cm), and B0 × Z0 the lowest (12.98 cm), representing a 36.43% increase.

It was observed that the three-way interaction of cultivar, zeolite, and organic-bio fertilizer which is h1 x B3 x Z3, recorded the largest head diameter (21.22 cm), and the one with the lowest (12.87 cm), a 39.34% increase in the first combination.

Explanation:

The variation of hybrids is based on their different genetic composition, which has an effect on physiological characteristics like photosynthesis, transpiration, and evapotranspiration, which further impacts vegetative and reproductive development, like head diameter.

Organic manure provides important nutrients, such as nitrogen, which improves vegetative growth. The growth of more vegetation gives more assimilates to the growing head. Biofertilizers contain microorganisms that fix atmospheric nitrogen in a form available to the plant, which contributes to further growth of the vegetation and reproductive structures.

As a mineral of nature, zeolite is a negative mineral (AlO_4^-) that positively influences soil characteristics, retains water, binds toxic substances, and alleviates the stress of the environment, which contributes to better plant growth and the development of heads (Wallace, 2020).

Number of Heads per Plant (heads plant^{-1})

Table 7 reveals that hybrid h1 was better than h2, with h1 giving a higher mean number of heads per plant (5.83), whereas h2 gave a lower mean (4.99), and this is a 14.40 increase in the case of h1. These findings are consistent with those of Ramadan (2015) and Al-Salhi (2019).

As far as organic-bio fertilization is concerned, treatment B3 (20 t ha^{-1} + fungal and bacterial inoculation) produced the highest mean number of heads (6.19), and the control B0 produced the lowest (4.32), which also corresponds to Al-Shammari et al. (2019).

In the case of zeolite, the maximum mean was obtained with Z3 (24 t ha $^{-1}$), which gave 6.18 heads per plant, and the control Z0 gave 4.38, which is consistent with Di Giuseppe et al. (2015).

Two-way interactions showed that:

Cultivar × Organic–Bio fertilizer: h1 × B3 gave the highest mean (6.67), while h2 × B0 recorded the lowest (4.93).

Cultivar × Zeolite: h1 × Z3 produced the highest mean (6.51), while h2 × Z0 had the lowest (4.17).

Organic–Bio fertilizer × Zeolite: B3 × Z3 gave the highest mean (7.39), and B0 × Z0 the lowest (3.55).

The three-way interaction among cultivar, zeolite, and organic–bio fertilizer showed that h1 × B3 × Z3 recorded the highest mean (7.91 heads plant^{-1}), while h2 × B0 × Z0 had the lowest (3.60).

Explanation:

Hybrid h1 was better than h2 in terms of the number of heads per plant because of its better vegetative characteristics that directly affect yield components.

B3 is performing well based on the fact that organic and biofertilizers increase vegetative growth, thus promoting reproductive growth and heads per plant.

Likewise, Z3 also stimulated vegetation growth and improved the condition of the soil, leading to natural enhancement of reproduction characteristics, such as the number of heads per plant.

Vitamin C Concentration (mg 100 g^{-1} fresh weight)

Table 8 indicates that hybrid h1 was better than h2 and had the highest mean concentration of vitamin C (92.29 mg 100 g $^{-1}$ fresh weight), with h2 having the lowest (90.66 mg 100 g $^{-1}$ fresh weight). The findings are in agreement with Saeed (2016).

In terms of organic-bio fertilization, treatment B3 had the highest mean (93.56 mg 100 g $^{-1}$) as compared to the control B0 (89.50 mg 100 g $^{-1}$) according to

Table 7. Effect of organic–bio fertilizers and zeolite on the number of heads per plant of two broccoli hybrids

Hybrid	Organic–Bio Fertilizer	Zeolite				Mean (Hybrid × Fertilizer)
		Z0	Z1	Z2	Z3	
H1	B0	3.75	4.22	4.75	5.40	4.53
	B1	4.91	5.33	6.17	6.83	5.81
	B2	4.30	4.79	5.59	5.92	5.15
	B3	5.40	6.28	7.10	7.91	6.67
H2	B0	3.60	3.94	4.43	4.78	4.97
	B1	4.60	5.07	5.93	6.42	5.50
	B2	3.84	4.27	4.90	5.33	4.58
	B3	4.66	5.20	6.11	6.87	5.71
LSD0.05		0.155				0.078
		Hybrid X Zeolite				
H1		4.59	5.15	5.90	6.51	5.83
H2		4.17	4.62	5.34	5.85	4.99
LSD0.05		0.077				0.048
		Organic–Bio Fertilizer X Zeolite				
B0		3.55	4.08	4.59	5.09	4.32
B1		4.75	5.20	6.05	6.62	5.65
B2		4.07	4.53	5.24	5.62	4.86
B3		5.03	4.74	6.60	7.39	6.19
LSD0.05		0.109				0.054
Average of Zeolite		4.38	4.88	5.62	6.81	
LSD0.05		0.548				

Al-Salman and Ibraheem (2020) because organic fertilizers are known to supply nitrogen that stimulates secondary metabolism, which is vital in the synthesis of active compounds.

In the case of zeolite, Z3 (93.56 mg 100 g^{-1}) had the highest level of vitamin C and Z0 (89.50 mg 100 g^{-1}) had the lowest level (Al-Aradi, 2021).

Two-way interactions indicated that:

Hybrid × Organic–Bio fertilizer: h1 × B3 had the highest mean (94.96 mg 100 g^{-1}), while h2 × B0 had the lowest (88.90 mg 100 g^{-1}).

Hybrid × Zeolite: h1 × Z3 gave the highest mean (94.54 mg 100 g^{-1}), while h2 × Z0 had the lowest (89.40 mg 100 g^{-1}).

Organic–Bio fertilizer × Zeolite: B3 × Z3 recorded the highest mean (96.54 mg 100 g^{-1}), whereas B0 × Z0 had the lowest (88.86 mg 100 g^{-1}).

The three-way interaction among hybrid, organic–bio fertilizer, and zeolite showed that h1 × B3 × Z3 produced the highest mean vitamin C content (98.51 mg 100 g^{-1}), while h2 × B0 × Z0 recorded the lowest (88.33 mg 100 g^{-1}).

Explanation:

Hybrid H1 was superior in vegetative properties, and this obviously resulted in high yield and quality factors such as vitamin C.

Treatments B3 and Z3 were associated with vegetative growth, nutrient status and metabolic process, leading to an increase in the vitamin C content in the broccoli heads.

Protein Content (%)

Table 9 indicates that hybrid h1 has outdone h2 with the highest mean protein content (3.92%), whereas h2 gave the lowest protein content (3.62%), which is an improvement of 7.65%. These findings are consistent with those of Saloom *et al*., (2019).

Table 8. Effect of organic–bio fertilizers and zeolite on vitamin C concentration in primary broccoli heads (mg 100 g^{-1} fresh weight)

Hybrid	Organic–Bio Fertilizer	Zeolite				Mean (Hybrid × Fertilizer)
		Z0	Z1	Z2	Z3	
H1	B0	89.40	89.89	90.30	90.87	90.11
	B1	90.23	91.29	93.47	95.39	92.59
	B2	90.00	90.88	91.83	93.40	91.52
	B3	91.66	93.81	95.86	98.27	94.96
H2	B0	88.33	88.70	89.11	89.47	88.90
	B1	89.82	90.41	91.27	92.81	91.05
	B2	89.47	90.12	90.88	91.75	90.55
	B3	90.11	91.27	92.76	94.57	92.17
LSD0.05		3.862				1.931
		Hybrid X Zeolite				
H1		90.32	91.46	92.86	94.54	92.29
H2		89.40	90.12	91.00	92.15	90.66
LSD0.05		1.931				0.965
		Organic–Bio Fertilizer X Zeolite				
B0		88.86	89.29	89.70	90.17	89.50
B1		89.97	90.85	92.37	94.10	91.82
B2		89.73	90.50	91.35	92.57	91.03
B3		90.88	92.54	94.31	96.54	93.56
LSD0.05		2.731				1.365
Average of Zeolite		89.86	90.79	91.93	93.34	
LSD0.05		1.365				

In the case of organic- bio fertilization, treatment B3 recorded the highest mean (4.07) and the lowest mean (3.46) in the control treatment, B0 with a percentage of 14.98, in line with Al-Sakmani (2026).

In the case of zeolite, the treatment Z3 had the highest protein content (4.17%), with Z0 having the lowest protein content (3.38) (Al-Fatlawi, 2023).

Two-way interactions:

Hybrid × Organic–Bio fertilizer: h1 × B3 had the highest mean (4.33%), while h2 × B0 recorded the lowest (3.10%), a difference of 28.40%.

Hybrid × Zeolite: h1 × Z3 showed the highest mean (4.42%), whereas h2 × Z0 had the lowest (3.31%).

Organic–Bio fertilizer × Zeolite: B3 × Z3 gave the highest mean (4.58%), while B0 × Z0 recorded the lowest (3.19%), a difference of 30.34%.

The three-way interaction among hybrid, organic–bio fertilizer, and zeolite revealed that h1 × B3 × Z3 achieved the highest mean protein content (4.92%), while h2 × B0 × Z0 recorded the lowest (3.10%), representing an increase of 36.99%.

Explanation:

The trends observed are an indication of the better vegetative development of h1 (leaf area, number of leaves) and this translates to high yield components, such as protein content. Organic bio-fertilizers and zeolite enhanced nutrient availability, metabolic activity, and nitrogen fixation, further enhancing protein accumulation in the head of broccoli.

Sulforaphane Content (mg kg^{-1})

Table 10 indicates that hybrid h1 was better than h2 with the highest mean content of sulforaphane (127.84mg/kg $^{-1}$) followed by the lowest (116.81mg/kg $^{-1}$), which is an 8.62 increase. The findings are consistent with Mahmoud (2020) and Sallom *et al.* (2015).

Table 9. Effect of organic–bio fertilizers and zeolite on protein content in broccoli heads (%)

Hybrid	Organic–Bio Fertilizer	Zeolite				Mean (Hybrid × Fertilizer)
		Z0	Z1	Z2	Z3	
H1	B0	3.28	3.40	3.68	3.83	3.54
	B1	3.50	3.74	4.22	4.63	4.02
	B2	3.32	3.66	3.87	4.30	3.78
	B3	3.72	4.32	4.38	4.92	4.33
H2	B0	3.10	3.25	3.57	3.64	3.39
	B1	3.40	3.62	3.79	3.93	3.68
	B2	3.26	3.51	3.80	3.83	3.61
	B3	3.50	3.66	3.89	4.25	3.82
LSD0.05		0.0899				0.045
		Hybrid X Zeolite				
H1		3.45	3.78	4.03	4.42	3.92
H2		3.31	3.51	3.76	3.92	3.62
LSD0.05		0.045				0.022
		Organic–Bio Fertilizer X Zeolite				
B0		3.19	3.32	3.62	3.73	3.46
B1		3.45	3.68	4.00	4.28	3.85
B2		3.29	3.58	3.83	4.08	3.69
B3		3.61	3.99	4.13	4.58	4.07
LSD0.05		0.064				0.032
Average of Zeolite		3.38	3.64	3.89	4.17	
LSD0.05		0.032				

In terms of the organic-bio fertilization, treatment B3 had the highest mean (137.36 mg kg $^{-1}$), and the control B0 had the lowest one (101.75 mg kg $^{-1}$), in line with Shafeek *et al.* (2016).

In application of zeolite, the treatment Z3 (20 t ha $^{-1}$) had the highest mean (137.35 mg kg $^{-1}$), with Z0 providing the lowest (107.55 mg kg $^{-1}$), which is consistent with Cabahilla *et al.* (2016).

Two-way interactions:

Hybrid × Organic–Bio fertilizer: h1 × B3 recorded the highest mean (141.84 mg kg^{-1}), while h2 × B0 had the lowest (94.69 mg kg^{-1}).

Hybrid × Zeolite: h1 × Z3 gave the highest mean (143.57 mg kg^{-1}), whereas h2 × Z0 recorded the lowest (101.61 mg kg^{-1}).

Organic–Bio fertilizer × Zeolite: B3 × Z3 produced the highest mean (153.52 mg kg^{-1}), while B0 × Z0 had the lowest (90.37 mg kg^{-1}).

The three-way interaction among hybrid, organic–bio fertilizer, and zeolite revealed that h1 × B3 × Z3 achieved the highest sulforaphane content (158.44 mg kg^{-1}), while h2 × B0 × Z0 recorded the lowest (83.81 mg kg^{-1}).

Explanation:

Hybrid h1 was superior in comparison to h2 because of its particular genetic composition, which dictates physiological and biochemical processes, nutrient uptake, photosynthesis, transpiration, and growth. Organic bio fertilizers enhance soil conditions and increase root growth and nutrient absorption. Biofertilizers also enhance vegetative development, leading to the accumulation of primary metabolites, which are precursors of secondary metabolites such as sulforaphane (Al-Asadi, 2018). Zeolite provides the necessary nutrients (Si, Al, Fe, Ca, Mg, K, P) in bioavailable form, which affects leaf growth and sulforaphane accumulation (Goyeneche *et al*., 2015).

CONCLUSION

The findings revealed that the hybrid Jassamine-F1 had higher performance

Table 10. Effect of organic–bio fertilizers and zeolite on sulforaphane content in broccoli heads (mg kg^{-1})

Hybrid	Organic–Bio Fertilizer	Zeolite				Mean (Hybrid × Fertilizer)
		Z0	Z1	Z2	Z3	
H1	B0	94.94	98.50	117.42	122.39	108.31
	B1	111.27	121.31	128.66	142.82	126.01
	B2	120.53	131.51	137.10	150.66	134.95
	B3	126.26	134.45	145.22	158.44	141.84
H2	B0	83.81	90.45	101.17	103.37	99.69
	B1	92.24	110.82	119.60	131.42	113.53
	B2	111.22	120.37	133.25	141.12	126.49
	B3	119.19	127.52	135.33	148.60	132.66
LSD0.05		10.993				5.497
		Hybrid X Zeolite				
H1		113.50	122.19	132.10	143.57	127.84
H2		101.61	112.20	122.33	131.12	116.81
LSD0.05		5.497				2.748
		Organic–Bio Fertilizer X Zeolite				
B0		90.37	94.46	109.29	112.88	101.75
B1		101.75	116.06	124.13	137.12	119.76
B2		115.87	125.94	135.17	145.89	130.71
B3		123.22	132.48	140.24	153.52	137.36
LSD0.05		7.773				3.887
Average of Zeolite		107.55	117.23	127.21	137.35	
LSD0.05		3.887				

across all measured traits than Corvet-F1. You also found a marked improvement in performance upon the introduction of the B3 treatment, which was the addition of 20 t ha^{-1} of organic fertilizer and both bacterial and fungal inoculation. The strongest values were recorded at this level among all organic-bio treatments. The Z3 grade of zeolite also had the highest mean, which supports its positive impact on growth and yield characteristics.

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Ethics Statement:

This study did not involve human participants or animals. All experimental procedures were conducted in accordance with institutional and national guidelines for plant research.

Originality and Plagiarism:

The author confirms that this manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. All sources used have been appropriately cited, and the manuscript has been prepared in compliance with plagiarism and publication ethics standards.

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The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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The author solely conceived and designed the study, conducted the experiments, collected and analyzed the data, and wrote and revised the manuscript.

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