Research Article

Effect of Nutrient Combinations and Plant Spacing on Yield and Oil Quality of Indian Mustard (*Brassica juncea* L.)

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Abstract | The study was conducted to investigate the effect of nine combinations of phosphate and potassium fertilizers (T0-P0K0, T1-P0K30 ,T3-P0K60, T4-P40K0, T5-P40K30, T6-P40K60, T7-P80K0, T8-P80K30 and T9-P80K60, kg ha^{-1}), and two spacings between plants (30 and 40cm). Additionally, the interaction between spacing and fertilizers on the yield and quality of the oil and the medicinally active ingredients of the seeds of Indian mustard was also studied. The experiment was conducted according to the factorial experiment method using a completely randomized block design with three replicates. The results showed the superiority of the T8 combination in seed yield, protein, oil, and volatile oil content of seeds, as well as a higher content of active ingredients, namely organ sulfur compounds, plant sterols, and antioxidants. and volatile nitrogen compounds. Moreover, the planting distance was superior in all traits when T8 combination was applied especially during planting at a distance of 40 cm. This combination also provided the highest yield of seeds, protein, and oil, and most active medicinal compounds. Taken together, the adoption of P80K30 with a 40 cm spacing between plants will yield a maximum productivity and quality in environmentally friendly fashion.

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Introduction

The mustard crop (*Brassica juncea* L.) belongs to the Brassicaceae family and is considered one of the most important oil seed crops globally, occupying approximately 24.27% of the total area cultivated with oilseed crops and contributing about 26.30% of global oil production (USDA, 2018). In the climate of Iraq and the Arab world, mustard is grown as a winter annual and is widely cultivated worldwide as an oilseed crop. It is a versatile crop with both medicinal and aromatic applications. Its seeds contain a high percentage of protein (20–25%) and oil (40.3–49.5%) (FAO, 2007). Mustard oil is widely used in alternative medicine due to its incorporation in many herbal remedies and is also applied in pharmaceutical, cosmetic, plastic, and biofuel industries, serving as a sustainable energy alternative (Sahu *et al.*, 2020; Komatineni *et al.*, 2023).

Mustard seed meal is a rich source of protein, making it valuable as animal feed to enhance milk and meat production (Chauhan *et al.*, 2020). Nutrient availability is a critical factor affecting all stages of crop growth. Phosphorus plays a key role in the formation of energy compounds such as ATP and nucleic acids, which positively impact metabolic efficiency, while potassium is essential for enzyme activation and the regulation of stomatal opening and closing, thus improving water-use efficiency and promoting carbohydrate and oil accumulation in seeds. When these two elements are present together in balance, they produce a complementary effect that enhances photosynthetic efficiency and maintains physiological balance in the plant (Chauhan *et al.*, 2020). In recent years, there has been increasing interest in plants rich in antioxidant compounds, including mustard. Its seeds are characterized by high concentrations of glucosinolates, which have been shown to play a significant role in reducing tumor growth, resisting various types of cancer, and lowering blood glucose levels (Lewis *et al.*, 2019; Ahmed *et al.*, 2020; Gök *et al.*, 2020).

Planting distance is another important factor affecting yield, as it influences the number and distribution of plants per unit area, the intensity of competition for growth resources, and the physiological processes of the mustard plant. These factors ultimately affect growth, productivity, and the quality of seeds and oil. Due to the limited studies and information available on mustard, and to increase its productivity and improve quality, it is necessary to investigate the factors influencing its growth and introduce it to regions suitable for its environmental tolerance, water scarcity resistance, and salinity resilience, aiming to provide fertilizer recommendations, including phosphorus and potassium, and determine the optimal planting distance for maximum yield and high-quality oil. The aim was to study the effect of phosphorus and potassium fertilizer combinations and planting distances between plants on oil yield and quality.

Materials and Methods

The field experiment was carried out at the Agricultural Research Station of the College of Agriculture, University of Basra, Karma Ali site (10 km north of the center of Basra Governorate). This was located on the meridian30°56'94.80" North and 47°75'24.93" East. During the agricultural season 2024/2025 in a silty sandy soil with a pH of 7.53, an EC of 7.53 DS^{-1}, and 0.2% organic matter, and ready quantity for each nitrogen, phosphorus, and potassium 20.07, 12.56 and 91.05 mg kg^{-1} soil respectively.

A total of nine combinations of phosphate and potassium fertilizers were used, namely:

- T0= P0K0 Kg ha^{-1}
- T1= P0K30 Kg ha^{-1}
- T2= P0K60 Kg ha^{-1}
- T3= P40K0 Kg ha^{-1}
- T4= P40K30 Kg ha^{-1}
- T5= P40K60 Kg ha^{-1}
- T6= P80K0 Kg ha^{-1}
- T7= P80K30 Kg ha^{-1}
- T8= P80K60 Kg ha^{-1}

Planting distance

The experiment, conducted using a randomized complete block design (RCBD) with three replications, involved plowing the land, harrowing it with disc harrows, leveling it, and then dividing it into three sections with a 50 cm spacing between them. Each section was further subdivided into 18 experimental units measuring 2 x 2 m^2, each containing five rows spaced 50 cm apart. Sowing was carried out manually on October 15, 2024 (Hassan, 2023), with 3-4 seeds placed in each hole. A nitrogen fertilizer supplement in the form of urea (N 46%) was applied at a rate of 240 kg N per hectare in two applications: the first 21 days after sowing and the second 21 days after the first application (Hassan *et al.*, 2022).

The patching process was carried out two weeks after planting and thinned to one plant after three weeks. Irrigation and weeding were also carried out to eliminate weeds as needed. Harvesting took place on 18/3/2025 after signs of crop maturity appeared, such as yellowing and drying of the mustard seeds and hardening of the seeds. The total yield, protein percentage, oil content, volatile oil content, and the allyl-isothiocyanate and benzene-isothiocyanate content of the seeds were calculated. β-Sitosterol, Campesterol, Vitamin E, Phenols, Thiazole, and Cyano3,4-Epithiobut.

Statistical analysis was performed using statistical software. statistician GenStat and the means were compared according to the test of least significant

Table1: *Effect of fertilizer combinations and plant spacing on yield and quality of mustard*

Volatile oil %	Oil yield (Mg ha^{-1})	Oil content %	Protein yield (Mg ha^{-1})	Protein content %	Seed yield (Mg ha^{-1})	Treatments	
1.076	0.501	33.79	0.225	13.28	1.363	S1	Plant spacing
1.113	0.604	34.65	0.317	14.12	1.585	S2	
NS	0.027	NS	0.015	0.371	0.0969	LSD ($P \leq 0.05$)	
0.233	0.173	22.11	0.086	11.00	0.786	T0	Fertilizer combinations
0.287	0.207	23.26	0.103	11.54	0.892	T1	
0.573	0.238	22.65	0.127	11.99	1.055	T2	
0.597	0.364	30.09	0.169	14.09	1.211	T3	
1.260	0.517	35.18	0.252	14.17	1.466	T4	
1.473	0.634	36.84	0.324	14.46	1.724	T5	
1.093	0.756	40.95	0.365	14.96	1.845	T6	
2.087	0.931	44.79	0.478	15.48	2.081	T7	
2.245	1.151	52.01	0.534	15.59	2.208	T8	
0.2083	0.057	3.074	0.032	0.787	0.0655	LSD ($P \leq 0.05$)	

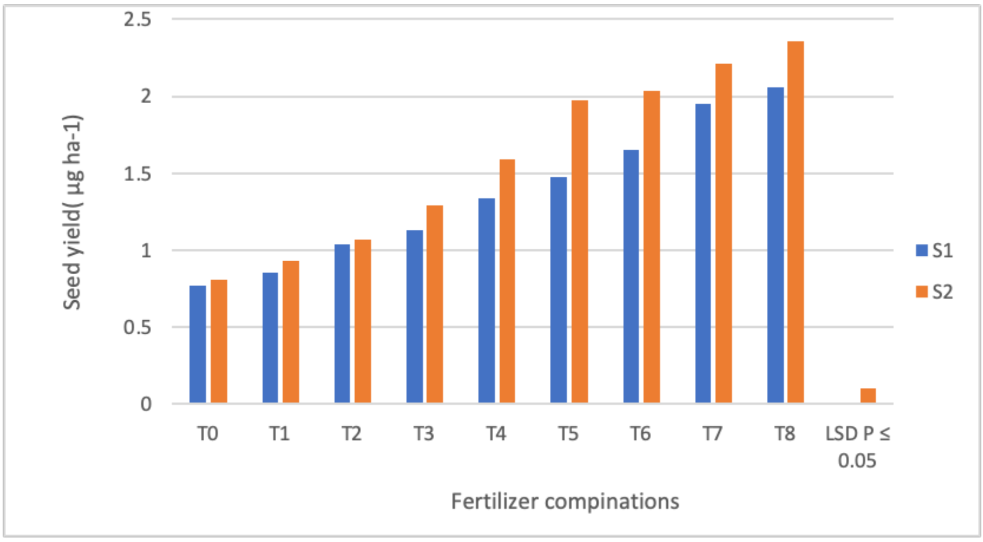

Figure 1: *Interaction of fertilizer combinations and spacing of plant on seed yield (Mg ha^{-1}).*

difference (LSD) at a probability of 0.05 (Al-Rawi and Khalaf Allah, 2000).

Results and Discussion

Plant Yield (Mg ha^{-1})

The data revealed that fertilizer combinations, planting distances, and interaction significantly affected this trait (Table 1). The combination T8 achieved the highest average seed yield of 2.208 Mg ha^{-1}, while the lowest average was at T0 reached 0.786 Mg ha^{-1}. These results are consistent with Sharma *et al.* (2020) and Singh *et al.* (2017). Table 1 show that the S2 spacing recorded the highest total plant yield with an average of 1.585 Mg ha^{-1}, while the S1 spacing recorded the lowest average amount 1.363 Mg ha^{-1}, that increase in yield condolences to low plant density which leads to improved plant photosynthesis efficiency. This may be a result of better availability of light, water and food resources, which was reflected in an increased rate of photosynthesis and the accumulation of carbohydrates and nutrients inside the seeds (Al-Obady and Shaker, 2021). This result was agreed with Kumar *et al.* (2023). The highest interaction was recorded at the combination T8×S2 on average 2.357 Mg ha^{-1} and less record of the combination T0 × S1 amounted to 0.766 Mg ha^{-1}. (Figure 1).

Protein in seeds (%)

The analysis of the data shown in Table 1 indicated that the combination of phosphate and potassium fertilizers and planting distances had a significant effect, whereas the interaction did not have a significant effect on this trait (Table 1). The combination of phosphate and potassium fertilizers was superior at treatments T8, T7, and T6 recorded the highest average of protein percentage, with averages of 15.59%, 15.48%, and 14.96% respectively. In contrast, treatment T0 gave the lowest protein percentage of 11.00%. The increase is attributed to the complementary effect of the phosphorus and potassium added to the plant in enhancing nitrogen uptake efficiency by increasing the activity of the nitrite enzyme, which is responsible for reducing nitrates and fixing nitrogen in the form of amino acids, thus promoting their formation as they constitute the building blocks of proteins. This is in addition to the role of phosphorus and potassium in supporting vital processes related to growth and protein synthesis (Rana *et al*., 2005; Jensen, 2003; Havlin, 2005). These results are consistent with Tyagi *et al*. (2022).

Protein yield (Mg ha^{-1})

Data shown in Table 1 show the significant effect of combinations phosphate and potassium fertilizer, planting distances, and their interaction on this trait. The combination T8 recorded the highest protein yield of 0.534 Mg ha^{-1}, while the control treatment recorded the lowest average of 0.086 Mg ha^{-1}, and did not differ significantly from the T1 combination which recorded 0.103 Mg ha^{-1}. The increase is attributed to the increase in the total seed yield. The S2 distance achieved the highest protein yield, with an average of 0.317 Mg ha^{-1}, representing a 40.89% increase compared to the S1 distance, which yielded the lowest average of 0.225 Mg ha^{-1}. This increase in protein yield at the wider distance is attributed to the higher protein percentage and seed yield, which in turn led to the higher protein overall. These results are consistent with those of Kaur *et al*. (2019) and Meena *et al*. (2022). The highest protein yield was obtained with T8 × S2 which was 0.598 Mg ha^{-1}, while the lowest yield was recorded at T0 × S1 at 0.083 Mg ha^{-}, and it did not differ significantly from the T0 × S2 combination and the T1 × S1 combination (Figure 2). The increase in protein yield when the level of phosphorus and potassium increases in conjunction with the widening of planting distances may be attributed to the improvement in the nutritional status of the plant and the reduction of competition between plants for elements, water and light, which led to an increase in the growth of the shoot and root systems and the efficiency of photosynthesis. The synergy between phosphorus and potassium was reflected in raising the efficiency of nitrogen uptake and its investment in building protein compounds, which ultimately led to an increase in protein yield (Kaur *et al*., 2019).

Oil in seeds (%)

The significant effect of phosphate and potassium fertilizer combinations was found, while the planting distance and the interaction did not have a significant effect on this trait (Table 1). The combination was superior the T8 treatment achieved the highest average oil content of 52.01%, while the control treatment recorded the lowest average of 22.11%, which did not differ significantly from the T1 and T2 combinations. The availability of nutrients leads to an increased ability of the plant to utilize and assimilate them into carbohydrates, which provide the energy necessary for fat synthesis and the transport and storage processes that occur within the plant. Phosphorus increases the availability of essential building blocks and enhances the activity of enzymes responsible

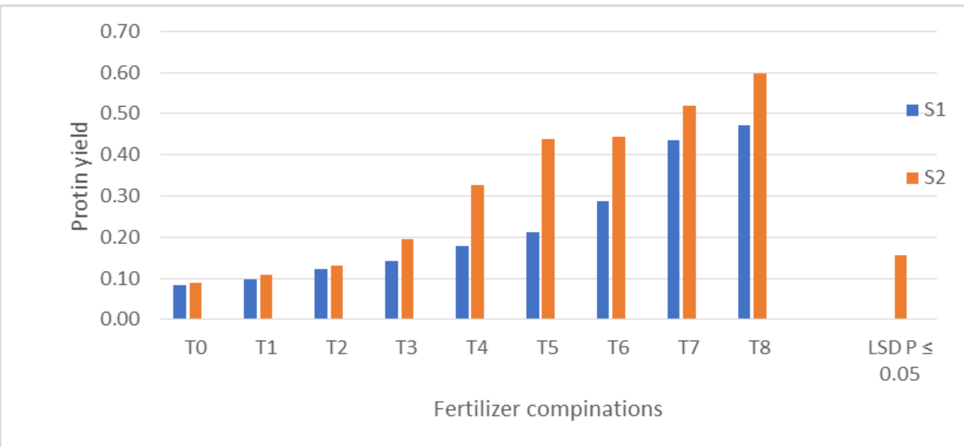

Figure 2: *Interaction of fertilizer combinations and spacing of plant on protein yield (Mg ha^{-1}).*

for fatty acid formation and lipid metabolism, thus affecting seed quality. Potassium acts as an internal regulator, maintaining cell balance and facilitating the movement of fatty compounds within the cell. This synergy between phosphorus and potassium creates an ideal metabolic environment that makes seeds more capable of storing oil in higher quantities (Subba and Srinivasarao, 1996). This result is consistent with Gill *et al*. (2021) and Lakhan *et al*. (2017).

Oil yield (Mg ha^{-1})

Table 1 shows that the combinations of phosphate and potassium fertilizers, planting distances, and the interaction between them had a significant effect on this trait. The combination the T8 treatment exhibited the highest seed oil yield, averaging 1.151 Mg ha^{-1}, while the control treatment recorded the lowest average yield of 0.173 Mg ha^{-1}. This result was not significantly different from the T1 and T2 combinations. The superiority of the T8 combination may be attributed to its superiority in both total seed yield and oil percentage. This finding is consistent with Potdar et al. (2019).

The S2 planting distance was superior and recorded the highest average oil yield with an average of 0.604 Mg ha^{-1}, while the S1 distance recorded the lowest average of 0.501 Mg ha^{-1}. This may be due to the superiority of the same distance in the seed yield characteristic. This result was consistent with Meena *et al*. (2022) and Kumar *et al*. (2023). The combination was superiorT8 × S2 recorded the highest oil yield of 1.273 Mg ha^{-1}, while the combination T0 × S1 gave the lowest yield of 0.171 Mg ha^{-1}, and did not differ significantly from the combination T0 × S2 and the fertilizer combination T1 and T2 at the distances S1 and S2 (Figure 3).

Volatile oil (%)

The phosphate and potassium fertilizer combinations had a significant effect, while planting distance and the interaction did not significantly affect this trait (Table 1). Combinations T8 and T7 achieved the highest average of volatile oil percentage, reaching 2.245% and 2.087%, respectively. In contrast, the control treatment T0 and combination T1 recorded the lowest average percentages, at 0.233% and 0.287%, respectively. The increase in volatile oil percentage in mustard seeds resulting from the addition of high rates of phosphorus and potassium fertilizer, phosphorus's role in promoting the formation of energy compounds (ATP and NADPH) necessary for secondary metabolic pathways responsible for glucosinolate production. Potassium, on the other hand, contributes to activating enzymes that regulate the synthesis of aromatic sulfur compounds and regulate the translocation of sulfur-containing amino acids such as methionine. This increases the accumulation of secondary metabolic products (isothiocyanates), which form the basis for volatile oil formation. Thus, this physiological pathway differs from the formation of ordinary oil stored as triglycerides, consistent with the results of Fahey *et al*. (2001).

Active medicinal compounds

Table 2 revealed the significant superiority of phosphate and potassium fertilizer combinations, planting distance, and interaction between them in medicinal active compounds. The planting distance did not register a significant effect on the compound. Benzene-Isothiocyanate and Butene-Isothiocyanates and compound, while the interference had no significant effect on the compound of the Butene-

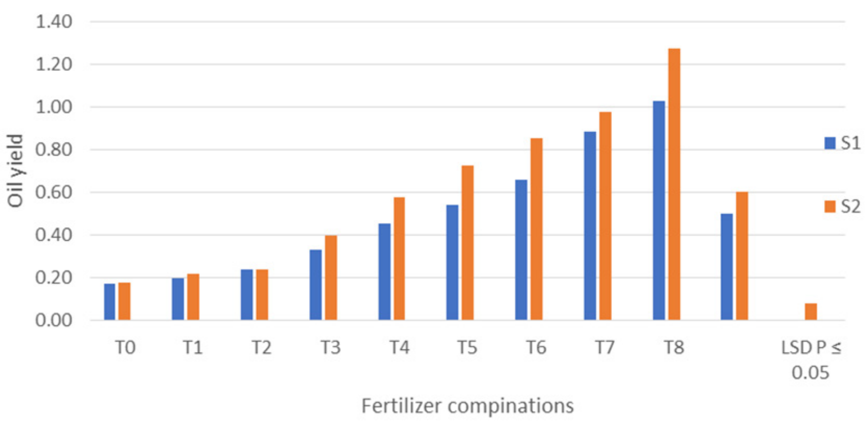

Figure 3: *Interaction of fertilizer combinations and spacing of oil yield (Mg ha^{-1}).*

Isothiocyanates the combination achieved T8 The highest percentage of organosulfur groups in the two compounds Allyl-isothiocyanate and Benzene-isothiocyanate on average,9.57 and 4.11% sequentially, while the lowest percentage was recorded at the treatment T0 For the compound Allyl-isothiocyanate on average,2.31% The combination was recordedT1Lowest average compound Benzene-isothiocyanate its amount0.72% and did not differ significantly from the combinations T2 and T3 and T6 which recorded 1.02 and 0.90 and 0.84% sequentially and did not differ significantly between them, as the two combinations recorded T7 and T8 highest average for the compound Butene-isothiocyanate reached 58.40 and 57.60% sequentially, and did not differ significantly from T1 which gave 50.10%The lowest percentage of the compound was recorded in the comparison treatment 35.10% and did not differ significantly from the combinations T1and T2 and T3 and T6 the combination also proved superior T8 recording the highest percentage of plant sterols with an average of 2.61 and 1.38% for the two compounds β-Sitosterol and Campesterol in succession, the lowest percentage of the compound was recorded.β-Sitosterol when treating the comparison with an average of 0.32%, and for the compound Campesterol when combining T1 the comparison treatment was an average of 0.42%, but the antioxidant group may surpass vitamin E on average, 1.72% at the combination T8 it differed significantly from all combinations, while the comparison treatment recorded and the two combinations T1 and T2.

The lowest percentage reached 0.34 and 0.45 and 0.51% sequentially and did not differ significantly it is noted from the table that the combination T5 it achieved the highest average percentage of phenols, with an average of 16.65%, and the combination was recorded T3 the lowest average was 3.31% and did not differ significantly from the comparison treatment that was recorded 3.56%. The volatile nitrogen group achieved the highest average percentage of the two compounds. Thiazole and Cyano-3,4-epithiobutane when combining T8 reached 6.35 and 43.69% respectively, while their percentages decreased upon treatment T0 to register a significant difference with an average of 0.57 and 2.05% sequentially. Compound superiority Allyl isothiocyanate at the distance S2 the highest percentage recorded was 5.67%, while the distance was recorded S1 the lowest percentage is 5.02%, but the two compounds achieved β-Sitosterol and Campesterol highest average at planting distance S2 reached 1.42 and 0.83% sequentially, while the percentage of both compounds decreased at the planting distance. S1 and it was recorded 0.76 and 0.44% sequentially, and the planting distance was superior S2 it recorded the highest percentage of antioxidants, and the highest percentage recorded was 0.97 and 8.77% for the two compounds sequentially, when the percentages decreased at the planting distance S1 on average 0.66 and 6.85% sequentially,

Table 2: *Effect of phosphorus and potassium fertilizer treatments and planting spacings on bioactive compounds in mustard seeds*

C3,4-ETB%	Thz%	Phenols%	Vit E%	Camp%	β-Sit%	Bu-ITC%	BITC%	AITC%	Treatments	
15.16	2.919	6.85	0.66	0.44	0.76	42.20	1.74	5.024	S1	Plant Spacing
21.92	3.603	8.74	0.97	0.83	1.42	46.00	1.84	5.670	S2	
0.540	0.1915	0.2884	0.043	0.0169	0.052	N.S	N.S	0.1699	LSD ($P \leq 0.05$)	
2.02	0.568	3.56	0.43	0.42	0.32	35.10	1.62	2.31	T0	Fertilizer combinations
5.17	0.920	7.14	0.45	0.42	0.45	37.20	0.72	3.15	T1	
8.58	1.093	7.97	0.51	0.47	0.49	37.80	1.02	4.18	T2	
8.76	2.863	3.31	0.58	0.45	0.69	37.90	0.90	3.17	T3	
17.10	4.030	4.48	0.78	0.48	0.86	45.90	1.47	5.72	T4	
23.97	4.038	16.65	0.86	0.67	1.58	50.00	2.22	7.04	T5	
23.02	3.918	4.21	0.68	0.59	1.02	37.10	0.84	5.14	T6	
35.51	5.567	9.62	1.32	0.86	1.81	58.40	3.48	7.85	T7	
43.69	6.353	13.18	1.72	1.38	2.61	57.60	4.11	9.57	T8	
1.147	0.4062	0.612	0.091	0.036	0.110	10.17	0.545	0.360	LSD ($P \leq 0.05$)	

AITC → Allyl isothiocyanate, BITC → Benzyl isothiocyanate, Bu-ITC → Butene isothiocyanate, β-Sit → β-Sitosterol, Camp → Campesterol, Vit E → Vitamin E, Phenols → Phenolic compounds, Thz → Thiazole, C3,4-ETB → 3,4-Epithiobutane.

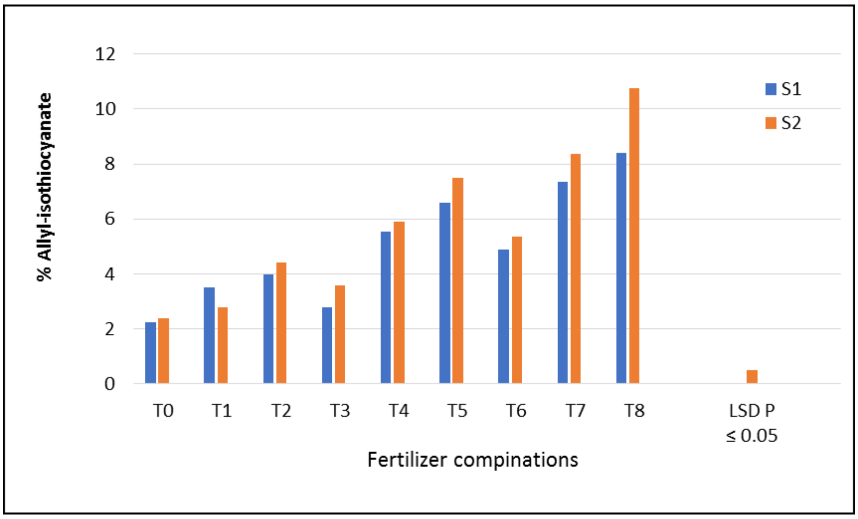

Figure 4: *Effect of Phosphorus and Potassium Fertilizer Combinations, Planting Spacings, and Their Interaction on Allyl Isothiocyanate*

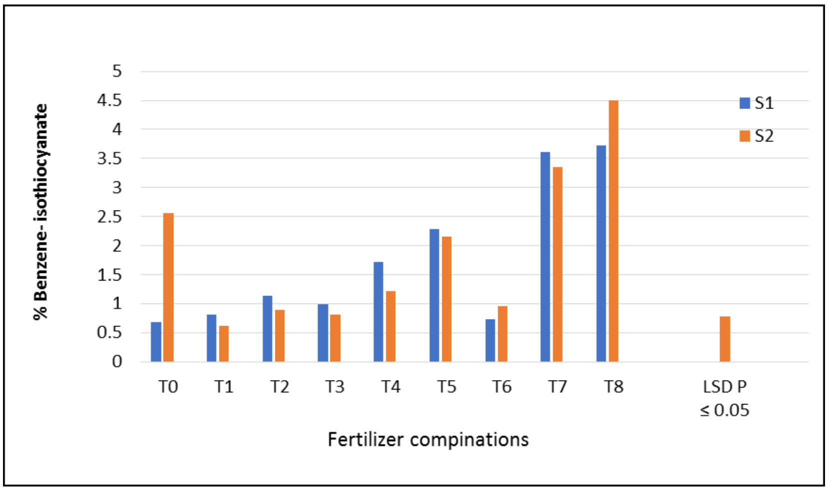

Figure 5: *Effect of Phosphorus and Potassium Fertilizer Combinations, Planting Spacings, and Their Interaction on Benzene-isothiocyanate*

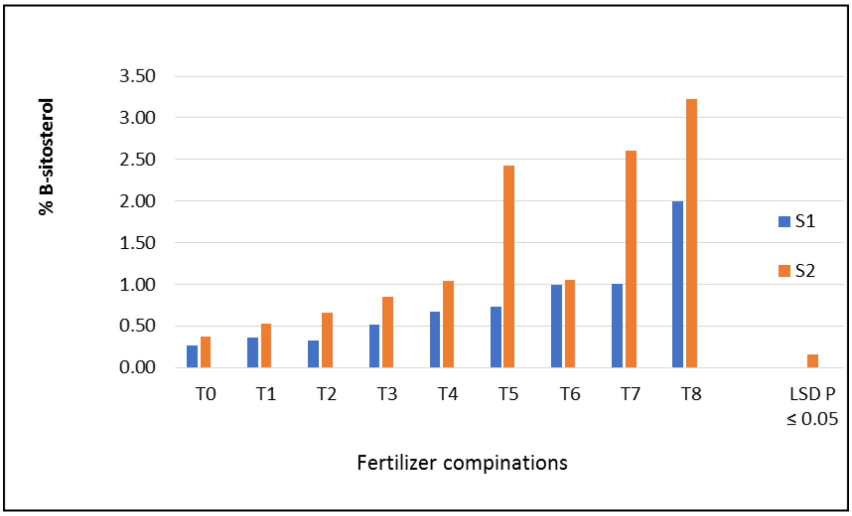

Figure 6: *Effect of Phosphorus and Potassium Fertilizer Combinations, Planting Spacings, and Their Interaction on β-Sitosterol*

and gave the planting distance S2 highest average for volatile nitrogen compounds on average reached 3.60 and 21.92% sequentially, while the planting distance was recorded S1 the lowest average was 2.92 and

15.16% sequentially. In the two Figure 4 and Figure 5 the combination T8 × S2 the highest percentage of composites was recorded Allyl-isothiocyanate and Benzene-isothiocyanate on average10.75% and 4.51% sequentially, while the lowest percentage was recorded when combining T0 × S1 on average, 2.24% and 0.68% for the two compounds sequentially, while the two figures showed 6and 7 the interference T8 × S2 achieve the highest ratio for the two compounds β-Sitosterol and Campesterol on average, 3.23 and 1.84% sequentially, while the comparison treatment was recorded at the distance S1 the lowest percentage reached 0.26 and 0.28% sequentially, and did not differ significantly from the combination T1 for the compound Campesterol that it reached 0.28%.

The interaction had a significant effect on the vitamin level E Phenols (Figure 6 and Figure 7) the highest percentage of vitamin was recorded. Its amount 2.02% when T8 ×S2, while the interference T5 × S2 the highest percentage of phenols averaged 17.81%, and the percentages of both compounds decreased when using the comparison and distance treatment. S1 on average 0.26 and 2.33% for the two compounds in sequence between the form 8 and 9 the interference T8 × S2 it achieved the highest percentage for the two compounds. Thiazole and Cyano-3,4-epithiobutane averaged 6.64% and 54.55% for the two compounds, respectively, while the percentages decreased in the T0 × S1 treatment, registering 0.53% and 1.67%, respectively. The increase in the percentage of active medicinal compounds in the high-level phosphate and potassium fertilizer combination (T8) is attributed to the fact that the high fertilizer levels increased photosynthesis and carbohydrate accumulation, which are used in the formation of glucosinolates that are subsequently hydrolyzed to yield isothiocyanates (Fahey *et al*., 2001). Phosphorus and potassium are crucial in plant biochemical processes that increase the proportion of secondary substances in the plant. Furthermore, the combined role of phosphorus and potassium in activating lipid metabolism pathways and their function as catalysts for sterol production and increased accumulation in mustard seeds (Singh *et al*., 2024) is also relevant.

Additionally, the addition of phosphorus increases the phenolic or vitamin E content. Potassium's contribution to the accumulation of these compounds was not a direct result of these two elements, but rather a consequence of their role in preparing the plant physiologically by enhancing metabolic activity and photosynthesis and providing the energy necessary for biosynthetic pathways (phenylalanine and phenylpropanoids), thus enabling the plant to produce these secondary compounds (Kruse, 2003). Increased levels of phosphorus and potassium led to an increase in the proportion of volatile nitrogenous substances. Phosphorus enhances enzyme activity and photosynthesis for protein synthesis, while potassium improves the transport of sugars and amino acids. Consequently, the nitrogen content in the seeds increased, leading to a higher protein content, as shown in Table 1. This, in turn, increased the accumulation of volatile nitrogenous compounds (Jensen, 2003; Rana *et al*., 2005; Havlin, 2005). The wider planting distance (S2) generally resulted in a significant increase in most active medicinal compounds compared to the planting distance (S1). This may be attributed to

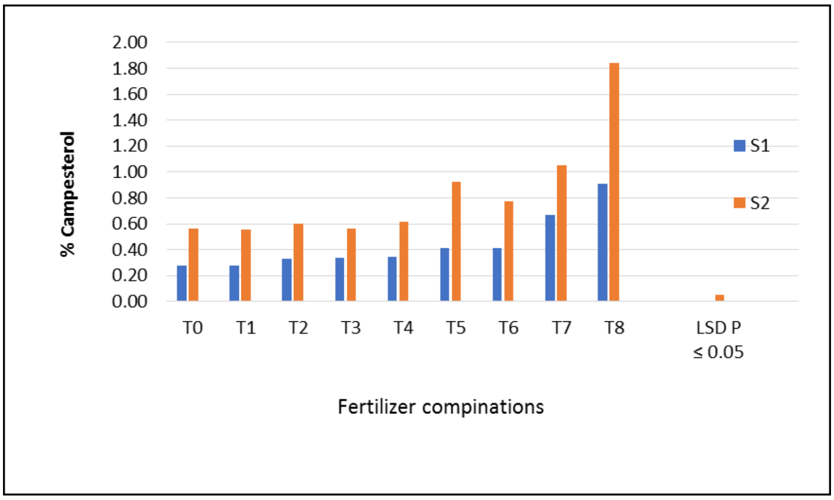

Figure 7: *Effect of Phosphorus and Potassium Fertilizer Combinations, Planting Spacings, and Their Interaction on Campesterol*

the fact that wider planting distances provide better conditions for root growth and nutrient uptake, as well as greater light interception by the plant and nutrient absorption, which enhances photosynthesis, increases the proportions and production of volatile nitrogenous substances, and increases antioxidants and other byproducts in the seeds (Gounikadi *et al*., 2022; Li *et al*., 2023). The interaction between phosphate and potassium fertilizer combinations and planting distance was significant in the proportions of all active medicinal compounds.

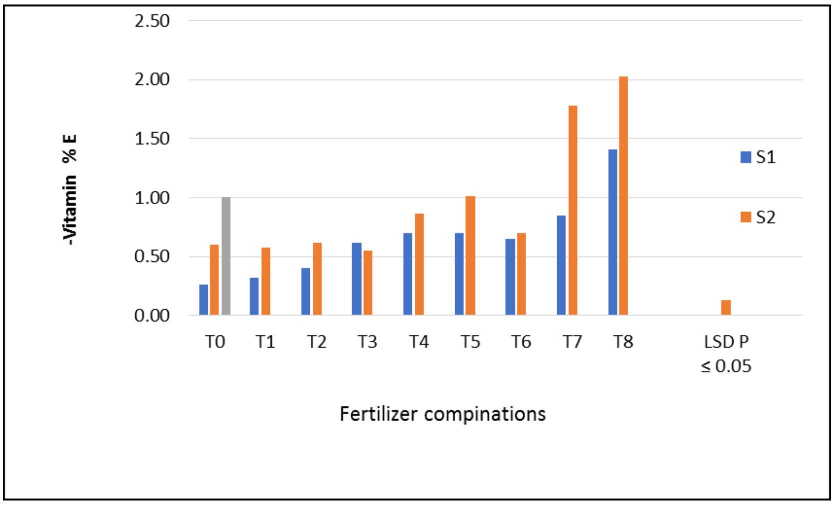

Figure 8: *Effect of phosphorus and potassium fertilizer combinations, planting spacings, and their interaction on vitamin E*

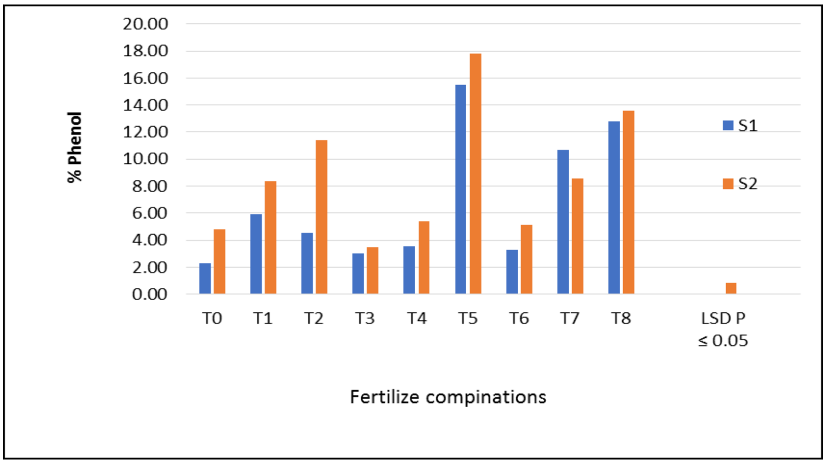

Figure 9: *Effect of phosphorus and potassium fertilizer combinations, planting spacings, and their interaction on phenol content in mustard seeds*

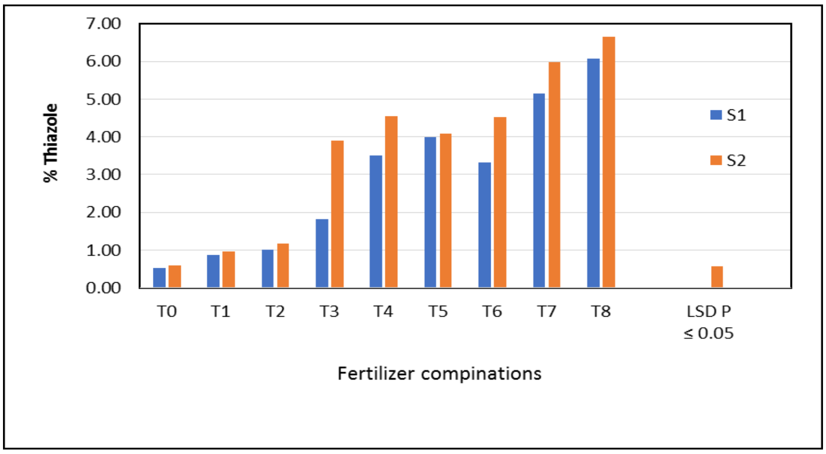

Figure 10: *Effect of phosphorus and potassium fertilizer combinations, planting spacings, and their interaction on thiazole content in mustard seeds*

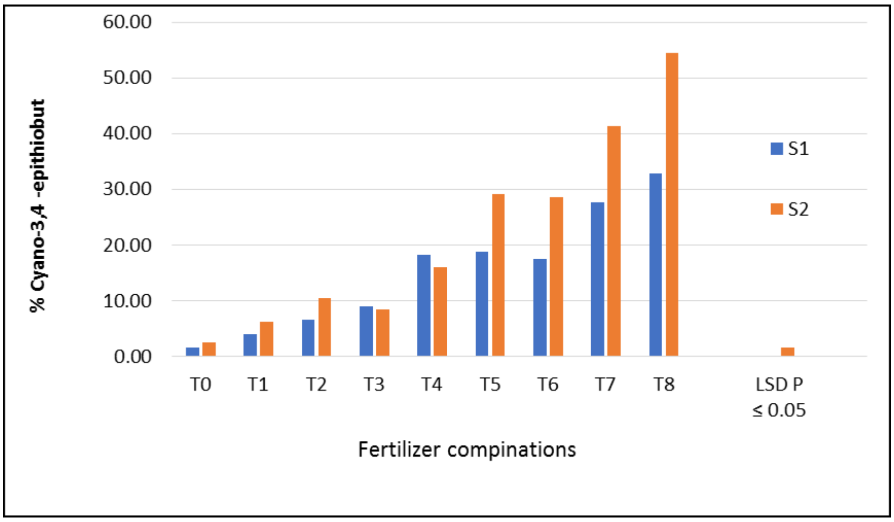

Figure 11: *Effect of phosphorus and potassium fertilizer combinations, planting spacings, and their interaction on cyano-3,4-epithiobutane content in mustard seeds*

Conclusions and Recommendations

A balanced supply of phosphorus and potassium, along with providing the appropriate distance for growth, contributes to enhancing the efficiency of nutrient absorption and improving the physiological processes responsible for the formation of oily and medicinal compounds in mustard seeds. Therefore, the adoption of the transaction can be recommended P80K30 with a 40 cm spacing between plants to achieve maximum productivity and quality in environmental conditions similar to southern Iraq.

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Novelty statement

This study reveals that combining P80K30 fertilization with a 40 cm plant spacing markedly improves seed yield, protein, oil, volatile oil, and key bioactive compounds, including organosulfur compounds, plant sterols, antioxidants, and volatile nitrogen compounds. The T8 treatment demonstrates a novel fertilization–spacing interaction that enhances both productivity and phytochemical quality in an environmentally friendly manner, offering a practical strategy for maximizing yield and seed quality.

Author's Contribution

Anfal Ameen Al-Aboud: monitored the data collection and field experiment, helped with the literature evaluation, and wrote the manuscript.
Sundus Abdulkariem Alabdulla: Conceived the idea, designed the study, supervision, modifies the manuscript and proof reading,.

Generative AI and AI-assisted technology statement

The authors declare that they did not use artificial intelligence techniques in writing this manuscript. The authors developed the research plan, collected the data, analyzed it, and discussed it.

Conflict of interest

No conflicts of interest have been declared by the authors.

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