International Journal of Plant & Soil Science

Volume 36, Issue 9, Page 880-891, 2024; Article no.IJPSS.123923
ISSN: 2320-7035

Assessing the Impact of Sulfur, Magnesium, and Acephate on Mustard Crop Performance

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2024/v36i95039

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/123923

Original Research Article

Received: 20/07/2024
Accepted: 22/09/2024
Published: 27/09/2024

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Cite as: *Patel, Krishna Kumar, Anil Kumar, Ravindra Kumar, Sanjeev Sharma, Kaushal Kumar, Sajneev Kumar, Ajay Kumar Baheliya, Pardeep Kumar, and Dev Narayan Yadav. 2024. "Assessing the Impact of Sulfur, Magnesium, and Acephate on Mustard Crop Performance". International Journal of Plant & Soil Science 36 (9):880-91. https://doi.org/10.9734/ijpss/2024/v36i95039.*

ABSTRACT

Field experiments were conducted to studies the interaction effect of sulphur, magnesium and acephate on growth parameters, yield components and yield of mustard during *rabi* season of 2022-23 and 2023-24 at students instructional farm, Chandra Shekhar Azad University of Agriculture & Technology, Kanpur under Central Plain Zone of Uttar Pradesh. The experiment consist of 18 treatments combinations in factorial randomized block design with three replications consisted of three levels of sulphur (0, 20 and 40 kg ha^{-1}), three magnesium levels (0, 10 and 20 kg ha^{-1}) and two pesticide levels (with acephate and without acephate). The results demonstrated significant improvements in growth parameters with the combined treatments, notably increasing plant height to 183.25 cm at 60 days after sowing. While plant population remained constant at 13.44 plants per square meter, dry matter accumulation rose from 27.13 g to 28.22 g per plant, and branching increased from 12.59 to 13.14 branches per plant. The S and Mg treatments synergistically enhanced leaf development, with the highest leaf counts observed in the S x Mg treatment. Yield attributes, including the number of siliques per plant and seeds per silique, were significantly improved, particularly with the S x Mg and S x Mg x I interactions. Seed production and stover yield were also notably increased, emphasizing the importance of integrated nutrient and pest management for optimizing mustard production.

Keywords: Mustard; sulphur; magnesium; growth; yield.

1. INTRODUCTION

Mustard (*Brassica juncea* L.), one of the most important oilseed crops globally, is extensively cultivated for its high oil content and valuable by products such as stover, which is used as fodder and organic manure. As a key contributor to edible oil production in countries like India, China, and Canada, mustard faces growing pressure to improve yields to meet rising global demands. However, achieving high yields consistently is a complex challenge, influenced by numerous agronomic factors, including nutrient management and pest control. Among the critical nutrients for oilseeds like mustard, sulfur and magnesium play essential roles in growth, development, and yield. Simultaneously, pest management, particularly control of aphids, often requires the application of insecticides like Acephate. Understanding how sulfur and magnesium, alongside insecticide use, affect mustard crop performance is crucial for optimizing production in a sustainable manner.

Sulfur (S) is a vital secondary macronutrient required for oilseed crops. It plays a critical role in various plant physiological and biochemical processes, including protein synthesis, chlorophyll formation, and nitrogen assimilation. In mustard, sulfur is essential for synthesizing glucosinolates, compounds that contribute to both the crop's flavor and its defense against pests [1]. Sulfur deficiency in soil is becoming increasingly widespread due to intensive cropping, higher crop yields, and the use of sulfur-free fertilizers. This deficiency can result in stunted growth, delayed flowering, and significant yield reductions [2]. Adequate sulfur application can enhance mustard yield by improving seed oil content, seed size, and overall plant vigor [3].

Magnesium (Mg), often referred to as the "central atom" of the chlorophyll molecule, is another essential nutrient. It is critical for photosynthesis, enzyme activation, and energy transfer within the plant. Magnesium deficiency, although less apparent than nitrogen or phosphorus deficiencies, can severely impair plant growth by reducing chlorophyll production, leading to lower photosynthetic activity and reduced crop productivity. In mustard, the impact of magnesium deficiency has been linked to poor root development, leaf chlorosis, and reduced seed quality [4]. The synergistic effects of sulfur and magnesium, with their combined application showing improved nutrient use efficiency and yield performance in mustard crops [5].

In addition to nutrient management, effective pest control is critical for ensuring mustard crop productivity. One of the most common and damaging pests of mustard is the mustard aphid (*Lipaphis erysimi*). Aphids attack the crop during the flowering and pod-setting stages, leading to significant yield losses. If left unmanaged, aphid infestations can reduce mustard yields by up to 30-50 %, depending on the severity of the attack [6]. Acephate, a widely used systemic organophosphate insecticide, is frequently applied to control aphids and other pests in mustard fields. Acephate acts on the nervous system of the pests, providing effective control and minimizing crop losses. However, there is growing concern about the over-reliance on chemical insecticides due to issues like pesticide resistance, environmental contamination, and adverse effects on non-target organisms [7].

Integrated nutrient and pest management practices are increasingly being explored to reduce the environmental impact of agriculture while maintaining or even improving crop yields. Sulfur has been shown to enhance plant resistance to aphids by stimulating the production of glucosinolates, which act as natural defence compounds [8]. Magnesium, by improving overall plant health and photosynthetic activity, also plays a role in enhancing crop resilience to biotic stresses. Thus, a well-balanced nutrient management approach could potentially reduce the dependence on chemical insecticides like Acephate, thereby promoting a more sustainable mustard production system [9].

Mustard production emphasize the critical role of these management practices and according to the latest report by the Indian Institute of Oilseeds Research (IIOR, 2023), mustard productivity in India remains below global standards, averaging around 1.3 tons per hectare, compared to the global average of 1.8 tons per hectare. In regions where sulfur and magnesium deficiencies are prevalent, yields are even lower, highlighting the urgent need for improved nutrient management strategies. Moreover, a study by Meena *et al.* [10] indicates that aphid-induced yield losses in mustard can be reduced by up to 35% with the application of sulfur and magnesium, alongside strategic insecticide use.

2. MATERIALS AND METHODS

The experiment was conducted at the Students Instructional Farm (SIF) of CSAUA&T, Kanpur, Uttar Pradesh, situated at 25º18' N latitude, 83º03' E longitude, and at an altitude of 80.71 meters above mean sea level. The site has a subtropical climate, characterized by hot summers and cool winters. During the crop growing periods of 2022-23 and 2023-24, the total rainfall recorded was 15.90 mm. The objective of the study was to evaluate the effects of sulfur, magnesium, and an insecticide treatment on mustard growth and yield. The experiment was designed as a Factorial Randomized Complete Block Design (FRBD) with three replications. The factors included: Factor A - sulfur at levels 0 kg (Control), 20 kg, and 40 kg; Factor Mg - magnesium at levels 0 kg (Control), 10 kg, and 20 kg per hectare; and an insecticide treatment and their treatment combination are mentioned below in the Table 1. Full doses of nitrogen (25 kg ha^{-1}), potash (6 kg ha^{-1}), and phosphorus (15 kg ha^{-1}) were applied at sowing. Sulfur and magnesium were applied according to the treatment levels, while the insecticide was applied as per the specified treatment. Fertilizers were applied using urea, diammonium phosphate (DAP), muriate of potash, elemental sulfur, and magnesium oxide.

The crop received three uniform irrigations: pre-sowing, at a critical growth stage, and pre-flowering. Standard agronomic practices were adhered to, and the crop was harvested in the second week of March in both years. Growth attributes were recorded at harvest, including plant height, plant population, number of leaves, number of branches, and grain, straw, and biological yield. The harvested crop was sun-dried and threshed manually. The grain yield was measured and converted to quintals per hectare. Additional measurements included test weight, biological yield, and harvest index. The total biological yield was calculated by subtracting the grain yield from the total yield. Data on plant height and plant population were recorded from marked areas. Samples for dry matter accumulation were sun-dried and then oven-dried at 65-70ºC until a constant weight was achieved. Yield attributes, such as the number of siliquae per plant and the number of seeds per siliqua, were also measured.

Statistical analysis of the data was conducted following Gomez and Gomez (1984) to determine significant differences among treatments. The methodology and analysis adhered to standard agronomic practices for crop management.

3. RESULTS AND DISCUSSION

3.1 Plant Height

Plant height increased with the combined application of sulfur (S), magnesium (Mg), and insecticide (I), although the increases was not statistically significant at most growth stages, except at 60 days after sowing (DAS) in both years. The minimum plant heights recorded were 22.09 cm in the first year and 23.15 cm in the second year at 30 DAS. In contrast, the maximum plant heights reached 182.53 cm in the first year and 183.25 cm in the second year at harvest. This trend of increased plant height with the combined treatments was consistent across both years.

The interaction of sulfur, magnesium, and insecticide yielded the highest plant heights compared to other treatment combinations throughout the experimentation period. This suggests a synergistic effect of these inputs on mustard growth. Similar findings have been reported in recent studies, where integrated nutrient management and pest control strategies were shown to significantly enhance crop growth and yield [11,12]. The combined application likely provided optimal nutrient availability and pest management, leading to improved plant growth and these interactions and their statistical significance are provided in Table 2.

3.2 Plant Population, Dry Matter Accumulation and Number of Branches

The application of sulfur, magnesium, and insecticide combinations (S x Mg, Mg x I, S x I, S x Mg x I) did not significantly influence mustard plant population at any growth stage over the two-year study period. The minimum plant populations were 13.53 plants per square meter in the first year, 13.35 plants per square meter in the second year, with a pooled average of 13.44 plants per square meter. This lack of significant impact on plant population suggests that these treatments do not substantially affect seed germination or early plant establishment. However, the study revealed that the combined use of sulfur, magnesium, and insecticide significantly enhanced dry matter accumulation and branching across all growth stages. In the first year, the minimum dry matter accumulation was 27.13 g per plant, which increased to 28.22 g per plant in the second year, with a pooled average of 27.68 g per plant. Similarly, the number of branches increased from 12.59 in the first year to 13.14 in the second year, with a pooled average of 12.86 branches per plant.

These results indicate that sulfur, magnesium, and insecticide combinations positively influence the biomass and branching characteristics of mustard, which are crucial for maximizing yield potential. Enhanced dry matter accumulation and increased branching could be attributed to improved nutrient availability and pest control, which contribute to better plant health and growth. Recent studies corroborate these findings, highlighting that nutrient management and pest control are integral to optimizing crop productivity [13], Nandhini *et al.,* 2024). The detailed interaction results are presented in Table 3, illustrating the significant effects of these treatments on mustard growth attributes.

3.3 No. of Leaves Per Plant

The number of leaves per mustard plant was significantly enhanced by the combined application of sulfur and magnesium (S x Mg) at all growth stages during both years. This treatment consistently produced the highest leaf count, indicating that sulfur and magnesium synergistically promote leaf development. Although other combinations, such as S x I, Mg x I, and S x Mg x I, also resulted in increased leaf counts, these changes were not statistically significant compared to S x Mg. The control treatment yielded the lowest leaf count, underscoring the beneficial role of nutrient supplementation. Specifically, treatment T_{18}, which included 40 kg of sulfur, 20 kg of magnesium, and insecticide, recorded the highest number of leaves, while T_{17}, with the same sulfur and magnesium levels but without insecticide, was a close second. These results align with recent findings that sulfur and magnesium can enhance leaf growth and overall plant health [14,15]. Enhanced leaf development likely contributes to improved photosynthesis and overall plant productivity.

3.4 Yield Attributes and Yield

3.4.1 No. of siliqua per plant and no. of seed per siliqua

The combined application of sulfur, magnesium, and insecticide (S x Mg, Mg x I, S x I, S x Mg x I) significantly enhanced the number of siliques per plant and seeds per silique in mustard. Notably, the S x Mg treatment consistently showed significant improvements for both traits across both years. The interaction effect of S x Mg x insecticide was particularly pronounced in the second year, further boosting these metrics. As the plants progressed through growth stages, the number of siliques and seeds per silique increased, with the lowest values observed under the control treatment (T_1). The highest values were achieved with treatment T_{18} (40 kg sulfur + 20 kg magnesium with insecticide), closely followed by T_{17} (40 kg sulfur + 20 kg magnesium without insecticide). This suggests that sulfur and magnesium enhance reproductive efficiency, and their combined effect with insecticide can further optimize seed production and the positive impacts of nutrient and pest management on seed yield and quality [16,17]. Detailed results are provided in Table 5.

Table 1. Detail of the treatment combinations

S. No.	Treatment Details	Symbol
1.	0kg S + 0kg Mg without Insecticide	$S_0\ M_0\ I_0$
2.	0kg S + 0kg Mg with Insecticide	$S_0\ M_0\ I_1$
3.	0kg S + 10kg Mg without Insecticide	$S_0\ M_{10}\ I_0$
4.	0kg S + 10kg Mg with Insecticide	$S_0\ M_{10}\ I_1$
5.	0kg S + 20kg Mg without Insecticide	$S_0\ M_{20}I_0$
6.	0kg S + 20kg Mg with Insecticide	$S_0\ M_{20}\ I_1$
7.	20kg S + 0kg Mg without Insecticide	$S_{20}\ M_0\ I_0$
8.	20kg S + 0kg Mg with Insecticide	$S_{20}\ M_0\ I_1$
9.	20kg S + 10kg Mg without Insecticide	$S_{20}\ M_{10}\ I_0$
10.	20kg S + 10kg Mg with Insecticide	$S_{20}\ M_{10}\ I_1$
11.	20kg S + 20kg Mg without Insecticide	$S_{20}\ M_{20}\ I_0$
12.	20kg S + 20kg Mg with Insecticide	$S_{20}\ M_{20}\ I_1$
13.	40kg S + 0kg Mg without Insecticide	$S_{40}\ M_0\ I_0$
14.	40kg S + 0kg Mg with Insecticide	$S_{40}\ M_0\ I_1$
15.	40kg S + 10kg Mg without Insecticide	$S_{40}\ M_{10}\ I_0$
16.	40kg S + 10kg Mg with Insecticide	$S_{40}\ M_{10}\ I_1$
17.	40kg S + 20kg Mg without Insecticide	$S_{40}\ M_{20}\ I_0$
18.	40kg S + 20kg Mg with Insecticide	$S_{40}\ M_{20}\ I_1$

Table 2. Interaction effect of S, Mg, & Insecticide on plant height at 30, 60, 90 DAS & harvesting stage

Treatment	Plant Height											
	30 DAS			60 DAS			90 DAS			at harvest		
	I^{st} year	II^{nd} year	Pooled	I^{st} year	II^{nd} year	Pooled	I^{st} year	II^{nd} year	Pooled	I^{st} year	II^{nd} year	Pooled
T_1	22.09	23.15	522.61	61.25	63.15	62.20	136.14	138.30	137.22	136.16	138.30	137.23
T_2	23.25	24.24	23.74	75.24	75.22	75.23	136.03	137.86	136.93	136.03	137.87	136.95
T_3	23.54	23.83	23.69	76.76	76.34	76.54	136.41	143.09	139.75	136.41	143.11	139.76
T_4	23.88	24.12	24.00	79.12	79.65	79.38	140.22	148.65	144.43	140.23	148.65	144.44
T_5	24.21	24.36	24.28	77.26	77.30	77.28	137.94	146.52	142.23	137.98	146.53	142.25
T_6	24.30	24.82	24.56	80.20	80.19	80.19	141.65	152.35	146.99	141.68	152.35	145.01
T_7	23.92	24.44	24.58	79.25	79.30	79.27	142.38	155.24	148.81	142.39	155.26	148.82
T_8	24.35	24.89	24.62	80.45	80.22	80.33	143.82	158.74	151.28	143.85	158.77	151.31
T_9	24.42	24.98	24.70	80.60	80.49	80.55	144.32	162.45	153.38	144.33	162.47	153.40
T_{10}	24.55	25.12	24.84	81.22	82.95	82.08	145.46	165.83	155.65	145.85	165.84	155.84
T_{11}	24.63	25.23	24.93	81.61	82.10	81.85	144.52	168.90	156.71	144.52	168.90	156.71
T_{12}	24.71	25.38	25.05	82.79	82.45	82.62	150.70	174.22	162.46	150.71	174.23	162.47
T_{13}	25.12	26.13	25.62	81.11	82.15	81.63	146.22	171.28	158.75	146.25	171.29	158.77
T_{14}	24.86	25.48	25.17	82.16	82.46	82.31	152.66	175.34	164.01	152.69	175.35	164.02
T_{15}	25.48	26.24	25.86	82.62	8275	82.68	170.44	178.74	174.59	170.48	178.75	174.61
T_{16}	25.86	26.78	26.32	82.72	82.80	82.76	170.42	180.52	175.46	170.45	180.52	175.48
T_{17}	26.12	27.15	26.63	82.90	82.86	82.88	181.84	181.45	181.65	181.84	181.48	181.66
T_{18}	26.43	27.35	26.89	83.41	83.54	83.48	182.52	183.24	182.88	182.53	183.25	182.89

	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%
S×Mg	0.36	NS	0.37	NS	0.151	NS	1.07	2.18	1.12	2.28	0.902	1.834	2.26	4.60	2.39	NS	1.648	3.350	2.13	4.33	2.33	NS	1.682	3.420
Mg×I	0.30	NS	0.30	NS	0.156	NS	1.78	0.87	0.91	NS	0.737	1.457	1.85	NS	1.95	NS	1.346	NS	1.74	NS	1.90	NS	1.374	NS
S×I	0.30	NS	0.30	NS	0.156	NS	1.78	0.87	0.91	1.86	0.737	1.497	1.85	NS	1.95	NS	1.346	NS	1.74	NS	1.90	NS	1.374	NS
S×Mg×I	0.52	NS	0.52	NS	0.270	0.549	1.51	3.08	1.59	3.23	1.276	2.593	3.20	NS	3.39	NS	2.330	NS	3.01	NS	3.30	NS	2.379	NS

Table 3. Interaction effect of S, Mg & Insecticide on Plant Population & Dry Matter accumulation

Treatment	Plant Population (m^{-2})						Dry Matter accumulation (gm $plant^{-1}$)						No. of Branches at 60 DAS					
	2022-23		2023-24		Pool		2022-23		2023-24		Pool		2022-23		2023-24		Pool	
T_1	13.53		13.35		13.44		27.13		28.22		27.68		12.59		13.14		12.86	
T_2	13.56		13.76		13.66		28.12		29.13		28.62		12.69		13.26		12.97	
T_3	13.78		13.92		13.85		28.75		29.75		29.25		12.86		13.69		13.28	
T_4	14.46		14.86		14.66		30.56		31.15		30.85		13.78		14.88		14.33	
T_5	13.95		14.09		14.03		29.46		30.75		30.11		13.10		14.13		13.61	
T_6	14.56		14.93		14.75		34.15		33.84		34.00		13.86		15.77		14.81	
T_7	13.89		14.65		14.27		32.78		33.65		33.21		13.12		14.64		13.88	
T_8	14.40		14.98		14.69		35.64		34.10		34.37		13.95		15.98		14.96	
T_9	14.51		15.12		14.81		36.45		37.42		36.93		14.12		16.34		15.23	
T_{10}	14.68		15.16		14.92		37.21		38.84		38.02		14.78		16.88		15.83	
T_{11}	14.87		15.36		15.11		37.88		38.46		38.17		15.10		17.24		16.13	
T_{12}	15.96		15.97		15.96		40.62		42.25		41.44		16.68		18.59		17.63	
T_{13}	14.92		15.39		15.15		39.13		40.60		39.46		15.59		17.46		16.52	
T_{14}	15.90		15.36		15.63		42.84		44.47		43.65		16.12		17.78		16.95	
T_{15}	16.14		15.48		15.81		46.60		48.22		47.41		16.96		18.22		17.59	
T_{16}	16.28		15.86		16.07		50.98		51.33		51.15		17.64		18.81		18.22	
T_{17}	16.86		16.00		16.43		53.75		54.50		54.12		18.79		19.16		18.97	
T_{18}	17.10		16.10		16.07		55.84		56.19		56.02		19.12		19.60		19.36	
Overall mean	14.96		15.02				38.22		39.05				15.05		16.42			
	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%	S.Ed±	CD at 5%
S×Mg	0.233	NS	0.207	NS	0.152	NS	0.565	1.148	0.637	1.294	0.387	0.786	0.211	0.429	0.259	NS	0.152	0.309
Mg×I	0.190	NS	0.169	NS	0.124	NS	0.461	NS	0.520	NS	0.316	NS	0.172	NS	0.212	NS	0.124	0.253
S×I	0.190	NS	0.169	NS	0.124	NS	0.461	NS	0.520	NS	0.316	0.642	0.172	NS	0.212	NS	0.124	0.253
S×Mg×I	0.329	NS	0.293	NS	0.216	NS	0.799	1.624	0.900	1.830	0.547	1.111	0.298	NS	0.367	NS	0.215	0.437

Table 4. Interaction Effect of S, Mg & Insecticide on No. of leaves $plant^{-1}$ at 30, 60, 90 DAS & at harvest

Treatment	No. of leaves $plant^{-1}$											
	30 DAS			60 DAS			90 DAS			at harvest		
	I^{st} year	II^{nd} year	Pooled	I^{st} year	II^{nd} year	Pooled	I^{st} year	II^{nd} year	Pooled	I^{st} year	II^{nd} year	Pooled
T_1	2.61	2.62	2.61	4.62	4.65	4.64	4.64	4.65	4.64	4.10	4.02	4.06
T_2	2.61	2.62	2.62	4.66	4.68	4.67	4.68	4.67	4.67	3.96	3.94	3.95
T_3	2.64	2.66	2.65	4.89	4.97	4.93	4.96	4.95	4.95	4.25	4.27	4.26
T_4	2.68	2.71	2.70	5.02	5.26	5.14	5.00	5.26	5.13	4.45	4.43	4.44
T_5	2.65	2.68	2.67	4.97	5.20	5.08	4.96	5.17	5.07	4.50	4.51	4.50

Treatment	No. of leaves plant^{-1}																							
	30 DAS						**60 DAS**						**90 DAS**						**at harvest**					
	Ist year		**IInd year**		**Pooled**		**Ist year**		**IInd year**		**Pooled**		**Ist year**		**IInd year**		**Pooled**		**Ist year**		**IInd year**		**Pooled**	
T$_6$	2.72		2.76		2.74		5.25		5.35		5.30		5.24		5.35		5.30		4.89		4.92		4.90	
T$_7$	2.70		2.73		2.71		5.12		5.23		5.18		5.10		5.23		5.16		4.74		4.75		4.74	
T$_8$	2.77		2.81		2.79		5.55		5.70		5.62		5.54		5.68		5.61		5.03		5.06		5.04	
T$_9$	2.85		2.90		2.87		5.86		6.10		5.98		5.84		6.08		5.96		5.58		5.57		5.58	
T$_{10}$	2.92		2.96		2.94		6.35		6.84		6.59		6.33		6.84		6.58		6.02		6.04		6.03	
T$_{11}$	2.98		3.05		3.01		6.81		7.05		6.93		6.80		7.04		6.92		6.24		6.25		6.24	
T$_{12}$	3.15		3.19		3.17		7.39		7.56		7.48		7.39		7.55		7.47		7.06		7.05		7.05	
T$_{13}$	3.09		3.15		3.12		7.22		7.40		7.31		7.21		7.37		7.29		6.78		6.80		6.79	
T$_{14}$	3.30		3.36		3.33		8.32		8.73		8.53		8.30		8.73		8.52		7.91		7.89		7.90	
T$_{15}$	3.65		3.71		3.68		9.15		9.40		9.27		9.15		9.39		9.27		8.81		8.83		8.83	
T$_{16}$	3.89		3.98		3.93		10.28		10.85		10.56		10.26		10.85		10.55		9.50		9.55		9.52	
T$_{17}$	4.24		4.32		4.28		11.47		11.87		11.67		11.47		11.86		11.66		10.35		10.33		10.34	
T$_{18}$	4.51		4.60		4.56		12.86		13.24		13.05		12.84		13.23		13.04		11.44		11.46		11.45	
	S.Ed±	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**
S×Mg	0.03	0.07	0.05	0.10	.0.030	0.061	0.12	0.24	0.11	0.23	0.084	0.172	0.10	0.21	0.08	0.17	0.067	0.135	0.09	0.18	0.09	0.19	0.74	0.151
Mg×I	0.02	NS	0.04	NS	0.025	NS	0.09	NS	0.09	NS	0.069	NS	0.08	NS	0.07	NS	0.054	NS	0.07	0.14	0.07	0.16	0.61	0.123
S×I	0.02	0.05	0.04	0.08	0.025	0.050	0.09	0.20	0.09	0.19	0.069	0.140	0.08	0.17	0.07	0.14	0.054	0.111	0.07	0.14	0.07	0.16	0.061	0.123
S×Mg×I	0.05	NS	0.07	NS	0.043	NS	0.17	NS	0.16	NS	0.119	NS	0.14	NS	0.12	NS	0.094	NS	0.12	0.25	0.13	NS	0.105	0.213

Table 5. Interaction Effect of S, Mg & Insecticide on number of Siliqua & number of seed per Siliqua

Treatment	No. of Siliqua/plant			No. of seed per Siliqua		
	2022-23	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**
T$_1$	208.65	209.22	208.93	9.05	9.10	9.07
T$_2$	210.22	212.64	211.43	9.10	9.12	9.11
T$_3$	212.57	214.14	213.36	9.12	9.17	9.15
T$_4$	218.66	217.56	218.10	9.88	9.95	9.92
T$_5$	215.44	216.50	215.97	9.45	9.64	9.54
T$_6$	225.36	227.45	226.40	10.34	10.41	10.37
T$_7$	220.36	223.40	221.88	10.20	10.15	10.18
T$_8$	228.10	227.11	227.61	11.30	11.39	11.34
T$_9$	235.49	236.50	235.99	11.36	11.41	11.39
T$_{10}$	239.55	240.70	241.12	11.48	11.75	11.61
T$_{11}$	243.20	245.46	244.35	11.86	11.90	11.88
T$_{12}$	250.47	251.19	250.83	12.56	12.67	12.61
T$_{13}$	246.80	248.64	247.72	11.97	12.02	11.99
T$_{14}$	258.16	261.40	259.78	12.59	12.53	12.57
T$_{15}$	267.23	270.14	268.68	12.66	12.87	12.76
T$_{16}$	276.60	279.24	277.92	12.86	13.60	13.23
T$_{17}$	287.33	288.63	287.98	13.34	14.10	13.72
T$_{18}$	296.14	298.55	297.34	14.10	14.75	14.42

Overall mean	241.13		242.69				11.29		11.47			
	S.Ed±	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**
S×Mg	3.405	6.922	3.579	7.275	2.315	4.705	0.180	NS	0.176	0.358	0.113	0.229
Mg×I	2.780	NS	2.922	NS	1.890	NS	0.147	NS	0.144	NS	0.092	NS
S×I	2.780	NS	2.922	NS	1.890	NS	0.147	NS	0.144	NS	0.092	NS
S×Mg×I	4.816	NS	5.061	NS	3.273	NS	0.254	0.517	0.249	0.506	0.159	0.323

Table 6. Interaction Effect of S, Mg & Insecticide on Seed, Stover Yield and Test Weight (gm)

Treatment	**Seed Yield**						**Stover Yield**						**Test Weight(gm)**					
	2022-23		**2023-24**		**Pooled**		**2022-23**		**2023-24**		**Pooled**		**2022-23**		**2023-24**		**Pooled**	
T_1	14.86		14.88		14.87		49.07		40.39		44.73		4.05		4.07		4.05	
T_2	14.89		14.93		14.91		49.13		50.46		49.79		4.13		4.15		4.14	
T_3	14.93		14.96		14.94		49.16		49.96		49.56		4.18		4.20		4.19	
T_4	14.97		15.04		15.01		49.10		50.38		49.74		4.26		4.25		4.25	
T_5	15.09		15.12		15.11		51.30		50.53		50.51		4.22		4.24		4.23	
T_6	15.24		15.26		15.25		48.83		50.96		49.89		4.32		4.34		4.32	
T_7	15.63		15.66		15.64		54.70		52.14		53.42		4.28		4.30		4.29	
T_8	15.88		15.94		15.91		52.91		52.92		52.91		4.35		4.40		4.38	
T_9	16.13		16.20		16.16		53.55		55.07		54.31		4.38		4.40		4.40	
T_{10}	16.39		16.42		16.40		55.07		55.17		55.12		4.44		4.45		4.44	
T_{11}	16.77		16.80		16.78		55.51		56.44		55.97		4.49		4.54		4.51	
T_{12}	17.13		17.16		17.14		56.87		58.17		57.51		4.56		4.59		4.57	
T_{13}	17.69		17.44		17.56		59.26		58.24		58.75		4.50		4.55		4.52	
T_{14}	18.21		18.24		18.22		61.73		61.64		61.69		4.60		4.66		4.63	
T_{15}	18.76		18.80		18.78		63.40		62.22		62.81		4.68		4.72		4.70	
T_{16}	19.36		19.39		19.37		65.23		65.52		65.38		4.74		4.77		4.76	
T_{17}	19.84		19.89		19.86		67.24		67.62		67.43		4.86		4.89		4.88	
T_{18}	20.14		20.18		20.16		67.46		67.43		67.44		4.94		4.96		4.95	
Overall mean	16.77		16.80				56.08		55.85				4.44		4.47			
	S.Ed±	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**
S×Mg	0.214	0.434	0.241	0.491	0.147	0.299	0.736	1.496	0.886	NS	0.605	1.229	0.074	NS	0.061	NS	0.055	NS
Mg×I	0.175	NS	0.197	NS	0.120	NS	0.601	NS	0.723	1.470	0.494	1.003	0.060	NS	0.050	NS	0.045	NS
S×I	0.175	NS	0.197	NS	0.120	0.244	0.601	1.221	0.723	1.470	0.494	NS	0.060	NS	0.050	NS	0.045	NS
S×Mg×I	0.302	NS	0.341	NS	0.208	NS	1.041	NS	1.253	2.547	0.855	1.738	0.104	NS	0.086	NS	0.078	NS

Table 7. Interaction effect of S, Mg & Insecticide on Biological Yield & Harvest index

Treatment	Biological yield						Harvest index					
	2022-23		2023-24		Pooled		2022-23		2023-24		Pooled	
T_1	63.92		55.27		59.60		23.24		26.92		26.92	
T_2	64.02		65.39		64.70		23.26		22.83		22.83	
T_3	64.09		64.92		64.50		23.30		23.04		23.04	
T_4	64.07		65.42		64.74		23.37		22.99		22.99	
T_5	66.39		65.65		66.02		22.73		23.03		23.03	
T_6	64.07		66.22		65.14		23.79		23.04		23.04	
T_7	70.33		67.79		69.06		22.22		23.10		23.10	
T_8	68.79		68.86		68.82		23.08		23.15		23.15	
T_9	69.68		71.27		70.47		23.15		22.72		22.73	
T_{10}	71.46		71.59		71.52		22.94		22.94		22.94	
T_{11}	72.27		73.24		72.76		23.20		22.94		22.94	
T_{12}	74.00		75.33		74.66		23.14		22.78		22.78	
T_{13}	76.94		75.68		76.31		22.99		23.04		23.04	
T_{14}	79.94		79.88		79.91		23.24		22.82		22.83	
T_{15}	82.16		81.02		81.59		23.26		23.20		22.20	
T_{16}	84.59		84.91		84.75		23.30		22.84		22.84	
T_{17}	87.08		87.51		87.29		23.37		22.72		22.72	
T_{18}	76.98		87.61		87.60		22.73		23.03		23.03	
Overall mean	72.27		72.64				23.13		23.17			
	S.Ed±	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**	**S.Ed±**	**CD at 5%**
S × Mg	1.102	2.240	1.219	NS	0.792	1.611	0.328	NS	0.354	0.721	0.315	0.641
Mg × I	0.900	1.829	0.995	2.023	0.647	1.315	0.268	NS	0.289	0.588	0.258	0.524
S × I	0.900	NS	0.995	NS	0.674	NS	0.268	NS	0.289	0.588	0.258	0.524
S × Mg × I	1.558	3.168	1.724	3.504	1.121	2.278	0.464	NS	0.501	1.019	0.446	0.907

3.4.2 Mustard seed production

The combined application of sulfur, magnesium, and insecticide (S x Mg, Mg x I, S x I, S x Mg x I) led to a significant overall increase in seed production, particularly in seed yield. Among the various treatments, the S x Mg interaction demonstrated the most effective results, significantly enhancing seed yield compared to other combinations. This suggests that sulfur and magnesium synergistically improve seed development, likely through enhanced nutrient availability and uptake. Detailed results, including the minimum and maximum seed values, are presented in Table 5. underscoring the notable impact of these interactions on seed output and these findings, indicating that sulfur and magnesium are crucial for optimizing seed yield [18-20].

3.4.3 Stover yield and test weight

The interaction effect of sulfur, magnesium, and insecticide also resulted in increased stover yield, with significant improvements observed specifically in stover yield. The S x Mg combination proved to be the most effective, outperforming other treatments. This enhancement in stover yield is likely due to the positive effects of sulfur and magnesium on plant biomass and overall growth. Detailed results, including the minimum and maximum stover yield values, are provided in Table 6. These results align with recent research highlighting the role of nutrient management in boosting stover production [21-23].

The combined treatments resulted in a non-significant increase in test weight, with the S x Mg interaction consistently showing the highest values among the treatments. Despite the lack of statistical significance, the S x Mg combination outperformed others in test weight. This indicates that while the effects on test weight were not substantial, sulfur and magnesium may still influence seed quality. Detailed results, including minimum and maximum test weight values, are presented in Table 6. Similar findings have been reported in recent studies, suggesting that nutrient applications can impact test weight, though the effects may be less pronounced [24,25].

3.4.4 Biological yield and harvesting index

The application of various combinations of sulfur, magnesium, and insecticide (S x Mg, Mg x I, S x I, and S x Mg x I) led to a significant improvement in the biological yield of mustard crops over two years. This enhancement in biological yield was consistently observed across both years, highlighting the beneficial effects of these treatments on overall crop biomass. However, an increase in the harvest index, which measures the efficiency of converting biomass into harvestable yield, was only noted in the second year. Among the different treatment combinations, the interaction of sulfur, magnesium, and insecticide (S x Mg x I) was particularly effective in boosting biological yield in both years. This suggests that the combined application of these inputs maximizes crop growth and productivity. Detailed results, including specific values and statistical analysis, are provided in Table 7. The integrated nutrient and pest management can significantly enhance crop biological yield and productivity [26,27]. These results underscore the importance of a holistic approach to crop management for optimizing mustard production [28,29].

4. CONCLUSIONS

It could be concluding that combined application of sulfur (S), magnesium (Mg), and insecticide (I) significantly improved various growth and yield parameters of mustard crops over two years. While plant height increased with these treatments, the enhancements were statistically significant only at 60 days after sowing, with maximum plant heights reaching 182.53 cm in the first year and 183.25 cm in the second year. The interaction of S, Mg, and I consistently resulted in the highest plant heights, indicating a synergistic effect. Despite no significant impact on plant population, which averaged 13.44 plants per square meter, the combined treatments notably improved dry matter accumulation and branching, with increases in dry matter from 27.13 g per plant to 28.22 g per plant, and branching from 12.59 to 13.14 branches per plant. These enhancements are attributed to better nutrient availability and pest control. Additionally, the number of leaves per plant was significantly higher with the S x Mg treatment, suggesting that sulfur and magnesium together promote leaf development. For yield attributes, the combined treatments, particularly S x Mg, significantly increased the number of siliques per plant and seeds per silique, with the most pronounced improvements observed in the second year. This indicates that sulfur and magnesium enhance reproductive efficiency. The treatments also significantly boosted seed production and stover yield, with S x Mg demonstrating the most effective results. Although test weight showed a non-significant increase, the S x Mg combination had the highest values, suggesting potential influences on seed quality. Overall, the combined application of sulfur, magnesium, and insecticide led to substantial improvements in biological yield, with the S x Mg x I interaction being particularly effective across both years. This indicates that integrated nutrient and pest management strategies are crucial for optimizing mustard production, as they enhance crop biomass and productivity.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/123923