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ORIGINAL RESEARCH ARTICLE



## Impact of sulfur and phosphorus fertilization on growth and yield of perilla oil crop (*Perilla frutescens*) under net house condition in Bangladesh

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### ABSTRACT

The current study aimed to evaluate the effects of sulfur (S) and phosphorus (P) fertilization on the growth and yield of *Perilla frutescens*, an emerging oilseed crop in Bangladesh. The experiment was conducted under net house conditions at the Agronomy Department, Bangladesh Agricultural University, Mymensingh, Bangladesh from July to December 2024. A Completely Randomized Design (CRD) scheme was followed, comprising four sulfur levels (0, 9.25, 18.5, and 27.75 kg ha<sup>-1</sup>) and four phosphorus levels (0, 20, 30, and 40 kg ha<sup>-1</sup>). Sulfur and phosphorus were supplied through gypsum and triple superphosphate (TSP), respectively. Growth parameters viz. plant height branch number, receme count, 1000-seed weight etc. were recorded along with biological yield and harvest index. The results revealed that both sulfur and phosphorus significantly ( $p < 0.05$ ) influenced perilla productivity. Sulfur application at 18.5 kg ha<sup>-1</sup> produced the highest seed yield (0.90 t ha<sup>-1</sup>), while higher or lower levels reduced yield performance. Similarly, phosphorus application at 30 kg ha<sup>-1</sup> maximized yield (1.09 t ha<sup>-1</sup>). Notably, the combined application of 18.5 kg S ha<sup>-1</sup> with 30 kg P ha<sup>-1</sup> yielded the highest productivity (1.50 t ha<sup>-1</sup>), outperforming sole applications of either nutrient. This interaction shows the synergistic role of balanced S and P fertilization in enhancing seed yield and harvest index. The study provides the experimental evidence on nutrient management for perilla in Bangladesh, indicating that moderate sulfur (100 kg gypsum ha<sup>-1</sup>) and phosphorus (150 kg TSP ha<sup>-1</sup>) fertilization can significantly improve growth and yield.

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### INTRODUCTION

*Perilla frutescens* L., commonly known as the beefsteak plant, is an annual herb of the Lamiaceae family native to several Asian countries, including China, India, Japan, Korea, and Thailand. It is naturally distributed in the northeastern and western Himalayas at elevations reaching up to 3300 m above sea level. In Bangladesh, the Ministry of Agriculture's National Seed Board has identified Perilla as SAU Perilla-1 (Golden Perilla BD), signifying its potential as a valuable edible oil crop (MoA, 2020; Mojumdar *et al.*, 2021). Cultivation has since expanded to the USA, Russia, and Europe due to its rising economic significance

and diverse germplasm attributes (Kim *et al.*, 2019; Ding *et al.*, 2012). Beyond its traditional use as a leafy vegetable (Ghimire *et al.*, 2017), Perilla is valued in oriental medicine for its antibacterial, antimicrobial, and anti-inflammatory properties (Igarashi & Miyazaki, 2013). Its seed oil is rich in polyunsaturated fatty acids (PUFAs), particularly omega-3 ( $\alpha$ -linolenic acid) and omega-6 (linoleic acid), which support human health by promoting cardiovascular function, metabolic regulation, and inflammation control (Asif, 2011; Joshi *et al.*, 2015). The oil yield (~40%) meets CODEX processing standards, and its high  $\alpha$ -linolenic acid content (40–68%) positions Perilla among the richest plant-based omega-3 sources, without detectable erucic acid (Chung

et al., 2013). Bangladesh, with over 165 million inhabitants, imports approximately 90 % of its edible oil needs, spending USD 1,574 million on edible oil and USD 354 million on oilseed imports during 2014–2015 (Haruna et al., 2010). Domestic oilseed crops like mustard and sesame contribute only 5–6% of consumption, constrained by limited area and yield declines (Chauhan et al., 2021; Jahan et al., 2019). Perilla's 1.3–1.5 t/ha yield potential and short kharif-2 growing season make it a promising diversification to reduce import dependency and enhance food security (Mojumdar et al., 2021).

Among essential plant nutrients, sulfur (S) and phosphorus (P) play critical roles in oilseed production. In Bangladesh, sulfur deficiency has become widespread due to intensive cropping, use of high-yielding varieties, and unbalanced fertilizer application (Islam et al., 2011). Similarly, phosphorus is vital for energy transfer, root development, flowering, and seed formation. Deficiency of P is common in acidic and low-fertility soils, which are prevalent in many regions of Bangladesh (Hussain et al., 2012). Despite its global recognition as a promising oilseed crop, *Perilla frutescens* has not yet been systematically evaluated in Bangladesh. Farmers and researchers lack scientific guidelines on its nutrient requirements, particularly the role of sulfur and phosphorus fertilization in optimizing growth and yield. The absence of agronomic recommendations poses a challenge to the successful introduction and expansion of perilla cultivation. Without this knowledge, farmers may adopt inappropriate fertilization practices, resulting in low productivity, poor seed quality, and limited economic viability. This study holds great significance for Bangladesh, where achieving crop diversification and reducing edible oil import dependency are national agricultural goals (MoA, 2020). By identifying suitable nutrient management practices for perilla, particularly with respect to sulfur and phosphorus, this research can provide a scientific basis for its domestication in Bangladesh. Moreover, optimizing nutrient use will enhance perilla's oil yield and quality, creating opportunities for commercialization in both domestic and export markets.

Although perilla cultivation and its medicinal properties have been studied in East Asia, very limited research has been conducted on its agronomy under South Asian agro-ecological conditions (Kang et al., 2013; Borhan et al., 2021). In Bangladesh, systematic trials to evaluate the impact of sulfur and phosphorus fertilization on perilla growth, yield, and oil content are very limited. The novelty of this research lies in generating first-hand scientific evidence on nutrient requirements of *P. frutescens* under controlled net house conditions in Bangladesh. By addressing this gap, the study will not only provide baseline agronomic recommendations but also open new avenues for research on crop diversification and sustainable oilseed production. Keeping the above points in mind, the present study aims to assess the effects of different levels of sulfur and phosphorus on the growth and yield of *Perilla frutescens*, and to determine the optimum sulfur and phosphorus levels required for maximizing seed yield and plant performance.

## MATERIALS AND METHODS

### Experimental site and duration

The experiment was carried out in the Net House of the Agronomy Department at Bangladesh Agricultural University (BAU), Mymensingh. This location is positioned 18 meters above sea level, at coordinates 24°75' N latitude and 90°50' E longitude. The field is part of the Old Brahmaputra Floodplain Agroecological Zone (AEZ-9), characterized by non-calcareous dark grey floodplain soils (UNDP & FAO, 1988). The experiment was carried out during the Kharif-2 and part of the Rabi season, spanning July 31 to November 21, 2024. The study site experiences a sub-tropical climate, characterized by high temperatures and heavy rainfall during Kharif (July–September) and lower temperatures with minimal rainfall during Rabi (October–November). Climatological data, such as temperature (°C), rainfall (mm), relative humidity (%), and sunshine duration (hrs), presented in Table 1.

### Experimental design and treatments

The experiment was structured as a Completely Randomized Design (CRD) with three replications, comprising 48 pots arranged in an open net house. The study examined the effects of sulfur (gypsum) and phosphorus (Triple Superphosphate) on perilla growth and yield. The treatment details have been presented in Table 1.

### Test crop

The study used Golden Perilla (*Perilla frutescens*), locally known as SAU Perilla-1, a high-yielding oilseed crop introduced from South Korea, demonstrating strong adaptability to Bangladesh's agro-climatic conditions.

### Pot preparation and fertilizer application

A total of 48 plastic pots, each with dimensions of 50 cm in diameter and 40 cm in depth, were utilized, with each pot containing 20 kg of treated soil. Urea, TSP, and MoP fertilizers were thoroughly mixed with the soil, with urea applied in two splits—half during soil preparation and half after transplanting.

### Transplanting and crop management

Healthy 25-day-old seedlings were transplanted on July 31, 2024, minimizing root damage. Intercultural operations included thinning, weeding, staking, irrigation, and manual harvesting from November 1st to 3rd week, 2024.

**Table 1.** Treatment details used for the study.

Sulfur doses (Applied as Gypsum)	Application rate (g/pot)
S <sub>0</sub> (0 kg ha <sup>-1</sup> )	0 g/pot
S <sub>1</sub> (50 kg ha <sup>-1</sup> )	0.85 g/pot
S <sub>2</sub> (100 kg ha <sup>-1</sup> )	1.70 g/pot
S <sub>3</sub> (150 kg ha <sup>-1</sup> )	2.60 g/pot
Phosphorus doses (Applied as TSP)	
P <sub>0</sub> (0 kg ha <sup>-1</sup> )	0 g/pot
P <sub>1</sub> (100 kg ha <sup>-1</sup> )	1.7 g/pot
P <sub>2</sub> (150 kg ha <sup>-1</sup> )	2.5 g/pot
P <sub>3</sub> (200 kg ha <sup>-1</sup> )	3.4 g/pot

### Measurement of growth and yield parameters

At harvest, key growth and yield attributes were measured using standard procedures. The parameters were plant height (cm), total number of branches per plant, number of flower-bearing branches/plant, number of flowering clusters/plant, number of seeds per raceme, 1000-seed weight (g), Seed yield (t ha<sup>-1</sup>), Stover yield (t ha<sup>-1</sup>), Biological yield (t ha<sup>-1</sup>) and Harvest Index (%) which was calculated as:

$$HI (\%) = \left( \frac{\text{Economical Yield (Seed Yield)}}{\text{Biological Yield}} \right) \times 100$$

### Statistical analysis

One-way ANOVA was used to test the effects of sulfur alone and phosphorus alone; two-way ANOVA was used to test their interaction using R software (v.4.2.1), and mean differences were assessed through Duncan's Multiple Range Test (DMRT) at a significance level of  $\alpha = 0.05$  (Gomez & Gomez, 1984). In all tests,  $p$  denotes the probability value from ANOVA (e.g.,  $p < 0.05$  indicates statistical significance); ( $p > 0.05$  indicates no statistical significance).

## RESULTS AND DISCUSSION

Sulfur and phosphorus application demonstrated a notable impact on the growth and productivity parameters of *P. frutescens*. Significant differences were observed among treatments for key parameters such as plant height, number of branches per plant, number of racemes, seeds per raceme, and harvest index.

### Effect of sulfur on growth and yield parameters

The sulfur treatments had a big impact on how tall the plants grew, how many branches they had, how many racemes they produced, how many seeds were in each raceme, and the harvest index (one-way ANOVA;  $p < 0.05$ ) (Table 2, Figure 1). The tallest plants were  $S_2$  (100 kg gypsum ha<sup>-1</sup>) = 66.08 cm, followed by  $S_1$  (50 kg) = 62.83 cm. ( $p < 0.05$ ). The lowest plant height (47.08 cm) was recorded in  $S_0$  (control) ( $p < 0.05$ ). Raceme production peaked at 33.50 per plant in  $S_2$ , significantly higher than  $S_0$  (20.42 per plant) ( $p < 0.05$ ). The highest 1000-seed weight

was observed in  $S_2$  (6.20 g), significantly higher than  $S_0$  (4.35 g). Harvest index improved with sulfur fertilization, with  $S_2$  (26.39%) outperforming  $S_0$  (18.42%), indicating enhanced yield efficiency ( $p < 0.05$ ). The application of sulfur (as gypsum) significantly influenced the growth and productivity of *P. frutescens*, aligning with findings in other oilseed and tuber crops. Sulfur plays a vital role in amino acid and chlorophyll synthesis, which supports vegetative vigor and yield formation (Asif, 2011). Its physiological role is well-documented in oilseed rape, where deficiency restricted sulfur translocation within leaves, impairing growth and photosynthesis (Blake-Kalff et al., 2000). In winter wheat, excessive sulfur reduced biomass quality, suggesting the importance of precise dosing (Jarvan et al., 2008). In this study, treatments with 100 kg gypsum ha<sup>-1</sup> ( $S_2$ ) demonstrated strong positive effects on raceme count, 1000-seed weight, and harvest index. Similar improvements in seed yield and oil quality with sulfur fertilization have been reported in mustard, sesame, and camelina (Hassani et al., 2021). Sulfur application also supported branching and seed development, which was observed in soybean trials under varying sulfur rates (Abido, 2018). In Perilla, these effects align with enhanced growth traits and reproductive efficiency.

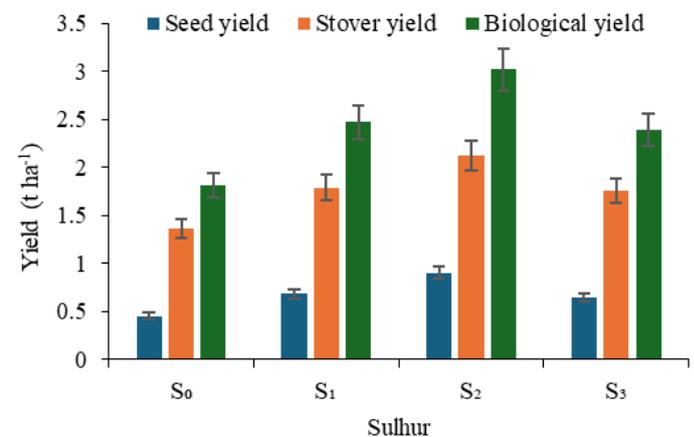


Figure 1. Effect of sulfur application on the seed yield, stover yield, and biological yield of the perilla oil crop.

Table 2. Effect of sulfur on the yield contributing characters and harvest index of perilla oil crop.

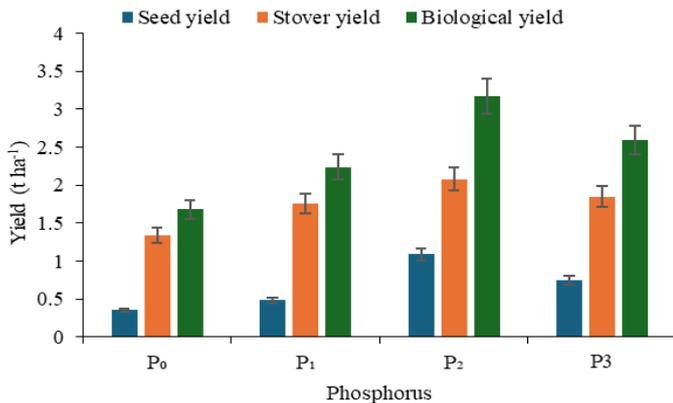
Sulfur	Plant height (cm)	No. of total branch plant <sup>-1</sup>	No. of effective branch plant <sup>-1</sup>	No. of racemes plant <sup>-1</sup>	No. of seeds raceme <sup>-1</sup>	1000-seed weight (g)	Harvest index (%)
S <sub>0</sub>	47.08c	3.50c	3.42c	20.42c	44.13b	4.35b	18.42c
S <sub>1</sub>	62.83a	4.08bc	4.08bc	22.25b	47.59b	4.65b	24.22b
S <sub>2</sub>	66.08a	6.67a	6.67a	33.50a	63.92a	6.20a	26.39a
S <sub>3</sub>	57.92b	5.42ab	5.42ab	31.33a	55.25ab	5.15ab	25.48ab
Level of significance	*	**	**	*	*	*	*
CV (%)	7.37	6.87	6.61	6.33	7.67	4.79	7.88

Values within a column that share the same letters indicate no significant differences. \*\* implies significance at the 1% ( $p \leq 0.01$ ) probability level, while \* denotes significance at the 5% ( $p \leq 0.05$ ) level  $S_0 = 0$  kg Gypsum ha<sup>-1</sup>,  $S_1 = 50$  Gypsum kg ha<sup>-1</sup>,  $S_2 = 100$  Gypsum kg ha<sup>-1</sup> and  $S_3 = 150$  Gypsum kg ha<sup>-1</sup>.

**Table 3.** Influence of phosphorus on yield-related traits and harvest index in the perilla oil crop.

Phosphorus	Plant height (cm)	No. of total branch plant <sup>-1</sup>	No. of effective branch plant <sup>-1</sup>	No. of racemes plant <sup>-1</sup>	No. of seeds raceme <sup>-1</sup>	1000-seed weight (g)	Harvest index (%)
P <sub>0</sub>	46.67b	3.50b	3.42b	18.00b	40.08c	4.54	18.25b
P <sub>1</sub>	52.67ab	4.33b	4.33b	22.08b	47.88b	4.95	19.22b
P <sub>2</sub>	72.25a	6.67a	6.67a	37.33a	63.92a	5.68	31.58a
P <sub>3</sub>	62.33ab	5.17ab	5.17ab	30.08ab	58.92a	5.19	25.48ab
Level of significance	*	*	*	*	*	NS	*
CV (%)	7.37	6.87	6.61	6.33	7.67	4.79	7.88

Means along with identical letters or without any symbols indicate no significant differences. \* = Signifies significance at the 5% probability level while NS = Denotes no significance; P<sub>0</sub> = 0 kg TSP ha<sup>-1</sup>, P<sub>1</sub> = 100 kg TSP ha<sup>-1</sup>, P<sub>2</sub> = 150 kg TSP ha<sup>-1</sup> and P<sub>3</sub> = 200 kg TSP ha<sup>-1</sup>.

**Figure 2.** Effect of phosphorus on the seed, stover and biological yield of perilla oil crop.

#### Effect of phosphorus on growth and yield parameters

Phosphorus application significantly impacted plant height, raceme count, seed numbers per raceme, and harvest index ( $p < 0.05$ ), but had no significant effect on 1000-seed weight (one-way ANOVA;  $p > 0.05$ ) (Table 3, Figure 2). P<sub>2</sub> (150 kg TSP ha<sup>-1</sup>) produced the tallest plants (72.25 cm), while P<sub>0</sub> (control) resulted in the shortest plants (46.67 cm) ( $p < 0.05$ ). Raceme count peaked at 37.33 per plant in P<sub>2</sub>, whereas the lowest count (18.00 per plant) was recorded in P<sub>0</sub> ( $p < 0.05$ ). Seed numbers per raceme were significantly higher in P<sub>2</sub> (63.92 seeds) than P<sub>0</sub> (40.08 seeds) ( $p < 0.05$ ). 1000-seed weight was not significantly different across treatments, suggesting phosphorus mainly influenced biomass accumulation rather than seed weight ( $p > 0.05$ ). The highest harvest index, P<sub>2</sub> (31.58%), was achieved than P<sub>0</sub> (18.25%) ( $p < 0.05$ ). Phosphorus application markedly improved vegetative traits such as plant height and branch number. Phosphorus aids root development, energy transfer, and flowering, as shown in soybean, chia, and sesame studies (Silva et al., 2020; Jahan et al., 2019). In sesame, phosphorus increased economic yield and productivity (Haruna et al., 2010), while in mustard and legumes, TSP applications significantly boosted seed weight and biomass (Chauhan et al., 2021). These results support the positive impact of P<sub>2</sub> (150 kg TSP ha<sup>-1</sup>) on Perilla productivity observed in the current experiment.

#### Interaction effects of sulfur and phosphorus

The combined application of sulfur and phosphorus exhibited a synergistic impact on perilla's growth and yield performance, significantly influencing plant height, branching, raceme count, seed numbers per raceme, and yield parameters (two-way ANO-

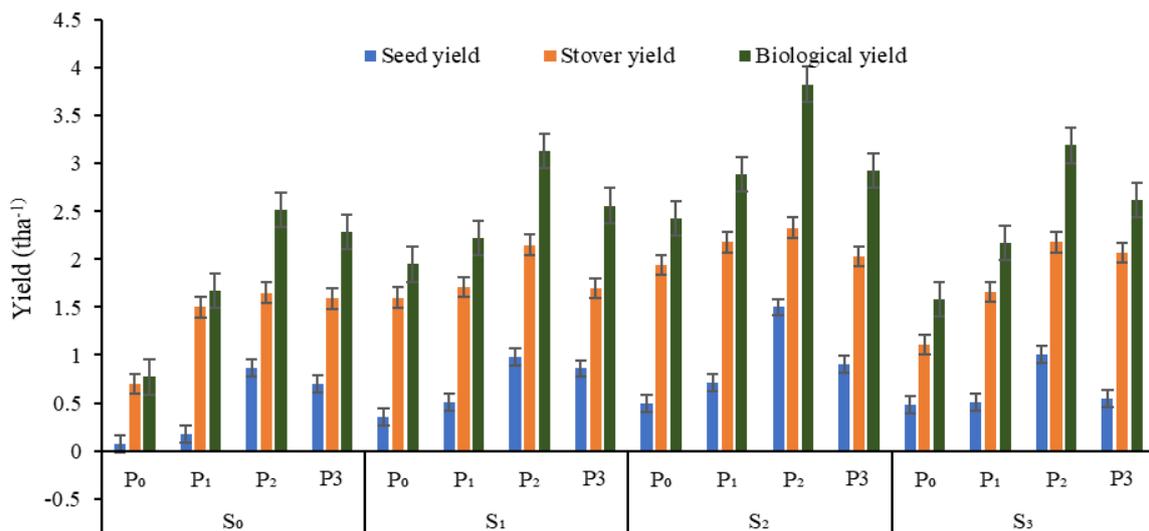
VA;  $p < 0.05$ ) (Table 4, Figure 3). The tallest plants (78.67 cm) were observed in S<sub>1</sub>P<sub>2</sub> (50 kg gypsum + 150 kg TSP ha<sup>-1</sup>), confirming phosphorus's role in height development when paired with sulfur. Branch count was highest in S<sub>2</sub>P<sub>2</sub> (100 kg gypsum + 150 kg TSP ha<sup>-1</sup>) (8 total, 8 effective branches per plant), suggesting that sulfur and phosphorus together enhance vegetative growth. Maximum raceme production (47.33 per plant) occurred in S<sub>2</sub>P<sub>2</sub> (100 kg gypsum + 150 kg TSP ha<sup>-1</sup>), indicating a strong interaction effect between sulfur and phosphorus on reproductive development. The highest seed yield (1.50 t ha<sup>-1</sup>), Stover yield (2.33 t ha<sup>-1</sup>), and biological yield (3.83 t ha<sup>-1</sup>) were observed under S<sub>2</sub>P<sub>2</sub> (100 kg gypsum + 150 kg TSP ha<sup>-1</sup>), confirming that balanced sulfur-phosphorus fertilization enhances perilla productivity. Harvest index reached its highest value (38.85%) in S<sub>2</sub>P<sub>2</sub> (100 kg gypsum + 150 kg TSP ha<sup>-1</sup>), demonstrating improved seed production relative to total biomass. These results confirm that S<sub>2</sub>P<sub>2</sub> (100 kg gypsum + 150 kg TSP ha<sup>-1</sup>) optimizes growth and yield performance in perilla, as illustrated in Figure 3. The combined S<sub>2</sub>P<sub>2</sub> treatment (100 kg gypsum + 150 kg TSP ha<sup>-1</sup>) achieved the highest seed yield (1.50 t ha<sup>-1</sup>), biological yield (3.83 t ha<sup>-1</sup>), and harvest index (38.85%), reflecting a synergistic effect between sulfur and phosphorus. Similar combined responses have been recorded in soybean and potato trials using S-P co-fertilization, leading to improved root biomass, nutrient uptake, and tuber development (Valle et al., 2022; Sharma et al., 2025). In mustard, integrated S-P management enhanced growth and seed production, further validating the importance of dual nutrient applications (Chauhan et al., 2021; Sharma, 2024). Interestingly, the tallest plants (78.67 cm) were recorded under S<sub>1</sub>P<sub>2</sub> (50 kg gypsum + 150 kg TSP ha<sup>-1</sup>), indicating a possible optimal hormonal or physiological balance for stem elongation.

In contrast, the S<sub>0</sub>P<sub>0</sub> control produced the lowest values across all traits, reaffirming the necessity of external sulfur and phosphorus input for achieving desirable growth and yield. Deficiency in sulfur and phosphorus limits protein synthesis, root formation, and flowering, as evidenced in multiple crops including canola, linseed, and tuber species (Sharma et al., 2025). The findings also reflect seed quality implications. Perilla oil is known for its high  $\alpha$ -linolenic acid content (Asif, 2011), and both genotype and nutrient environment influence oil quality (Mojumdar et al., 2021). Oil enhancement and oxidative stability in omega-3-rich seeds like Perilla were also reported under targeted fertilization in designer lipid systems (Dhiman et al., 2025). Supporting this,

**Table 4.** Interaction effect of sulfur and phosphorus on yield attributes and harvest index in the perilla oil crop.

Sulfur: Phosphorus	Plant height (cm)	No. of total branch plant <sup>-1</sup>	No. of effective branch plant <sup>-1</sup>	No. of racemes plant <sup>-1</sup>	No. of seeds raceme <sup>-1</sup>	1000-seed weight (g)	Harvest index (%)
S <sub>0</sub> P <sub>0</sub>	27.33c	1.00d	0.67d	7.33d	27.00d	4.00b	8.13c
S <sub>0</sub> P <sub>1</sub>	36.00bc	2.33cd	2.33cd	15.00cd	33.59c	4.09b	10.02bc
S <sub>0</sub> P <sub>2</sub>	70.00ab	6.67ab	6.67ab	30.99a-d	58.33b	4.79ab	27.70a-c
S <sub>0</sub> P <sub>3</sub>	55.00a-c	4.00b-d	4.00b-d	29.33a-d	57.67b	4.53b	27.84a-c
S <sub>1</sub> P <sub>0</sub>	51.33a-c	3.00b-d	3.00b-d	17.33b-d	32.67c	4.01b	18.60a-c
S <sub>1</sub> P <sub>1</sub>	5k8.33a-c	3.33b-d	3.33b-d	20.67a-d	40.33c	4.71ab	21.19a-c
S <sub>1</sub> P <sub>2</sub>	78.67a	5.67a-c	5.67a-c	28.00a-d	62.00ab	5.17ab	29.34ab
S <sub>1</sub> P <sub>3</sub>	65.00a-c	4.33a-d	4.33a-d	23.00a-d	55.00b	4.73ab	27.74a-c
S <sub>2</sub> P <sub>0</sub>	61.67a-c	5.67a-c	5.67a-c	25.00a-d	58.67b	5.36ab	18.12a-c
S <sub>2</sub> P <sub>1</sub>	65.67a-c	6.33ab	6.33ab	29.00a-d	62.67ab	6.03ab	21.97a-c
S <sub>2</sub> P <sub>2</sub>	73.33ab	8.00a	8.00a	47.33a	68.00a	7.13a	38.85a
S <sub>2</sub> P <sub>3</sub>	63.67a-c	6.67ab	6.67ab	32.67a-d	66.33a	6.27ab	26.63a-c
S <sub>3</sub> P <sub>0</sub>	46.33a-c	4.33a-d	4.33a-d	22.33a-d	42.00c	4.78ab	28.14a-c
S <sub>3</sub> P <sub>1</sub>	52.67a-c	5.33a-c	5.33a-c	23.67a-d	55.00b	4.98ab	23.68a-c
S <sub>3</sub> P <sub>2</sub>	67.00a-c	6.33ab	6.33ab	44.00ab	67.33a	5.62ab	30.41ab
S <sub>3</sub> P <sub>3</sub>	65.67abc	5.67a-c	5.67a-c	35.33a-c	56.67b	5.24ab	19.70a-c
Level of significance	*	*	*	*	*	*	*
CV (%)	7.37	6.87	6.61	6.33	7.67	4.79	7.88

Means within the same column that are marked with the same letters do not significantly distinct from each other. \* = Significant at 5% level of probability.

**Figure 3.** Interaction effect of sulfur and phosphorus on the yield of perilla oil crop.

Chung et al. (2013) demonstrated Perilla oil's potential in improving lipid profiles and n-3 fatty acid concentrations, reinforcing the significance of nutrient strategies for nutritional enhancement. Additionally, differences among Perilla germplasms across geographies emphasize the influence of agro-climatic factors on fatty acid composition and seed performance (Ding et al., 2012). Volatile compound variability tied to season and accession also reflects genotype-environment interactions (Ghimire et al., 2017), which may be moderated further by customized nutrient inputs. Statistical validation followed the procedures outlined by Gomez & Gomez (1984), supporting the reliability of these treatment effects under controlled net house conditions. Overall, the integration of 100 kg gypsum and 150 kg TSP ha<sup>-1</sup> emerges as a practical and productive strategy for maximizing seed yield, harvest index, and plant performance in Perilla, with comparable benefits to those observed in other high-value oil and tuber crops.

## Conclusion

Sulfur and phosphorus fertilization significantly influenced the growth and yield performance of *P. frutescens* under field conditions in Bangladesh. The combined application of 50 kg gypsum with 150 kg of TSP ha<sup>-1</sup> resulted in the tallest plants (78.67 cm), while the application of 100 kg gypsum with 150 kg of TSP ha<sup>-1</sup> yielded the highest seed yield (1.50 t ha<sup>-1</sup>), Stover yield (2.33 t ha<sup>-1</sup>), biological yield (3.83 t ha<sup>-1</sup>), and harvest index (38.85%). These findings affirm the synergistic interaction between sulfur and phosphorus in promoting vegetative growth, reproductive development, and resource-use efficiency in *P. frutescens*. Based on these results, a balanced fertilization strategy with 100 kg gypsum and 150 kg TSP ha<sup>-1</sup> is recommended to maximize productivity in Bangladesh's agroecosystems.

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## DECLARATIONS

**Authors' contribution statement:** Conceptualization, methodology: M.A.Y., M.R.R., M.A.S. and S.R.; Software, validation: M.A.Y., S.R. and M.T.I.; Writing-original draft preparation: M.A.Y. and S.R.; Writing-review and editing: M.R.R., S.R., M.A.Y. and M.T.I.; Supervision: M.R.R. and M.A.S. All authors have reviewed and approved the final version of the manuscript for publication.

**Conflicts of interest:** The authors affirm that there are no conflicts of interest associated with this research.

**Ethics approval:** Since this study did not involve human or animal subjects, ethical clearance was not required.

**Consent for publication:** All co-authors have reviewed and consented to the publication of this manuscript in AAES.

**Data availability:** The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

**Supplementary information:** The supplementary data, such as raw data, additional figures, detailed methodologies of this study can be obtained from the corresponding author upon reasonable request.

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