International Journal of Plant & Soil Science

Volume 38, Issue 6, Page 31-36, 2026; Article no.IJPSS.156836
ISSN: 2320-7035

Synergistic Effects on Silicon and Selenium on Growth, Yield and Protein Content in Blackgram (*Vigna mungo* L.) Grown in Coastal Saline Soil

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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/2026/v38i66099

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://pr.sdiarticle5.com/review-history/156836

Original Research Article

Received: 15/02/2026
Published: 27/05/2026

Abstract

Salinity stress severely limits pulse productivity in coastal agro-ecosystems by inducing ionic imbalance and oxidative damage. Although silicon and selenium are known to enhance plant stress tolerance individually, information on their combined application under coastal saline soil conditions is limited. A pot experiment was conducted during January to April 2024 at the Department of Soil Science and Agricultural Chemistry, Annamalai University, Tamil Nadu, India, to evaluate the interactive effects of silicon and selenium on growth, yield and protein content of blackgram (*Vigna mungo L.*). Treatments consisted of graded levels of silicon and selenium applied individually and in combination along with recommended dose of fertilizers. The combined application of selenium at the rate of 2 ppm and silicon at the rate of 50 kg ha^{-1} significantly

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Cite as: *Sriram, K., Senthilvalavan, P., & Manivannan, R. (2026). Synergistic Effects on Silicon and Selenium on Growth, Yield and Protein Content in Blackgram (Vigna mungo L.) Grown in Coastal Saline Soil. International Journal of Plant & Soil Science, 38(6), 31–36. https://doi.org/10.9734/ijpss/2026/v38i66099*

improved plant height, dry matter production, nodulation, yield attributes and grain yield (1224 kg ha^{-1}) compared to control. Protein content and protein yield were also maximized under the same treatment. The improved performance may be attributed to enhanced nutrient uptake, improved physiological efficiency and alleviation of salinity-induced stress. The study highlights the synergistic role of silicon and selenium in improving productivity and grain quality of blackgram under coastal saline soil conditions.

Keywords: Vigna mungo; salinity stress; silicon; selenium; nutrient interaction; coastal saline soil.

1. Introduction

Pulses hold significant value in Indian agriculture due to their high protein content, as well as their abundance in vitamins, minerals, and specific fibers. They are famously referred to as the "Poor man's meat" and "rich man's vegetable" (Singh et al., 2015). Blackgram (*Vigna mungo* L.) is a pivotal pulse crop in India and South Asia. It holds a key place in Indian agriculture, boasting a high protein content of about 26%, nearly three times that of cereals. Silicon (Si) enhances plant resistance to various stresses like drought, salinity and pests by strengthening cell walls, improving nutrient uptake, and boosting overall plant health and yield (Malik et al., 2021). Selenium [Se], a vital micronutrient, promotes plant growth and stress tolerance, improves antioxidant defenses, and mitigates the negative effects of soil pH on plant growth. Absorbed from the soil, selenium can biofortify crops, enhancing their nutritional value for human and animal consumption (Hassan et al., 2020).

Salinity stress, due to high soil salt concentrations, negatively impacts crop growth and productivity, leading to osmotic stress, ion toxicity, and oxidative stress, which result in reduced water uptake, nutrient imbalances, and impaired photosynthesis. Coastal salinity is a major factor leading to poor crop yields over approximately 3.1 million hectares (Arulmathi and Porkodi, 2020). Coastal saline soils present particular challenges, including a light texture, poor exchange properties, low nutrient and water retention capacity, low organic carbon levels, and deficiencies in both macro and micronutrients (Sekaran et al., 2020). In coastal regions, salinity stress is becoming increasingly severe due to seawater intrusion, poor drainage and climate change, which significantly affect pulse crop productivity. Therefore, identifying suitable nutrient management strategies that can alleviate salinity stress while enhancing yield and quality is of great importance for sustainable agriculture.

Several studies have reported the beneficial role of silicon and selenium in improving plant growth and stress tolerance under adverse environmental conditions. Silicon enhances structural stability and reduces ion toxicity, while selenium improves antioxidant defense and physiological efficiency. Their combined application has shown promising results in improving crop performance under salinity stress in cereals and horticultural crops. However, limited information is available on their synergistic effect in pulse crops, particularly blackgram under coastal saline soil conditions. Recent studies indicate that silicon (Si) and selenium (Se) enhance plant tolerance to salinity stress by improving growth and overall performance. Their combined application has shown synergistic effects in improving plant productivity under stress conditions. However, most studies are limited to cereals and horticultural crops, with very limited information available on pulse crops, particularly blackgram under coastal saline soils. Although the individual effects of Si and Se are well documented, their combined influence on growth, yield attributes, and grain protein content in blackgram under saline conditions remains insufficiently explored (Xu et al., 2020). Therefore, the present study was undertaken to evaluate the synergistic effect of silicon and selenium on growth, yield and grain protein content of blackgram under coastal saline soil conditions.

2. Materials and Methods

A pot culture experiment was conducted at the pot-culture yard, Department of Soil Science and Agricultural Chemistry, Faculty of Agriculture, Annamalai University, Tamil Nadu, India, during January to April 2024. The experiment was designed to maintain uniform salinity stress conditions and ensure precise nutrient application. The experimental soil was sandy loam in texture, collected from a coastal saline field of Pichavaram village. The soil was low in available nitrogen and phosphorus and medium in available potassium. The mechanical composition comprised 65.06% sand, 23.90% silt and 10.28% clay. The bulk density and particle density were 1.53 and 2.62 Mg m^{-3}, respectively, with a pore space of 41.6%. The soil belongs to Typic ustifluvent. The soil reaction and electrical conductivity confirmed its saline nature. The experiment consisted of ten treatments laid out in a completely randomized design (CRD) with three replications. The recommended dose of fertilizers

(RDF) (25:50:25 kg $N:P_2O_5:K_2O$ ha^{-1}) was applied as per crop recommendation. Selenium was applied at concentrations of 1, 2 and 3 ppm, while silicon was applied at rates equivalent to 25, 50 and 75 kg ha^{-1}. The experiment was conducted in plastic pots of 10 kg capacity filled with 8 kg of air-dried soil. The pots were maintained under open conditions in the pot culture yard. Blackgram seeds were sown at the rate of 3 seeds per pot and later thinned to 2 plants per pot to maintain uniform plant population. Irrigation was carried out using non-saline water at regular intervals to maintain optimum moisture conditions throughout the crop growth period. Silicon was applied through diatomaceous earth, a natural source of amorphous silica, which provides a slow and sustained release of plant-available silicon. Sodium selenate (Na_2SeO_4) was used as the selenium source due to its higher solubility and greater bioavailability for plant uptake.

Growth parameters including plant height, dry matter production, leaf area index, and number of branches were recorded at different growth stages. Plant height was measured from the base to the tip of the main shoot. Leaf Area Index (LAI) was calculated as leaf area per unit ground area (dimensionless). Yield attributes such as number of pods per plant, pod length, number of seeds per pod, 100-seed weight, grain yield, and haulm yield were recorded to assess crop productivity. Seed protein content was calculated by multiplying nitrogen percentage in grain with the conversion factor 6.25 (Piper, 1966). Soil pH and electrical conductivity (EC) were analyzed to confirm the saline nature of the soil (Jackson, 1973). The experiment was laid out in a Completely Randomized Design (CRD) with three replications and the data were statistically analyzed using analysis of variance (ANOVA).

3. Results and Discussion

3.1 Growth Parameters

The application of silicon and selenium significantly improved the growth parameters of blackgram under coastal saline soil conditions (Table 1). In general, the combined application of silicon and selenium produced a greater response than their individual application, clearly indicating a synergistic effect.

Among the treatments, T9 (RDF + selenium @ 2 ppm + silicon @ 50 kg ha^{-1}) recorded the highest plant height (51.8 cm), number of branches $plant^{-1}$ (11.25), number of leaves $plant^{-1}$ (21.6), leaf area index (2.74), chlorophyll content (46.75 SPAD), and number of nodules $plant^{-1}$ (29.08). This treatment was closely followed by T8 (RDF + selenium @ 1 ppm + silicon @ 25 kg ha^{-1}), which also showed marked improvement over the control and individual nutrient applications. The control treatment (T1) recorded the lowest values for all growth parameters.

The enhanced vegetative growth under combined application of silicon and selenium may be attributed to better regulation of ionic balance, improved nutrient uptake, stronger photosynthetic activity and protection against salinity-induced oxidative stress (Taha et al., 2021). Silicon likely reduced sodium toxicity and improved tissue structural stability, whereas selenium may have enhanced antioxidant defence and chlorophyll preservation. These combined effects would have favoured higher leaf development, greater nodulation, and increased biomass accumulation. Similar findings have been reported (Berahim et al., 2021, Hossain et al., 2021). The observed improvement in growth parameters under combined application of silicon and selenium clearly indicates their complementary role in mitigating salinity stress. Silicon plays a crucial role in maintaining ionic homeostasis by reducing sodium uptake and enhancing potassium absorption, thereby improving overall plant metabolism. Selenium, on the other hand, contributes to enhanced antioxidant activity, protecting plants from oxidative damage caused by salinity stress. The combined application therefore results in improved cell division, leaf expansion and nodulation, which ultimately contribute to better vegetative growth.

3.2 Dry Matter Production and Yield Attributes

Dry matter production, yield attributes, and yield of blackgram were significantly influenced by the different treatments (Table 2). The highest dry matter production at harvest was recorded in T9 (35.72 g pot^{-1}), followed by T8 (33.88 g pot^{-1}), whereas the lowest was observed in the control (23.19 g pot^{-1}). Yield-contributing traits followed a similar trend, with T9 recording the highest pod length (8.24 cm), number of pods $plant^{-1}$ (19.55) and number of seeds pod^{-1} (7.89). Although 100-seed weight did not differ significantly among treatments, a slight numerical increase was observed under combined application, with T9 recording the highest value (3.58 g).

Table 1. Effect of silicon and selenium on growth parameters of blackgram at harvest

Treatments	Plant height (cm)	Number of branches plant⁻¹	Number of leaves plant⁻¹	Leaf area index (cm²)	Chlorophyll content (SPAD)	Number of nodules plant⁻¹
T1 – RDF (control)	23.4	6.15	11.8	1.01	22.28	16.51
T2 – RDF + Se @ 1 ppm	34.1	7.92	15.3	1.64	30.82	21.25
T3 – RDF + Se @ 2 ppm	30.8	7.35	14.2	1.43	27.96	19.11
T4 – RDF + Se @ 3 ppm	27.5	6.79	13.1	1.22	25.13	17.85
T5 –RDF + Si @ 25 kg ha⁻¹	37.3	8.49	16.5	1.85	33.65	23.37
T6 – RDF + Si @ 50 kg ha⁻¹	40.5	9.05	17.6	2.06	36.45	25.48
T7 – RDF + Si @ 75 kg ha⁻¹	45.4	10.09	19.4	2.31	41.15	26.65
T8 – RDF + Se @ 1 ppm + Si @ 25 kg ha⁻¹	48.6	10.66	20.5	2.53	43.95	27.88
T9 – RDF + Se @ 2 ppm + Si @ 50 kg ha⁻¹	51.8	11.25	21.6	2.74	46.75	29.08
T10 – RDF + Se @ 3 ppm + Si @ 75 kg ha⁻¹	42.2	9.51	18.2	2.10	38.26	25.50
S. Ed	1.39	0.26	0.52	0.09	1.235	0.45
CD (p = 0.05)	3.0	0.55	1.14	0.21	2.71	0.95

Table 2. Effect of silicon and selenium on dry matter production, yield attributes and yield of blackgram

Treatments	Dry matter production (g pot⁻¹)	Pod length (cm)	Pods plant⁻¹	Seeds pod⁻¹	100-seed weight (g)	Grain yield (kg ha⁻¹)	Haulm yield (kg ha⁻¹)
T1	23.19	4.85	8.04	4.01	3.39	763	1290
T2	27.23	6.02	12.13	5.31	3.46	952	1656
T3	26.88	5.65	10.91	4.89	3.45	935	1591
T4	25.01	5.31	9.55	4.46	3.41	881	1420
T5	28.03	6.41	13.46	5.74	3.48	976	1677
T6	29.91	6.78	14.98	6.18	3.49	1030	1746
T7	31.96	7.41	17.12	6.90	3.53	1078	1806
T8	33.88	7.78	18.23	7.40	3.54	1142	1876
T9	35.72	8.24	19.55	7.89	3.58	1224	1947
T10	30.66	7.05	15.95	6.45	3.53	1052	1788
S. Ed	0.792	0.147	0.504	0.195	0.04	23.49	29.64
CD (p = 0.05)	1.75	0.32	1.10	0.41	NS	53.0	68.0

Grain and haulm yields were also significantly enhanced by silicon and selenium application, with combined treatments outperforming individual applications. T9 recorded the highest grain yield (1224 kg ha⁻¹) and haulm yield (1947 kg ha⁻¹), followed by T8 (1142 and 1876 kg ha⁻¹, respectively), while the control recorded the lowest values (763 and 1290 kg ha⁻¹). Compared with the control, T9 increased grain yield by 60.4% and haulm yield by 50.9%. The superior performance under T9 indicates that the combined application of silicon and selenium improved assimilate production and partitioning, resulting in enhanced vegetative growth and reproductive efficiency under saline conditions. Silicon-alone treatments also performed better than selenium-alone treatments, but the maximum response was observed under combined application, confirming their synergistic effect. These improvements may be attributed to enhanced physiological efficiency, better chlorophyll retention, and increased tolerance to salinity stress, which is in agreement with earlier findings (Hu et al., 2022).

The significant increase in yield and yield attributes under combined nutrient application may also be attributed to improved translocation of photosynthates from source to sink. Under saline conditions, assimilate partitioning is often impaired; however, silicon helps maintain structural integrity of vascular tissues, while selenium improves enzymatic activity associated with carbohydrate metabolism. These combined effects enhance reproductive efficiency and ultimately result in higher grain and haulm yield.

3.3 Protein Content and Protein Yield

Protein content and protein yield were significantly influenced by the application of silicon and selenium (Table 3). The highest protein content (29.84%) and protein yield (365 kg ha^{-1}) were recorded under T9, followed by T8, which recorded 27.97% protein content and 319 kg ha^{-1} protein yield. The lowest values were recorded in the control treatment, with 15.94% protein content and 121 kg ha^{-1} protein yield.

The increase in protein content under combined application may be attributed to improved nitrogen assimilation and enhanced metabolic activity in plants. Selenium is known to promote protein synthesis through its role in nitrogen metabolism and antioxidant protection, whereas silicon improves nutrient absorption and reduces salinity-induced physiological injury (Khan et al., 2023, Al Murad and Muneer, 2022). The combined application of these nutrients therefore created a favourable environment for greater protein accumulation in grain. The increase in protein yield under T9 was further supported by the substantial rise in grain yield. Similar improvements in grain quality with selenium and silicon application have been reported by Nawaz et al. (2015), Lara et al. (2024). The enhancement in protein content also indicates improved nitrogen assimilation and metabolic efficiency in plants treated with silicon and selenium. Selenium is known to influence enzyme systems involved in nitrogen metabolism, while silicon enhances root growth and nutrient absorption. The combined effect leads to improved amino acid synthesis and protein accumulation in seeds, thereby improving grain quality under saline stress conditions.

Table 3. Effect of silicon and selenium on protein content and protein yield of blackgram

Treatments	Protein content (%)	Protein yield (kg ha^{-1})
T1	15.94	121
T2	21.40	203
T3	20.78	194
T4	18.90	166
T5	22.03	215
T6	23.75	244
T7	26.09	281
T8	27.97	319
T9	29.84	365
T10	25.00	263
S. Ed	0.763	8.085
CD (p = 0.05)	1.60	17.0

4. Conclusion

The present study demonstrated that the integrated application of silicon and selenium significantly improved the growth, yield, and protein content of blackgram grown in coastal saline soil. Among the treatments, RDF + selenium @ 2 ppm + silicon @ 50 kg ha^{-1} (T9) proved to be the most effective, recording the highest values for plant growth, nodulation, chlorophyll content, dry matter production, yield attributes, grain yield, haulm yield, protein content and protein yield. The results confirm that silicon and selenium act synergistically in mitigating salinity stress and enhancing both productivity and grain quality of blackgram. Therefore, the integrated use of selenium @ 2 ppm and silicon @ 50 kg ha^{-1} along with the recommended dose of fertilizers may be considered a promising nutrient management strategy for blackgram cultivation in coastal saline soils. However, the present findings are based on pot culture conditions and further validation under field conditions is necessary before large-scale recommendation. Future research should focus on field-level evaluation, long-term soil health impact and economic feasibility of silicon and selenium application in coastal saline regions.

Disclaimer (Artificial Intelligence)

The authors declare that generative AI tools were used only for language editing and formatting purposes. The scientific content, data analysis and interpretation are entirely the original work of the authors.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/156836