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Optimizing Silica and Mycorrhiza Application Rates and Modes for Enhancing Growth and Yield of Okra (*Abelmoschus esculentus* L.)

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Abstract
A pot culture experiment was conducted at the Regional Fruit Research Station, Vengurla during the Rabi season of 2024–25 to evaluate the effect of different methods and levels of mycorrhiza and silica application on the growth, physiology, and yield of okra (*Abelmoschus esculentus* L.) under lateritic soil conditions. The experiment was laid out in a factorial randomized block design with eighteen treatment combinations and three replications. Treatments consisted of recommended dose of fertilizers (RDF) in combination with different application methods of mycorrhiza (seed treatment, drenching, and soil application) and silica (soil application, foliar spray, and seed treatment) at three levels (B1, B2, and B3). Observations were recorded on growth parameters (plant height, number of leaves, shoot and root weight, shoot and root volume) and yield. The study concludes that silica soil application at 15 kg ha^{-1}, in combination with recommended fertilizers, is a promising strategy to improve growth, nutrient-use efficiency, and yield of okra. The complementary roles of silica and mycorrhiza in enhancing structural strength, stress tolerance, and root development suggest their potential as eco-friendly inputs for sustainable okra production in lateritic soils.

Keywords: Arbuscular mycorrhizal fungi, lateritic soils, Okra, silica, sustainable crop production

Introduction
Arbuscular mycorrhizal fungi (AMF) are key soil microorganisms that form symbiotic relationships with plant roots by producing specialized structures such as arbuscules and vesicles. These structures facilitate the bidirectional transfer of nutrients and carbon, enabling plants to acquire essential elements such as phosphorus and nitrogen more efficiently, while providing carbohydrates to the fungus. The external hyphal network of AMF extends beyond the root rhizosphere, substantially increasing the root's absorptive surface area and improving access to otherwise unavailable soil nutrients. In addition to enhancing nutrient uptake, AMF confer tolerance to abiotic stresses such as acidity, salinity, and drought, and they play an important role in improving soil fertility and plant productivity. Silicon (Si), the second most abundant element in the Earth's crust, has recently been recognized as a beneficial nutrient for many crops. Although not considered essential, Si contributes to improved plant growth by strengthening cell walls, enhancing photosynthesis, and increasing tolerance to both biotic and abiotic stresses. Silicon fertilization has been shown to reduce the effects of soil acidity, stabilize organic matter, and improve microbial activity in the rhizosphere. Moreover, silicon application enhances nutrient-use efficiency and crop yield, with particularly strong effects under stress conditions such as drought, salinity, and pest infestation. Okra (*Abelmoschus esculentus* L.), an important vegetable crop widely cultivated in tropical and subtropical regions, holds nutritional, economic, and medicinal significance. Despite its importance, okra production is often limited by poor soil fertility, nutrient deficiencies, and environmental stresses, leading to suboptimal yields. Conventional reliance on chemical fertilizers alone is not sustainable, necessitating the exploration of eco-friendly alternatives such as biofertilizers and silicon supplementation to enhance productivity while maintaining soil health. Given the complementary roles of AMF and silicon in nutrient acquisition, stress tolerance, and soil fertility improvement, their combined application may provide a sustainable strategy for enhancing growth and yield in okra

cultivation. However, limited research exists on the synergistic effects of these two factors in vegetable crops under different soil conditions. The present study was therefore undertaken to evaluate the effect of silica and mycorrhiza on the growth, yield, and physiological performance of okra, with the aim of identifying strategies for improving nutrient-use efficiency and sustainable crop production.

2. Materials and Methods

The pot culture experiment was conducted at the Regional Fruit Research Station in Vengurla during the Rabi season of 2024-25. The research site is situated in the Konkan region of Maharashtra, covering a narrow strip of land measuring 30,728 square kilometers. It is geographically positioned at 17°45'02" North latitude and 73°10'55" East longitude. The area falls within the 19.2 Agro-ecological sub-region, specifically the Central and South Sahyadris, characterized by a transition from hot, moist, and semi-humid to humid ecological conditions. The soil types in this region range from deep sandy loam to clayey red and lateritic soils, which influence the agricultural practices and crop growth in the area.

The study involved a total of eighteen treatment combinations, arranged in a factorial randomized block design with three replications. The experimental factors included two main variables: factor A, which represented the source and method of application, and factor B, which indicated the level of application. Factor A comprised six modes: A1 (Mycorrhiza seed treatment at 100g per 3kg of seed), A2 (Mycorrhiza drenching at 100g per acre), A3 (Mycorrhiza soil application at 100g per acre), A4 (Silica granules soil application at 5kg per hectare), A5 (Silica foliar application at 0.1% orthosilicic acid), and A6 (Silica seed treatment at 1% orthosilicic acid). Factor B included three levels: 1x (the specified dose), 2x (twice the dose), and 3x (three times the dose). The eighteen treatment combinations were as follows: T1 (RDF + Mycorrhiza seed treatment at 100g/3kg seed), T2 (RDF + Mycorrhiza seed treatment at 200g/3kg seed), T3 (RDF + Mycorrhiza seed treatment at 300g/3kg seed), T4 (RDF + Mycorrhiza drenching at 100g/acre), T5 (RDF + Mycorrhiza drenching at 200g/acre), T6 (RDF + Mycorrhiza drenching at 300g/acre), T7 (RDF + Mycorrhiza soil application at 100g/acre), T8 (RDF + Mycorrhiza soil application at 200g/acre), T9 (RDF + Mycorrhiza soil application at 300g/acre), T10 (RDF + Silica soil application at 5kg/ha), T11 (RDF + Silica soil application at 10kg/ha), T12 (RDF + Silica soil application at 15kg/ha), T13 (RDF + Silica foliar application at 0.1%), T14 (RDF + Silica foliar application at 0.2%), T15 (RDF + Silica foliar application at 0.3%), T16 (RDF + Silica seed treatment at 1%), T17 (RDF + Silica seed treatment at 2%), and T18 (RDF + Silica seed treatment at 3%).

The pots were filled with cultivable lateritic soil sourced from the experimental site, with each pot containing an average of 10 kg of soil. The experiment utilized the Mahyco Bhindi No. 10 variety. Two seeds were sown in each pot, and after 15 days, only one healthy seedling was retained while the other was removed. Fertilizer application followed recommended guidelines, with a total dose of 100:50:25 N:P_2O_5:K_2O kg per hectare, divided into three applications at sowing, 30 days after sowing (DAS), and 50 DAS. Phosphorus was applied as a basal dose. Nitrogen, phosphorus, and potassium were supplied through urea, single super phosphate, and muriate of potash, respectively. For mycorrhizal seed treatment, a few drops of water were added to the formulation to create a mixture, which was then used to treat the seeds. Mycorrhizal formulations were applied through drenching by mixing with water and applying 15 days after sowing, and also by mixing with vermicompost for soil application at the same interval. Seeds were pre-treated by immersing in an ortho silicic acid solution for 30 minutes before sowing. Silica granules were incorporated into the soil 15 days after sowing, and foliar application of ortho silicic acid was performed 25 days after sowing at the required concentration. Harvesting involved collecting fresh, young, tender fruits, with weights recorded separately for each pot. A total of 15 harvests were conducted up to 120 days of crop growth. Throughout the experiment, various growth parameters such as plant height, number of leaves per plant, shoot and root weights, as well as shoot and root volumes, were measured at different growth stages to assess plant development.

3. Results and Discussion

3.1. Plant height

The analysis revealed that various methods of applying mycorrhiza and silica (A) significantly affected plant height at harvest. Specifically, treatment A4, which involved soil application of silica granules at 5 kg per hectare, resulted in the greatest average plant height. This was notably higher than most other treatments, with the exception of treatments A2 and A3, which showed comparable results. Additionally, the different levels of application (B) also had a significant impact on plant height. The highest mean height was observed in treatment B3, which involved the highest application level of three times. Although the interaction between the methods of application (A) and levels of application (B) was statistically non-significant, some numerical differences among the treatment combinations were still evident.

The data suggests that higher application levels consistently promote increased plant growth, likely due to the combined effects of silica and mycorrhiza in improving physiological processes and providing structural support throughout the crop's development. Similar results have been reported by Gong *et al*. (2014) [5], who observed greater plant height, leaf area, and dry matter in wheat plants grown in pots with silicon applied prior to sowing. These findings are further supported by studies from Gowda *et al*. (2015) [6], Pati *et al*. (2016) [12], Cuong *et al*. (2017) [4], Vashi *et al*. (2019) [17], and Mahendran *et al*. (2021) [8], confirming the positive impact of silicon and mycorrhiza on crop growth and development.

3.2. Number of leaves

Although the influence of various silica and mycorrhiza application methods (A) was not statistically significant, some numerical differences were noted. The highest average number of leaves was observed in treatment A4, where silica granules were applied to the soil at a rate of 5 g per acre. The effect of application levels (B) was statistically significant; the treatment B3, which involved the highest application level of 3x, resulted in the maximum average number of leaves. This consistent trend of increasing leaf count with higher application levels indicates that elevated amounts of silica and mycorrhiza may promote vegetative growth even at harvest, likely due to sustained nutrient availability and enhanced physiological functions. Concerning the interaction between application method and level (A × B), although it was not statistically significant, the highest leaf number was recorded in the combination A4B3, where silica granules were applied to the soil at a rate of 15 kg per hectare.

It is important to note that the application of fertilizers and silica can significantly improve nutrient fixation, leading to an increase in the availability of nutrients within the soil. This enhancement in nutrient availability subsequently supplies more essential elements to plants, promoting greater growth, better morphological development, and increased dry matter accumulation. Similar findings have been reported by Vashi *et al.*, (2019) [17] and Mahendran *et al.*, (2021) [8], supporting the positive impact of these amendments on plant development and soil nutrient dynamics.

3.3. Shoot weight

The study examined the impact of various silica and mycorrhiza application methods. It was observed that the application method significantly influenced the results. The highest average shoot weight was achieved with treatment A4, which involved applying silica granules to the soil at a rate of 5 kg per hectare. This result was comparable to treatment A2, where mycorrhiza was applied through soil drenching at 100 grams per acre, as well as treatment A3, which involved soil application of mycorrhiza at the same rate, and treatment A5, where foliar application of silica was performed using 0.1% orthosilicic acid. Among different application levels, the maximum mean shoot weight was recorded in treatment B3, which utilized the highest application level of three times the base amount. Although the interaction between silica and mycorrhiza treatments (A × B) was not statistically significant, some numerical differences were observed in the data.

The application of silica to soil appears to have enhanced the structural integrity and water-holding capacity, thereby supporting increased biomass production. Additionally, treatments involving soil-based mycorrhiza and foliar silica sprays may have contributed to more efficient nutrient transfer and physiological processes within the plant, resulting in similar improvements in shoot growth. As the levels of silica and mycorrhiza applications increased, there was a corresponding rise in shoot biomass, likely due to improved nutrient absorption, better water retention, and heightened physiological activity during the plant's development. It is important to note that the increased nutrient availability, facilitated by the proper use of fertilizers and silica, can boost the nutrient content in the soil, leading to greater nutrient uptake by plants. This process results in enhanced growth, better morphological development, and increased dry matter accumulation. Similar findings have been reported by Vashi *et al.* (2019) [17] and Mahendran *et al.* (2021) [8], supporting the positive impact of silica and mycorrhiza treatments on plant growth and development.

3.4. Shoot volume

The study revealed that different methods of applying silica and mycorrhiza did not produce statistically significant differences, although some numerical variations were noted. The level of application (B) showed a significant impact, with the highest average shoot volume observed in treatment B3, which involved the highest application level of three times. This level resulted in a shoot volume significantly greater than B1 and comparable to B2, which involved a double application. The interaction between the application method and level (A × B) was not statistically significant; however, the highest shoot volume was observed in the combination A4B3, where silica granules were applied to the soil at a rate of 15 kg per hectare.

The application of silica and mycorrhiza has been shown to significantly enhance shoot growth, primarily through promoting cellular expansion, improving water retention, and facilitating better nutrient uptake. It is important to note that the increased fixation of nutrients, achieved through the recommended use of fertilizers combined with silica, can elevate the nutrient availability in the soil. This, in turn, supplies more nutrients to the plant, leading to increased growth, better morphological development, and greater allocation of dry matter. Similar findings have been reported by Vashi *et al.* (2019) [17] and Mahendran *et al.* (2021) [8], supporting the positive impact of these amendments on plant development.

3.5. Root weight

The study revealed that different methods of applying silica and mycorrhiza had statistically significant effects on root weight. The highest average root weight was observed in treatment A2, which involved applying Mycorrhiza via drenching at a rate of 100 g per acre. This result was comparable to treatment A3, where Mycorrhiza was applied through soil at the same rate. The application levels themselves showed significant differences, with the highest mean root weight recorded in treatment B3, which involved the highest application level, three times the base amount. This treatment significantly outperformed the others in terms of root weight. However, the interaction between the application methods and levels (A × B) was not statistically significant, although there were notable numerical differences among the treatments.

The data suggest that increasing the application of mycorrhiza correlates with a rise in root biomass, likely because of better root growth, increased nutrient uptake, and overall plant health. Similar findings have been reported by Wei *et al.* (2021) [18] and Ugwoke and Onyishi (2009) [15], who demonstrated that mycorrhiza can promote root development and expansion.

3.6. Root volume

The primary impact of various methods of silica and mycorrhiza application was observed to significantly increase the average root volume, particularly in treatment A2, which involved Mycorrhizal drenching at a rate of 100 g per acre. This result was comparable to treatment A3, which consisted of Mycorrhizal soil application at the same rate. When examining the levels of application, the highest average root volume was recorded in treatment B3, which employed the maximum application level of three times, and this was statistically similar to treatment B2, which used a double application level. The interaction between the application methods and levels (A × B) did not show a statistically significant effect.

The increased root weight observed with the application of mycorrhizal soil can be explained by the improved colonization of roots and the enhanced uptake of nutrients facilitated by mycorrhizal fungi. These application methods foster a more effective symbiotic relationship, resulting in greater root biomass due to better absorption of water and essential nutrients, particularly phosphorus. The steady rise in root volume with higher application levels may be linked to increased root growth and more efficient water and nutrient transport, aided by both silica and mycorrhiza. Similar findings have been reported by Wei *et al.* (2021) [18] and Ugwoke and Onyishi (2009) [15], who demonstrated that mycorrhiza can promote root development and growth.

3.7. Yield

The treatment labeled A4, which involved applying silica granules to the soil at a rate of 5 kg per hectare, resulted in the highest average fruit yield, and this result was comparable to yields achieved through foliar application of 0.1% orthosilicic acid, soil application of mycorrhiza, and drenching with 100 g per acre. Among different application levels, the highest mean fruit yield was observed in treatment B3, which involved the highest application level of three times the base amount, and this was significantly higher than the second highest level, B2, which was applied twice. The interaction between the treatment types and levels (A × B) was statistically significant, with the maximum fruit yield recorded in the combination A4B3, which included silica soil application at 15 kg per hectare. This combination was also comparable to other treatments such as mycorrhiza drenching at 300 g per acre, mycorrhiza soil application at 300 g per acre, silica soil application at 10 kg per hectare, and foliar silica application at 0.2%. Although some differences were not statistically significant, they indicate a possible synergistic effect between certain sources and higher application levels, suggesting that combining specific treatments and increasing application rates could enhance fruit yield.

The increased fruit production observed with silica soil application can be primarily linked to improved nutrient absorption, strengthened cell walls, and enhanced stress resilience, all facilitated by silica presence in the root zone. Foliar applications of silica and treatments involving mycorrhiza in the soil also demonstrated positive effects, likely due to their roles in boosting photosynthesis, optimizing water use efficiency, and improving root-soil interactions. This pattern suggests that higher levels of silica and mycorrhiza application contribute to increased yield potential by promoting overall vegetative growth, efficient nutrient uptake, and reproductive success. Numerous studies have indicated that silicon (Si) can help mitigate various biotic and abiotic stresses, thereby increasing crop yields even under non-stressful conditions (Camargo *et al.* 2017; Liang *et al.* 2015) [3, 7]. These findings are consistent with research by Prakash *et al.* (2011) [13], Alam *et al.* (2019) [1], Vashi *et al.* (2019) [17], and Pallavi and Prakash (2021) [11], which collectively support the beneficial role of silica and mycorrhiza in enhancing plant productivity and stress tolerance.

Table 1: Effect of different levels of mycorrhiza and silica application on plant height of okra at harvest

Plant height (cm)				
Source and Method	**Levels of Application**			
	B1	**B2**	**B3**	**Mean**
A1	55.33	57.00	60.66	57.66
A2	60.33	62.33	62.00	61.55
A3	53.66	60.00	61.66	58.44
A4	58.33	62.66	66.33	62.44
A5	52.00	57.00	60.00	56.33
A6	51.00	52.33	62.00	55.11
Mean	55.11	58.55	62.11	
	A	B	A×B	
SEM	1.32	0.93	2.29	
CD	3.80	2.69	NS	

Table 2: Effect of different levels of mycorrhiza and silica application on number of leaves of okra at harvest

No. of leaves				
Source and Method	**Levels of Application**			
	B1	**B2**	**B3**	**Mean**
A1	18.33	23.33	23.33	21.66
A2	20.00	24.66	26.33	23.66
A3	20.00	25.33	25.00	23.44
A4	21.00	23.66	27.00	23.88
A5	22.66	21.66	25.66	23.33
A6	23.00	22.66	22.66	22.77
Mean	20.83	23.55	25.00	
	A	B	A×B	
SEM	0.68	0.48	1.18	
CD	NS	1.39	NS	

Table 3: Effect of different levels of mycorrhiza and silica application on shoot weight of okra plant

Shoot weight (g)				
Source and Method	**Levels of Application**			
	B1	**B2**	**B3**	**Mean**
A1	21.66	22.00	23.00	22.22
A2	24.33	26.00	25.33	25.22
A3	21.83	25.66	28.00	25.16
A4	23.66	25.33	28.66	25.88
A5	21.83	25.66	27.00	24.83
A6	21.33	21.66	26.33	23.11
Mean	22.44	24.38	26.38	
	A	B	A×B	
SEM	0.74	0.52	1.29	
CD	2.14	1.51	NS	

Table 4: Effect of different levels of mycorrhiza and silica application on shoot volume of okra plant

Shoot volume (cm^3)				
Source and Method	**Levels of Application**			
	B1	**B2**	**B3**	**Mean**
A1	21.66	21.66	24.16	22.50
A2	22.50	24.16	24.16	23.61
A3	20.00	23.33	24.16	22.50
A4	25.00	25.00	25.83	25.27
A5	23.33	25.83	24.16	24.44
A6	20.00	21.66	23.33	21.66
Mean	22.08	23.61	24.30	
	A	B	A×B	
SEM	0.78	0.55	1.36	
CD	NS	1.59	NS	

Table 5: Effect of different levels of mycorrhiza and silica application on root weight of okra plant

Root weight (g)				
Source and Method	**Levels of Application**			
	B1	**B2**	**B3**	**Mean**
A1	17.66	18.50	19.50	18.55
A2	19.33	20.50	19.83	19.88
A3	17.00	19.16	21.16	19.11
A4	15.33	18.00	18.33	17.22
A5	15.66	14.00	15.66	15.11
A6	14.00	15.33	17.00	15.44
Mean	16.50	17.58	18.58	
	A	B	A×B	
SEM	0.43	0.30	0.75	
CD	1.24	0.88	NS	

Table 6: Effect of different levels of mycorrhiza and silica application on root volume of okra plant

Root volume (cm^3)				
Source and Method	**Levels of Application**			
	B1	**B2**	**B3**	**Mean**
A1	15.66	16.00	17.00	16.22
A2	18.00	18.66	18.00	18.22
A3	15.66	17.00	18.66	17.11
A4	14.16	16.00	17.66	15.94
A5	12.50	13.33	14.16	13.33
A6	13.33	13.33	14.16	13.61
Mean	14.88	15.72	16.61	
	A	B	A×B	
SEM	0.48	0.33	0.83	
CD	1.38	0.97	NS	

Table 7: Effect of different levels of mycorrhiza and silica application on fruit yield of okra

Fruit yield (g)				
Source and Method	Levels of Application			
	B1	B2	B3	Mean
A1	102.50	95.83	104.16	100.83
A2	103.16	122.66	125.33	117.05
A3	98.16	122.33	124.66	115.05
A4	103.33	124.83	138.33	122.16
A5	112.00	129.00	121.33	120.77
A6	97.33	122.33	118.16	112.61
Mean	102.75	119.50	122.00	
	A	B	A×B	
SEM	2.84	2.01	4.93	
CD	8.18	5.79	14.18	

4. Conclusion

The present investigation clearly demonstrated that the different modes of application of mycorrhiza and silica, significantly influenced the growth and yield performance of okra under lateritic soil conditions. Among the different modes of application, silica soil application (A4) consistently recorded superior performance in terms of plant height, shoot weight, and fruit yield, while mycorrhiza soil drenching (A2) and soil application (A3) proved most effective in enhancing root growth and root volume. With respect to levels of application, the highest level (B3, 3x) produced significantly higher values for most growth and yield attributes, indicating a strong positive response to increased inputs. The interaction effect (A × B) was particularly evident for yield, where the combination of silica soil application at higher levels (A4B3) gave the maximum fruit yield.

Overall, the study suggests that silica soil application @ 15 kg ha^{-1} (A4B3) is a promising strategy to enhance growth, physiological efficiency, and yield of okra. The results highlight the complementary roles of silica in strengthening plant structure and improving stress tolerance, and of mycorrhiza in enhancing root development and nutrient uptake. These findings support the integration of silica and mycorrhiza with recommended fertilizers as a sustainable approach for improving okra productivity, nutrient-use efficiency, and soil health under lateritic soil conditions.

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