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Synergistic Effects of Silicon and Mycorrhiza on Sorghum Grown under Saline Water Irrigation

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Authors' contributions

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

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ABSTRACT

Salinity stress is a major constraint to crop productivity, affecting physiological processes such as photosynthesis and disrupting osmotic and ionic balance. Exogenous application of silicon has been shown to enhance plant tolerance to salinity by improving photosynthetic efficiency, metabolic activity and molecular responses. Similarly, mycorrhizal fungi help to mitigate salinity-induced stress by enhancing nutrient uptake. To investigate the combined effects of silicon and mycorrhiza on sorghum under saline irrigation, a field experiment was conducted in 2022 at farmer's field in Kuppuchipalayam village, Karur District, Tamil Nadu. The study included five silicon levels (0, 50, 100, 150, and 200 kg/ha) applied through diatomaceous earth and three mycorrhiza levels (0, 25,

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and 50 g/plant), under saline water irrigation with an electrical conductivity of 10 dS/m. The experiment was laid out in a factorial randomized block design (FRBD) with two replications, using sorghum *var*. K12 as the test crop. Results revealed that both silicon and mycorrhiza significantly alleviated the negative effects of salinity, improving plant growth and yield. Plant height, leaf area index (LAI), chlorophyll content (SPAD) and dry matter production (DMP) increased with higher silicon levels, peaking at 200 kg Si/ha, resulting in respective increases of 9.2%, 53.6%, 19.0%, and 25.1% over the control. Yield parameters such as number of ear heads/m², no. of filled grains/ear head, grain yield and stover yield were also maximized at this level, with the highest grain and stover yield reaching 4286.3 kg/ha and 7096.7 kg/ha, showing 25.4% and 21.7% increases over control. Mycorrhiza application at 50 g/plant significantly enhanced all measured parameters over 25 g/plant and control, with grain and stover yields increasing by 10.3% and 10.7%, respectively. The interaction between silicon and mycorrhiza was significant, with the best performance observed at 200 kg Si/ha + 50 g VAM/plant, resulting in yield improvements of 40.5% (grain) and 33.4% (stover) compared to untreated control.

Keywords: Sorghum; salinity; silicon and mycorrhiza.

1. INTRODUCTION

Salinity in agriculture is a global problem (Al-Karaki, 2006). “Saline stress can greatly impact the growth and productivity of crops. Salinity triggers ionic imbalance in plant tissue cells, leading to ion toxicity and osmotic stress, which ultimately adversely affects plant growth and yield” (Tester & Davenport, 2003). In recent years, the use of silicon and VAM has gained attention as potential remedies (Zhu et al., 2004).

“Silicon (Si), the second most abundant element in the Earth’s crust, has been found to alleviate salt stress in rice, barley, wheat, and cucumber” (Gong *et al.,* 2006; Liang et al., 2006; Saqib *et al*., 2008; Zhu *et al*., 2004; Epstein,1999). “Several studies have reported that Si supplementation mitigates the adverse effects of biotic stresses such as bacterial, fungal, and viral pathogens as well as infestation of insect pests” (Liang *et al*., 2015; Song *et al*., 2016) “and abiotic stresses such as toxicity of heavy metals, plant salinity and drought” (Ahmed *et al*., 2014; Keller *et al*., 2015; Ma *et al*., 2016; Maghsoudi *et al*., 2016). “It has been reported that ion accumulation is reduced by decreasing plant transpiration due to silica deposits in the leaves” (Matoh *et al*., 1986). “Si is taken up by plant roots from the soil in the form of silicic acid [Si $(OH)_4$]” (Ma and Yamaji 2015) “where it is deposited within plant tissue as SiO2, commonly known as phytoliths or silica bodies. Past studies of Si application to maize plants have revealed that the application decreased leaf transpiration rates under water stress and thereby improved the plant’s water status” (Gao *et al*., 2004, 2006).

“VAM is a type of beneficial fungi that forms a symbiotic relationship with plant roots. The role of AMF in enhancing plant tolerance to heavy metals depends on the AMF species, plant genotype and type of metal in the soil” (Sudova *et al.,* 2008). “AM colonization enhances plant resistance to salinity, improves plant productivity, increases nutrient absorption” (Garg & Bhandari, 2016), “maintains ion equilibrium and facilitates water uptake” (Ruiz-Lozano *et al*., 2012).”AM have been reported to enhance Si uptake in mycorrhizal plants of Glycine max” (Yost & Fox, 1982) and Zea mays (Clark & Zeto 2000). “AM through extramatrical hyphae can help the absorption and translocation of more nutrients than without symbiosis with AM” (Guo *et al.,* 2010) “especially phosphate ions (Sharda & Koide, 2010). Growth in saline soils was increased by inoculation with Glomus sp, with AM plants having increased phosphate and decreased Na concentrations in shoots compared to uninoculated controls” (Pfeiffer & Bloss, 1988; Giri & Mukerji, 2004).

“Millet is a group of small-grained cereal grown around the world for food and fodder. Among various millets, Sorghum (Sorghum bicolour L.) is the most important cereal crop after wheat, rice, maize and barley in the country. Sorghum species are native to tropical and subtropical regions of Africa and Asia that belongs to family Poaceae. Meanwhile, Si + PGPR can improve and promote the growth of mungbean, so it might be used in a farming system to reduce the effects of salinity stress” (Ahmed *et al*.,2020). Silicon has been shown to enhance plant tolerance to salinity, while VAM can improve nutrient uptake and plant resilience. This study aims to investigate the effectiveness of silicon and VAM in alleviating saline stress in sorghum crop.

2. MATERIALS AND METHODS

2.1 Experimental Site

The field experiment was conducted in field located at Kuppuchipalayam village, Manmangalam taluk in Karur district, Tamil Nadu, India to understand the response of sorghum to dual application of silicon and mycorrhiza under saline water irrigation. The experimental soil was loamy sand with the pH and EC of 7.62 and 2.83 dSm^{-1}respectively. The irrigation water contains Ph and EC of 8.57 and 11.21 dSm^{-1} respectively. It is geographically located at 11.02^{0} N latitude and 78.11^{0} E longitudes with an attitude of 121 meters above mean sea level (MSL). The weather of the experimental area during the cropping period was moderately warm with hot summer. The maximum temperature fluctuates between 27.84°C to 30.85°C with a mean of 29.19°C, while the minimum temperature ranges from 15.45°C to 22.93°C with a mean value of 19.96°C. The relative humidity ranges from 76 to 86 percent with a mean of 81 percent. The experiment consisted of fifteen treatments and was laid out in factorial randomized block design (FRBD) with two replications. M_0-Non inoculated, M_1- inoculated *Glomus mosseae* (25g per plant) and M2- inoculated *Glomus mosseae* (50g per plant) were tried along with different Silicon levels of Si_0-0, Si_1-25, Si_2- 50, Si_3-75 and Si_4-100 Kg ha^{-1}) through Diatomaceous earth. Recommended dose of 90:45:45 kg of NPK ha^{-1} was applied in the form of Urea, SSP and MOP respectively to all the treatments. Silicon and RDF were applied basally whereas VAM has been applied after 30 DAS. The VAM inoculum was applied near root zone of sorghum by placement method (Laing & Adandonon, 2005). Sorghum variety K12 was chosen for the study. The plant growth parameters like plant height, leaf area index (LAI), chlorophyll content and DMP and the yield parameters like no. of earheads/m2, no. of filled grains/earhead, stover yield and grain yield were recorded at vegetative, flowering and harvest stages.

3. RESULTS AND DISCUSSION

3.1 Growth Attributes

The application of silicon 200 kg ha^{-1} along with VAM inoculated plants (50 g per plant) showed significant increase in growth attributes over other treatments. The application of silicon (200 kg ha^{-1}) and VAM (50 g per plant) recorded highest plant height of 58.45, 167.09 and 180.68 cm at vegetative, flowering and harvest stages respectively and the lowest was recorded in control where RDF alone applied (Table 1). Tripathi *et al.* (2013) reported that in sorghum, silicon had enhanced the crop quality, yield and growth and protected the plants from various biotic and abiotic hurdles. Vesicular-arbuscular mycorrhizae (VAM) enhance plant growth through increased nutrient uptake, stress tolerance and disease resistance (Sharma et al., 1992). Similarly, the highest LAI (Table 2) and chlorophyll content (Table 3) was recorded in the application of silicon 200kg ha^{-1} and VAM 50 g per plant viz., 2.75 & 6.21 and 33.75 & 40.15 during vegetative and flowering stages respectively and this increases 40.36 % & 51.52 % and 79.97 % & 76.88 % of LAI and chlorophyll content during vegetative and flowering stages respectively over control. Liang (1998) stated that Si enhanced the growth of salt treated barley, by improving the chlorophyll content and photosynthetic activity of leaf cell organelles of barley. The highest dry matter content was recorded in the application of silicon (200 kg/ha) and VAM (50g per plant) as 2456 and 8798 kg ha^{-1} during vegetative and flowering stages respectively which increases 61.56 % and 72.42 % respectively over control (Table 4). Thus, increase in plant growth resulted in high dry matter content. As an integral part of the root system, VAM interact with other microorganisms in soil and result in increased root exudation approaching about 25% of the plant dry matter production (Sharma *et al*., 1992).

3.2 Yield Attributes

The yield attributes were recorded highest in in the application of silicon 200 kg/ha and VAM 50 g per plant over all other treatments. The number of earheads/m^2 and number of filled grains/ earhead were recorded highest in the treatment where silicon and VAM were applied at the highest dosage level (silicon 200 kg/ha and 50g per plant) as 23.50 and 943.16 which increases over 64.08% and 76.58% respectively over control (Table 5). The grain and stover yield were recorded highest in the treatment 4507 kg ha^{-1} and 7415 kg ha^{-1} respectively with the application of silicon 200 kg/ha and VAM 50 g per plant and this increases 70.59% and 74.95% respectively over control (Table 6). The increase in grain and stover yield might be due to the increase in crop growth and yield characteristics and Si that helps

Table 1. Effect of graded levels of silicon and VAM on plant height (cm) of sorghum at different stages

VAM Levels / Si levels	Vegetative stage				Flowering stage				Harvest stage			
	VAM_0	**VAM_{25}**	**VAM_{50}**	**Mean**	**VAM_0**	**VAM_{25}**	**VAM_{50}**	**Mean**	**VAM_0**	**VAM_{25}**	**VAM_{50}**	**Mean**
Si_0	38.45	41.48	42.94	40.99	144.99	146.78	150.37	147.38	158.05	161.51	165.09	161.55
Si_{50}	42.52	48.55	51.22	47.40	148.11	154.2	157.87	153.29	162.25	167.82	169.87	166.65
Si_{100}	49.64	51.22	53.57	51.48	152.99	156.69	159.04	156.24	167.43	169.62	171.02	169.36
Si_{150}	51.33	52.97	54.58	52.96	156.73	160.00	162.91	159.54	169.69	172.72	175.07	172.49
Si_{200}	53.11	55.6	58.45	55.78	160.51	165.12	167.09	164.24	172.5	175.8	180.68	176.33
Mean	47.05	49.96	52.15		152.66	156.79	159.25		165.98	169.49	172.35	
	Si	VAM	Si x VAM		Si	VAM	Si x VAM		Si	VAM	Si x VAM	
SE_d	0.359	0.278	0.621		0.483	0.374	0.837		0.275	0.213	0.476	
CD (p 0.05)	0.718	0.556	1.243		0.967	0.749	1.674		0.550	0.426	0.952	

Table 2. Effect of graded levels of silicon and VAM on leaf area index (LAI) of sorghum at different stages

VAM Levels / Si levels	Vegetative stage				Flowering stage			
	VAM_0	**VAM_{25}**	**VAM_{50}**	**Mean**	**VAM_0**	**VAM_{25}**	**VAM_{50}**	**Mean**
Si_0	1.11	1.23	1.34	1.22	3.20	3.43	4.11	3.58
Si_{50}	1.24	1.57	2.02	1.61	3.64	4.22	4.46	4.10
Si_{100}	1.72	2.15	2.38	2.08	3.91	4.60	4.97	4.49
Si_{150}	2.06	2.27	2.48	2.26	4.20	5.15	5.60	4.98
Si_{200}	2.23	2.47	2.75	2.48	4.82	5.49	6.21	5.50
Mean	1.67	1.93	2.18		3.95	4.57	5.07	
	Si	VAM	Si x VAM		Si	VAM	Si x VAM	
SE_d	0.026	0.020	0.046		0.043	0.033	0.075	
CD (p 0.05)	0.053	0.041	0.092		0.087	0.067	0.150	

in stimulating biotic and abiotic stress. Pati *et al*., (2016) also reported a significant increase in grain and straw yields of rice with increasing Si level. VAM helps in increasing nutrient uptake and translocating these nutrients to reproductive parts that helps in increase grain yield. Stover yield is dependent on vegetative growth as use of silicon and VAM increased plant height and dry matter production which resulted in higher stover yield. The increases in both grain and stover yields might be attributed to the beneficial effect of Si in increasing growth and yield attributes (Prakash *et al*., 2011, Pati *et al.*, 2016).

Table 3. Effect of graded levels of silicon and VAM on chlorophyll content (SPAD value) of sorghum at different stages

VAM Levels / Si levels	Vegetative stage				Flowering stage			
	VAM_0	**VAM_{25}**	**VAM_{50}**	**Mean**	**VAM_0**	**VAM_{25}**	**VAM_{50}**	**Mean**
Si_0	26.99	27.87	28.95	27.94	30.87	32.97	33.78	32.54
Si_{50}	27.87	28.54	29.58	28.66	33.59	34.04	35.65	34.43
Si_{100}	28.45	29.58	30.57	29.53	34.16	35.67	36.75	35.52
Si_{150}	28.62	30.33	32.05	30.32	35.30	37.02	38.10	36.81
Si_{200}	31.11	32.78	33.75	32.55	37.28	38.76	40.15	38.73
Mean	28.61	29.82	30.98		34.24	35.69	36.89	
	Si	VAM	Si x VAM		Si	VAM	Si x VAM	
SE_d	0.290	0.225	0.503		0.486	0.221	0.495	
CD (p 0.05)	0.581	0.450	1.006		0.572	0.443	0.991	

Table 4. Effect of graded levels of silicon and VAM on DMP (kg/ha) of sorghum at different stages

VAM Levels / Si levels	Vegetative stage				Flowering stage			
	VAM_0	**VAM_{25}**	**VAM_{50}**	**Mean**	**VAM_0**	**VAM_{25}**	**VAM_{50}**	**Mean**
Si_0	1512	1659	1748	1639.6	6372	6763	7117	6750.6
Si_{50}	1704	1807	1888	1799.6	6593	7279	7700	7190.6
Si_{100}	1822	2028	2058	1969.3	7264	7530	7869	7554.3
Si_{150}	2013	2117	2272	2134.0	7641	8054	8415	8036.6
Si_{200}	2154	2345	2456	2318.3	7987	8548	8798	8444.3
Mean	1841.0	1991.2	2084.4		7171.4	7634.8	7979.8	
	Si	VAM	Si x VAM		Si	VAM	Si x VAM	
SE_d	2.958	2.291	5.123		57.437	44.490	99.483	
CD (p 0.05)	5.916	4.582	10.247		114.874	88.981	198.967	

Table 5. Effect of graded levels of silicon and VAM on yield attributes of sorghum

VAM Levels / Si levels	Number of ear heads/ m^2				Number of filled grains/ ear head			
	VAM_0	**VAM_{25}**	**VAM_{50}**	**Mean**	**VAM_0**	**VAM_{25}**	**VAM_{50}**	**Mean**
Si_0	15.06	15.34	15.76	15.39	722.33	765.99	775.16	754.99
Si_{50}	16.43	17.82	18.74	17.66	782.16	810.45	835.10	809.23
Si_{100}	17.06	18.00	19.25	18.10	798.16	825.60	861.45	828.40
Si_{150}	18.71	20.12	21.75	20.19	832.66	856.10	900.60	863.12
Si_{200}	20.45	22.15	23.50	22.03	848.83	883.16	943.16	891.72
Mean	17.54	18.68	19.80		796.8	828.26	862.49	
	Si	VAM	Si x VAM		Si	VAM	Si x VAM	
SE_d	1.075	0.832	1.861		6.336	4.908	10.975	
CD (p 0.05)	2.150	1.665	3.723		12.673	9.816	21.950	

Table 6. Effect of graded levels of silicon and VAM on grain yield and stover yield of sorghum

VAM Levels / Si levels	Grain yield (kg/ha)				Stover yield (kg/ha)			
	VAM_0	VAM_{25}	VAM_{50}	Mean	VAM_0	VAM_{25}	VAM_{50}	Mean
Si_0	3198	3427	3630	3418.3	5557.9	5869.16	6067.1	5831.4
Si_{50}	3474	3715	3764	3651.0	5750.6	6227.5	6462.1	6146.7
Si_{100}	3665	3825	3959	3822.3	6131.15	6450.6	6807.1	6462.9
Si_{150}	3846	4169	4218	4077.6	6424.0	6760.5	7067	6783.8
Si_{200}	4002	4350	4507	4286.3	6800.5	7074.6	7415.0	7096.7
Mean	3640.6	3897.2	4015.6		6132.8	6476.5	6786.6	
	Si	VAM	Si x VAM		Si	VAM	Si x VAM	
SE_d	55.802	43.224	96.65		56.213	43.543	97.364	
CD (p 0.05)	111.604	86.448	193.303		112.427	87.086	194.729	

4. CONCLUSION

In the farmer's field, growth of the sorghum crop was severely affected by salinity stress. From the field experiment carried out in the farmer's field, it can be concluded that the application of silicon 200 kg/ha and VAM 50 g per plant increased the growth and yield of sorghum crop under saline stress condition. In future aspects, the application of silicon (200 kg/ha) along with VAM (50g per plant) can be recommended to alleviate saline stress condition.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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

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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