Journal of Plant Nutrition

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/lpla20

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To cite this article: Kallen Kaaria, Joseph Gweyi-Onyango & Catherine Muui (2023): Silicon amendment – influence on sorghum growth, yield, and nutrient uptake under water stress, Journal of Plant Nutrition, DOI: 10.1080/01904167.2023.2222132

To link to this article: https://doi.org/10.1080/01904167.2023.2222132

Published online: 12 Jun 2023.

JOURNAL OF PLANT NUTRITION
https://doi.org/10.1080/01904167.2023.2222132

Silicon amendment – influence on sorghum growth, yield, and nutrient uptake under water stress

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ABSTRACT
Silicon enhances plant growth and development, alleviating the effects of biotic and abiotic stresses. Drought severe abiotic stress that hampers plant growth and production globally, posing threat to food security. Mass production of sorghum is crucial to eradicating the present increasing food insecurity in water-stressed regions. The study evaluated the effects of silicon on nutrients uptake, growth and yield of sorghum under different water regimes. A two-season field trial was carried out to evaluate two sorghum varieties (seredo and Machakos local red), silicon (with silicon and without silicon) under three irrigation regimes (20%, 40% and 60%) laid out in Randomized Completely Block Design in a factorial arrangement replicated thrice. Data was collected on growth, yield and nutrients uptake, which was subjected to analysis of variance using R software. Results showed that Seredo variety had the highest root dry weight (123.5 g) and longest roots (51.4 cm). At 60% water regime and silicon amendment enhanced sorghum growth better than other treatments. Seredo variety recorded the highest grain yield (4.82tha^{-1}), phosphorus (95.53 kg ha^{-1}), nitrogen (32.16 kg ha^{-1}), K (76.06 kg ha^{-1}), calcium (3919.00 kg ha^{-1}) and magnesium (165.02 kg ha^{-1}). Seredo had the maximum harvest index of 0.41. At 40% water regime, Seredo variety amendment with Si produced the highest grain yields and nutrients uptake. Si amendment can improve sorghum growth and yield under water stress conditions, as indicated by high grain yield and nutrients uptake achieved at 40% water regime. The use of Silicon is recommended for improving sorghum productivity in regions experiencing low rainfall.

ARTICLE HISTORY
Received 19 January 2021
Accepted 25 May 2023

KEYWORDS
Drought growth; silicon amendment; sorghum; yield

Introduction

Sorghum (*Sorghum bicolor* L. Moench) is a major staple food in the semi-arid regions across Asia and Africa (Younis et al. 2007; Khan et al. 2006). It plays a key role in our diets since over 90% of the sorghum produced is used as human food (Reddy 1987). Under the effects of continuous drought, sorghum is well adapted due to its ability to tolerate water stress. This is attributed to; its dense and prolific roots system that provides a large surface area for water absorption, reduced leaf area, therefore, lowering the amount of water loss through transpiration, presence of motor cells along the midrib that helps in leave rolling during moisture stress thus reducing water loss through the leaves, and its ability to maintain stomata opening at low levels of leaf water potential through osmotic adjustment (Younis et al. 2000). Although sorghum yields are still low and unstable because of several environmental constraints such as drought stress being experienced

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globally (Reddy et al. 2007). Therefore, there is a need to increase and stabilize its production to curb food insecurity.

Silicon (Si) being the second most abundant element in the soil has gained significant attention as an essential nutrient for its positive effects on growth and productivity of crops under abiotic stresses (Kang et al. 2015; Tayyab et al. 2018; Moradtalab et al. 2019). Plants absorb silicon in form of soluble mono silicic acid that is translocated to the shoot through either active or passive mechanism where it polymerizes to form phytoliths (Zhu and Gong 2014; Garg and Bhandari 2016; Ma and Yamaji 2015). It is known to confer positive effects to plants such as reduction of plant water loss through transpiration (Kim et al. 2016), reduction of toxic absorption, and increased stiffness and strength of plant cell walls (Ma and Yamaji 2006; Garg and Singh 2018). Also, it's known to provide plants defence mechanisms to diseases and insects damages (Cuong et al. 2017; Frew et al. 2017; Garg and Singh 2018). As well many studies have shown that silicon is a beneficial nutrient that mitigates abiotic and biotic stress in plants (Moradtalab et al. 2019). Findings by Emam et al. (2014) showed ameliorative effects of silicon in plants under water stress. Shen et al. (2010) also reported that silicon can alleviate damages caused by drought in soybeans. Further, Kurdali et al. (2019) highlighted the importance of silicon to maintain water status of chickpea under low water moisture. Zhang et al. (2017) reported that silicon mitigates adverse effects of water stress on soybean.

Drought is one of the major severe abiotic stresses that hamper plant growth and production globally (Begum et al. 2019; Tayyab et al. 2018). It is well known that soil moisture influences numerous features of plant growth and development and therefore extended water stress severely diminishes plant output. Water stress hinders physiological traits of plants such that it causes a reduction in transpiration rate, photosynthesis rate, and chlorophyll content and also it affects stomatal conductance hence negatively influencing on crop yields (Anjum et al. 2011). Besides that, drought also reduces nutrient uptake due to stomatal closure as an immediate response to plants upon being exposed to water stress thus reducing production (Moradtalab et al. 2019). Moreover, low soil moisture happening during different development stages of the crop may reduce its final yields (Cakir 2004). Abiotic stresses on crop production have been increased by climate change and agricultural malpractices for instance excessive use of pesticides and fertilizers consequently degrading the ecosystem (Begum et al. 2019). Hence, we aimed at investigating the effect of silicon amendment on sorghum growth, yield and nutrient uptake under water stress. This is because, by use of silicon, injuries caused by water stress are mitigated since silicon provide multifarious benefits to crops (Ma and Yamaji 2006; Ahmed et al. 2011; Tripathi et al. 2016).

Materials and method

Description of the study area

The field trials were carried out at Yatta NYS field station in Machakos County, Kenya during the dry season. The area lies between Latitude − 1.088439 south and Longitude 37.476116 east. The rainfall pattern is bimodal having two rainy seasons (long rains between March and May and short rains between October and December). Average temperature ranges between 29 °C and 36 °C while the average rainfall received is 450-800 mm per year. The experiment was carried out in two cycle (seasons) (December 2019 to April 2020) and (April 2020 to July 2020). Before land preparation, soil samples were collected at (0–20 cm depth) for determination of physical and chemical parameters using procedures by Okalebo et al. (2002) as shown in Table 1.

Table 1. Selected physical and chemical characteristics of the experimental soil.

pH (1:2.5, soil: water)	Total organic carbon (%)	Soil organic matter (%)	Total nitrogen (%)	Available phosphorus (%)	Exchangeable potassium (%)	Exchangeable magnesium (%)	Exchangeable calcium (%)	EC (mhos/cm)	Bulky density (g/cm^3)	Field water capacity (%)	Sand (%)	Silt (%)	Clay (%)	Soil textural class
6.33	0.18	0.31	0.06	0.01	0.07	0.44	1.26	0.023	1.56	22.7	76	14	10	Loamy sand

Experimental design, crop establishment and management

The experiment was laid out in Randomized Complete Block Design (RCBD) in a factorial arrangement replicated three times. The experimental factors were; Sorghum varieties (Machakos local red and Seredo), water regimes {60% Field capacity (FC), 40% Field capacity (FC) and 20% Field capacity (FC) and Silicon (Si) levels (with or without). This gave a total of 12 experimental treatments that were replicated three times. Healthy sorghum seeds were planted as recommended at a spacing of 75 cm between the rows and 25 cm within the rows in plots measuring 3 m x 3 m. Silicon was applied targeting the roots of the crop two weeks after planting at a rate of 0.1 mg per plant. Thereafter, three water levels were introduced at flora initiation at the late phase of plant vegetative stage four weeks after planting. Field water capacity was measured every day using a moisture meter to check on depletion of water stored in the soil. Irrigation occurred at three water regime levels when soil water content fell below 60% FC, 40% FC and 20% FC of initial values. This was done throughout the experiment period. The plants were subjected to the natural day and night weather conditions that were held constant. Fertilizers were also added with phosphorous (P) being added at 45 kg ha^{-1} P (3.44 g P per plant) during planting (19th December 2019), while nitrogen (N) at 180 kg ha^{-1} N (5.87 g N per plant) was introduced as a top dressing (Galal 2016) four weeks after planting and replicated in the subsequent season. All agronomic practices were maintained throughout the experimental period.

Data collection

Determination of plant growth parameters

Different growth parameters were measured during plant growth. The parameters included; root dry weight and root length. Destructive sampling was done on the two outer rows on each experimental plot. Three plants on each experimental plot were uprooted and were used to determine root length and root dry weight. This was done as from the sixth week after planting and thereafter biweekly until grain filling. Root length was measured using a meter rule. The samples were dried in an oven at 60 °C for 72 h till they reached a constant weight. Root dry weight was measured using an electronic weighing balance from the three plants from each experimental plot and average recorded.

Yield and its component

During harvesting, the above-ground biomass for each experimental net plot was weighed and recorded. The stover samples were dried in an oven at 60 °C for 72 h till they reached a constant weight and weight recorded. Yield data was determined after harvesting of the net plot. Threshed grains were dried in an oven at 60 °C for 72 h till the moisture content was at 12 °C, weighed using a weighing balance. The weight in kilogram was transformed into kg ha^{-1}. Net plot harvest index (HI) for each experimental unit was determined by dividing grain weight by the total of the above-ground biomass multiplied by 100. The HI was calculated according to Leport et al. (2006).

Nutrient analysis and uptake in plant tissues

Plant samples and grains from the experimental plots were collected at harvesting and transferred to the laboratory for nutrient analysis. The plant's stover samples collected were washed, rinsed with deionized water, cut into pieces and dried at 70 °C for 48 h, while the grains were only washed, rinsed and dried. A blender was used to grind the dried plant stover and grains that were stored ready for analysis.

Nutrient extraction was done by acid digestion of the samples followed by spectrometry analysis (Okalebo et al. 2002). A weight of 0.3 g of ground plant tissue sample and grain sample from each experimental plot was weighed and put into a clean dry digestion tube. A volume of 10 ml of digestion mixture that consist of 3.2 g of salicylic dissolved in 100 ml of sulfuric acid- selenium mixture was added to each sample and reagent blank tubes. The samples were digested by heating at 110 °C for 1 h. The temperature was raised to 360 °C for 4 h until the solution was colorless. The sample digestates were then allowed to cool. After cooling, the content was topped to the 50 ml mark with distilled water and used for the analysis of N, P, potassium (K), calcium (Ca) and magnesium (Mg) concentrations following procedures described below. Plant tissue and grains Phosphorus was determined using the colorimetric method following the procedure by Okalebo et al. (2002). Standards and sample absorbance were measured using ultraviolet-visible spectrophotometer (UV) at the wavelength of 880 nm. Calibration curve of the standards series, concentration against the absorbance was plotted. The slope was used to calculate P concentration as shown in equation 1. P uptake was calculated using equation 2.

$$\%\ \mathrm{P} = \frac{(a-b) \times V \times f \times 100}{1000 \times W \times 1000} \tag{1}$$

$$\mathrm{P\ uptake}\ \left(\mathrm{kg\ ha^{-1}}\right) = \frac{\%P \times drymatter(kg\ ha^{-1})}{100} \tag{2}$$

The total Nitrogen in the digestate was determined by Kjeldahl distillation method following procedures described by Okalebo et al. (2002). Percentage N in the plant tissue and N uptake in grain samples were calculated using equations 3 and 4, respectively.

$$\%\mathrm{N} = \frac{(a-b) \times V \times 100}{1000 \times W \times al \times 100} \tag{3}$$

$$\mathrm{N\ uptake}\ \left(\mathrm{kg\ ha^{-1}}\right) = \frac{\%N \times drymatter(kg\ ha^{-1})}{100} \tag{4}$$

Total K concentration in the digestate samples was determined using flame photometry (Okalebo et al. 2002). The concentration of the K in the plant tissue and grain samples was expressed into a percentage using equation 5 while K uptake was determined using equation 6.

$$\%\mathrm{K,\ Ca,\ Mg} = \frac{(a-b) \times V \times f \times 100}{1000 \times W \times 1000} \tag{5}$$

$$\mathrm{K,\ Ca,\ Mg\ uptake}\ \left(\mathrm{kg\ ha^{-1}}\right) = \frac{\%K \times drymatter\ (kg\ ha^{-1})}{100} \tag{6}$$

The concentration of total Ca and Mg in the digestate was determined using the atomic absorption spectrophotometry (AAS). The concentration and uptake of Ca and Mg were determined using equation 5 and 6, respectively.

Data analysis

Data on growth parameters, grain and stover yields and harvest index and nutrients uptake was analyzed using one-way analysis of variance (ANOVA) test. Data for each season and the experiment was analyzed separately. Statistical analyses were performed using R software, version 4.0.2 for windows. Significant means were separated using Tukey's test at 5% significance level.

Results

Plant growth parameters

There were significant differences ($p < 0.001$) in root dry weight among sorghum varieties, soil moisture stress and silicon. Seredo variety had superior root dry weight of 107.00 g and 94.75 g in week 15 in cycle one and two respectively (Table 2). Root dry weight increased with the amount of water applied such that 60% water regime recorded the highest root dry weight throughout the growth period and this trend applied to both cycle one and two. Generally, 20% of water regime had the lowest root dry weight 95.00 g and 80.41 g in week 15 cycle one and two respectively as illustrated in (Table 2). Nevertheless, the application of silicon significantly increased root dry weight in both cycles. Silicon applied treatments recorded maximum root dry weight115.20 g, 102.92 g cycle one and two in week 15 while lowest root dry weight 68.26 g was observed in treatments without silicon in cycle two (Table 2). Further, there was significant ($p < 0.001$) interaction in the influence of the varieties, water levels and Silicon on root dry weight of sorghum cycle 1 and 2 (Figures 1 and 2). Seredo variety amended with Silicon exhibited higher root dry weight 123.5 g 86th week in cycle one under 60% water regime (Figure 1c). Controls among the water regime treatments recorded the lowest root dry weight in cycle one and two (Figures 1 and 2).

Results of this study revealed that sorghum varieties were significantly different ($p < 0.001$) in terms of the root length in both cycles. Seredo variety recorded the highest root length of 44.05 cm in cycle one week 15 (Table 3). Water regimes had significant effect on root growth at $p < 0.001$.

The highest root length 47.10 cm and 40.10 cm was reported in cycle one and cycle two week 15 respectively and this happened in the plants under high moisture level (60%). As well, 60% water regime gave maximum root length across the weeks in the two cycles (Table 3). Application of silicon triggered a significant ($p < 0.001$) increase in the root length of sorghum in the two cycles as compared with treatments without silicon. Maximum root length 46.00 cm and 39.00 cm was recorded in week 15 in cycle one and two respectively (Table 3). As shown in Figures 3 and 4 depicting the two cycles, the interaction of varieties, water regimes and Silicon was significant ($p < 0.001$) across the experimental period. Machakos local red had the lowest root length of 49.1 cm and 41.4 cm when interacted with silicon under 60% water level compared to Seredo variety that showed superiority in root length recording 51.4 cm and 45.1 cm 86 days in

Table 2. Mean root dry weight (g) as affected by sorghum varieties, water stress and silicon both experimental cycles.

Root dry weight (g)								
Weeks	Week 6		Week 9		Week 12		Week 15	
Cycles	C1	C2	C1	C2	C1	C2	C1	C2
Variety								
Mlr	7.83a	6.92b	10.63b	9.63b	54.57b	44.57b	91.40b	76.42b
Srd	8.87a	5.83a	17.83a	12.83a	60.04a	50.04a	107.00a	94.75a
P-value	***	***	***	***	***	***	***	***
Water regime (%)								
20wr	6.29c	4.69c	12.73c	9.47c	52.66c	42.31c	95.00c	80.41c
40wr	7.59b	6.02b	13.89b	10.75b	57.31b	46.89b	99.60b	84.33b
60wr	9.66a	8.42a	16.08a	13.48a	61.95a	52.72a	103.00a	92.02a
P-value	***	***	***	***	***	***	***	***
Silicon								
Control	5.58b	3.97b	12.01b	8.74b	49.19b	38.67b	83.20b	68.26b
Si	10.12a	8.79a	16.46a	13.73a	65.42a	55.94a	115.20a	102.92a
P-value	***	***	***	***	***	***	***	***

Means followed by the same letter within the column are not significantly different at alpha = 0.05. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns = not significant, Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); Srd = Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; C = Experiment cycle.

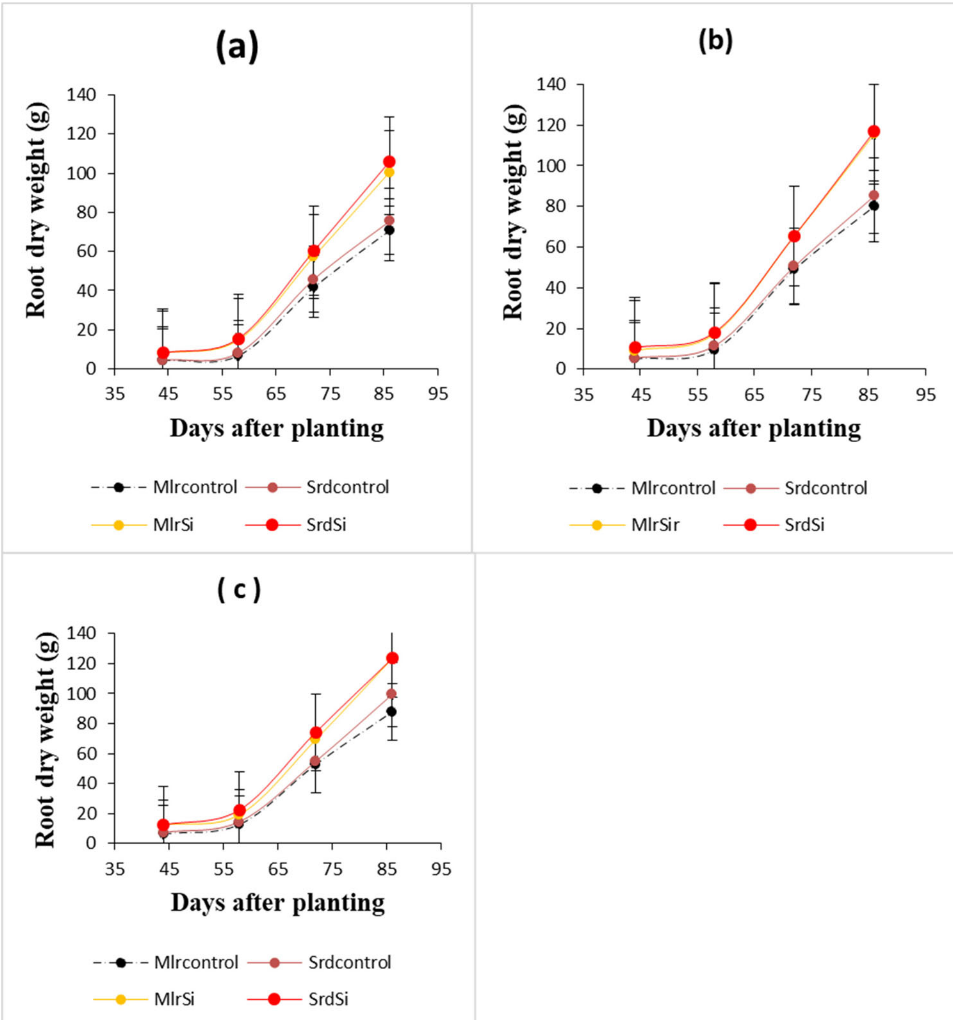

Figure 1. Interactive effects between varieties, water levels and silicon sorghum root dry weight cycles 1.
Srd = Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); (a)= 20%wr, (b)= 40%wr and (c)= 60%wr.

the two cycles respectively (Figures 3 and 4). Seredo variety recorded the highest root length and a similar trend was observed in all the weeks in the two cycles.

Yield and yield component

Stover yield, grain yield and harvest index were significantly ($p < 0.001$) affected by sorghum varieties in both cycles (Table 4). Seredo variety recorded the highest stover yield (8.00 tha^{-1}), grain yield (4.40 tha^{-1}) and harvest index (0.39) respectively in cycle one. Also, results obtained from the study showed that stover yield, grain yield and harvest index were significantly ($p < 0.001$) affected by water regimes. Both the stover and grain yields of plants exposed to water stress (20%) were significantly inferior resulting in 6.50 $tha^{-1,}$ 4.60 tha^{-1} and 3.30 tha^{-1}, 2.50tha^{-1}cycle one and two respectively as compared with water regime 40% that accumulated 8.50tha^{-1}, 6.10 $tha^{-1}$and 4.80 $tha^{-1}$and 3.50 tha^{-1}in cycle one and two respectively (Table 4). Although the water regime 20% recorded the highest harvest index of 0.36 and 0.35 in cycle one and two (Table 3).

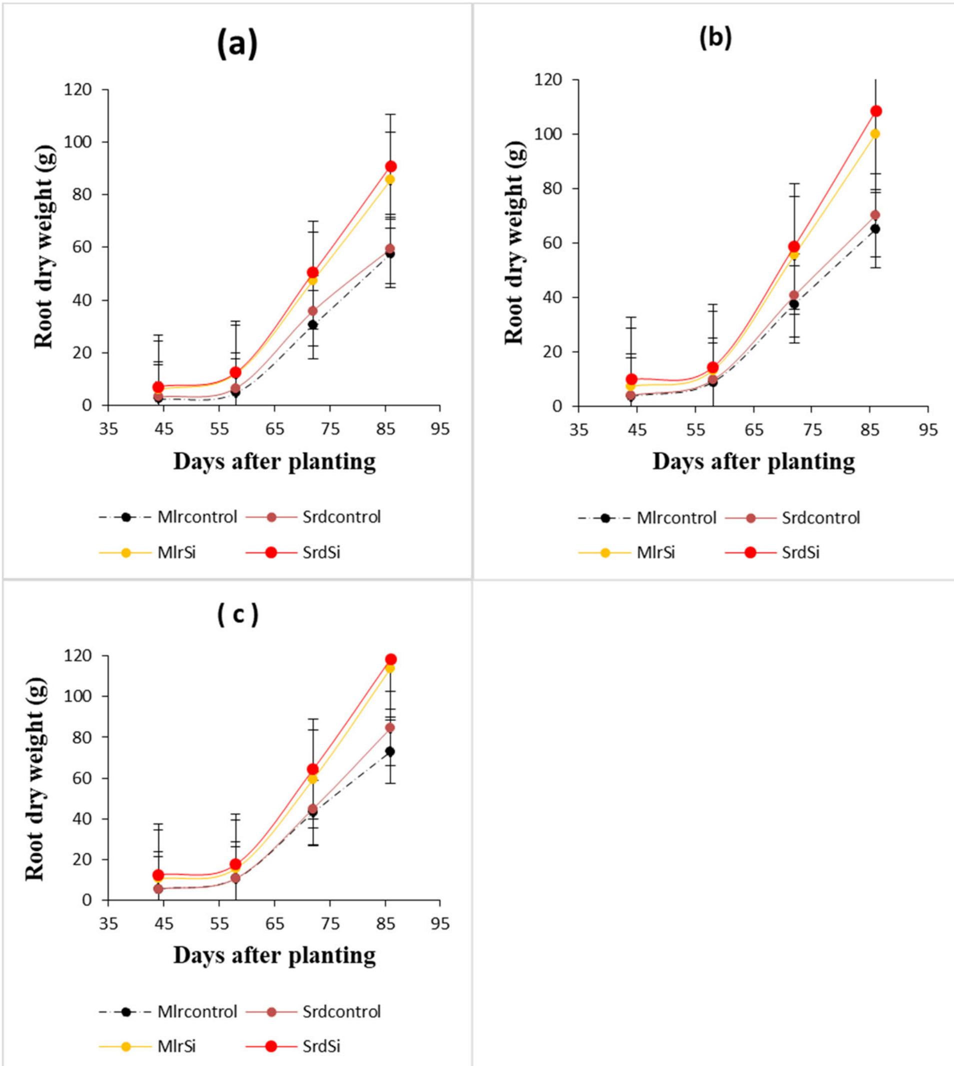

Figure 2. Interactive effects between varieties, water levelsand silicon sorghum root dry weight cycles 2.
Srd = Seredo sorhugm variety; Mlr = Machakos local red sorghum variety Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

However, 60% water regime recorded low stover and grain yield and harvest index compared to 40% water regime (Table 4). Silicon application led to significant differences ($p < 0.001$) in sorghum stover yield, grain yield and harvest index (Table 4). In the two cycles, silicon non-amended treatments had the lowest stover yields recording 6.10 $tha^{-1}$and 4.30 tha^{-1} in cycle one and cycle two. On the other hand, the highest stover yield was obtained in silicon amended treatments recording 9.00 tha^{-1}, 6.30 tha^{-1} in cycle one and two respectively. The lowest grain yields 2.90 tha^{-1}2.20 tha^{-1}were recorded in non-amended treatments in cycle one and two respectively. Silicon amended treatments recorded the highest yield with 5.10 tha^{-1}3.70 tha^{-1} in cycle one and two respectively. The highest harvest index was observed on treatments supplied with silicon 0.36 tha^{-1}, 0.35 tha^{-1}while the treatments without silicon had the lowest recording 0.33 tha^{-1}, 0.34 tha^{-1}cycle one and two as illustrated in Table 4. There was a significant interactive effect at ($p < 0.001$) between varieties, water regimes, and silicon amendment on the grain yield where Seredo variety under 40% water level amended with silicon resulted in the highest stover weight

Table 3. Mean root length (cm) as affected by sorghum varieties, water levels and silicon cycle1 and 2.

Root length (cm)								
Weeks	Week 6		Week 9		Week 12		Week 15	
Cycles	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**
Variety								
Mlr	9.82b	9.62b	31.32a	24.32b	35.19b	30.69b	42.52b	34.05b
Srd	11.62a	9.77a	27.88b	20.88a	38.69a	32.19a	44.05a	38.52a
P-value	***	***	***	***		***	***	***
Water regime (%)								
20wr	8.81c	7.79c	26.47c	19.47c	33.93c	31.37b	40.00c	33.00c
40wr	10.27b	9.24b	29.24b	22.24b	36.87b	28.43c	42.76b	35.76b
60wr	13.07a	12.05a	33.09a	26.09a	40.02a	34.52a	47.10a	40.10a
P-value	***	***	***	***		***	***	***
Silicon								
control	8.91b	7.88b	26.54b	19.54b	34.17b	28.67b	40.57b	33.57b
Si	12.53a	11.50a	32.66a	25.66a	39.71a	34.21a	46.00a	39.00a
***	***		***		***	***	***	***

Means followed by the same letter within the column are not significantly different at alpha = 0.05. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns = not significant, Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); Srd = Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; C = experiment cycle.

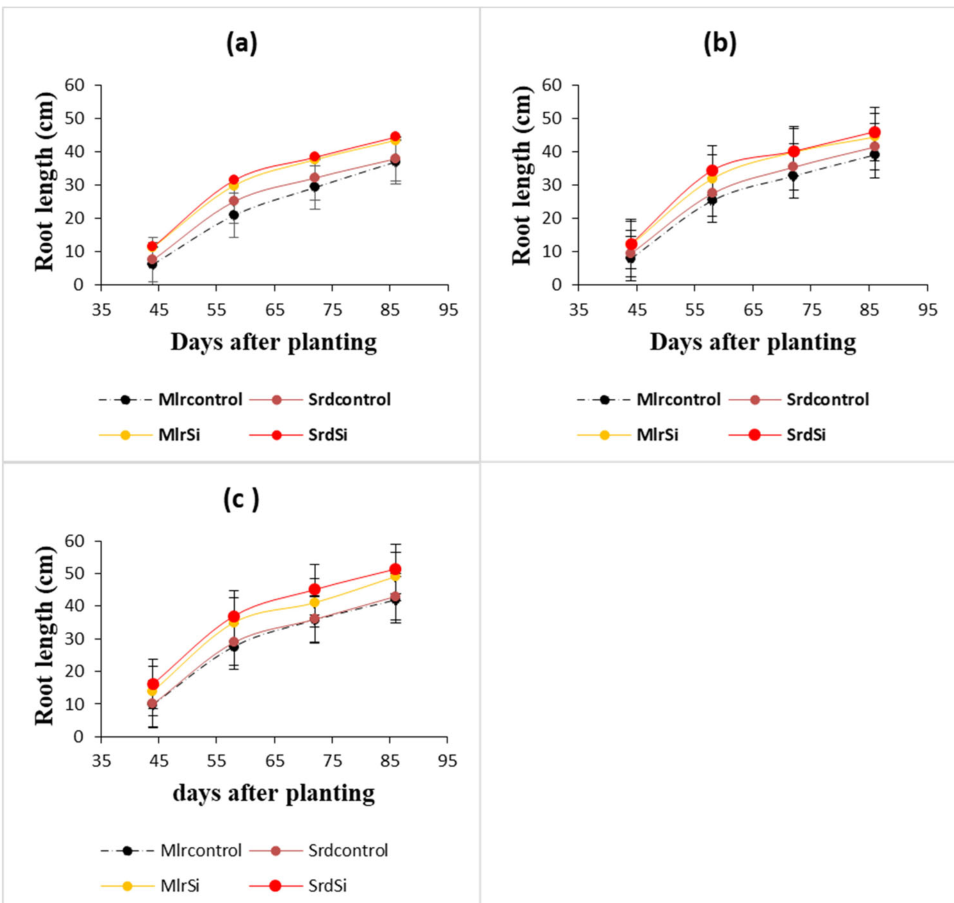

Figure 3. Interactive effects between varieties, water levels and silicon on sorghum root length cycle 1.
Srd = Seredo sorhugm variety; Mlr = Machakos local red sorghum variety Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

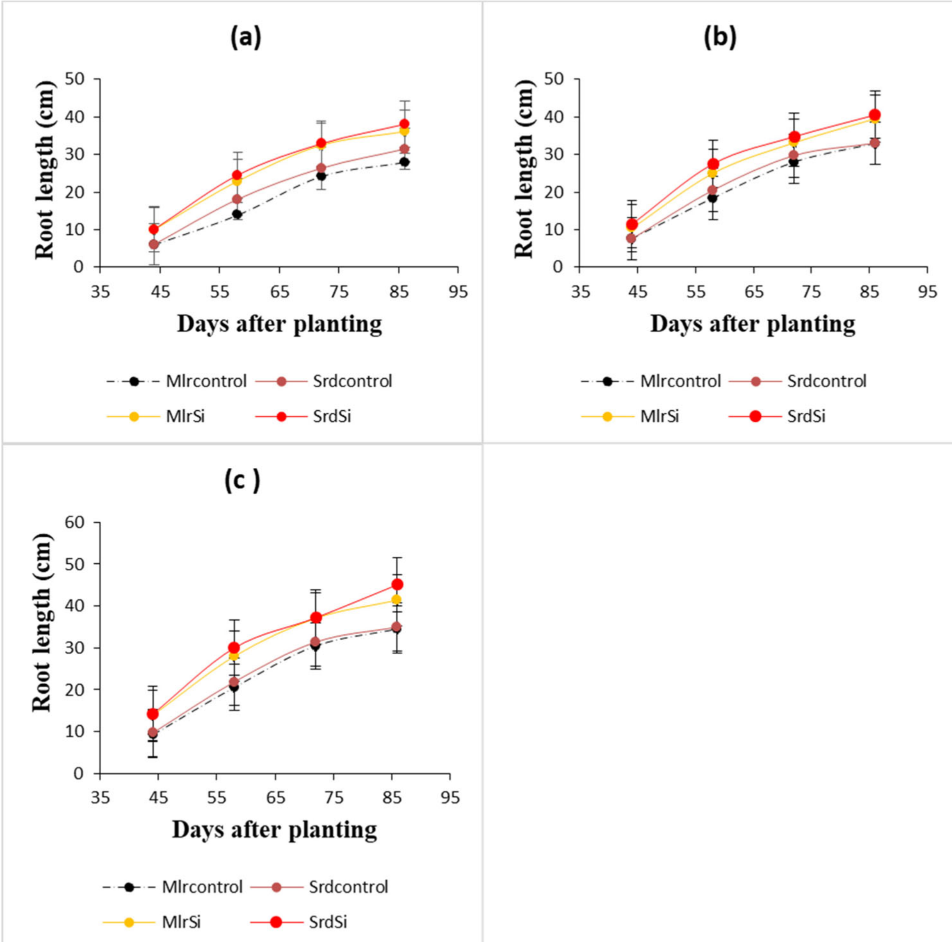

Figure 4. Interactive effects between varieties, water levels and silicon on sorghum root length cycle 2.
Srd = Seredo sorhugm variety; Mlr = Machakos local red sorghum variety Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); (a)= 20% wr, (b)= 40% wr and (c)= 60% wr.

Table 4. Yield and yield components as affected by sorghum varieties, water stress and, silicon in both experiment cycle.

	Stover yield (tha^{-1})		Grain yield (tha^{-1})		Harvest index	
Cycles	C1	C2	C1	C2	C1	C2
Variety						
Mlr	7.2b	5.0b	3.6b	2.2b	0.30b	0.33b
Srd	8.0a	5.6a	4.4a	3.7a	0.39a	0.35a
P-value	***	***	***	***	***	***
Water regime (%)						
20Wr	6.5c	4.6c	3.3c	2.5c	0.36a	0.35a
60Wr	7.8b	5.3b	4.0b	2.9b	0.34c	0.33c
40Wr	8.5a	6.1a	4.8a	3.5a	0.35b	0.34b
P-value	***	***	***	***	***	***
Silicon						
control	6.1b	4.3b	2.9b	2.2b	0.33b	0.33b
Si	9.0a	6.3a	5.1a	3.7a	0.36a	0.35a
P-value	***	***	***	***	***	***

Means followed by the same letter within the column are not significantly different at alpha = 0.05. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns = not significant, Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); Srd = Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; C = Experiment cycle.

Table 5. Interactive effects between sorghum varieties, water stress and silicon on plant Stover yield (tha^{-1}), grain yield (tha^{-1}) and harvest index.

			Stover yield (tha-1)		Grain yield (tha^{-1})		Harvest index	
Varieties	Wr	A	C1	C2	C1	C2	C1	C2
Srd	60	Si	8.22bc	5.70bc	4.65ab	3.85b	0.34abcd	0.39abc
	60	Control	5.88g	3.99fg	2.85 cd	2.22ef	0.31bcd	0.36bcd
	40	Si	9.03a	6.56a	4.82a	4.58a	0.37ab	0.40ab
	40	Control	6.87f	4.30ef	3.23c	2.42de	0.33abcd	0.39abc
	20	Si	7.57de	4.72d	3.50c	2.97c	0.41a	0.41a
	20	Control	2.77i	2.62i	2.07def	1.89g	0.30bcd	0.35 cd
Mlr	60	Si	7.76 cd	5.34c	3.76bc	2.06fg	0.32bcd	0.28e
	60	Control	4.96h	3.23h	1.87ef	1.33hi	0.27 cd	0.29e
	40	Si	8.63ab	5.97b	4.58ab	2.58d	0.33abcd	0.30e
	40	Control	6.07g	3.73g	2.13de	1.45h	0.29 cd	0.28e
	20	Si	7.05ef	4.58de	2.86 cd	1.82g	0.35abc	0.32de
	20	Control	2.24i	2.06j	1.19f	1.11i	0.26d	0.28e
P-value	**V*Wr*A**		***	***	***	***	***	***

Means followed by the same letter within the column are not significantly different at alpha = 0.05. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns = not significant, Si = With Silicon; V = varieties, A = amendements, Wr = Water regime (20%, 40% and 60% field capacity); Srd = Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; C = Experiment cycle.

Table 6. Mean phosphorus uptake, potassium uptake, nitrogen uptake, calcium uptake and magnesium uptake by the plant as affected by sorghum varieties, water levels and Silicon experimental cycle 1 and 2.

	P uptake ($kgha^{-1}$)		K uptake ($Kgha^{-1}$)		N uptake ($Kgha^{-1}$)		Ca uptake ($Kgha^{-1}$)		Mg uptake ($Kgha^{-1}$)	
Cycles	C1	C2	C1	C2	C1	C2	C1	C2	C1	C2
Variety										
Mlr	100.3b	70.9b	57.5b	35.4b	31.5b	18.6b	3131.0b	1925.0b	148.5b	95.6b
Srd	111.1a	102.6a	69.7a	39.5a	34.7a	23.1a	3296.0a	2652.0a	172.1a	114.2a
P-value	***	***	***	***	***	***	***	***	***	***
Water regime (%)										
20Wr	84.7c	76.9c	57.26c	33.2c	28.9c	17.9c	3006.0c	2068.0c	131.3c	92.9c
60Wr	105.6b	86.3b	63.77b	37.7b	33.2b	19.5b	3079.0b	2253.0b	165.4b	102.0b
40Wr	126.7a	97.2a	69.79a	41.6a	37.2a	25.0a	3466.0a	2544.0a	184.2a	119.8a
P-value	***	***	***	***	***	***	***	***	***	***
Silicon										
control	80.1b	68.4b	51.33b	26.6b	26.6b	15.9b	2839.0b	1859.0b	123.6b	86.3b
Si	131.2a	105.1a	75.88a	48.4a	39.7a	25.7a	3589.0a	2718.0a	197.0a	123.5a
P-value	***	***	***	***	***	***	***	***	***	***

Means followed by the same letter within the column are not significantly different at alpha = 0.05. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns = not significant, Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); Srd = Seredo sorhugm variety; Mlr = Machakos local red sorghum variety; C = Experiment cycle.

(9.03 tha^{-1}) and grain yield (4.82 tha^{-1}) in cycle one (Table 5). Although the highest harvest index (0.41) was observed under Seredo interacting with 20% water regime in combination with silicon amendment as shown in Table 5. Machakos local red variety recorded the lowest stover yield (2.06 tha^{-1}) and grain yield (1.11 tha^{-1}) under 20% water regime without silicon amendment cycle two, while the lowest HI (0.26) was observed under the same interactive treatment but in cycle one (Table 5).

Nutrient analysis and uptake in plant tissues

The statistical analysis showed significant differences ($p < 0.001$) on sorghum P uptake by the varieties, water levels and Silicon. Seredo variety resulted in the highest 111.1 kg ha^{-1} and102.6 kg ha^{-1}phosphorus uptake per plant compared to Machakos local red in the two cycles respectively (Table 6). Water stress significantly decreased P uptake by the sorghum in the two cycles whereas optimum P uptake 126.7 kg ha^{-1} was observed under 40% water level cycle one while the lowest

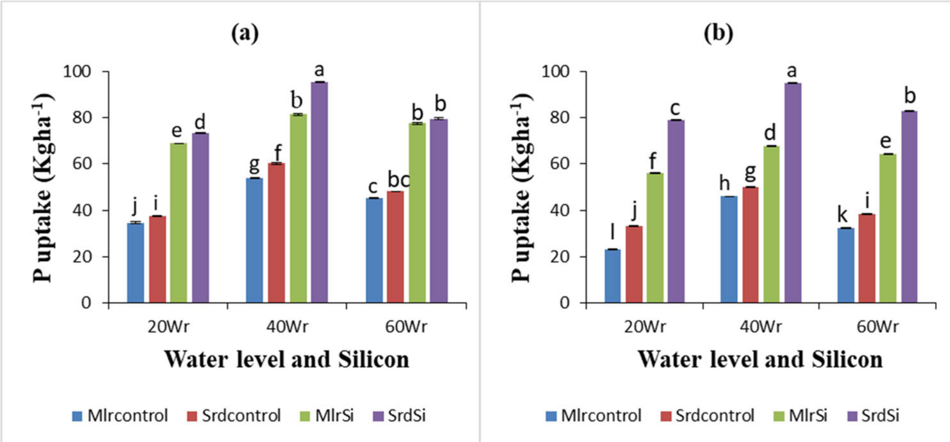

Figure 5. Interactive effects between varieties, water levels and Silicon on sorghum phosphorus uptake cycle 1and 2. Srd = Seredo variety; Mlr = Machakos local red variety Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); (a)=Cycle 1, (b)=Cycle 2.

was recorded under 20% water level cycle two. Silicon significantly increased P uptake by the plant in both cycles compared to the control (Table 6). Interactive effects between varieties, water regimes and silicon on sorghum P uptake at maturity stage was significant ($p < 0.001$) in the two cycles. Application of silicon amendments under 40% water level significantly increased uptake of P by the plant in both cycles (Figure 5). Seredo variety under 40% water level showed more response to P uptake due to silicon amendments exhibiting high P uptake 95.53 kg ha^{-1}(Figure 5) than Machakos local red 81.46 kg ha^{-1} in the cycle one.

Statistical analysis of the study results showed that there was variability in the sorghum potassium uptake due to varieties, water levels and Silicon. Results showed that there were significant differences ($p < 0.001$) in the above-ground K accumulation of the plant due to varieties. Seredo variety had higher 69.7 kg ha^{-1} and 39.5 kg ha^{-1}accumulation of K than that of Machakos local red 57.5 kg ha^{-1} and 35.4 kg ha^{-1}in both cycles respectively (Table 6). Above ground, potassium uptake was significantly ($p < 0.001$) influenced by the water levels. Maximum K accumulation was noted under 40% water regime recording 69.79 kg ha^{-1}in cycle one and whereas the lowest 33.2 kg ha^{-1} was recorded under 20% v in cycle two. Furthermore, the results revealed that silicon amendment significantly ($p < 0.001$) increased sorghum K uptake (Table 6). Moreover, there was significant ($p < 0.001$) interactive differences between varieties, water levels and Silicon on the aboveground accumulation of K. Interaction revealed that Seredo variety and Silicon under 40% water regime resulted in the greatest 76.06 kg ha^{-1}and 45.83 kg ha^{-1}of K uptake in cycle one and two respectively (Figure 6).

The amount of N accumulated by the sorghum exhibited significant variations ($p < 0.001$) due to varieties, water levels and silicon (Table 6). Highest N uptake 34.7 kg ha^{-1}and 23.1 kg ha^{-1} were observed under Seredo variety in both cycles respectively compared to Machakos local red. Total above-ground N of sorghum under 20% water regime was the lowest 28.9 kg ha^{-1},17.9 kg ha^{-1} in the two cycles respectively. Maximum N uptake 37.2 kg ha^{-1}cycle one was recorded under 40%water regime higher than that obtained at 60% water regime 33.2 kg ha^{-1}. Sorghum grown in soil amended with Silicon accumulated significantly ($p < 0.001$) higher N levels than the controls in the two cycles as shown in (Table 6). There was significant ($p < 0.001$) interactive effects between varieties, water regimes and Silicon in nitrogen accumulation by sorghum at maturity stage (Figure 7). Application of 40% water regime and silicon resulted to Seredo variety accumulating the greatest N 32.16 kg ha^{-1}, 20.17 kg ha^{-1} in aboveground biomass in the two cycles respectively.

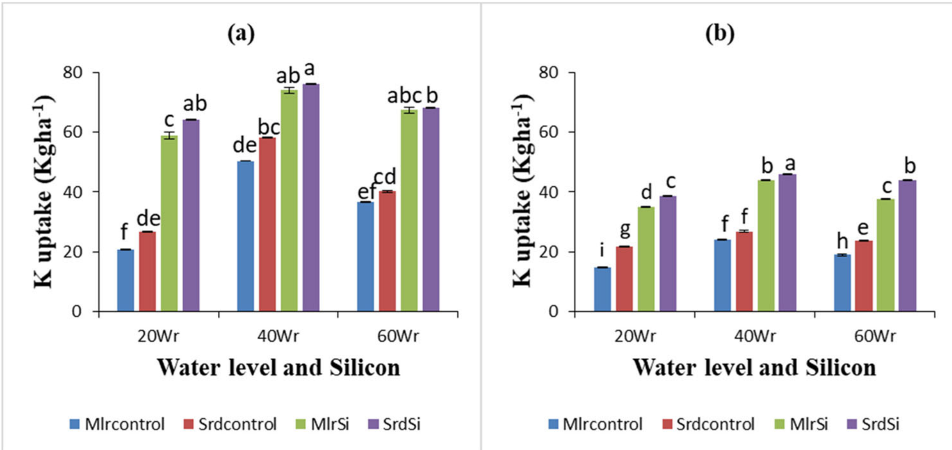

Figure 6. Figure 4.14: Interactive effects between varieties, water levels and on sorghum potassium uptake cycle 1and 2.
Srd = Seredo variety; Mlr = Machakos local red variety Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); (a)=Cycle 1, (b)=Cycle 2.

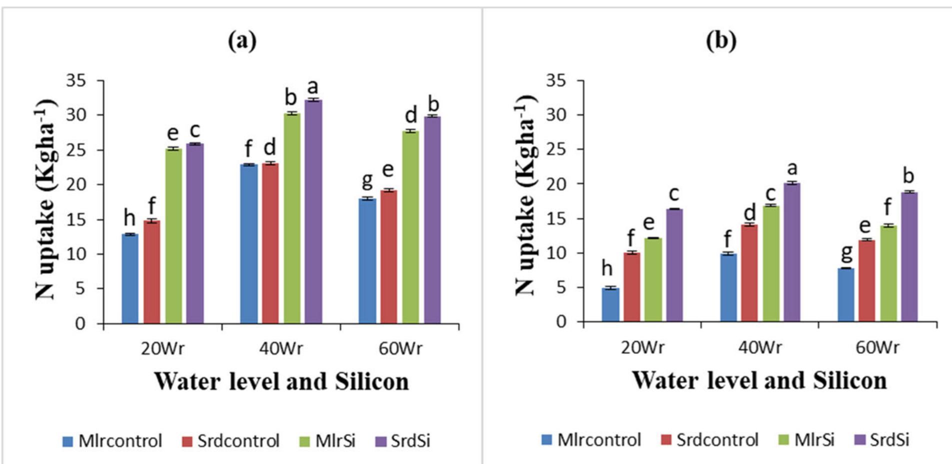

Figure 7. Interactive effects between varieties, water levels and Silicon on sorghum nitrogen uptake cycle 1and 2.
Srd = Seredo variety; Mlr = Machakos local red variety Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); (a)=Cycle 1, (b)=Cycle 2.

The research results indicated that calcium uptake by sorghum plant varied significantly ($p < 0.001$) due to varieties, water levels and silicon (Table 6). Seredo variety recorded the maximum Ca 3296.0 kg $ha^{-1}$and 2652.0 kg ha^{-1} accumulation in the above ground biomass in the two cycles compared to Machakos local red that recorded the lowest Ca uptake 3131.0 kg $ha^{-1}$and 1925.0 kg ha^{-1} in both cycles respectively. Drought stress had significant effects ($p < 0.001$) on Ca uptake since calcium accumulation reduced as the water stress increased and was lowest in plants grown under 20% water regime. Significant differences ($p < 0.001$) were observed on silicon amended plants compared to those grown without silicon. The greatest values of nutrient accumulation 3589.0 kg $ha^{-1}$of the plant were found in plant treated with silicon cycle one, while the lowest was observed under plants without Silicon treatment cycle two. The study results displayed that there were significant interactive differences ($p < 0.001$) between the varieties, water levels and silicon on the plant Ca uptake (Figure 8). The maximum Ca uptake 3919 kg $ha^{-1}$was recorded in Seredo variety amended with Silicon under 40% water regime in cycle one. Similarly, the trend remained so in cycle two as shown in Figure 8.

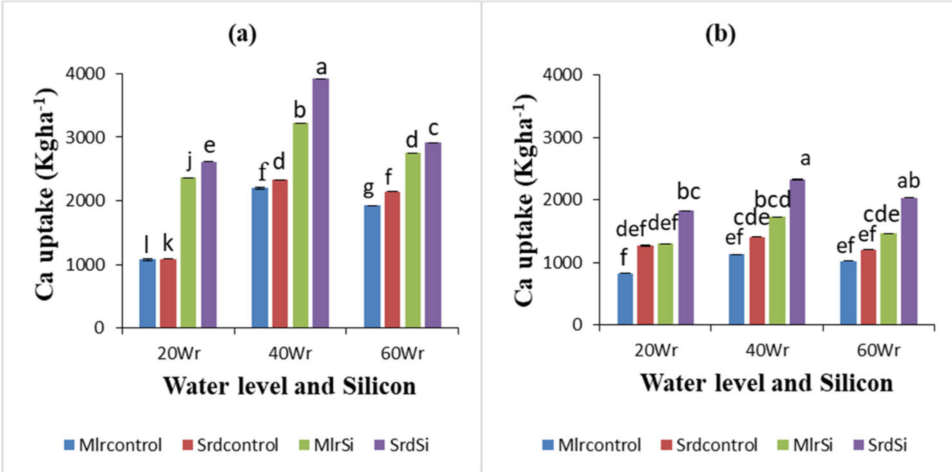

Figure 8. Interactive effects between varieties, water levels and Silicon on sorghum calcium uptake cycle 1and 2.
Srd = Seredo variety; Mlr = Machakos local red variety Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); (a)=Cycle 1, (b)=Cycle 2.

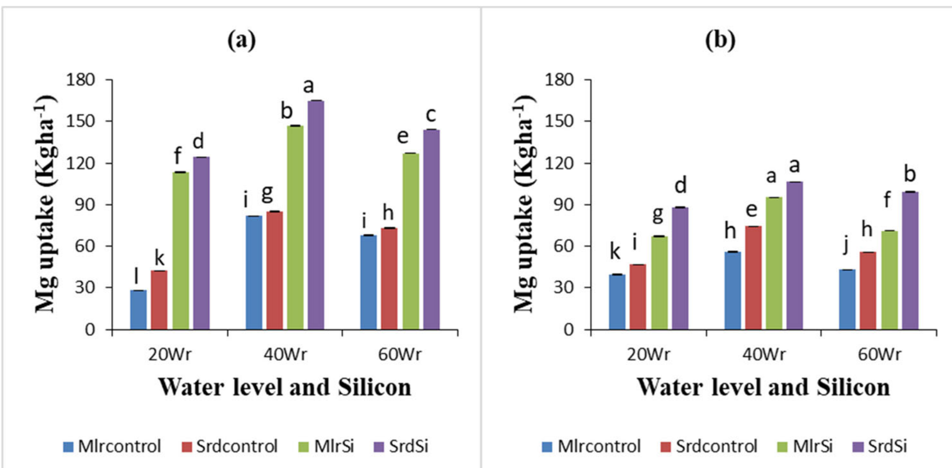

Figure 9. Interactive effects between varieties, water levels and Silicon on sorghum magnesium uptake cycle 1and 2.
Srd = Seredo variety; Mlr = Machakos local red variety Si = With Silicon; Wr = Water regime (20%, 40% and 60% field capacity); (a)=Cycle 1, (b)=Cycle 2.

There were significant ($p < 0.001$) effects of varieties, water levels and silicon on magnesium plant uptake both cycles as illustrated in Table 6. Maximum Mg uptake 172.1 kg ha^{-1}was observed in Seredo variety in cycle one while the lowest uptake 95.6 kg ha^{-1}was recorded in Machakos local red variety cycle two. Drought stress significantly affected Mg accumulation in the above ground biomass as presented in Table 6. Silicon amendment recorded high uptake of mg 197.0 kg ha^{-1}and 123.5 kg ha^{-1} in the two cycles respectively than non-Silicon amended plants. Based on the results of the study, there was a positive interaction between the varieties, water levels and silicon on sorghum Mg uptake (Figure 9) in the two cycles. The highest uptake of Mg165.02 kg ha^{-1}, 106.4 kg ha^{-1}was recorded in Seredo variety and silicon amended treatments under 40% water regime in both cycles respectively.

Discussion

Plant growth parameters

The study demonstrated that improved variety (Seredo) performed better than local variety (Machakos local red) in terms of root dry weight (Table 2) this could be due to their differences in genetic make-up. This study showed that water is an important factor in determining root dry weight. Increased moisture levels resulted in increased root dry weight (Table 2). This observation was in support of some previous studies (Yang et al. 2011). Blum and Arkin (1984) recognized soil moisture as a key factor affecting sorghum root distribution in the soil profile. Cakir (2004) also, reported that total dry matter accumulation was affected by soil water deficit. Besides report by Ndiso et al. (2016) indicated that a decrease in root and plant growth could be attributed to reduced cellular expansion and deterioration in photosynthesis resulting from water stress.

The findings from the study also displayed that silicon amended treatments were more superior in root biomass accumulation than those not amended (Table 2). These confirmations signify that silicon has an enhancing influence on plant production (Guntzer et al. 2012). Sivanesan and Park (2014), Khenizy and Ibrahim (2015) reported that Silicon plays a role in improving growth and yield of various plants by alleviating stress and nutrients imbalance.

The findings of the study revealed that low moisture in the soil (20%) (Table 3) compromised the root length of the sorghum plant since root length in the treatment ragged behind. According to Moreira et al. (2018) lack of water indirectly or directly affects several cellular physiological processes in plants. Also, Abdel-Salam, Alatar, and El-Sheikh (2018) reported that water stress is a universal problem that reduces plant growth, flower yield and other physiological processes of the majority of the field and ornamental economical crops. Increased root length on silicon treatments showed the benefits of silicon in improving cell turgor, cell wall metabolism and enhancement of cell enlargement as reported by (Ramy and Atef 2019). This is because silicon is an important role in enhancing water uptake and adequate nutrients supply (Ramy and Atef 2019).

Yield and yield component

Highest stover and grain yields and harvest index were recorded in Seredo variety than Machakos local red in both cycles (Table 4). This variation could be due to Seredo being an improved variety. Seredo variety gave the highest harvest index (Table 4) although it was shorter than Machakos local red variety. The results corroborated with those of (Prihar and Stewart 1991), who reported that the harvest index was independent of plant size. Water stress decreased the grains yields, above-ground biomass and harvest index. The yield under 20% water regime was lower than the yield under 40% water regime which recorded the highest yield. This study agrees with the results of Cakir (2004) who reported that the occurrence of low soil moisture during development stages of corn may reduce final grain and above-ground biomass. Also, Fan et al. (2020) reported that plants under water stress closes their stomata to reduce water loss through transpiration, this causing restriction of carbon dioxide into the plant reducing photosynthesis performance hence low production. Low soil moisture can also attribute to chlorophyll degradation and reducing the rate of its synthesis thus reducing the performance of the crop up to the yield (Marenco and Lopes 2005). Besides, the harvest index was low due to moisture stress. The results are similar to those of Wenzel and Van Rooyen (2001) who reported that severe moisture stress resulted in an average yield loss of 44% thus affecting the harvest index and on average, resistant varieties to moisture stress and intermediately resistant varieties were reported to have been resistant to harvest index loss.

The study revealed that supplementation of soil with silicon ameliorates effects of drought stress in sorghum by significantly improving the growth and its productivity. Plants supplied with silicon had high grain and stover yield (Table 4) even under the lowest water level in the soil.

These results concur with the report by Shen et al. (2010) that indicates that silicon could alleviate soybean damage under low soil moisture due to increased chlorophyll contents and photosynthesis. The findings are in agreement also with those obtained by other authors. For instance, Fawaz and Mohammad (2013) highlight that silicon helps in the maintenance of water status in water-stressed chickpea. Zhang et al. (2017) also reported that silicon improves physiohormonal attribute of soybean that help in the mitigation of water stress as a result of improving the yield. Also, studies by Emam et al. (2014) reported ameliorative effects of silicon on water stress and its mechanism in the alleviation of low soil moisture that leads to high yield production. Moreover studies by Liu et al. (2015) showed the ability of silicon to regulate aquaporins genes, the ability that could be partly responsible for water uptake in sorghum under drought thus enhances water stress resistance. Silicon can also help in retaining water in plant tissues by reducing transpiration and partial blocking the transpiration bypass flow (Gunes et al. 2008) which improves water economy of plant and maintain an efficient absorption of mineral elements, therefore, improving yield.

Nutrient analysis and uptake in plant tissues

This superiority of Seredo variety in P uptake as shown in Table 6 could be attributed to its dense and prolific roots compared to Machakos local red that supported the higher acquisition of the P. Results also showed that water deficit considerably decreased P uptake by the plants. Water stress has been reported to decrease P concentration in plant leading to a decrease of soil pore diameter that reduces P mobility by Celiktopuz et al. (2021). Similarly, Hosseinzadeh and Ahmadpour (2018) study indicated that farmlands facing moisture stress generally have deficiencies of N,P,Ca and K. Silicon supplementation led to better uptake of P reducing the injurious effects of the water stress. Silicon amendments demonstrated to be vastly beneficial improving P uptake by the plant and its translocation to above-ground biomass.

The results showed that nitrogen uptake differed broadly in both varieties of the sorghum used. This implies that the varieties differed in their ability to utilize the amendment supplied during the experiment. Sorghum grown under the lowest water level (20% water regime) had the lowest N uptake (Table 6). This is in support of report (Celiktopuz et al. 2021) who indicated that the occurrence of nitrogen deficiency is linked to water deficit in the soil. Additionally, Tadayyon et al. (2018) described that availability of water increases absorption of micronutrients in the plant tissues due to accessibility of N in the soil. However, there was an observed decrease in N accumulation with increasing water level (60% water regime) (Table 6). This could be as a result of nutrient dilution in the total dry matter which is likely to be associated with dilution factor (Faloye et al. 2019). Silicon amendments increased N uptake by the sorghum plant as revealed by the study results. This corresponds with the study by Neu et al. (2017) who reported that treating wheat plants with silicon amendments boosted nutrient use efficiency of the plant at all levels. Further, Neu et al. (2017) added that silicon can improve nutrient uptake by wheat plants especially nitrogen and phosphorus. Correspondingly, Alsaeedi et al. (2019) specified that silicon improves uptake of many nutrients such as nitrogen.

Above ground decreased K (Table 6) in sorghum plant could be attributed to low moisture in the soil that reduced its solubility hence decreasing its absorption by plant roots (Hosseinzadeh and Ahmadpour 2018). Additionally, drought could have caused a reduction in the mobility of the K^+ in the soil and activity of root membrane transporters (Shabala and Pottosin 2014). Also, drought is known to increase the radial and axial hydraulic resistance of roots, which reduces root hydraulic conductance affecting water transport thus low nutrients absorption. Nevertheless, the results of the study contradicted with Tadayyon et al. (2018) whose report indicated that an increase in drought stress increased K concentration in the plant tissues. Moisture deficit stress decreased K uptake by sorghum plants as revealed by the study results. Similar results were obtained by Ibrahim et al.

(2016), Elrys and Merwad (2017) and Markovich et al. (2017). Potassium element is known to play vital roles to plants such as plant growth, opening and closing of the stomata, turgor and osmo-regulation regulator, photosynthesis regulation as well as improve drought tolerance (Tadayyon et al. 2018). Uptake and accumulation of K in the sorghum plant tissue intensely corresponded to the amendments of silicon as shown from the study results. Application of Silicon intensively increased K uptake compared to the control. Similarly, Kaya et al. (2006) and Dong et al. (2018) reported that silicon under water stress increased K concentration in Maize. Also, Alsaeedi et al. (2019) research revealed that silicon nutrition increased K uptake by cucumber, sugarcane and barley. As well, Sudhakar et al. (2006) demonstrated that silicon enhances uptake of K. Conversely, the results from this research exhibited that silicon nutrition was found to be efficient in improving K uptake. This could be elucidated as silicon increases the activity of H^+- ATPase which increases cellular uptake of K by activating K^+ channels and carriers across the plasma membrane.

The significant differences in the uptake of the Ca (Table 6) by the plant shows that there was a varietal difference in the accumulation of the Ca by the sorghum plants. This is in support of Tadayyon, Nikneshan, and Pessarakli (2018) study that indicated that calcium concentration in tomatoes varied with the cultivar. The research results exhibited that decrease in soil moisture reduced the accumulation of Ca in aboveground biomass of the sorghum. Calcium ions are vital secondary messengers in the plants that are known to stimulate physiological functions in the cells of plants in response to water stress and regulates the growth of the polar cells that help the plant in adaptation to stress (Tadayyon et al. 2018). The reduction in Ca uptake shown by the study is consistent with the results obtained by Celiktopuz et al. (2021) who reported that water stress decreased N, P, K, Ca and Mg concentration in strawberry. Also, Celiktopuz et al. (2021) and Sardans et al. (2008) found similar results. Plant's nutrients are transported from soil to the roots *via* diffusion thus low soil moisture reduces the absorption and uptake of nutrients (Celiktopuz et al. 2021). Moreover, the results from the study disagree with Jaleel et al. (2007) studies that reported that Ca concentration increased under water stress conditions. Silicon amended plants gave the greatest values of Ca uptake compared to control that gave the lowest uptake. These results were in concurrence with results by Elrys and Merwad (2017) and Merwad (2018) who reported that silicon amended plants had more Ca uptake than non-amended.

The results showed that there was a varietal difference in their Mg uptake with Seredo variety recording higher Mg values than Machakos local red. Results of the study (Table 6) showed that an increase in water stress decreased Mg accumulation in the sorghum aboveground biomass. These discoveries agree with Tadayyon et al. (2018) who reported that under drought stress Mg concentration in tomato plant was found to decrease. Additionally, Celiktopuz et al. (2021) underlined that the severity of drought stress reduced Mg concentration of plants. Also, Moradtalab et al. (2019) research indicated that generally low soil moisture negatively affects the nutritional status of the plants causing deficiencies in Zn, Mn, Cu and Fe. Regarding the role of silicon, more Mg uptake was recorded under the treatments amended with silicon compared to treatments without silicon. Greger et al. (2018) described that silicon affects the availability, uptake and translocation of nutrients from shoots to roots of plants. Also, reported that silicon nutrition increased the uptake and translocation of Mg in plants. Similarly, previous studies by Alsaeedi et al. (2019) and Neu et al. (2017), mentioned that silicon improves nutrient uptake in plants.

Conclusion

Sorghum cultivation is extremely important in the world. Therefore, it's necessary to enhance sorghum production under adverse climatic conditions. It can be concluded that Silicon can be used to influence sorghum growth, yield and nutrient uptake under moisture stress. Findings from this research indicate that soil moisture might have a crucial role in enhancing Si nutrient availability, thereby leading to more accumulation.

Disclosure statement

The authors declare no conflict of interest.

Funding

The authors are grateful to the National Research Fund for funding part of the research work.

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