Performance of selected soybean (*Glycine max*) varieties grown in Kalahari sands under different irrigation regimes

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Abstract
The increased demand for soybean (Glycine max (L.) Merrill) for human and animal consumption, vegetable oil extraction, and soil fertility improvement through biological nitrogen fixation has led to the expansion of its production to even marginal areas under rainfed farming systems. Production in dryland areas is constrained by drought, among other challenges. This study, therefore, sought to assess the performance of selected soybean varieties that were sourced locally and regionally and grown in Kalahari sands under different watering regimes before flowering. Seven soybean varieties (Kabanyolo 1, Maksoy 1N, Maksoy 4M, Namsoy 3N, Nam 1, Solitaire, and UG5) were studied for growth and yield performance under various watering regimes. The study was conducted at Lupane State University experimental plots. Soybean plants were grown in 9 l buckets arranged following a randomized complete block design with seven varieties in three blocks. Three irrigation regimes were used (soil saturation capacity, 50% soil saturation capacity, and 25% soil saturation capacity) up to flowering, after which the plants were sufficiently rainfed and supplemented through irrigation up to physiological maturity. Data were collected at physiological maturity (stem height, pod length, pods per plant, number of seeds per pod, nonviable pod percentage, 100-seed weight, and total grain weight per plant). Irrigation regimes and variety independently influenced most parameters that were assessed in soybeans. All the variables were significantly affected except for the % nonviable pod under the three irrigation regimes. Maksoy 4M, Nam 1, and Namsoy 3N performed better than the other varieties, while UG5 and Solitaire were the least performers in most of the variables measured. Irrigating to 50% soil saturation capacity and below suppressed growth and yield. Varieties that outperformed others can be used by breeders to improve their tolerance to pre-flowering drought stress.

Keywords: drought stress, yield components, preflowering, soil saturation capacity

Introduction

Rainfed farming systems widely practiced in semiarid tropics (SATs) and other dryland parts of the world are increasingly constrained by climate change and variability [1, 2]. The most salient effects of the unfolding phenomenon in the region are the shift in rainfall patterns characterized by reduced amounts and uneven spatial and temporal distributions. Zimbabwe is one of the countries that has been hardly hit by the impacts of climate change and variability given its location. The southern parts of the country, such as Lupane, which is in agroecological zone IV (450-650 mm of rainfall), are characterized by Kalahari sands and severe drought episodes. Drought was defined by [3], as a period of low rainfall below normal and insufficient availability of soil moisture. Thus, the need to shift to more adaptive farming methods, such as early or dry planting, before the onset of effective rains, especially for crops of economic and food security importance. However, in addition to the prevailing climatic conditions in a particular area, the soil type also plays a significant role in determining the level of drought stress endured by crops.

Soybean (*Glycine max* (L.) Merrill is a typical important crop known to be sensitive to drought stress but its worldwide demand has seen its production extending to rainfed conditions in dryland regions of the SAT, including Zimbabwe [4]. Fagerai *et al.*, [5], argued that soybean has a wide spectrum of adaptation to diverse climatic and edaphic conditions, hence its prominence in rainfed farming systems by resource-poor farmers. Soybean is a very important legume crop that provides a cheap source of vegetable oil and proteins for both humans and livestock [6]. It is also ideal for soil improvement through its ability to biologically fix nitrogen. The world annual production of soybean is 334 million metric tons, and Brazil is the largest producer worldwide, followed by the United States and Argentina [7]. In Africa, the leading producers are Nigeria, South Africa, Uganda and Zimbabwe [8]. South Africa, a neighbour close to Zimbabwe produced 1.45 million metric tons of the crop in the 2017/18 agricultural farming season [9]. In Zimbabwe, soybean contributes approximately 2-3% to the agriculture gross domestic product (AGDP) and is cultivated largely in Mashonaland Central, Mashonaland West and Mashonaland East [10]. This compared well with the average global annual growth rates of 2.5% from 2010 to 2020 [11].

Drought stress, which often coincides with heat stress [12], is reportedly a major constraint on the growth and yield of soybean crops [13]. However, as in most crops, the effects of moisture stress on growth and yield are dependent on genotype, growth stage, timing and intensity of stress [14, 15]. Soybean requires 450-750 mm of water in a growing season ranging from 90-120 days, although it varies with variety, atmospheric temperatures and soil conditions [16]. The susceptibility of soybean to drought stress during its reproductive stages (onset of flowering to pod filling) has been extensively researched and reported [17, 18, 19, 20]. Some of the reported detrimental effects of water deficit during reproductive stages include flower abortion, which leads to a reduced number of pods, number of seeds per pod, total weight per seed and consequently reduced yield [21, 22, 23], indicated that the water requirements of soybean crops are low during the early vegetative growth stage, gradually increases and reach a maximum during the reproductive stage and then declines as the plants mature. However, moisture stress at any given growth stage may be injurious to the physiology, morphology and biochemistry of any crop depending on the intensity and duration, consequently reducing growth and yield [24, 25]. As such, the vegetative stage is not exempted from the effects of drought, although the ultimate yield is of great concern.

Drought stress during the vegetative stages affects physiological processes such as cell division and enlargement, which are key in leaf expansion, stem and root elongation [26]. Other physiological processes, such as gaseous exchange, transpiration, photosynthesis and translocation, are also very sensitive to drought stress [27]. Reduction or total arrest of such physiological processes will certainly result in poor crop growth and yield [18] confirmed that preflowering drought stress shortens the reproductive stages of soybean plants, causing early flowering and pod formation, which results in severe yield losses. Thus, there is a need for drought-tolerant varieties, even at vegetative stages. This will enable minimum supplementary irrigation to save on already scarce water for early planted crops before the onset of rains without any significant yield losses. Early planting is a promising adaptive farming strategy in the face of climate change and variability that has seen delays in the onset of the rainy season in the southern parts of Africa. In as much as the effects of drought on both vegetative and reproductive stages of soybean have been studied, differences in cultivars, drought intensity and experimental conditions result in variation in results. A number of soybean varieties have been developed in eastern and southern Africa by various seed companies, research institutions and private breeders since the inception of soybean breeding programs, but there is less empirical evidence to support farmers' choice of drought-tolerant varieties for marginal areas [28].

Genotypic variations in soybean responses to drought depending on intensity, duration and timing in soybean cultivars that show tolerance have been established [15]. However, there is very little that has been done to characterize soybean varieties used in this study in terms of growth, yield and water requirements, particularly on Kalahari Sands, which dominate the southern parts of Africa. Continued drought spells have caused soybean production to be solely centered on farmers who can afford irrigation throughout the season, while resource-poor farmers who depend on rainfed production encounter difficulties in their farming activities. According to [20], negative rainfall deviations from the average by at least 20% are termed meteorological drought, resulting in a soil moisture deficit leading to severe agricultural drought. This could be more severe in arid areas that are dominated by highly porous soils, such as Kalahari sands, which require high and well-distributed rainfall or supplementary irrigation throughout the season to avoid drought stress. However, if soybean is successfully grown in soils with inherently poor fertility, it can go a long way in improving the soil at reduced cost, especially for resource-poor farmers who cannot afford inorganic fertilizers. Moreover, as supported by [29], the assessment of crop responses to different soil moisture levels and growth stages can provide better insights into irrigation water exploitation and possibly better yields even under water-limited conditions. This study therefore sought to assess the performance of selected soybean varieties that were sourced locally and regionally grown in Kalahari sands under different irrigation regimes before flowering.

Materials and Methods

Study site description

The study was conducted at Lupane State University (LSU) experimental plots (18.9300°S, 27.7593°E) during the 2019/2020 season. The mean annual temperature in Lupane is 21.4°C, and the mean annual rainfall is 581 mm or 48.5 mm per month. The driest month is June, with 0mm of rainfall. In January, the precipitation reaches its peak, with an average of 137 mm. The warmest month of the year is October, with an average temperature of 25.5°C. At 15°C on average, June is the coldest month of the year. The soil type in Lupane State University experimental plots is sandy and loamy sand derived from Aeolian Kalahari Sands. The site was selected as a representative semiarid area of Matabeleland North in Zimbabwe.

Planting and experimental design

Seven varieties of soybeans, Kabanyolo 1, UG5, Maksoy 4M, Maksoy 1N, Namsoy 3N, and Nam 1, were obtained from Uganda, and one variety Solitaire was used as a control from the local markets. 9 *l* plastic pots were ¾ filled with Kalahari sands obtained from one of the experimental plots at LSU, and five seeds were planted in each pot. Planting was done at the beginning of October to avoid rains at vegetative stages. Then, thinning was performed after 3 weeks to 2 plants per pot. No fertilizer was added, and the source of fertilization was assumed to be the residuals of cattle dung from the previous season, which is recommended for legumes under smallholder farming where inputs are limiting. A potted two factorial experiment was set up following a randomized complete block design with 7 varieties each planted in 9 litre buckets as treatments in 3 blocks. Blocking was done according to sun orientation. Three irrigation regimes were used as follows: (T1: 2500 ml per week, which was determined as the soil saturation capacity of the soil that was used, also taken as a control), T2: 50% saturation capacity, i.e. water applied in T1 (1250 ml per week) and T3: 25% of soil saturation capacity (625 ml per week), where two equal splits of the amounts were applied twice a week (Days 1 and 4 of the week). The saturation capacity of the soil was determined using an adapted direct gravimetric method described by [30]. Three buckets were filled with soil, and water was poured in until it started dripping through holes from the bottom of the pots. The amount of water that had been poured in each bucket was recorded, and an average was calculated and then taken as the saturation capacity of the soil.

Table 1: Descriptions of watering treatments

Treatment	Description
T1	soil saturation capacity
T2	50% soil saturation capacity
T3	25% soil saturation capacity

Irrigation was done twice a week. Irrigation treatments were applied when the plants attained 2-3 true leaves and stopped at the R_1 (onset of flowering) stage. After this stage, all the potted plants were sufficiently rainfed and supplemented through irrigation where and as when necessary. The pots were kept in an open space throughout the trial period.

Measurements and data collection

Growth parameter

Plant stem height at physiological maturity

Stem height was measured at physiological maturity using a tape measure directly from the soil to the tip of the plant.

Yield and its components

Pod length

Five pods were picked at random, and their length was measured using a ruler at physiological maturity.

Pod Number/plant

Pods were plucked from individual plants at physiological maturity and then counted.

Number of seeds/pod

Ten pods were randomly selected from each treatment, and then the seed number per pod was determined. The total was average and the figure obtained.

Percentage Non-viable pods = $\frac{\textit{empty pods}}{\textit{total pods}} \times 100$

This was determined after harvesting by counting empty pods produced and related them to the total number of pods per plant.

Seed yield (grams per plant)

After harvesting, shelling was performed, and seeds were put in separate containers. All the seeds produced per plant were weighed on an analytical balance.

100 seed weight

The plants were harvested separately, and pods were sun-dried for one week and then shelled. One hundred seeds from each plant were weighed on an analytical balance.

Data analysis

Count data were transformed using square root transformation, and then all data were subjected to normality tests using the Shapiro-Wilk tests and homogeneity of variance using Bartlett's test to test assumptions of analysis of variance (ANOVA) in GenStat version 13th edition [31]. Data were then subjected to a two-way ANOVA following a (7 x 3) factorial in an RCBD with three blocks using the following statistical model:

$$Y = \mu + \alpha + ß_i + ßj + ß_{ij} + \tau$$

Where:

Y = response

μ = mean

α = effect of blocking

$ß_i$ = effect of variety

$ßj$ = effect of irrigation regime

$ß_{ij}$ = effect of interaction of variety and irrigation regime

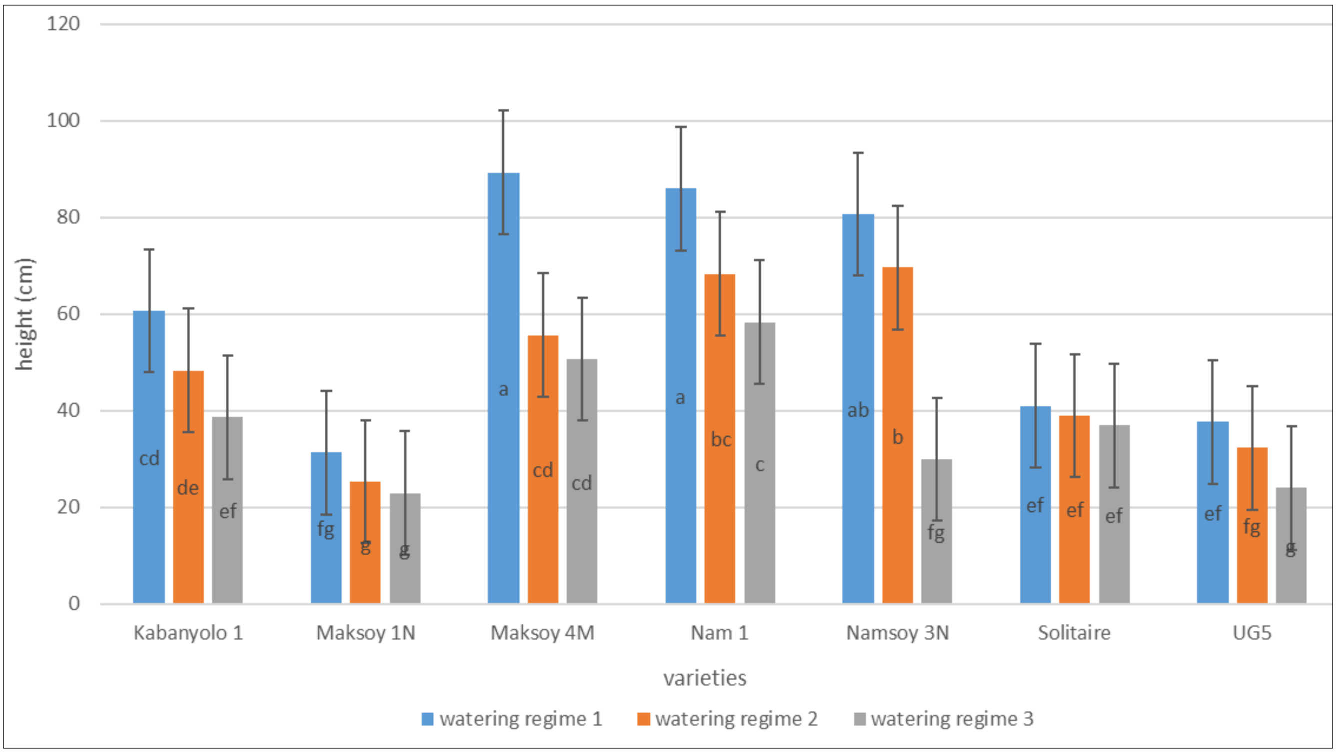
τ = residual error

Where significant differences were detected, means were separated using Fischer's least significant differences (LSD) as a post hoc analysis at the 95% level of significance.

Results and Discussion

Effect of watering regimes on the height of soybean genotypes

Analysis of variance results revealed that there were significant differences ($P<0.01$) for all the sources of variation that were assessed, i.e., variety, watering regimes, and variety × watering regime interactions, on stem height measured (in cm) at physiological maturity. Watering to soil saturation capacity (2500 mm) a week only promoted significantly higher stem height growth in Maksoy 4N and Nam1 varieties, which was significantly different from even the second watering regime (50% of soil saturation capacity). However, these two varieties still had significantly taller plants under the treatment where the least amount of water (25% of soil saturation capacity) was supplied when compared to the other five varieties. The Maksoy 1N and Solitaire varieties did not show any differential response to the three watering regimes in terms of stem height, while Maksoy 1N and UG5 produced the shortest plants under all three watering regimes.



Bars indicated using different letters were significantly different (P < 0.05). Vertical bars on each bar denote the LSD (12.768) that was used to separate means.

Fig 1: Interaction of watering regime and soybean varieties on stem height at physiological maturity

The differential response of soybean varieties to the amount of water supplied in terms of stem length in this study was influenced by the type of growth habit assumed by soybean varieties. In Maksoy 4M and Nam 1, varieties thought to be indeterminate showed some significant sensitivity to reduced amounts of water supplied through reduced stem elongation. Water stress that occurs before flowering usually interferes with normal stem height because it affects cell division and elongation, which are important physiological processes in the growth of plants. The effect of variety on crop performance was also postulated by [23], who found that different soybean varieties vary in their response to drought stress. This was observed in varieties such as Nam 1 and Maksoy 4M, which grew taller than other varieties under water-depressed conditions. A study conducted by [29], reported that plants exposed to water deficit during the branching stage had the shortest final height.

Influence of variety and watering regimes on soybean yield and its components

In all the yield components that were assessed, no significant interactions were observed between variety and watering regime ($P \geq 0.05$). However, significant independent effects of variety and watering regime were observed in five yield components that were assessed except for % nonviable pods (Table 2). Watering regime had no significant effect on nonviable pod percentage, while variety type had a significant effect. As depicted by the mean square error, variety and watering regime contributed more to the number of pods per plant, pod length, 100 seed weight and seed yield.

Table 2: ANOVA results for yield components in each assessed under three watering regimes in seven soybean varieties

Sources of variation	Degrees of freedom	Mean squares					
		Podplant^{-1}	Seedspod^{-1}	Pod length (cm)	% non-viable pods	100 seed weight (g)	Seed yield (g per plant)
Block	2	962.3	0.143	0.610	0.016	20.82	836.3
Variety	6	13701.5***	0.439*	0.408***	0.40*	47.63***	1189.1***
Watering regime	2	14611.0***	1.714***	0.841***	0.007ns	159.08***	2376.9***
Variety × watering regime	12	963.1ns	0.232ns	0.126ns	0.048ns	3.54 ns	112.7 ns
Residual	40	687.9	0.143	0.082	0.012	8.33	116.0
Total	62	152428.9	14.86	10.14	1.079	1021.169	21553.3

*** <0.001; **< 0.01; *<0.05; ns- not significant

Influence of variety on yield and its components

All the variables were significantly influenced by the type of variety ($P < 0.05$), as shown by the summarized ANOVA results for the assessed variables (Table 3).

Table 3: Summary table of means for yield components assessed for seven genotypes

	Means of various yield components					
Varieties	**Pods/plant**	**Seeds/ pod**	**Pod length (cm)**	**%non- viable pods**	**100 seed weight (g)**	**Seed yield (g per plant)**
Kabanyolo 1	86.4b	2.44ab	4.38b	0.18b	12.40b	34.5b
Maksoy 1N	109.4ab	2.67a	4.41b	0.30a	11.77b	21.3c
Maksoy 4M	115.7a	2.44ab	4.59ab	0.15b	15.08a	39.0ab
Nam 1	114.7a	2.33ab	4.34bc	0.21ab	15.49a	49.4a
Namsoy 3N	108.1ab	2.56a	4.72a	0.16b	16.54a	41.2ab
Solitaire	19.6c	2.22b	4.23bc	0.18b	10.08b	19.9c
UG5	41.4c	2.00b	4.07c	0.08b	13.98ab	22.3bc
Overall mean	85.0	2.381	4.397	0.180	13.34	32.5
Fpr	<0.001	0.014	<0.001	0.011	<0.001	<0.001
LSD (0.05)	24.99	0.360	0.273	0.106	2.75	12.28
%CV	30.8	15.9	6.5	62.0	21.2	39.6

Means shown using different letters were significantly different at p<0.05

Influence of watering regime on yield components in soybeans

Watering treatments that were assessed had a significant (P < 0.05) influence on all the yield-related variables that were assessed in the study except for % nonviable pods. The means of yield and its components are shown in Table 4.

Table 4: Means of yield components assessed in soybeans under three watering regimes

	Means of six yield components					
Watering regimes	**Pods/plant**	**Seeds/ pod**	**Pod length (cm)**	**%Non- viable pods**	**100 seed weight (g)**	**Seed yield (g per plant)**
Saturation capacity	107.7a	2.67a	4.58a	0.18	16.34a	43.3a
50% saturation capacity	91.3b	2.38b	4.43a	0.16	13.68b	32.1b
25% saturation capacity	56.1c	2.095c	4.18b	0.195	10.84c	22.1c
Overall mean	85.0	2.381	4.397	0.180	13.62	32.5
Fpr	<0.001	<0.001	<0.001	0.853ns	<0.001	<0.001
LSD (0.05)	0.1786	0.2357	0.1786	0.0695	1.80	8.04
%CV	6.5	15.9	6.5	62.0	21.2	39.6

Means shown using different letters were significantly different at p<0.05

Pod length

Analysis of variance results revealed that variety had a significant effect (P<0.01) on pod length (Table 3). There were significant differences in the performance of varieties in terms of pod length. Namsoy 3N had the longest pods, although they were not significantly different from Maksoy 4M. UG5 had the shortest pods with a mean of 4.07 cm, though it was not significantly different from Solitaire. Watering regime had a significant effect (P<0.01) on pod length (Table 4). A 25% saturation capacity significantly suppressed pod length; however, no significant differences were observed between plants under 100% saturation capacity and 50% saturation capacity.

In moisture-depressed environments, key physiological processes are affected, which results in poor allocation of resources, and as a result, pods become small in size. This effect of preflowering water shortage on pod length can be explained by the concept of a compensation effect. According to [32], the compensation effect is an important self-regulatory mechanism used by plants to defend against environmental stresses or injuries. Crops tend to grow rapidly after a dry period, and they compensate for the loss that had been caused by water shortages. Crops that have a high compensation effect are able to recover from water shortages after normal irrigation. UG5 and Solitaire had the shortest pods among the other varieties. This difference was due to varietal type; some varieties produce large pods, while others produce small pods. They differ in their genetic make-up; hence, their performances tend to vary.

Number of pods per plant

Variety had a significant influence (P<0.01) on the number of pods per plant. Maksoy 4M and Nam 1 had the highest number of pods per plant, though they were not significantly different from Maksoy 1N and Namsoy 3N. Solitaire and UG5 yielded the lowest pod numbers (Table 3). Watering regime had a significant effect (P<0.01) on the number of pods per plant. Statistical differences were observed between the means of the three watering regimes that were assessed with plants under 100% soil saturation capacity yielding the highest average of 108 pods per plant and the ones under 25% soil saturation capacity with the lowest average of 56, thus a 48% decrease (Table 4).

The reduction in the number of pods on soybean under drought stress occurs because water shortages affect flowering and pollination. Under severely water-depressed environments, floral abortion occurs, and some plants may even fail to flower. A relationship was noted between stem length and pod number. This is in accordance with the study done by [33], who found similar results on this relationship. The impact of stem length on pod number occurs because flowers are borne at the nodes. The more nodes produced, the greater the potential of producing more flowers and pods. This was true with genotypes such as Nam1 and Maksoy 4M, which were taller than others. They performed better in terms of the number of pods owing to their greater height. However, there is an exception to this relationship between stem length and pod number. This is explained by the case of Maksoy 1N, a short statured variety. This genotype was the shortest among others under all watering treatments, yet it produced more pods regardless of the stem length.

Number of seeds per pod

Variety significantly (P<0.05) influenced the number of seeds per pod (Table 3). There were significant differences between the means of varieties, and the highest values were recorded in Maksoy 1N and Namsoy 3N. UG5 had the lowest number of seeds per pod compared to the other varieties. Watering to 50% and 25% soil saturation capacity significantly reduced (P<0.01) the number of seeds per pod (Table 4).

There was a notable relationship between pod length and the number of seeds produced per pod. It was observed that varieties that had shorter or smaller pods had fewer seeds produced per pod. Pods have to reach their maximum length before seeds develop inside [34]. This was the case for varieties such as UG5 and Solitaire, which produced fewer seeds. Under normal circumstances, soybeans are able to produce four-seeded pods, while others produce three, but due to water shortage, they tend to produce fewer or even empty pods.

Percentage non-viable pods

As shown in Table 3, variety had a significant effect (P<0.05) on the nonviable pod percentage. Statistical differences were observed between varieties, and Maksoy 1N had the highest pod mortality, followed by Nam 1, and UG5 had the lowest. The watering regime had no significant effect (P > 0.05) on the nonviable pod percentage, but the greatest variability was observed in this parameter, as shown by the % coefficient of variation (Table 4).

Pod viability was not affected by preflowering water shortages. However, varieties performed differently from each other in terms of % nonviable pods. This shows that the genotypes had varied abilities in photosynthate translocation. Some were able to efficiently transfer the products of photosynthesis to the pods during pod filling and development, while others, such as Maksoy 1N, were not that efficient, thus recording a high percentage of non-living pods [35], postulated that there is low pod mortality in crops exposed to water shortages during the seedling and branching stages.

100 seed weight

Analysis of variance results revealed that variety had a significant effect (P<0.01) on 100-seed weight (Table 3). There were significant differences in the performance of the varieties. Namsoy 3N had the highest grain weight, though it was not significantly different from Maksoy 4M and Nam 1. Solitaire had the lowest grain weight with a mean of 10.08, though it was not significantly different from Maksoy 1N. Watering regime had a significant effect (P<0.01) on 100-seed weight (Table 4). Statistical differences were observed between the means of three levels that were assessed with the sufficiently watered treatments (100% saturation capacity) having the highest average of 16g and the treatments that received the least amount (25 % of soil saturation capacity) with the lowest average of 11g. Different varieties had varied seed sizes, and some were very minute, which caused significant differences in 100 seed weight. Different seed sizes led to some seeds weighing less than others even though the quantity was the same. Regardless of the variety, the watering regime had an influence on the 100-weight of all the crops.

Seed yield (grams per plant)

Variety showed a significant influence (P<0.01) on seed yield. Nam 1 had the highest seed yield per plant, though it was not significantly different from Namsoy 3N and Makoy 4M. Solitaire and Maksoy 1N had the lowest seed yield per plant, and their means were not significantly different from each other (Table 3). Watering regime significantly affected (P<0.01) seed yield, and significant differences were observed between the means of the three levels of water stress that were assessed. The plants that received the least amount of water had reduced grain yield per plant by nearly 50% of the yield obtained under non-moisture-limited plants.

A relationship between stem height, pod number and seed yield was observed. This relationship was seen in varieties such as Nam 1 and Maksoy 4M. They produced taller plants that had more pods and thus had a larger grain weight. This is in agreement with the findings of [36], who gave a report on this relationship between stem length and yield. Another relationship was noted between % nonviable pods and seed yield. This was the case for Maksoy 1N, which produced many pods but recorded the lowest seed yield because of high pod mortality. This variety had a larger percentage of nonviable pods, which contributed to the low yield of seeds. According to [37], soybean is more sensitive to water stress during germination and reproduction, and water shortages during the early vegetative stage have little effect on yield. However, in this study, it was noted that preflowering water shortage has an influence on soybean yield because it affects stem length, which is a contributor to yield in some varieties. Severe water deficits can cause dehydration of vegetative tissue, resulting in low grain yield [38]. Some crops are permanently inhibited from growing, and they tend to give low yields even if rehydration is done.

Conclusion and future perspective

The varieties that were assessed performed differently in terms of stem height, yield and related components that were assessed. Maksoy 4M, Nam 1 and Namsoy 3N performed better than the other varieties. UG5 and Solitaire were the least performers in all the variables measured. Soil moisture levels of 50% soil saturation capacity and below during vegetative stages significantly reduce yield and most of its related components in assessed soybean varieties when grown in Kalahari sands. Thus, the varieties need sufficient supplementary irrigation during vegetative stages if planted before the onset of effective rains to avoid yield losses. Varieties that outperformed others can be used by breeders to improve their tolerance to preflowering drought stress.

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References

1. Singh P, Wani SP, Pathak P, Sahrawat KL, Singh AK. “Increasing crop productivity and effective use of water in rainfed agriculture”, In: E. Boelee ed. Integrated Watershed Management in Rainfed Agriculture, CRC

Press, London, UK, 2011, p315-347.
2. Mavhura E, Manatsa D, Mushore T. "Adaptation to drought in arid and semi-arid environments: case of the Zambezi Valley, Zimbabwe", Journal of Disaster Risk Studies, 2015; 7:1-7. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6043727/#. [Accessed Dec.2 2020].
3. Boyer JS. "Plant productivity and environment", Science, 1982; 218(4571):443-448. [Online]. Available: https://www.science.org/doi/10.1126/science.218.4571.443. [Accessed July, 5, 2020]
4. Dalzotto MB. "Selection of Drought-Tolerant Soybean Lines Using a Field Screening Method and Identification of QTLs for Slow Wilting and Nitrogen Fixation Associated with Drought-Tolerance", MSc. Thesis, University of Arkansas, Fayetteville, USA, 2016 [Online]. Available: http://scholarworks.uark.edu/etd/1761.
5. Fageria NK, Baligar VC, Jones CA. "Growth and mineral nutrition of field crops", *2nd Ed*. New York, Marcel Dekker, Inc., 1997.
6. Iqbal N, Hussain S, Raza MA, Yang CQ, Safdar ME, Brestic M, *et al*. "Drought Tolerance of Soybean (Glycine max L. Merr.) by Improved Photosynthetic Characteristics and an Efficient Antioxidant Enzyme Activities under a Split-Root System", Frontier Physiology, 2019; 10:786. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fphys.2019.00786/full. [Accessed September, 7, 2020]
7. Colussi J, Schnitkey G. "New Soybean Record: Historical Growing of Production in Brazil." *farmdoc daily*, (11):49, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, March 30, 2021. [Online]. Available: https://farmdocdaily.illinois.edu/2021/03/. [Accessed November, 20,2021]
8. Murithi HM, Beed F, Tukamuhabwa P, Thomma BPHJ, Joosten MHAJ. "Soybean production in eastern and southern Africa and threat of yield loss due to soybean rust caused by Phakopsora pachyrhiz", Plant Pathology, 2016; 65(2):176-188. [Online]. Available: https://bsppjournals.onlinelibrary.wiley.com/doi/full/10.1111/ppa.12457. [Accessed January, 20, 2021]
9. International Institute of Tropical Agriculture (IITA), "Annual report, IITA", Ibadan, Nigeria, 2018.
10. Zimbabwe Vulnerability Assessment Committee (ZimVAC), "Rural livelihoods Assessment. Food and Nutrition Council", 2014, 17(10), SIRDC. [Online]. [Available: https://reliefweb.int/report/zimbabwe/zimbabwe-vulnerability-assessment-committee-zimvac-2014-rural-livelihoods-assessment].
11. Siamabele B, Moral MT. (Reviewing editor), "The significance of soybean production in the face of changing climates in Africa, Cogent Food & Agricultue", 2021, 7(1). [Online] Available: https://www.tandfonline.com/doi/citedby/10.1080/23311932.2021.1933745. [Accessed April, 4, 2021]
12. Zandalinas SI, Sales C, Beltrán J, Gómez-Cadenas A, Arbona V. "Activation of secondary metabolism in citrus plants is associated to sensitivity to combined drought and high temperatures", Frontiers in Plant Science, 2017; 7:1954. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC522011. [Accessed June, 17, 2021].
13. Arya H, Singh MB, Bhalla PL. "Towards Developing Drought-smart Soybeans". Frontiers in Plant Science, 2021, 12 [Online]. Available: https://www.frontiersin.org/articles/10.3389/fpls.2021.750664/full. [Accessed March, 28, 2022]
14. Madanzi T, Chiduza C, Richardson SJ, Kageler T Muziri. "Effects of different plant populations on yield of different soybean (Glycine max (L.) Merrill) varieties in a smallholder sector of Zimbabwe", Journal of Agronomy, 2012; 11:9-16 [Online]. Available: http://ir.msu.ac.zw:8080/xmlui/handle/11408/438. [Accessed June, 7, 2021]
15. Buezoa J, Sanz-Saezb A, Morana JF, Sobaa D, Aranjueloa I, Estebanc R. "Drought tolerance response of high-yielding soybean varieties to mild drought: physiological and photochemical adjustments", Physiologia Plantarum, 2019; 166(1):88-104. [Online]. Available: https://onlinelibrary.wiley.com/doi/full/10.1111/ppl.12864. [Accessed 13 March 2020].
16. Ludwig B, Geisseler D, Michel K, Joergensen KRG, Schulz E, Merbach II, *et al*. "Effects of fertilization and soil management on crop yields and carbon stabilization in soils. A review", Agronomy Sustainable Development, 2011; 31:361–372. [Online]. Available: https://link.springer.com/article/10.1051/agro/2010030. [Accessed May, 3, 2020].
17. Westgate ME, Peterson CM. "Flower and pod development in water-deficient Soybean (Glycine max L. Merr.)", Journal of Experimental Botany, 1993; 44(1):109-117. [Online]. Available: https://academic.oup.com. [Accessed June 7 2020]
18. Desclaux D, Huynh TT, Roumet P. "Identification of soybean plant characteristics that indicate the timing of drought stress". Crop Science, 2000; 40(3):716-722 [Online]. Available: https://acsess.onlinelibrary.wiley.com/doi/abs/10.2135/cropsci2000.403716x. [Accessed September 5, 2020]
19. Pedersen P, Lauer JG. "Soybean growth and development in various management systems and planting dates", Crop Science, 2004; 44(2):508-515 [Online]. Available: https://acsess.onlinelibrary.wiley.com/doi/abs/10.2135/cropsci2004.5080. [Accessed August 22 2020]
20. Jhaa PK, Kumar SN, Inesa AVM. "Responses of soybean to water stress and supplemental irrigation in upper Indo-Gangetic plain: Field experiment and modeling approach", Field Crops Research, 2018; 219:76-86. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0378429017308298. [Accessed July 7, 2020].
21. Gebre MG, Earl HJ. "Soil Water Deficit and Fertilizer Placement Effects on Root Biomass Distribution, Soil Water Extraction, Water Use, Yield, and Yield Components of Soybean [*Glycine max* (L.) Merr.] Grown in 1-m Rooting Columns, Frontiers of Plant Science, 2021; 12:581127. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fpls.2021.581127/full. [Accessed May, 30, 2022].

22. Saitoh K, Mahmood T, Kuroda T. "Effect of moisture at different growth stages on flowering and pod set in determinate and indeterminate soybean cultivars", Japanese Journal of Crop Science (Japan), 1999; 68(64):537-544. [Online]. Available: https://agris.fao.org/agris. [Accessed May 7, 2021]
23. Borges R. "How soybeans respond to drought stress", University of Wisconsin-Extension-Cooperative Extension, 2004.
24. Kisman M. "Effects of drought stress on growth and yield of soybean". Science Philosophy, Bogor Agricultural University, Indonesia, 2003.
25. Mirakhori M, Paknejad F, Moradi F, Ardakani M, Zahedi H, Nazeri P. "Effect of drought stress and methanol on yield and yield components of soybean Max" (L17), American Journal of Biochemistry and Biotechnology, 2009; 5(4):162-169. [Online]. Available: https://thescipub.com/abstract/ajbbsp.2009.162.169.[Accessed May 7, 2021].
26. Hussain HA, Hussain S, Khaliq A, Ashraf U, Anjum SA, Men S, *et al*. "Chilling and Drought Stresses in Crop Plants: Implications, Cross Talk, and Potential Management Opportunities", Frontiers in Plant Science, 2018; 9:393. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fpls.2018.00393. [Accessed, March, 9, 2020].
27. Gerten D, Rost S. "Development and Climate Change: Climate change impacts on agricultural water stress and impact mitigation potential. Potsdam Institute for Climate Impact Research (PIK)", Washington, DC: World Bank, 2010. [Online]. Available: Bank. https://openknowledge.worldbank.org/handle/10986/9064., 2010.
28. Walker T, Alwang J (Eds). "Crop improvement, Adoption and Impact of Improved varieties in Food Crops in Sub-Saharan Africa, CGIAR Consortium of International Agricultural Research Centers, Montpellier, France, 2015.
29. Wei Y, Jin J, Jiang S, Ning S, Liu L. "Quantitative response of soybean development and yield to drought stress during different growth stages in the huaibei plain", China Agronomy, 2018; 8(7):97. [Online]. Available: https://www.mdpi.com/2073-4395/8/7/97. [Accessed June' 17, 2021].
30. Souza CC, Oliveira FA, Silva IF, Amorim Neto MS, "Evaluation of methods of available water determination and irrigation management in "terra roxa" under cotton crop", Revista Brasileira de Engenharia Agricola e Ambiental, 2000; 4(3):338-342 [Online]. Available: https://www.cabdirect.org/cabdirect/abstract/20013024422. Accessed June 9 2021].
31. Payne RW, Harding SA, Murray DA, Soutar DM, Baird DB, Glase AI, *et al*. "The guide to GenStat Release 13 part 2: statistics". VSN International Hernel Hempstead, UK, 2010.
32. Dong S, Jiang Y, Dong Y, Wang L, Wang W, Ma Z, *et al*. "A study on soybean responses to drought stress and rehydration". Saudi journal of biological sciences, 2019; 26(8):2006-2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1319562X19301378. [Accessed September, 17, 2020].
33. Wijewardana C, Reddy KR, Alsajri FA, Irby T, Krutz J, Golden B. "Quantifying soil moisture deficit effects on soybean yield and yield component distribution patterns.", Irrigation Science, 2018; 36:241-255. [Online]. Available: https://link.springer.com/article/10.1007/s00271-018-0580-1. [Accessed December, 7, 2019]
34. Bertolli SC, Rapchan GL, Souza GM. "Photosynthetic limitations caused by different rates of water-deficit induction in Glycine max and Vignaunguiculata", Photosynthetica, 2021; 50(3):329-33. [Online]. Available:https://link.springer.com/article/10.1007/s11099-012-0036-4. [Accessed August 20, 2021].
35. Kobraee S, Shamsi K. "Response of Soybean to drought stress", Azad University, Kermanshah, Iran, 2012. [Online]. Available: https://crops.extension.iastate.edu/cropnews/2012/06/soybean-response-drought. [Accessed 3, July, 2020].
36. Mangena PP. "Water stress: morphological and anatomical changes in soybean (Glycine max L.) plants," in Plant, Abiotic Stress and Responses to Climate Change. ed. V. Andjelkovic, London: Intech Open, 2018, 9-31.
37. Serraj R. "Effects of drought stress on legume symbiotic nitrogen fixation: physiological mechanisms". Indian Journal of Experimental Botany, 2003; 41(10):1136-1141. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/15242280. [Accessed October, 17, 2021]
38. Wang L, Zu W, Dong S, Liu L, Xu Y, Li X. "Effects of drought stresses and times on compensation effect after re-watering in soybean", Transations of the Chinese Society of Agricultural Engineering (TCSAE), 2015; 31(11):150-156. [Online] Available: https://www.scienceopen.com/document_file/1cc034d2-5ec5-44db-acf0-973a4ccec80a/PubMedCentral/1cc034d2-5ec5-44db-acf0-973a4ccec80a.pdf. [Accessed August 15, 2021].