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Influence of varying soil moisture on growth and yield of Chia (*Salvia hispanica l.*) in Meru County, Kenya.

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Article Info

KEY WORDS

Plant Dry weight

Gravimetric Water Content

Relative Water Content

Seed yield

Water stress

Abstract

Chia plant has been described as tolerant to low soil moisture content, but its response to low soil moisture content at different growth stages is unknown. A field experiment was conducted in March-June and June -October 2021 to determine the influence of different soil moisture regimes on the growth and yield of Chia. A randomized complete block design with three replications was used. Chia plants were subjected to four soil moisture regimes; (i)watering to the seedling stage (seedling), (ii) watering to the vegetative stage (vegetative), and (iii) watering to the flowering stage (flowering) (iv) continuous watering (control). High soil moisture of 89-93 %, significantly increased ($p \leq 0.05$) the vegetative growth of Chia plants. Plant height, stem diameter and number of leaves increased by 65-180%, 100-109% and 92-565%, respectively. 20-40% reduction in the available soil water to the plant decreased growth of Chia. Low soil moisture of 30-32 % caused plants to produce 172-220% less seed yield than control plants. Seasonal variation was noted, with increased vegetative growth and seed yield reported in the March-June 2021 season compared to the June-October 2021 season. Decreased vegetative growth and yields was a result from inhibition of cell enlargement or cell division under reduced soil moisture. The study recommends watering to the flowering stage as the best practice for water saving and increasing Chia production in Kenya.

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Introduction

Chia (Salvia hispanica L.) is a biannual oleaginous and herbaceous plant belonging to the Lamiaceae family. Chia is commercially produced in Argentina, USA, Mexico, China, Australia, Colombia and Guatemala due to its nutritious seeds (Muñoz et al., 2013). Demand for Chia is increasing both for the local and export market. In Kenya, commercial production of Chia is found in several counties including Meru (Gitau et al., 2019). Despite the high demand of this crop the supply is still very low (Cassiday, 2017), this can be attributed to limited information on the agronomic management of Chia (Njoka et al., 2022).

Chia can be grown under all soils and climatic conditions in rain-fed and irrigated fields (Bochicchio et al., 2015). Chia Famers in Meru County rely on rain as the main source of water for farming, however the over reliance to the unreliable rainfall has led to low seed production (Sandström et al., 2020). Meru experiences unexpectedly heavy rainfall in April and continues through the end of May and is commonly known as the long rains, while the short rains begin from mid-September to November (Nyakundi et al., 2010). Chia has a growing period ranging between 90 -150 days (Bochicchio et al., 2015), and with the given rainfall period of 2 months this could have detrimental effects on the growth and development of the Chia plant. In a survey conducted in Kenya, Nyeri county, Gitau et al. (2019) reported that 90% of the farmers produced as low as 30 kilograms of seed compared to a potential of two tonnes per hectare. Poor soil moisture during production could be one of the main causes of the low production of Chia in Kenya.

Planting of Chia in Kenya begins during the rainy season when the soil moisture is relatively high, while harvesting occurs during the dry periods when the soil moisture is low. However, with the change in the rainfall patterns in Kenya, the soil moisture keeps changing with the water distribution in the soil (Recha et al., 2016). This has caused low soil moisture during the critical stages of growth of the plant hence death or low seed yield. Chia's normal growth and function are disrupted by the decline in soil moisture (Silva et al., 2016). To alleviate this problem, the effects of soil moisture on growth and yield of Chia need to be understood. In other oil crops such as sunflower, plants that were produced under 100% full irrigation, produced a higher seed yield of 2049 kg per hectare, while those that had low soil moisture of 65% irrigation produced a lower seed yield of 1710 kg per hectare (Eltarabily et al., 2020).

Arid and semi-arid regions in Kenya occupy approximately 80 % of the total land area (Ndiritu, 2021). Demand for Chia across the country has led to crop production in ASALs regions, despite increasing water scarcity being a major concern. As the need to produce more food with limited water increases, soil moisture management strategies focusing on increasing agricultural water efficiency must be developed. This study seeks to determine the influence of soil moisture on the growth and yield of Chia in Meru County, Kenya.

Materials and Methods

Site Description

The study was conducted in the field at the Meru University of Science and Technology at the department of agriculture from 14th March to 22nd June 2021, and a repeat was from 27th June to 10th October 2021.

Experimental Materials and Procedures

Chia plants were subjected to different soil moisture regimes. These include; (i) seedling stage (watering seedlings for one week after transplanting and thereafter no watering), (ii) vegetative stage (watering until 50 % of the plants had produced their fourth pair of leaves and thereafter no watering), (iii) flowering stage (watering plants until 50 % of the plants had flowered and thereafter no watering)) (iv) control (continuous watering until 50 % of plants had brown-coloured leaves). Plants were watered three times per week to attain a field capacity of 90-95 %. The experiment was laid out in a randomized complete block design and replicated three times. Twelve plots were raised, each measuring 2 m by 2m. A distance of 1 m separated plots while the edges were raised to prevent water loss. Each plot accommodated five rows with five plants, with 30 cm spacing between the rows and 30 cm spacing within the rows. Chia plants were sheltered from rainfall through a movable transparent polythene sheet.

Cultural Practices

The seedbed preparation started one month before planting, and the land was cleared and ploughed using a disc plough that passed at a depth of 30 cm. Leveling and demarcation of the plots were carried out manually.

White and black spotted chia were first sown uniformly in shallow drills of 2 cm deep and 5 cm apart on a nursery bed raised to measure 1 m by 1 m. Twenty-one days after sowing, seedlings had attained

2-3 true leaf stage transplanting was done in shallow holes spaced at 30 cm by 30 cm.

The experimental field was kept free from weeds by constant hand and hoe weeding during the vegetative and reproductive phases.

Harvesting was carried out when Chia leaves turned yellow and dried in the field. Chia spikes were then picked from the plant and threshed manually. Winnowing was done using trays to separate the chaff from the seeds. Clean seeds were weighed immediately to determine the yield per plant.

Data collection

Soil moisture measurements

% Soil Moisture Content

Three plants per plot were selected for soil moisture content measurement, which was determined using a soil moisture meter on weekly bases. Three measurements were taken around the plant by inserting the moisture meter at a depth of 10-15cm inside the soil. Soil moisture content was determined before watering and after watering. At 90-95 % field capacity, the Soil moisture content was between 22-24 %.

% Soil Gravimetric water content (GWC)

Soil samples at a depth of 30cm were taken from the plots using a soil auger on weekly bases. The soils were dried at 105°C for 48 hours, and the gravimetric soil water content (GWC %) was determined and expressed on a dry weight basis as follows:

where GWC denotes the gravimetric soil water content, FW denotes the fresh weight of soil, and DW

$$GWC\ \% = \left(\frac{FW - DW}{DW}\right) x\ 100$$

denotes the dry weight of soil. At 90-95 % field capacity, the Gravimetric water content was between 38-40 %.

Vegetative Growth Measurements

Branches, stem diameter, height, leaf length and Leaves

At the beginning of the experiment, five plants per treatment were marked for expansive growth measurement. The number of fully formed leaves was counted manually, while the plant height was measured using a meter rule from the base of the Chia plant stem at the soil level to the apex. Stem diameter was measured with the help of a digital vernier calliper at 10 cm height from the soil surface, while the leaf length was measured using a centimetre ruler from the leaf base to its tip. Stem diameter, height and number of leaves were measured weekly and stopped when there was no more growth. The number of branches was measured at harvest, while the leaf length was measured every four days.

Plant water Status

% Leaf relative water content (LRWC)

Leaf Relative Water Content (LRWC) was determined on plants every week. The youngest leaf on the main stem, which had fully formed, was picked from the plants at 1100-1300 and quickly weighed to obtain the fresh weight. The leaf was placed in distilled deionised water in a Petri dish and left at 20°C in dim illumination for 24 hours. The turgid weight was obtained after blotting; thereafter, the leaves were dried at 100°C to a constant weight to obtain the dry weight.

$$RWC\ \% = \left(\frac{FW - DW}{TW - DW}\right) x\ 100$$

RWC % was computed as:

Where; RWC denotes the Relative leaf water content, FW denotes the fresh weight of the leaf, DW denotes the leaf's dry weight, and TW denotes the turgid weight of the leaf.

Plant dry weight

Five harvests were done periodically from each plot; during planting; one week after planting, at different stages of growth which include the vegetative stage (50 % of the plants had produced their fourth pair of leaves, flowering stage (50 % of the plants had produced flowers) and maturation (50 % of plants had brown coloured leaves.

During the five periodic harvests, plants were cut at the base and separated into leaves, stems and roots. Roots were carefully picked by hand and washed. Afterwards, they were placed in an air oven at 65°C until they reached a constant weight. The dry weight of leaves; the dry weight of stem; the dry weight of spikes; and the dry weight of roots were measured

Seed weight

At harvest, the seed yield per plant and 1000 seed sizes were weighed using a digital weighing scale.

Statistical Analysis

Data collected were analyzed using the general linear model (GLM) procedure of Statistical Agricultural software (SAS 2005), and the least significant difference (LSD) was employed to show the mean difference between treatments. LSD test was used to separate means that were different at 5% levels of significance. Graphs and tables were attained using

Systat 14 software and an excel package. Non-linear regression functions were used to establish the relationship between growth and soil moisture.

Results

Soil Moisture Content and Gravimetric Water Content

Watering plants to the seedling stage significantly reduced soil moisture content between weeks 2 to 10. (Fig 1 A, and B). At week ten, the soil moisture from plants watered to the seedling stage was 32.8 % in March-June 2021 and 30 % in June-October 2021. Control plants maintained a higher soil moisture content of 89.1 % and 87.1% in March-June 2021 and June-October 2021, respectively. From week 8-10, plants were watered to the seedling stage, and the vegetative stage had a constant moisture content. There were significant differences between plants watered to the vegetative stage and plants watered to the seedling stage in March-June 2021 season. Plants watered to the vegetative stage had higher soil moisture of 42.6 % in March-June than plants watered to the seedling stage. However, the difference was not recorded in June-October 2021 season.

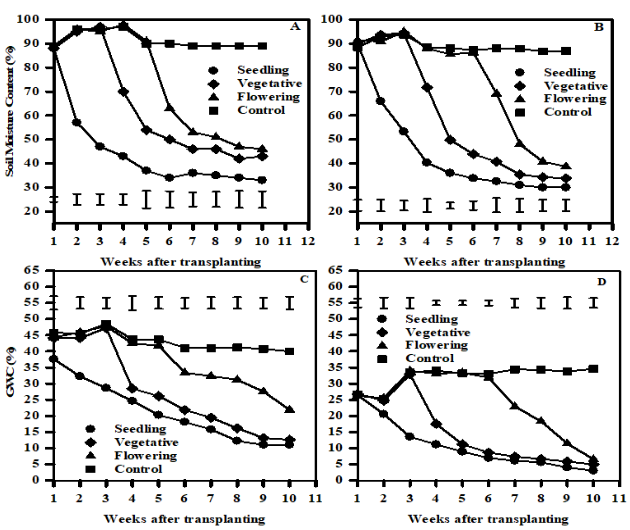


Figure 1: *Soil moisture content and Gravimetric water content as influenced by varying Soil moisture Regimes during the March -June 2021 (A and C) and June-October 2021 (B and D) seasons.*

Plants watered to the seedling stage had soils with significantly lower gravimetric water content (GWC %) between weeks 2 to 10 (Fig 1 C, and D). At week ten, plants watered to the seedling stage had soils with a GWC of 10.87 % and 3.48 % during the March-June and June-October 2021 seasons, respectively. In both seasons, the GWC of soils for plants watered to the seedling stage and plants watered to the vegetative stage had no significant differences. A sharp decrease in the gravimetric water content of the soils was recorded at week four and week 6 in plants watered to the vegetative and flowering stages, respectively. Control plants had higher significant GWC % soils from weeks 1 to 10. The GWC ranged from 34.56 % in the June-October season and 39.97 % in the March-June 2021 season. Soils, where plants were watered to different plant growth stages, had seasonal differences in the GWC %. In the March-June season, the GWC was higher, ranging between 10.87-21.83 %, while June-October, the GWC was lower, ranging between 3.48-6.54%. Gravimetric water content increased linearly as a function of the moisture content.

Relative Water Content

Control plants had a higher significant leaf relative water content (RWC %) between 2-10 weeks (Fig 2 A, and B). At the termination of RWC measurements, control plants had RWC ranging from 93.69 % in the March-June season and 88.67 % in June-October 2021 season and with a moisture level of 89.1 % and 87.1% respectively. Plants watered to the seedling stage and with a moisture level ranging 30-32% had significantly lower RWC of 52.33 % in March-June and 59.64 % in June-October 2021 season as compared to control plants. However, plants watered to the vegetative stage and those watered to the flowering stage had no significant differences from those watered to the seedling stage.

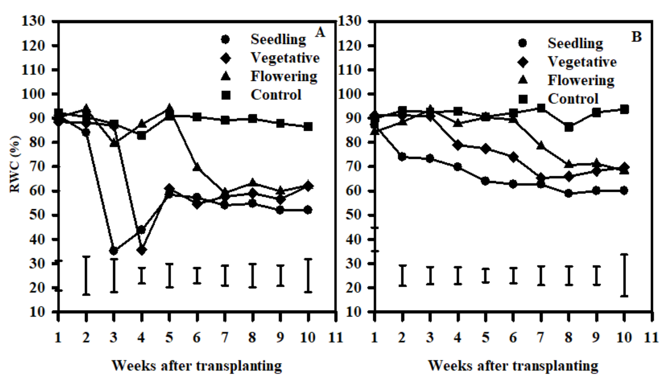


Figure 2: *Relative water content of Chia leaves as influenced by varying Soil moisture Regimes during the March-June 2021 (A) and June-October 2021 (B) seasons.*

Leaf Growth

Plants supplied with water to the seedling stage had significantly fewer leaves between 6-10 weeks (Fig 3 A and B). In the 10th week, plants that received water until the seedling stage (with a soil moisture of

30-32%) had fewer leaves ranging from 47 in June-October and 145 in March-June 2021, respectively. Control plants with a moisture level of 89-93% had a significantly higher number of leaves ranging from 313 in June-October and 356 in the March-June 2021 seasons. Although control plants significantly increased the number of leaves compared to plants

watered to the flowering stage during the March-June season, the difference was not significant in the June-October 2021 season. During the March-June 2021 season, plants that received water for vegetative growth had a significantly higher number of leaves than those that received water to the seedling stage. However, this difference was not observed in the June -October 2021 season. In the March-June 2021 season, the number of leaves was higher than that recorded in the June-October 2021 season. In the 10th week, when the collection of the number of leaves was terminated, the number of leaves ranged between 185-356 and 47-313 in the March-June and June-October 2021 seasons, respectively.

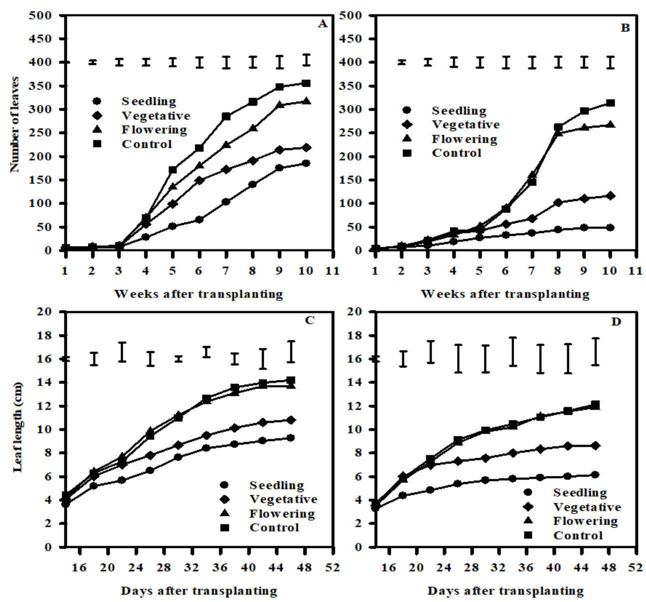
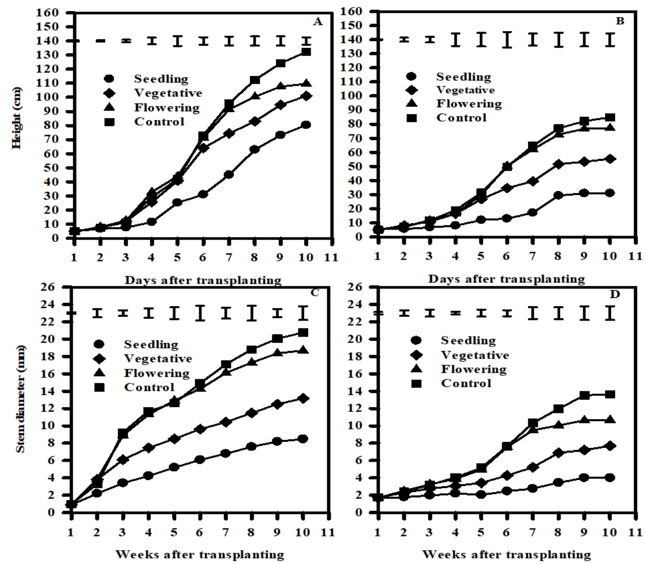


Figure 3: *Number of leaves and Leaf length of Chia as influenced by varying Soil moisture Regimes during the March-June 2021 (A and C) and June-October 2021 (B and D) seasons.*

Control plants with a soil moisture of 89-93 % had a significantly longer leaf length from day 24 to 48 (Fig 3 C and D). On day 48, when leaf length measurements were terminated, control plants had a leaf length ranging from 12.13 cm in the June-October season and 14.20 cm in the March-June 2021 season. In both seasons, the leaf length of the control plants and plants watered to the flowering stage had no significant differences. Plants watered to the seedling stage had a shorter leaf length than plants watered to the vegetative stage.

The leaf length of plants watered to the seedling stage was 9.27 cm and 6.13 cm in the March - June and June - October 2021 seasons, respectively. The leaf length in both seasons varied, whereas March - June season plants had a higher leaf length ranging 9.27 - 14.20 cm as compared to plants in the June - October 2021 season with a lower leaf length ranging 6.13 - 12.13 cm.



Stem elongation and expansion

Figure 4: *Stem height and Stem diameter of Chia as influenced by varying Soil moisture Regimes during the March-June 2021 (A and C) and June-October 2021 (B and D) seasons.*

Control plants were significantly taller between 6-10 weeks (Fig 4 A and B). At the termination of the height measurement readings when soils had a moisture level of 89-93%, control plants ranged between 132 cm and 85cm in the March-June and June-October 2021 seasons, respectively. In addition, control plants were significantly taller than plants watered to the flowering stage in the March-June season. However, this was not evident in the June-October season. Plants watered to the seedling stage produced significantly lower heights from 3-10 weeks. The heights ranged between 30.73 cm in June-October and 80.33 cm in March-June 2021 seasons.

All watering regimes recorded a sharp increase in plant height on the 6th week but slowed down on the 9th week. In the different seasons, there were notable height differences. During the March-June season, taller plants ranging from 80-132 cm were recorded, while shorter plants ranging from 30-84 cm were recorded in the June-October 2021 season.

Plants watered to the seedling stage had significantly thinner stems as compared to control plants (Fig 4 C, and D). At harvest plants watered to seedling stage with a soil moisture of 30-32%, had stem diameters ranging 8.48 mm in March-June season and 3.82 mm in June-October 2021. Control plants had significant, thick stem diameters, followed by plants watered to the flowering stage and plants watered to the vegetative stage. Control plants had thicker stem diameters ranging from 13.63 mm to 20.77 mm in June-October and March-June 2021, respectively. Stem diameters varied between seasons, where March-June season plants had thicker stem diameters ranging from 8.48-20.77 mm, while June-October 2021 season plants had thinner stem diameters ranging from 3.82-13.63 mm.

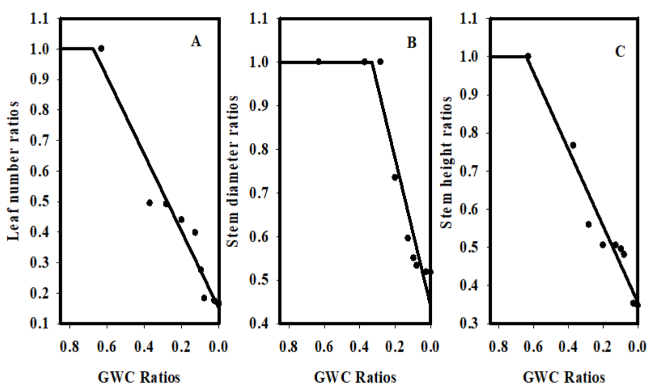


Figure 5: *Leaf number ratio (A), stem diameter ratio (B) and Stem height ratio (C) of Chia as functions of gravimetric water content (GWC) ratio as influenced by varying Soil moisture Regimes during the June-October 2021 season.*

The leaf number, stem diameter and plant height ratios, of chia significantly decreased with decrease in the available soil water to the plant in June-October 2021 season (Fig 5 A, B and C). Leaf number and stem height of Chia decreased once the water available to the plant went below 0.6 (Fig 5 A and C). A gravimetric water content ratio of 0.6 and below the number of leaves and plant height decreased linearly. Chia stem diameter ratio maintained a plateau when the available water to the plant was above 0.4 GWC ratio, however when the water available to the plant fell below 0.4 GWC ratio the stem diameter decreased linearly (Fig 5 B). The response reported in

season 2 during the June-October 2021 season was not reported during the March-June 2021 season.

Dry Weight

Control plants had significantly higher total dry weight when compared to those plants watered to the seedling stage from 28-90 days after sowing (DAS) (Table 1). At 90 DAS, the total dry weight of plants in the control treatment had a dry weight that ranged from 83.74 g in the June-October and 140.16 g in the March-June 2021 seasons. From June-October 2021, control plants had a significantly higher dry weight than plants watered to the flowering stage. However, this was not the same case in the March-June 2021 season. 90 DAS, plants watered to the seedling stage had significantly lower dry weight ranging between 17.99 g in June-October and 30.78 g in the March-June 2021 season. During the March-June 2021 season, plants watered to vegetative stage had a significantly higher dry weight than those watered to the seedling stage.

In Contrast, the difference observed during the March-June season was not recorded in the June-October 2021 season. In both seasons, all treatments had an increase in the dry weight from 21-90 DAS. Seasonal differences in the total dry weight were also evident. During the March-June season, plants attained a total dry weight ranging from 30.78-140.16 g, while June-October 2021 season, plants attained a dry weight of 17.99-83.74 g.

Seed Yield

Control plants had a higher significant seed yield per plant in both seasons compared to plants watered to the seedling stage (Table 2). The yield per plant in control (moisture level 89-93 %) ranged from 25.68 g in June-October to 38.15 g in March-June 2021. Despite control plants recording a higher yield per plant, no significant difference was observed when compared to plants watered to the flowering stage. Plants watered to the seedling stage had a lower seed yield per plant, ranging from 11.92 g in the March-June season to 9.44 g in June-October 2021.

A higher seed yield per plant ranging from 11.92-38.15 g was recorded in the March-June season, while a low seed yield ranging between 9.44-25.68g was recorded in June-September 2021 season. There were no significant differences in a thousand seed yields in the different soil moisture regimes. A 1000 seed yield ranging from 1.23-1.29 g and 1.22-1.28g was recorded in March-June and June-October 2021 seasons, respectively.

Discussion

Control plants maintained a higher gravimetric water content and soil moisture throughout the growth period. Plots with plants watered to the seedling stage had a decreased soil moisture content and gravimetric water content as compared to control plants. Control plants had a higher gravimetric water content ranging between 35-40%. These results agree

Dry weight per plant

	March-June 2021					June-October 2021				
	21 DAS	28 DAS	42 DAS	64 DAS	90 DAS	21 DAS	28 DAS	42 DAS	64 DAS	90 DAS
Control	0.03a	1.024a	18.46a	41.45a	140.16 a	0.03a	1.38a	5.59a	38.48a	83.74a
Flowering	0.04a	1.003a	17.36a	36.25b	109.08 a	0.04a	1.08a	5.37a	36.41a	65.58b
Vegetative	0.04a	0.999a	5.31b	20.44c	66.69b	0.03a	0.86b	2.07b	9.07b	30.93c
Seedling	0.03a	0.283b	5.08b	5.92d	30.78c	0.03a	0.26c	0.72c	4.51b	17.99c
LSD	0.017	0.45	4.76	4.98	32.32	0.009	0.33	0.48	6.14	13.14
P	ns	0.0394	0.0017	<.0001	0.0018	ns	0.0022	<.0001	0.001	0.0002
CV	36.96	27.02	20.64	9.59	18.67	13.79	18.32	6.95	13.89	13.27

Table 1: *Total dry weight of Chia as influenced by varying soil moisture regimes*

Chia Seed Yield

	March-June 2021		June-October 2021	
	1000 seed Yield (g)	Yield plant^{-1} (g)	1000 seed yield (g)	Yield plant^{-1} (g)
Control	1.29a	38.15a	1.28a	25.68a
flowering	1.28a	32.09a	1.28a	24.79a
Vegetative	1.26a	23.72ab	1.23a	17.35b
Seedling	1.23a	11.92b	1.22a	9.44c
LSD	0.24	17.7	0.22	2.91
P	ns	0.0464	ns	<.0001
CV	9.52	33.47	8.73	7.54

Table 2: *Chia seed yield as influenced by varying soil moisture regimes.*

with Lemoine et al. (2018), who reported 40 - 50% in well-watered plots compared to 20% in drought-stressed plots. Similarly, Chen et al. (2015) reported that well-watered sorghum plants maintained 80-90% soil moisture while plants planted under drought conditions decreased from 66 % to 26.7%. The decreased moisture content resulted from plants utilizing the moisture left in the soil and evaporation of water from the soil. The reduced plant canopy from plants watered to the seedling and vegetative stage also increased the evaporation rate, consequently leading to low soil moisture. The plant water requirement was high at the vegetative and flowering stages; thus, decreased soil moisture was reported in the 5th to the 9th week.

The LRWC of control plants was 57-60% higher than plants watered to the seedling stage. The higher RWC in control plants indicate that the plant had a higher water status than plants with a low RWC. Plants watered to the seedling stage had a lower water status due to low moisture content in the soil. The declining relative water content is usually associated with a lower photosynthetic rate and stomatal conductance. A decline in the RWC has also been reported to be caused by lower water availability for cell expansion (Wubetu, 2018). Similar findings have also been reported in the soya plant (He et al., 2016) and sorghum plant (Chen et al., 2015). Water stressed plants with soil moisture ranging 20-25% had a RWC content ranging 60-70%, while watered plants with soil moisture of 85-90 % had a RWC ranging between 80-90%. Contrary to these findings, Silva et al. (2021) reported a higher RWC of 82% when Chia plant was subjected to 40% water stress.

The varying soil moisture regimes influenced the vegetative growth of Chia. The number of leaves in control plants was 92 %-565% more than plants watered to the seedling stage. Under low soil moisture of between 30-40%, Chia plants reduced the number of leaves in response to reducing the moisture lost through transpiration. Under low soil moisture (30-40%), the plant had decreased number of leaves due to inhibition of growth associated with changes in cell size and cell division, leading to reduced leaf production. The reduction in the number of leaves could also be a mechanism of Chia to tolerate water stress or water conservation strategy under the limited soil moisture available. Chia leaf growth is sensitive to a slight water deficit (Herman et al., 2016), which could have inhibited their growth. Similarly, Papazoglou et al. (2020) reported a 46 % reduction in the number of leaves when castor bean was irrigated to 70 % soil moisture compared to stressed plants at 40 %. In another study, maize plants under deficit irrigation produced 10% fewer leaves than full irrigation 100 % (Piscitelli et al., 2022).

Control Plants had an increased leaf length of 53-97% compared to plants watered to the seedling stage. The longer leaves in control plants meant that the plant had a larger surface area to lose water through transpiration. The larger leaves also meant more photosynthesis was occurring, thus increasing growth. On the contrary, plants watered to the seedling stage had a smaller leaf size to reduce the amount of water lost through the leaves. Under water stress or low water availability in the soil, the plant growth rate is usually low, and the leaf expansion rate is reduced (Song et al., 2019). The same results have been reported in maize plants, where the leaf length increased by 13% in irrigated plants (above -30K kPa) compared to drought-stressed plants (Sah et al., 2020). In tomato plants, the leaf length increased by 21 % in 60 % irrigated plants compared to 25 % irrigated plants (Medyouni et al., 2021). In agreement with these findings, several studies reported a reduction of approximately 47-72% in the leaf area when chia plants were un-irrigated compared to 100 % irrigation (Lovelli et al., 2019; Silva et al., 2020).

Plant height of chia increased by 65-180% in control plants as compared to plants that were watered to the seedling stage. The result shows that plant height increased due to high soil moisture and decreased due to water stress. Decreased plant height could result from inhibition of cell enlargement or cell division under water stress. The findings agree with Fouad et al. (2018), who recorded a reduction of 11-13% in the plant height of Chia at 120 % irrigation compared to 80% irrigation. 8% reduction in the stem height of rice was also reported in unirrigated fields compared to 100% full irrigation (Ahmadikhah & Marufinia, 2016). The highest differences in plant height between control plants and plants watered to the seedling stage were observed in the second season, which was attributed to the dry period experienced in June-October 2021.

Plants were watered to the seedling stage; the stem diameter decreased by 144-256% compared to control plants. The thicker stems in well-watered plants (control) resulted from the storage of photo-assimilates synthesized by the larger number of leaves. These results are in general agreement with the study conducted for the sunflower plant, where Buriro et al. (2015) found thicker stems of 5.29cm in plants irrigated at (30, 45, 60, 75 and 90 DAS) as compared to irrigation done at (30 and 45 DAS) and produced a thinner stem diameter of 3.29 cm. Contrary to these results, Soothar et al. (2021) reported no significant difference in moisture depletion regimes at 30% and 70%. In the June-October season, plants watered to seedling stage had thinner stems compared to those in the April-July season. This difference resulted from the dry season experienced in the June-October 2021 season that a high evaporation rate could characterize. In recent studies, stem diameter measurements have been used to measure the water status of the plant (Meng et al., 2017). The decrease in the stem diameter are also related to the changes in the solar radiation as well as the energy load at the surface of the transpiring leaves (Buriro et al., 2015).

Leaf number, stem diameter and stem height ratios were negatively influenced by 20-40% decrease in the available soil water to the plant. Decline in number of leaves, stem height and stem diameter show that Chia growth processes in regards to; leaf initiation, stem expansion and elongation are sensitive to reduced soil water available to the plant.

The total dry weight of plants watered to the seedling stage decreased by 355-365% in comparison to control plants. The decrease in the total dry weight was a result of low vegetative growth. With the low number of leaves, the surface area for photosynthesis was low, hence decreasing the production of photoassimilates. A higher total dry weight in well-watered plants indicates a higher photosynthesis rate associated with increased stomatal conductance. Chia stomatal conductance is closely related to water availability and atmospheric evaporative demand (Herman et al., 2016).The reduced dry weight in the July-October 2021 season was also as a result of high temperature experienced (Appendix 1 A). (Lovelli et al. (2019) reported similar findings, where non-irrigated Chia plants decreased by 318-383% in the dry weight compared to 100 % fully irrigated plants. In support of these findings, Assaha et al. (2016) reported a 59%, 65%, and 57% reduction in the leaf, stem and root dry weight of huckleberry when they were subjected to water stress (irrigated once a week) as compared to control plants (irrigated regularly).

Seed yield per plant in the control treatment increased by 172-220% compared to plants watered to the seedling stage. A higher number of leaves produced in control plants contributed to the synthesis of food through photosynthesis, thus high yields. Low soil moisture of 40 % could have caused chia plants to partially close their stomata, reducing CO2 for photosynthesis (Silva et al., 2020). These results have been supported by Herman et al. (2016), who reported a yield increase of 50 % when Chia plants received 100% irrigation compared to 40 % irrigation. However, Contrary results have been reported by Soothar et al. (2021), who found an 18% increase in seed yields under 70 % soil moisture depletion compared to 30 % soil moisture depletion.

A greater 1000 seed size was also recorded in control plants; however, the weight of the seed size was not significantly different in all treatments. Contrary to these findings, Herman et al. (2016) reported 83% increase in the weight of 1000 seed sizes from plants irrigated at 40 % compared to 100% irrigation. Soothar et al. (2021) reported a higher seed index of 14% when sunflower plants grow under 30 % soil moisture depletion compared to 70 % soil moisture depletion. Watering of Chia to the flowering stage did not result in flower abortion or low yields as reported in soya beans when plants were stressed during reproduction and grain filling (Farooq et al., 2017).

Conclusion

The study demonstrated that decrease of soil water to the plant by 20-40 %, reduced growth and negatively affected seed yield of Chia plant. Chia plants Watered to maturity and flowering stage resulted in increased growth and yields. Chia's seedling and vegetative stages demonstrated to be sensitive to low soil moisture, thus leading to low growth and yields. Understanding the moisture requirement of Chia at different growth stages is a prerequisite for increasing Chia seed yield in Kenya. Although watering to maturity produced superior crops, watering to flowering stage was the best practice that could guarantee increased yields, especially in arid and semi-arid areas of Kenya. In addition, more work must be done to develop Chia varieties that tolerate a reduction of 20-40% soil water to the plant.

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