Original Research Article

Green gram-sorghum intercropping: effects on crop microclimate, competition, resource use efficiency and yield

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ABSTRACT

A better understanding of cereal-legume interactions could improve the implementation of intercrop systems for cropping intensification. These interactions affect crop microclimate and the efficiency of utilizing growth resources such as water and nitrogen. In this study, four morphologically contrasting green gram varieties with close phenological ranges were intercropped with sorghum, variety Seredo. The four green gram varieties were the tall N26 and dwarf types KS20, Karembo, and Biashara. The intercrop arrangements were: double alternate rows of sorghum and green gram (double row), single alternate rows of sorghum and green gram (single row), and single crops of each green gram variety and sorghum as control. Treatments were laid out in split plot design with intercrop arrangement as main plots and green gram variety in subplots. Intercropping reduced soil temperature, canopy temperature, vapor pressure deficit and crop water stress index. For green gram, overall water use efficiency (WUE) and nitrogen use efficiency (NUE) were lower under intercropping by 2.6 kg ha^{-1} mm^{-1} and 1.65 kg kg^{-1}, respectively compared with sole crop. Intercropped sorghum reduced WUE by 3.5 kg ha^{-1} mm^{-1} and NUE by 1.9 kg kg^{-1}. Intercropped sorghum reduced the yield by 26% and green gram by 23%. However, the yield decline was significantly higher under single row (1.1 t ha^{-1}) compared with double row crop arrangement (0.6 t ha^{-1}). Variety N26 out-yielded the other green gram varieties, irrespective of crop arrangement. Green gram yield was driven by increase in WUE and NUE while soil and canopy temperatures were dependent on vapor pressure deficit. However, these trait associations and temperature alterations were weak in sorghum yield determination. While intercropping promotes crop intensification, this study demonstrates that double-row intercropping could be efficient than single-row in enhancing green gram-sorghum complementarity for increased grain yield, WUE, NUE and the regulation of crop microclimate.

Keywords: temperature, intercropping, water use efficiency, nitrogen use efficiency, vapor pressure deficit

1. INTRODUCTION

Cereal-legume intercropping has the potential for increased crop system productivity and improve ecosystem services to the understory crop by altering the crop microclimate

(Bremer et al., 2024; Wang et al., 2020). Dryland agriculture has been threatened by frequent droughts, high temperatures, and inadequate nutrients in the soil leading to reduced crop yields (Fang et al., 2024; Harisha et al., 2024). Intercropping offers better opportunities in crop microclimate and enhanced efficient use of resources to sustainably improve agricultural productivity (Vaja and Pankhaniya, 2023). Studies have demonstrated that intercropping increases yield compared to sole crops by utilizing resources such as water and nitrogen (Fang et al., 2024; Zhang et al., 2023). However, interspecific competition between cereal and legumes may lead to decreased yield (Bremer et al., 2024; Pierre et al., 2022). To maximize the yield of companion crops, intercrop systems should be designed to maximize resource use such as water, solar radiation, and nutrients through proper crop arrangements and varieties (Tang et al., 2020; Wang et al., 2020).

Water and nitrogen are considered the most limiting factors of crop productivity in dryland areas (Fang et al., 2024). To mitigate adverse climatic effects, crop productivity can be improved through an intercropping system that enhances interactions between both WUE and NUE (Zhang et al., 2023). However, nitrogen uptake by crops is influenced by soil moisture availability and high temperature hence drought conditions can lead to simultaneous limitations in both water and nitrogen for crops leading to decreased NUE (Kherif et al., 2023). Sole crops such as mung bean, soybean, and groundnut recorded the highest NUE over their intercropping patterns of single and double rows (Lyngdoh et al. 2020). Dryland agriculture has been threatened by moisture shortage, high temperatures, and soil infertility (Fang et al., 2024). Given the present and future situation of water scarcity and efficiency, researchers should therefore focus on crop intensification through a sustainable intercropping system (Ninanya et al., 2021).

Environmental factors such as soil temperature, air temperature, solar radiation, and relative humidity are vital in crop growth and development (Shumet et al., 2022; Wang et al., 2020). These agrometeorological factors can balance competition and complementarity for resources between species and improve overall productivity in intercropping systems (Žalac et al., 2023). Canopy temperature is an important physiological indicator of stress conditions in plants that is influenced by environment, variety, and crop management (Jiang 2022; Changan et al., 2019; Hou et al., 2019). In drylands, the shaded environment in understory crops could effectively reduce the air and canopy temperature of plant leaves during the day (Chen and Xing, 2022; Tang et al., 2022; Thapa et al., 2018). Evidence alludes to the use of canopy temperature in detecting water stress in plants and established that it does not always lead to increased yield (Ninanya et al., 2021; Thapa et al., 2018). However, lower canopy temperatures and higher yields are reported in jujube-cotton intercrop systems (Ai et al., 2021) and sorghum-tomato systems (Gebru, 2015).

Soil temperature impacts crop growth and development which is influenced by soil water content and shading which affects rooting activity (Gitari et al., 2019; Ai et al., 2021). For instance, high soil temperature decreases moisture content which further decreases nutrient absorption by plants leading to reduced growth and yields (Li et al., 2016, Daniel et al., 2022). Intercropping systems lowered soil temperature which eventually increased soil water content and crop productivity (Li et al., 2016; Nyawade et al., 2019). Vapor pressure deficit (VPD) drives transpiration, regulating water movement in the plant by minimizing water loss from moist soil (Amitrano et al., 2019; Grossiord et al., 2020). High VPD has been associated with leaf anatomy and nutrient status often leads to a decrease in growth and productivity in crops (López et al., 2021). Intercropping maize with sorghum lowered VPD within the canopy and produced greater yield in maize plants (Thapa et al., 2018). These agrometeorological factors could modify crop microclimate in an intercropping system.

Crop microclimate improvement and resource use efficiency in intercropping systems are essential for sustainable crop intensification (Ninanya et al., 2021). Water and nitrogen management should be optimized simultaneously to increase grain yield, especially in dryland areas of southeastern Kenya. The objectives of this study were to: (i) determine the effect of different green gram varieties and crop arrangement patterns on crop microclimate parameters and; (ii) assess whether variety and crop arrangement interactions improve resource use efficiency in sorghum-green gram intercropping. It was hypothesized that optimizing crop arrangement patterns would enhance crop microclimate and improve the resource use efficiency of the two crops in southeastern Kenya.

2. MATERIAL AND METHODS

2.1. Experiment sites

Field experiments were conducted in Mwala and Katangi, both in southeastern Kenya during the 2022 short rains season. Mwala site is located at 1^{o}21´29´´S, 37^{o}27´41´´E and 1252 m elevation while Katangi is at 1^{o}40´13´´S, 37^{o}68´18´´E and 1051 m altitude. Mwala site is in the low midland agroclimatic zone (LM-3) while Katangi falls in the drier LM-4 zone. Both sites have two rainy seasons in a year, which are distributed in a long rains season from March to May and a short rains season from October to December. The long-term average annual rainfall in both sites is 300-700 mm and the air temperature range is 17-35 ^{o}C (Manzi et al., 2023; Ndolo, 2019). Soils are well-drained red-brown to clay with pH 6 (Namoi et al., 2014).

2.2. Treatments and experiment design

The intercropping intimacy between four green gram varieties and one sorghum variety (Seredo) was investigated. The four green gram varieties were two old varieties (N26 and KS20) that were released in the 1990s and two new varieties (Biashara and Karembo) which were developed in 2017 (Karimi et al., 2019). These varieties were early maturing, tolerant to aphids, resistant to powdery mildew, and high-yielding (Karimi et al., 2019). Sorghum variety Seredo is high yielding, able to survive in harsh conditions, tolerate birds, matures early, and is widely grown in southeastern Kenya (Njagi et al., 2019; Moi, 2021). Crops were grown under three crop arrangement systems that included: single alternate rows of green gram and sorghum (single row), double alternate rows of green gram and sorghum (double row), and control of both sole green gram and sole sorghum. Treatments were laid out in a randomized complete block design with a split-plot arrangement and replicated three times. The crop arrangement system assumed the main plots while the green gram variety formed the subplots.

2.3. Crop husbandry

The land was ploughed before sowing to a fine tilth. Plots of length 11.5 m and width of 6 m, and separated by 0.5 m alleys were demarcated. In the sole crop plots, green gram was sown 0.5 m inter-row and 0.15 m intra-row (13 plants m^{-2}) while sorghum was sown 0.6 m between rows and 0.2 m between plants (8 plants m^{-2}). In the single-row arrangements, the inter-row spacing between adjacent sorghum and green gram rows was 0.3 m. The intra-row spacing of sorghum plants was 0.2 m, while that of two adjacent green gram plants was 0.15 m. For double-row intercropping, the inter-row spacing between sorghum and green gram was 0.90 m, and the intra-row spacing of sorghum plants was 0.20 m while in green gram plants were 0.15 m. In both single and double rows, a uniform density of about 11 green gram plants m^{-2} and 8 sorghum plants m^{-2} was maintained. Both crops were sown at the same time.

The major nutrients (N: P_2O_5: K_2O) and well-decomposed farm yard manure were applied as per the crop requirements after the initial soil analysis. At sowing, plots in Mwala received 20 kg N ha^{-1}, 11 kg P ha$^{-1,}$ and 16 kg K ha^{-1} of farm yard manure while Katangi plots received 45 kg N ha^{-1} and 115 kg P ha^{-1} as basal fertilizer. Sorghum received a basal dose of 57.5 kg N ha^{-1} and was later top dressed with 19.5 kg N ha^{-1} at stem elongation and 19.5 kg N ha^{-1} at anthesis. Manual hand weeding was done periodically to keep the field free from weeds. Insect pests such as fall armyworm (*Spodoptera frugiperda*) in sorghum and sucking bugs in green gram were identified and managed effectively using broad-based insecticides while powdery mildew and blight in green gram were controlled with mancozeb fungicide.

2.4. Data collection

2.4.1. Weather data and soil sampling

Daily rainfall data was obtained from meteorological stations located near the experiment sites. Air temperature and relative humidity were obtained from onsite measurements using ANENG HS-1 weather station thermometer and hygrometer respectively, and measured at 2 m above grass canopy in clear sky between 1100 and 1300 hours.

Soils were sampled before the sowing and harvesting stage at 0-30 cm depth. Soil pH was measured using a pH meter in a soil-suspension deionized water solution with the ratio = 1:2.5. Organic carbon was determined by the Walkley and Black wet oxidation method (Spertus, 2021), while total nitrogen was analyzed by Kjeldahl acid digestion method (Sáez-Plaza et al., 2013). Olsens' method was used to determine available soil phosphorus (De Silva et al., 2015), while potassium was measured using a flame photometer (Potdar et al., 2021).

2.4.2. Green gram and sorghum yield

Green gram plants were harvested at maturity in the net plot for grain yield determination. The total grain yield (t ha^{-1}) was calculated after drying the grains for at least a week to about 12.5% water content. Mature sorghum heads were harvested from the net plots and threshed to remove seeds from the heads. The total grain yield (t ha^{-1}) was determined after drying the grains to about 12.5% water content.

2.4.3. Canopy temperature and soil temperature

Leaf temperature was recorded using a handheld DT8220 infra-red thermometer placed at a right angle beside the crops. Soil temperature data was collected using a 20-inch stainless steel soil thermometer in the middle of the plots to avoid the effects of the edges.

2.4.4. Soil water content and water use efficiency

Soil water content was measured at the planting and harvesting stage. Soils were sampled and drilled from the center of plots and oven-dried at 110 ^{o}C for 48 h to constant weight and then gravimetric soil water content was calculated. Soil bulk density was evaluated by collecting undisturbed soil samples (Zhang et al., 2022). Volumetric water content was estimated by multiplying the measured gravimetric water content by the corresponding soil bulk density (Fang et al., 2024). Water use efficiency (WUE, kg ha^{-1} mm^{-1}) was calculated as the ratio between grain yield and water use in the system (Fang et al., 2024).

2.4.5. Nitrogen uptake and nitrogen use efficiency

At physiological maturity, five plants were randomly uprooted from each plot and then separated into stover/straw and grains. The plant samples were oven-dried at 105 ^{o}C for one hour and further dried at 80 ^{o}C to attain constant dry weight. The N content of the samples was determined using the Kjeldahl method and the total N uptake was computed by adding the N content of grain to the N content of the stover/straw (Raza *et al.,* 2019). The N uptake was calculated by multiplying the total dry matter with N content (Lyngdoh et al., 2020).

Nitrogen use efficiency (NUE, kg kg^{-1}) was computed as the ratio of N output in harvested products against the amount of N input (EU Nitrogen Expert Panel, 2015).

2.4.6. Vapor pressure deficit and crop water stress index

The vapor pressure deficit is determined by getting the difference between saturation vapor pressure and actual vapor pressure (Grossiord et al., 2020). The crop water stress index is computed using air temperature and canopy temperatures of both stressed and non-stressed crops (Katimbo et al., 2022).

2.5. Data analysis

Before statistical analyses, all data collected on various parameters were analyzed using the Shapiro-Wilk test for normal distribution and homogeneity of variables. When normality was not met data was transformed while when normality was met, data were subjected to R software version 4.3.3.0 using two-way analysis of variance. Treatment means were separated using Fisher's least significant difference (LSD) at $P \leq 0.05$. All data were expressed as means ± standard error of the mean (SEM). Simple linear regression analyses explored relationships between parameters.

3. RESULTS

3.1. Weather data and soil characteristics

Total rainfall in Mwala was 227 mm while in Katangi was 191 mm (Table 1). This amount is about 90% of the long-term average for the short rains season in each site. While the rainfall amount fell below the estimated 250 mm critical water requirement to maximize yield in green gram (Mugo et al., 2020) and 300 mm for sorghum (Moi, 2021), both crops did not experience significant moisture deficit. The mean air temperature range was 24 to 30 ^{o}C while relative humidity was 47 to 64%, which is typical of the growing season.

Soils sampled were moderately acidic in Katangi (5.7-7.2) and of low fertility. Total nitrogen (0.8-1.5 g kg^{-1}) and phosphorus (13-26 mg kg^{-1}) were low, while organic carbon (9.8-17.6 g kg^{-1}) was low to moderate, and potassium (8.4-11.6 g kg^{-1}) was adequate. Soil bulk density within the root zone was of the range 1.08-1.37 g cm^{-3}, and could not restrict root growth. Nitrogen and phosphorus were supplied through the application of inorganic fertilizer.

Table 1. Monthly rainfall (mm), mean air temperature (ºC), and mean relative humidity (%) in Mwala and Katangi during the 2022 short rains experiment season

Site and month	Rainfall (mm)	Temperature (ºC)	Relative humidity (%)
Mwala			
October 2022	0	26.9	56.4
November 2022	194.1	25.4	46.8
December 2022	16.8	24.2	47.6
January 2023	16.1	25.4	52.4
Total rainfall	227.0		
Katangi			
October 2022	0	28.9	64.2
November 2022	139.7	29.4	60.8
December 2022	44.7	29.2	57.7
January 2023	6.4	30.2	55.4
Total rainfall	190.8		

3.2. Green gram and sorghum grain yield

Significant interactions (P < .001) between variety and crop arrangement on green gram grain yield were observed (Table 2). Across the two sites, sole crops out-yielded (0.91 t ha^{-1}) those crops grown under single row (0.62 t ha^{-1}) and double row (0.75 t ha^{-1}). However, higher yield decline occurred under single row compared with double row crop arrangement. While grain yield among the varieties changed with crop arrangement, variety N26 outperformed the rest in both sites. Sorghum yield was significantly (P < .001) influenced by crop arrangement (Table 2). The sole crop recorded the highest yield (2.2 t ha^{-1}), while the yield of intercropped sorghum was reduced in a single row by 35.8% lower than the sole crop.

Table 2. Grain yield (t ha^{-1}) of green gram varieties grown under sole crop or intercropped with sorghum in single and double row arrangement in Mwala and Katangi during the 2022 short rains experiment season

Site & variety	Sole crop	Single	Double	Mean	Sorghum grain yield	
Mwala						
N26	1.30 ± 0.01a	0.89 ± 0.01c	1.08 ± 0.01b	1.09 ± 0.01a	Sole crop	3.2 ± 0.03a
Biashara	1.12 ± 0.02a	0.79 ± 0.01c	0.95 ± 0.02b	0.95 ± 0.02b	Single row	2.1 ± 0.04c
Karembo	0.76 ± 0.02a	0.53 ± 0.01c	0.65 ± 0.02b	0.65 ± 0.02c	Double row	2.7 ± 0.05b
KS20	0.60 ± 0.01a	0.36 ± 0.01c	0.49 ± 0.02b	0.48 ± 0.02d	Mean	2.7 ± 0.04
Mean	0.95 ± 0.02A	0.64 ± 0.01C	0.79 ± 0.02B			
Katangi						
N26	1.20 ± 0.02a	0.82 ± 0.02c	0.95 ± 0.03b	0.99 ± 0.02a	Sole crop	2.1 ± 0.03a
Biashara	0.89 ± 0.02a	0.66 ± 0.01c	0.80 ± 0.02b	0.78 ± 0.02b	Single row	1.3 ± 0.03c
Karembo	0.74 ± 0.01a	0.52 ± 0.01c	0.62 ± 0.02b	0.63 ± 0.01c	Double row	1.7 ± 0.04b
KS20	0.62 ± 0.01a	0.35 ± 0.03c	0.45 ± 0.02b	0.47 ± 0.02d	Mean	1.7 ± 0.03
Mean	0.86 ± 0.02A	0.59 ± 0.02C	0.71 ± 0.02B			

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different at 5% probability level.

3.3. Water and nitrogen use efficiency

As shown in Table 3, water use efficiency (WUE) was affected by variety, crop arrangement, and their interactions. Sole green gram was the most efficient in terms of water use (3.9 kg ha^{-1} mm^{-1}) followed by double row (2.8 kg ha^{-1} mm^{-1}) and lowest in a single row (2.4 kg ha^{-1} mm^{-1}). Intercropping green gram with sorghum reduced WUE in a single row by 38% in comparison with sole crops. Variety N26 enhanced WUE (3.6 kg ha^{-1} mm^{-1}), but declined by 11% in Biashara and 21% in Karembo compared with N26. Intercropping green gram with sorghum reduced NUE by 63% in a single row and 54% in a double row compared with the sole crop.

Table 3. Water use efficiency (kg ha^{-1} mm^{-1}) and nitrogen use efficiency (kg kg^{-1}) of green gram varieties grown under sole crop or intercropped with sorghum in single and double row arrangement in Mwala and Katangi during 2022 short rains experiment season

Site & variety	Water use efficiency (kg ha^{-1} mm^{-1})				Nitrogen use efficiency (kg kg^{-1})			
	Sole crop	Single	Double	Mean	Sole crop	Single	Double	Mean
Mwala								
N26	4.55 ± 0.05a	2.88 ± 0.05c	3.25 ± 0.05b	3.56 ± 0.05a	3.44 ± 0.55a	1.25 ± 0.06b	1.36 ± 0.33b	2.02 ± 0.31a
Biashara	3.82 ± 0.06a	2.76 ± 0.04c	3.00 ± 0.07b	3.19 ± 0.05b	2.76 ± 0.25a	1.06 ± 0.16b	1.15 ± 0.09b	1.66 ± 0.17ab
Karembo	3.50 ± 0.07a	2.36 ± 0.04c	2.79 ± 0.05b	2.88 ± 0.04c	2.34 ± 0.40a	0.93 ± 0.03b	1.06 ± 0.13b	1.44 ± 0.19b
KS20	3.30 ± 0.04a	1.60 ± 0.06c	2.07 ± 0.07b	2.32 ± 0.05d	2.22 ± 0.63a	0.89 ± 0.08b	0.98 ± 0.11b	1.36 ± 0.27b
Mean	3.79 ± 0.06A	2.40 ± 0.05C	2.78 ± 0.06B		2.69 ± 0.46A	1.03 ± 0.08B	1.14 ± 0.17B	
Katangi								
N26	4.46 ± 0.09a	2.90 ± 0.10c	3.33 ± 0.13b	3.56 ± 0.11a	1.59 ± 0.27a	0.60 ± 0.03b	0.80 ± 0.11b	1.00 ± 0.14a
Biashara	4.09 ± 0.10a	2.56 ± 0.06c	3.12 ± 0.08b	3.26 ± 0.08b	1.28 ± 0.29a	0.43 ± 0.04b	0.73 ± 0.26b	0.81 ± 0.20ab
Karembo	3.76 ± 0.04a	2.24 ± 0.06c	2.53 ± 0.09b	2.84 ± 0.06c	1.17 ± 0.09a	0.40 ± 0.07b	0.62 ± 0.04b	0.73 ± 0.07b
KS20	3.61 ± 0.06a	1.75 ± 0.13c	2.44 ± 0.03b	2.60 ± 0.07d	1.05 ± 0.10a	0.36 ± 0.00b	0.51 ± 0.05b	0.64 ± 0.12b
Mean	3.98 ± 0.07A	2.36 ± 0.09C	2.86 ± 0.08B		1.27 ± 0.19A	0.45 ± 0.05B	0.67 ± 0.12B	

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different at 5% probability level.

3.4. Soil and canopy temperature

There were significant differences ($P < 0.05$) between crop arrangement on soil and canopy temperatures (Table 4). The seasonal soil temperature was higher in the sole crop (21.7-23.8 ^{o}C) relative to the single row (21.0-22.3 ^{o}C). Soil temperature was always lower in N26 (21.5 ^{o}C), while KS20 recorded the highest soil temperature (22.6 ^{o}C) in the soil layer (0-20 cm). The sole crop had higher canopy temperature (18.1-22.2 ^{o}C) than those in double row (18.0-23.1 ^{o}C) and single row (17.7-20.2 ^{o}C). N26 recorded lower canopy temperatures than other varieties (Table 4).

Table 4. Soil temperature (^{o}C) in the 0-20 cm layer and canopy temperature of green gram varieties grown under sole crop or intercropped with sorghum in single and double row arrangement in Mwala and Katangi during 2022 short rains experiment season

Site & variety	Soil temperature				Canopy temperature			
	Sole crop	Single	Double	Mean	Sole	Single	Double	Mean
Mwala								
KS20	23.8 ± 0.02a	22.3 ± 0.09b	23.1 ± 0.04a	23.1 ± 0.05a	22.2 ± 0.03a	20.2 ± 0.20b	20.9 ± 0.08b	21.1 ± 0.10a
Karembo	23.6 ± 0.17a	22.2 ± 0.05b	22.6 ± 0.02b	22.8 ± 0.08b	21.6 ± 0.32a	20.5 ± 0.18b	20.7 ± 0.12b	20.9 ± 0.21b
Biashara	22.1 ± 0.10a	21.8 ± 0.03b	21.9 ± 0.03b	21.9 ± 0.05c	20.0 ± 0.25a	19.7 ± 0.08b	19.6 ± 0.06b	19.8 ± 0.13c
N26	22.0 ± 0.05a	21.2 ± 0.03b	21.5 ± 0.09b	21.6 ± 0.08c	19.9 ± 0.31a	18.9 ± 0.10b	18.9 ± 0.01b	19.2 ± 0.14c
Mean	22.9 ± 0.09A	21.9 ± 0.05B	22.3 ± 0.05B		20.9 ± 0.23A	19.8 ± 0.14B	20.0 ± 0.07B	
Katangi								
KS20	22.4 ± 0.02a	21.9 ± 0.04b	22.1 ± 0.04a	22.1 ± 0.03a	19.2 ± 0.03a	18.3 ± 0.07b	18.4 ± 0.03b	18.6 ± 0.04a
Karembo	22.2 ± 0.02a	21.9 ± 0.02b	22.0 ± 0.02a	22.0 ± 0.02a	18.6 ± 0.05a	18.1 ± 0.01b	18.3 ± 0.06b	18.3 ± 0.04a
Biashara	21.8 ± 0.01a	21.5 ± 0.02a	21.6 ± 0.01a	21.6 ± 0.01b	18.2 ± 0.04a	18.0 ± 0.02a	18.0 ± 0.05a	18.1 ± 0.04b
N26	21.7 ± 0.05a	21.0 ± 0.32b	21.4 ± 0.08a	21.4 ± 0.15b	18.1 ± 0.01a	17.7 ± 0.04b	17.9 ± 0.09a	17.9 ± 0.05b
Mean	22.0 ± 0.03A	21.6 ± 0.10B	21.0 ± 0.04B		18.5 ± 0.03A	18.0 ± 0.04B	18.2 ± 0.06A	

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different at 5% probability level.

3.5. Vapor pressure deficit and crop water stress index

Vapor pressure deficit (VPD) was different among the green gram varieties where N26 scored the lowest VPD (1.2 kPa) (Table 5). The crop arrangement system had a higher effect on VPD where the single row recorded the lowest VPD of 1.2 kPa Crop water stress index (CWSI) varied among the green gram varieties where KS20 exhibited the lowest water stress (CWSI = 0.22). The single row recorded the lowest CWSI of 0.29 while the sole crop had the highest value of 0.58 (Table 5). There was a weak relationship between grain yield and CWSI.

Table 5. Vapor pressure deficit (kPa) and crop water stress index of green gram varieties grown under sole crop or intercropped with sorghum in single and double row arrangement in Mwala and Katangi during 2022 short rains experiment season.

Site & variety	Vapor pressure deficit				Crop water stress index			
	Sole crop	Single	Double	Mean	Sole crop	Single	Double	Mean
Mwala								
KS20	1.89 ± 0.04a	1.59 ± 0.20b	1.75 ± 0.10a	1.74 ± 0.14a	0.41 ± 0.01a	0.10 ± 0.13c	0.20 ± 0.02b	0.24 ± 0.05c
Karembo	1.78 ± 0.06a	1.46 ± 0.10b	1.64 ± 0.11a	1.63 ± 0.23a	0.44 ± 0.27a	0.30 ± 0.06b	0.34 ± 0.02b	0.36 ± 0.12b
Biashara	1.75 ± 0.04a	1.35 ± 0.12b	1.56 ± 0.17a	1.55 ± 0.21b	0.77 ± 0.06a	0.40 ± 0.05c	0.61 ± 0.05b	0.59 ± 0.05a
N26	1.69 ± 0.05a	1.40 ± 0.14b	1.51 ± 0.03a	1.53 ± 0.17b	0.90 ± 0.10a	0.50 ± 0.02b	0.64 ± 0.03b	0.68 ± 0.07a
Mean	1.78 ± 0.05A	1.45 ± 0.14B	1.62 ± 0.10A		0.63 ± 0.13A	0.33 ± 0.07B	0.45 ± 0.03B	
Katangi								
KS20	1.17 ± 0.02a	1.00 ± 0.11b	1.09 ± 0.04b	1.09 ± 0.06a	0.30 ± 0.02a	0.10 ± 0.03b	0.20 ± 0.03b	0.20 ± 0.03b
Karembo	1.11 ± 0.04a	0.91 ± 0.08b	1.02 ± 0.09b	1.01 ± 0.07b	0.40 ± 0.05a	0.20 ± 0.01b	0.30 ± 0.02b	0.30 ± 0.03b
Biashara	1.09 ± 0.04a	0.86 ± 0.10b	0.96 ± 0.06a	0.97 ± 0.07b	0.50 ± 0.00a	0.20 ± 0.02b	0.50 ± 0.03a	0.40 ± 0.03b
N26	1.07 ± 0.06a	0.72 ± 0.12b	0.94 ± 0.08a	0.91 ± 0.09b	0.90 ± 0.03a	0.50 ± 0.05c	0.70 ± 0.09b	0.70 ± 0.06a
Mean	1.11 ± 0.04A	0.87 ± 0.10B	1.00 ± 0.07B		0.53 ± 0.03A	0.25 ± 0.03B	0.43 ± 0.05B	

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different at 5% probability level.

3.6. Crop aggressivity

From the intensity of interspecific competition, green gram was the dominant species with positive values in all treatments while sorghum was the dominant species. Green gram variety Biashara had an aggressivity of 0.57 as averaged across the two sites (Table 6).

Table 6. Aggressivity of green gram varieties grown under sole crop or intercropped with sorghum in single and double row arrangement in Mwala and Katangi during 2022 short rains experiment season

Site & variety	Green gram aggressivity			Sorghum aggressivity		
	Single	Double	Mean	Single	Double	Mean
Mwala						
N26	0.38 ± 0.01ab	0.54 ± 0.04a	0.46 ± 0.03a	-0.38 ± 0.01ab	-0.54 ± 0.04a	-0.46 ± 0.03a
Biashara	0.52 ± 0.04a	0.53 ± 0.02a	0.53 ± 0.03a	-0.52 ± 0.04b	-0.53 ± 0.02b	-0.53 ± 0.03a
Karembo	0.55 ± 0.02a	0.58 ± 0.01a	0.57 ± 0.02a	-0.55 ± 0.02b	-0.57 ± 0.01b	-0.57 ± 0.02a
KS20	0.27 ± 0.03b	0.41 ± 0.02ab	0.34 ± 0.03b	-0.27 ± 0.03a	-0.41 ± 0.02ab	-0.34 ± 0.03b
Mean	0.43 ± 0.03B	0.52 ± 0.02A	0.48 ± 0.03	-0.43 ± 0.03A	-0.52 ± 0.03B	-0.48 ± 0.03
Katangi						
N26	0.44 ± 0.02ab	0.34 ± 0.02bc	0.39 ± 0.02a	-0.44 ± 0.02bc	-0.34 ± 0.02ab	-0.39 ± 0.02a
Biashara	0.59 ± 0.03a	0.62 ± 0.05a	0.61 ± 0.04a	-0.59 ± 0.03c	-0.62 ± 0.04c	-0.61 ± 0.04a
Karembo	0.50 ± 0.04ab	0.49 ± 0.02ab	0.50 ± 0.03a	-0.50 ± 0.04bc	-0.49 ± 0.03a	-0.50 ± 0.03bc
KS20	0.18 ± 0.01c	0.18 ± 0.01a	0.18 ± 0.01b	-0.18 ± 0.01a	-0.18 ± 0.01a	-0.18 ± 0.01b
Mean	0.43 ± 0.03A	0.41 ± 0.03B	0.42 ± 0.03	-0.43 ± 0.03B	-0.41A ± 0.03	-0.42 ± 0.03

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different at 5% probability level.

3.7. Relationship between green gram grain yield and nitrogen and water use efficiency

Green gram yield had a weaker relationship with nitrogen use efficiency ($R^2 = 0.34$) in Mwala and ($R^2 = 0.47$) in Katangi (Figures 1a and 1b). Green gram yield was dependent on water use efficiency ($0.4 \leq R^2 \leq 0.5$) in both sites (Figures 1c and 1d).

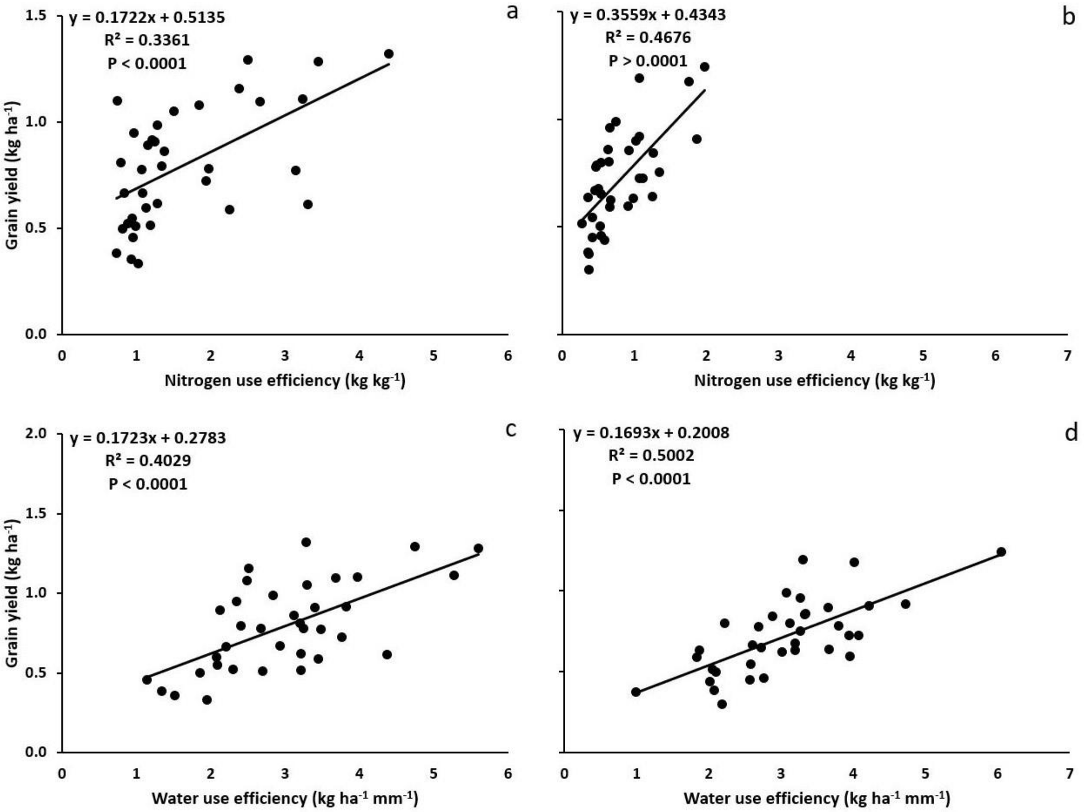

Figure 1. Association between green gram grain yield and nitrogen use efficiency in Mwala (a) and Katangi (b), and the relationship between green gram grain yield and water use efficiency in Mwala (c) and Katangi (d). Lines are least square linear regressions. N = 36.

3.8. Relationships between soil temperature, canopy temperature, and vapor pressure deficit

Soil temperature was weakly dependent on vapor pressure deficit ($0.20 \leq R^2 \leq 0.37$) (Figures 2a and 2b). Similarly, canopy temperature had a weaker relationship with vapor pressure deficit ($0.17 \leq R^2 \leq 0.33$) (Figures 2c and 2d). The relationship between canopy temperature and soil temperature was fitted to a strong positive linear equation ($R^2 \geq 0.84$) (Figures 2e and 2f).

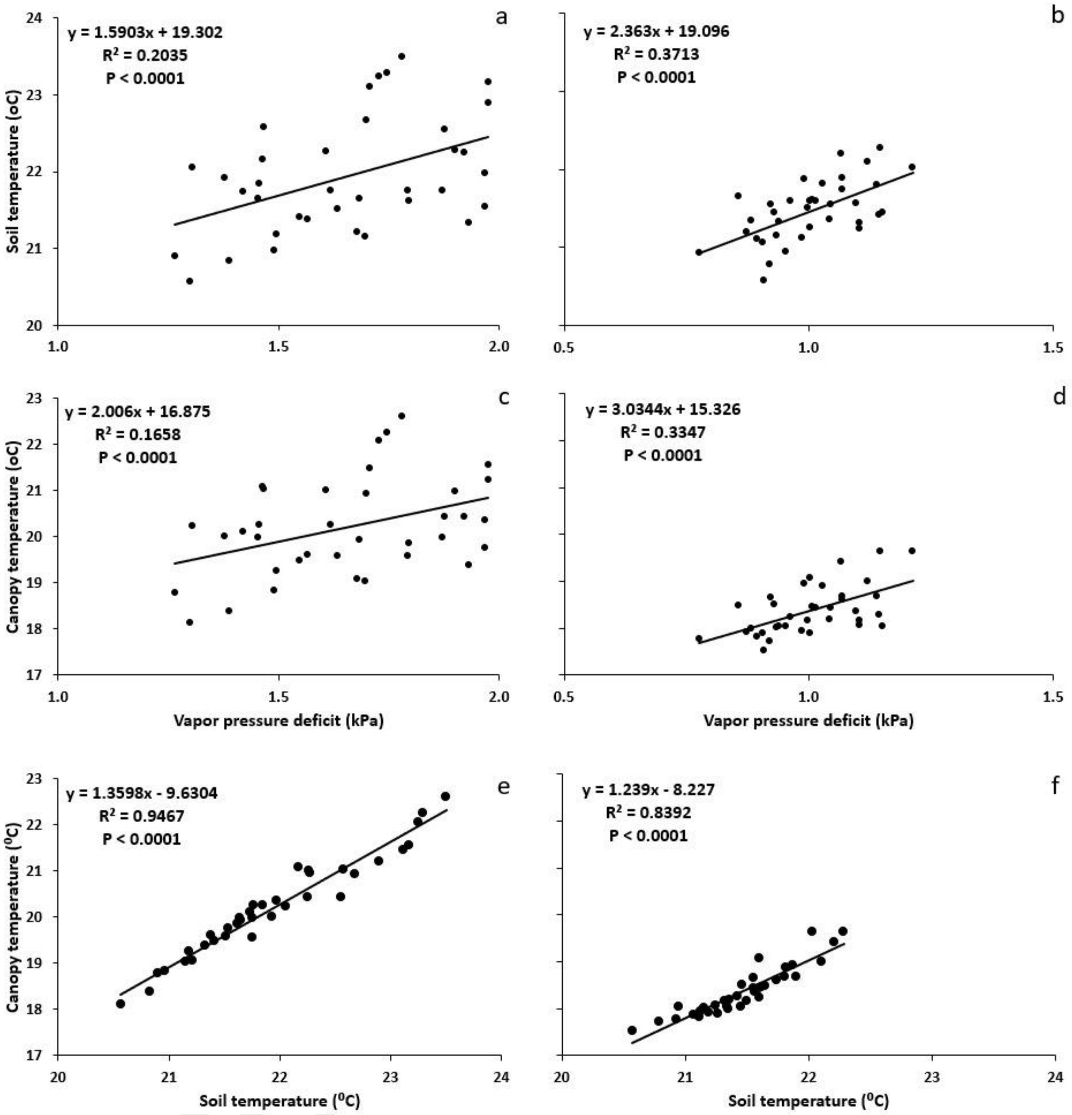

Figure 2. Association between green gram soil temperature and vapor pressure deficit in Mwala (a) and Katangi (b), the correlation between canopy temperature and vapor pressure deficit in Mwala (c) and Katangi (d), and the relationship between canopy temperature and soil temperature in Mwala (e) and Katangi (f). Lines are least square linear regressions. N = 36.

Table 7. Water use efficiency (WUE), nitrogen use efficiency (NUE), vapor pressure deficit (VPD), canopy temperature, soil temperature, and crop water stress index of sorghum intercropped with green gram in Mwala and Katangi during the 2022 short rains experiment season

Site and crop arrangement	WUE (kg ha^{-1} mm^{-1})	NUE (kg kg^{-1})	VPD (kPa)	Canopy temp. (°C)	Soil temp. (°C)	Crop water stress index
Mwala						
Sole crop	13.0 ± 0.04a	5.8 ± 0.02a	2.03 ± 0.02a	22.9 ± 0.24a	24.3 ± 0.27a	0.8 ± 0.02a
Single row	8.4 ± 0.02c	2.8 ± 0.03c	1.46 ± 0.02c	19.7 ± 0.32c	23.2 ± 0.34b	0.2 ± 0.01c
Double row	10.7 ± 0.04b	3.8 ± 0.03b	1.65 ± 0.01b	21.9 ± 0.41b	23.6 ± 0.32b	0.6 ± 0.02b
Mean	10.7 ± 0.03	4.1 ± 0.03	1.71 ± 0.02	21.5 ± 0.32	23.7 ± 0.31	0.5 ± 0.02
Katangi						
Sole crop	13.1 ± 0.04a	2.6 ± 0.03a	2.0 ± 0.03a	21.7 ± 0.36b	25.5 ± 0.35b	0.3 ± 0.01b
Single row	8.3 ± 0.02c	0.9 ± 0.02c	1.3 ± 0.02c	21.8 ± 0.28b	26.6 ± 0.28a	0.4 ± 0.01b
Double row	10.7 ± 0.04b	1.7 ± 0.02b	1.6 ± 0.02b	22.6 ± 0.22a	26.6 ± 0.36a	0.7 ± 0.02a
Mean	10.7 ± 0.03	1.7 ± 0.02	1.6 ± 0.02	22.0 ± 0.29	26.2 ± 0.33	0.5 ± 0.01

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different at 5% probability level.

3.9. Relationship between grain yield and nitrogen and water use efficiency

Regression analysis between grain yield, nitrogen use efficiency, and water use efficiency revealed significant positive associations (Figures 3a to 3d). Results show that sorghum grain yield had a linear correlation with nitrogen use efficiency ($R^2 \geq 0.62$) (Figures 3a and 3b) and water use efficiency ($R^2 \geq 0.54$) (Figures 3c and 3d).

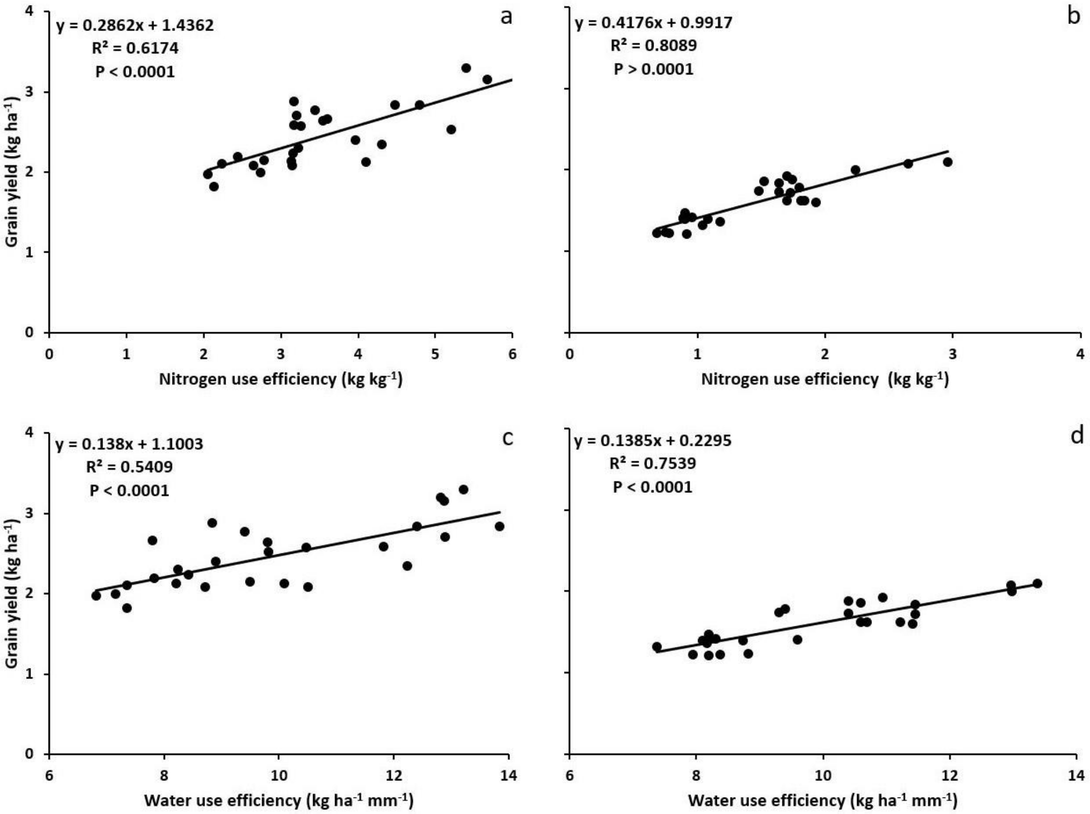

Figure 3. Association between sorghum grain yield and nitrogen use efficiency in Mwala (a) and Katangi (b), and the relationship between sorghum grain yield and water use efficiency in Mwala (c) and Katangi (d). Lines are least square linear regressions. N = 27.

3.10. Relationship between soil temperature, vapor pressure deficit, and canopy temperature

Soil temperature was dependent on vapor pressure deficit ($R^2 = 0.58$) (Figure 4a) in Mwala and ($R^2 = -0.46$) (Figure 4b) in Katangi. There was a weak relationship between canopy temperature and soil temperature ($R^2 = 0.36$) (Figure 4c) in Mwala and ($R^2 = 0.23$) (Figure 4d) in Katangi.

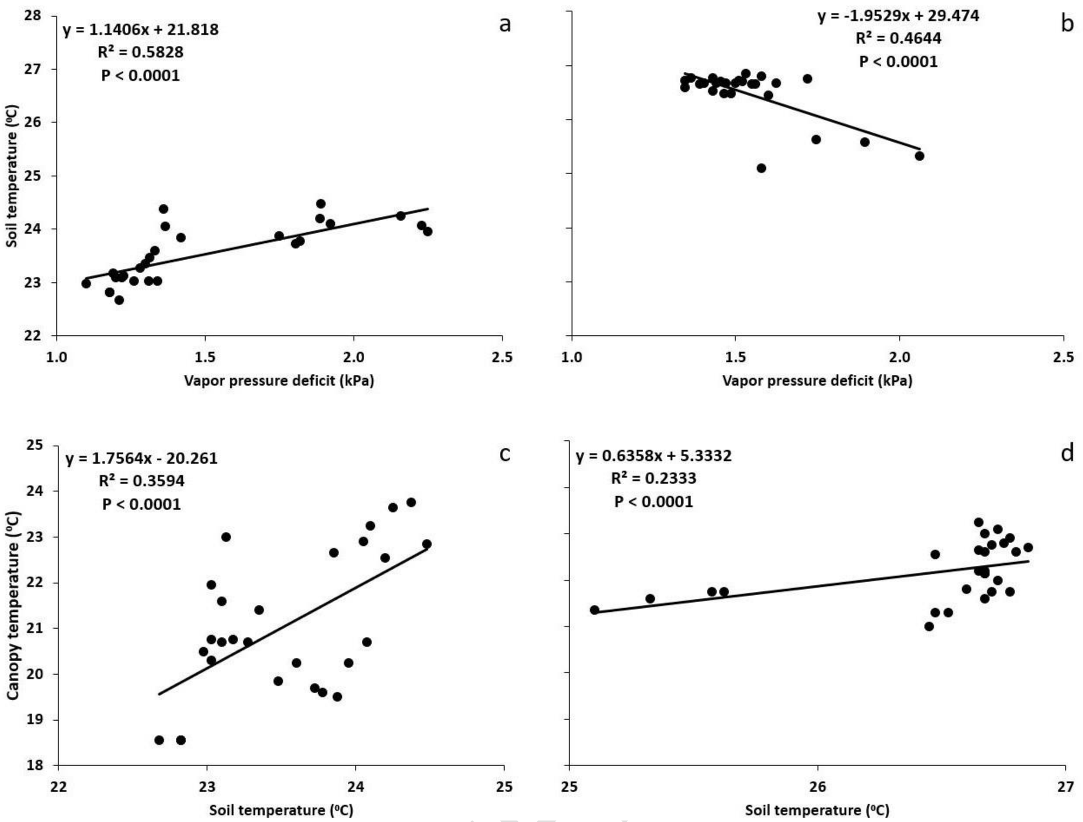

Figure 4. Soil temperature (ºC) as a function of vapor pressure deficit (kPa) in Mwala (a) and Katangi (b), and soil temperature (ºC) as a function of canopy temperature (ºC) in Mwala (c) and Katangi (d). Lines are least square linear regressions. N = 27.

4. DISCUSSION

4.1. Grain yield and companion crop aggressivity

Intercropping significantly reduced grain yield, both in double row (18%) and in single row (47%) arrangements compared with sole crops. The positive values of aggressivity in green gram and negative values in sorghum among the intercrops indicate that green gram was better in the acquisition of resources in this arrangement except in a single row under KS20. These results revealed that non-aggressive crops such as green gram can be better than aggressive sorghum crops, due to varying levels of competition in the acquisition of water and nitrogen across the system (Harisha et al., 2024). Similar results of the dominant behavior of legumes when intercropped with cereals were documented by Wang et al. (2021). This may therefore require adjusting the crop arrangement system to decrease interspecific competition for resources.

4.2. Water and nitrogen use efficiency

Inter-specific competition in intercropping may lead to either negative or positive effects on yield depending on water and nutrient availability (Feng et al., 2021; Zhang et al., 2022). Variety N26 recorded higher WUE by 1.1 kg ha^{-1} mm^{-1} compared with the least variety KS20 which could be linked to variety differences. WUE in the sole system was more productive per unit of water used than those in the intercropped system. This could be due to the absence of competition for resources (Chen et al., 2022; Xie et al., 2021). Similar results were reported by Lyngdoh et al. (2020) and Kherif et al. (2023). Therefore, further studies need to be done to ascertain to what extent intercropping would be advantageous to green gram without affecting the yield of both crops.

Cereal-legume intercropping increases the ability of the absorption and utilization of nitrogen by crops and thus improves NUE (Zhang et al., 2022). Sole sorghum recorded the highest NUE of 4.2 kg kg^{-1} which implies that sorghum was more efficient in utilizing nitrogen over green gram. This could be linked to enhanced N uptake by deep-rooted sorghum plant roots (Raza et al., 2019). Variety N26 registered the highest value of NUE which could be related to the cumulative effect of the high content of nitrogen in grains and various characteristics of the green gram varieties (Kiponda et al., 2023; Lyngdoh et al., 2020). Further studies are therefore recommended to verify the decreased NUE in intercropping arrangements and whether NUE could benefit subsequent crops in the following season.

4.3. Modification of soil and canopy temperature

Soil temperature fluctuations affect rooting activity which further influences nutrient uptake, water infiltration, and biomass accumulation in plants (Setiawan, 2022). Intercropping lowered soil temperature by 7.2 ^{o}C in single row and 7.1 ^{o}C in double row during the crop growing period. This was probably caused by the canopy shading of the intercropped plants which decreased the radiation and the heating effect on the soil surface reducing evapotranspiration (Ai et al. 2021). Similar results were reported by Shumet et al. (2022) and Nyawade et al. (2019).

Leaf temperature is an important parameter that affects plant physiological and biochemical processes indicating plant water status, water use, and stress level (Setiawan, 2022). Intercropping lowered the canopy temperature during the growth stages of green gram by 7.7 to 9.5 ^{o}C in a single row. The present results demonstrated higher grain yields in green gram variety (N26) having lower canopy temperature than varieties with higher canopy temperature. Reduced canopy temperature was probably brought about by plant architecture, plant water availability, and reduced soil temperature in intercropping systems (Luan and Vico, 2021). Management of canopy temperature in plants therefore, is a good tool that can be used to optimize crop yield (Ninanya et al., 2021; Thapa et al., 2018).

4.4. Relationships between traits as drivers of yield

Water and nitrogen are interdependent factors that can be regulated by agronomic interventions to optimize crop yield (Gao et al., 2023). This study identified positive correlations between grain yield and water use efficiency ($R^2 \geq 0.40$) and nitrogen use efficiency ($0.34 \leq R^2 \leq 0.47$). Despite the yield decline in intercropped green gram, it was established that if water is not a limiting factor, sorghum-green gram intercropping in dryland regions has a lot of potential for increasing water and nitrogen productivity. Water and nutrient availability could have been affected by rainfall distribution which was below the long-term average (Table 1) as reduced nitrogen uptake by plants is affected by water status in the soil which is a major challenge in dryland areas (Begam et al., 2024). Decreased grain yield in intercropping could be linked to interspecies competition of water and nitrogen which depended on species type, water, and nutrient availability (Kherif et al., 2023). It is worth mentioning that in this study, WUE is a stronger driver of yield ($R^2 \geq 0.40$) than NUE ($0.34 \leq R^2 \leq 0.47$) in green grams while in sorghum NUE ($0.61 \leq R^2 \leq 0.81$) is the strong driver.

5. CONCLUSION

This study demonstrates that despite the yield decline in the intercropping system, double row could be effective than single row in enhancing green gram-sorghum complementarity for increased grain yield, WUE and NUE and the regulation of crop microclimate. Variety N26 recorded the lowest canopy and soil temperature and highest values of NUE and WUE indicating that it was more suitable for growing in the study area. Further research is needed to confirm these results under different seasons and geographical locations.

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