Australian Journal of Crop Science AJCS

Aust J Crop Sci. 19(06):680-688 (2025) | https://doi.org/10.21475/ajcs.25.19.06.p332 ISSN:1835-2707

Green gram and sorghum yield as affected by diverse intercrop planting configurations

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Submitted:* *13/02/2025

Revised:* *09/04/2025

Accepted:* *12/04/2025

Abstract: Crop arrangement patterns in intercrop systems affect resource efficiency and yield of the companion crops. The degree of interaction within and between species in intercrop systems depends on crop life cycle and morphology. Experiments were carried out to determine the effect of row-intercrop arrangement on four phenologically close but morphologically contrasting varieties of green gram (*Vigna radiata* L.) intercropped with sorghum (*Sorghum bicolor* L.) in southeastern Kenya. Split-plot design was used, with crop arrangement (sole crop, single and double-row intercrop) as main plots and green gram variety in the subplots. Four green gram varieties of N26, KS20, Karembo, and Biashara were intercropped with sorghum variety Seredo. Sole crops of each green gram variety and sorghum were added as control. Variety N26 had a large canopy, quicker growth rate (7.2 g m^{-2} day^{-1}), and out-yielded the other varieties by 1.09 t ha^{-1}. Sole crops of green gram (irrespective of variety) and sorghum recorded higher growth rates and yield compared with intercrop systems. However, crops grown in double row, out-yielded those in single row arrangement. Green gram yield was a function of the number of branches and seed number m^{-2} while sorghum yield was directly proportional to tiller number and grain number m^{-2}. Results imply that the yield of green gram intercropped with sorghum could be improved through the use of varieties with rapid growth rates and wider intercrop strips to maximize intraspecific and interspecific interactions.

Keywords: single row; double row; crop growth rate; land equivalent ratio; competition.
Abbreviations: ATER_area time equivalent ratio; $CaCl_2$_calcium chloride; CGR_crop growth rate; cm_centimeters; °C _degrees celsius; g_grams; ha_hectares; LER_land equivalent ratio; LM_low midland; m^{-2}_square meters; mm_millimeters; pH_potential of hydrogen; R^2_coefficient of determination; SEM_standard error of mean; t_ton

Introduction

Cereal-legume intercropping often increases crop system productivity and efficiency but in some instances yield could be reduced (Bremer et al., 2024). Intercropping is the simultaneous growing of two or more crops on the same land area, either simultaneously or in relay sequence (Ewansiha et al., 2018). In the dryland areas of Kenya, sorghum (*Sorghum bicolor* L.) is often intercropped with drought-tolerant legumes such as green gram (*Vigna radiata* L.) (Okeyo et al., 2020). To maximize the yield of companion crops, intercrop systems are designed in a way that minimises competition for resources (Tang et al., 2020; Maclaren et al., 2023).

The design of intercrop systems manipulates both spatial and temporal arrangement of crops, which largely depends on the crop life cycle, morphological traits and crop-specific agronomic requirements (Layek et al., 2018). In southeastern Kenya, farmers intercrop sorghum with green gram either in the same row or in alternating rows, and in the same hole (Wambua et al., 2017). Irrespective of the arrangement, there are some degrees of competition for growth resources. Competition consists of an intraspecific and an interspecific component, where individuals of the same species or different species are negatively affected, respectively (Hailu et al., 2018; Gao et al., 2021).

Crop arrangement patterns affect resource efficiency, such as water and nutrient uptake, and radiation capture (Abbas et al., 2021). In dryland Ethiopia, the yield of haricot bean (*Phaseolus vulgaris* L.) reduced significantly due to shading by intercrop sorghum (Hailu & Geremu, 2021). Under these conditions, the short-statured green gram were shaded by sorghum could grow taller and reduce branching, radiation capture, and use efficiency (Li et al., 2021). In arid Pakistan, double-row intercropping of green gram with maize (*Zea mays* L.) out-yielded the sole crops (Wang et al., 2021). However, mechanisms contributing to either yield increase or decline under different intercrop arrangements are only partially understood.

Plant morphological differences potentially contribute to intercrop compatibility by regulating intra and interspecific competition (Wu et al., 2022). Tall and dense canopy legumes would require wider spacing when intercropped with cereals (Sun et al., 2019). Common green gram varieties in Kenya have a relatively close phenological range but are morphologically different (Karimi et al., 2019). Varieties such as Biashara, Karembo, and KS20 are short stature with relatively open canopy while N26 is tall and has a large dense canopy (Karimi et al., 2019; Mulwa et al., 2023). Against the backdrop of these diverse green gram varieties, yield maximization would require appropriate intercrop arrangement with cereals to enhance competitive, complementary, and facilitative interactions for higher yield. This study investigated the growth and yield of four morphologically contrasting green gram varieties under different intercrop row arrangements with sorghum.

Results

Rainfall during the experiment seasons

Total rainfall in Mwala was 227 mm and 190 mm in Katangi which is typical of the long-term average for short rains in the region (Figure 1). Further, its distribution was characteristic of the two sites but the critical stages of both crops did not suffer significant moisture stress.

Yield and biomass of green gram

Significant interactions ($P < 0.001$) between variety and crop arrangement on green gram grain yield and dry matter were measured (Table 1). Variety N26 out-performed KS20 variety by 0.56 t ha^{-1} grain yield and 2.15 t ha^{-1} biomass. Across the two sites, sole green gram out-yielded (0.91 t ha^{-1}) double row by 21% and single row by 47%. However, in relation to the other varieties, the yield of KS20 was markedly reduced under single and double-row intercropping compared with the sole crop system. The number of pods m^{-2} and seeds pod^{-1} were significantly affected by variety and crop arrangement. While sole crops of green gram had more pods and seeds per pod, the double-row system surpassed the single row (Table 2). Consistent with grain yield, variety N26 had larger pods and the least was KS20.

Growth traits of green gram

The effects of variety, crop arrangement, and their interactions were significant ($P < 0.01$) on branches plant^{-1} and plant height. Variety N26 had a dense canopy, with an average of 7 primary branches plant^{-1}, and the crops were taller compared with the other varieties (Table 3). Irrespective of variety, sole crops of green gram had larger canopies but canopy size was less suppressed under double row. Biomass accumulation during the critical window was rapid for N26 but KS20 had the slowest crop growth rate (Table 4). Rapid growth rates of 7.0 g m^{-2} day^{-1} were measured under the sole crop, while the double-row exceeded the single-row by 1.5 g m^{-2} day^{-1} (Table 4).

Drivers of green gram yield

In Mwala, green gram grain yield was strongly dependent on the number of branches plant^{-1} ($R^2 = 0.96$), number of seeds pod^{-1} ($R^2 = 0.94$) and number of pods m^{-2} ($R^2 = 0.82$). Similarly, in the drier Katangi, yield was directly proportional to branches ($R^2 = 0.94$), seeds pod^{-1} ($R^2 = 0.80$) and pods m^{-2} ($R^2 = 0.77$) (Figure 2).

Yield and growth of sorghum

Sorghum yield and yield components were significantly ($P < 0.001$) influenced by crop arrangement (Table 5). Sole crop recorded the highest yield, while the yield of intercropped sorghum was reduced in a single row by 0.95 t ha^{-1}. Sole sorghum recorded the highest grain number (4530 m^{-2}) and biomass (6.4 t ha^{-1}) than the intercropped patterns. Sole crop produced more tillers m^{-2} (6.2) than single row (2.4) and double row (4.2) (Table 5). Crop growth rate (CGR) was affected by crop arrangement, where a single row significantly reduced CGR by 5.8 g m^{-2} day^{-1}.

Yield drivers of sorghum

Regression analysis between grain yield and crop growth traits revealed significant positive associations (Figure 3). Results show that sorghum grain yield had a linear correlation with grain number ($R^2 = 0.85$), biomass at harvest ($R^2 = 0.73$), and number of fertile tillers m^{-2} ($R^2 = 0.32$). This implies that an increase in each of these attributes improved the sorghum yield.

System productivity index

Land equivalent ratio (LER) data in Table 4 revealed over 54% yield advantage of intercropping green gram and sorghum. Furthermore, the total LER was insignificantly ($P \leq 0.05$) higher in the intercropped system than that of the sole crop. Therefore, the intercropped system showed a greater productivity advantage than the sole crop system.

Discussion

Optimization of plant spacing and arrangement, both within and between species, reduces competition for water, nutrients, and light. Present results show that the spatial arrangement of green gram and sorghum in an intercrop system impacts growth and yield, irrespective of the morphology of the tested crops. While sole crops maximized yield, double-row intercropping potentially minimized intraspecific and interspecific competition compared with single-row intercropping.

Table 1. Grain yield (t ha^{-1}) and above-ground biomass (t ha^{-1}) of four green gram varieties grown as sole crops and intercropped with sorghum in single and double alternate rows in Mwala and Katangi during the 2022 short rains season.

Site and Variety	Grain yield (t ha^{-1})				Biomass (t ha^{-1})			
	Sole crop	Single row	Double row	Mean	Sole crop	Single row	Double row	Mean
Mwala								
N26	1.30 ± 0.01a	0.89 ± 0.01e	1.08 ± 0.01c	1.09 ± 0.01a	6.8 ± 0.03a	4.3 ± 0.11d	5.1 ± 0.04c	5.4 ± 0.10a
Biashara	1.12 ± 0.02b	0.79 ± 0.01f	0.95 ± 0.02d	0.95 ± 0.02b	5.5 ± 0.02b	3.6 ± 0.14f	4.3 ± 0.03d	4.5 ± 0.11b
Karembo	0.76 ± 0.02e	0.53 ± 0.01j	0.65 ± 0.02h	0.65 ± 0.02c	3.9 ± 0.04e	2.8 ± 0.08h	3.3 ± 0.04g	3.3 ± 0.10c
KS20	0.60 ± 0.01i	0.36 ± 0.01l	0.49 ± 0.02k	0.48 ± 0.02d	2.7 ± 0.04i	1.7 ± 0.09k	2.1 ± 0.02j	2.2 ± 0.08d
Mean	0.95 ± 0.02A	0.64 ± 0.01C	0.79 ± 0.02B		4.7 ± 0.03A	3.1 ± 0.11C	3.7 ± 0.08B	
Katangi								
N26	1.20 ± 0.02a	0.82 ± 0.02d	0.95 ± 0.03b	0.99 ± 0.02a	2.7 ± 0.03a	1.6 ± 0.05e	1.9 ± 0.04c	2.1 ± 0.03a
Biashara	0.89 ± 0.02c	0.66 ± 0.01g	0.80 ± 0.02e	0.78 ± 0.02b	2.3 ± 0.03b	1.4 ± 0.04g	1.8 ± 0.03d	1.8 ± 0.03b
Karembo	0.74 ± 0.01f	0.52 ± 0.01i	0.62 ± 0.02h	0.63 ± 0.01c	1.6 ± 0.04f	1.3 ± 0.02j	1.4 ± 0.03h	1.4 ± 0.30c
KS20	0.62 ± 0.01h	0.35 ± 0.03k	0.45 ± 0.02j	0.47 ± 0.02d	1.2 ± 0.04j	0.8 ± 0.03l	0.9 ± 0.02k	1.0 ± 0.10d
Mean	0.86 ± 0.02A	0.59 ± 0.02C	0.71 ± 0.02B		2.0 ± 0.04A	1.3 ± 0.04C	1.5 ± 0.03B	

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different from each other by the Fisher's test at 5% probability.

Table 2. Number of pods m^{-2} and number of seeds pod^{-1} of four green gram varieties grown as sole crops and intercropped with sorghum in single and double alternate rows in Mwala and Katangi during 2022 short rains season.

Site and Variety	Pods m^{-2}				Seeds pod^{-1}			
	Sole crop	Single row	Double row	Mean	Sole crop	Single row	Double row	Mean
Mwala								
N26	328 ± 4.43a	204 ± 5.18e	226 ± 3.70d	252 ± 3.93a	13.1 ± 0.33a	10.5 ± 0.13cd	11.6 ± 0.20b	11.7 ± 0.22a
Biashara	293 ± 7.68b	173 ± 3.85g	196 ± 3.70ef	221 ± 5.00b	11.2 ± 0.12c	10.3 ± 0.18d	11.0 ± 0.31c	10.8 ± 0.20b
Karembo	244 ± 4.43c	141 ± 3.39h	173 ± 4.44g	186 ± 4.17c	9.6 ± 0.31e	8.6 ± 0.23g	9.4 ± 0.27e	9.2 ± 0.27c
KS20	184 ± 6.69f	107 ± 3.70i	135 ± 0.74h	142 ± 4.37d	9.0 ± 0.20f	7.9 ± 0.13i	8.3 ± 0.18h	8.4 ± 0.17d
Mean	262 ± 5.81A	156 ± 3.74C	182 ± 3.15B		10.7 ± 0.24A	9.3 ± 0.17C	10.1 ± 0.24B	
Katangi								
N26	208 ± 4.43a	110 ± 5.18cd	131 ± 4.62c	150 ± 4.74a	14.1 ± 0.29a	10.8 ± 0.67b	13.3 ± 0.41a	12.7 ± 0.46a
Biashara	163 ± 4.94b	96 ± 3.70f	119 ± 4.12d	126 ± 4.25b	13.3 ± 0.41a	10.7 ± 0.33ab	12.3 ± 0.13b	12.1 ± 0.29ab
Karembo	139 ± 4.69c	93 ± 3.39f	100 ± 0.00e	111 ± 2.69c	11.9 ± 0.64b	10.5 ± 0.37ab	11.1 ± 0.44b	11.2 ± 0.48b
KS20	111 ± 4.43d	75 ± 4.12g	84 ± 3.16d	90 ± 3.90d	10.8 ± 0.42b	8.8 ± 0.42c	9.6 ± 0.31c	9.7 ± 0.38c
Mean	155 ± 4.62A	93 ± 4.10C	109 ± 2.98B		12.5 ± 0.44A	10.2 ± 0.45C	11.6 ± 0.32B	

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different from each other by the Fisher's test at 5% probability.

Table 3. Number of branches plant-1 and plant height (cm) of four green gram varieties grown as sole crops and intercropped with sorghum in single and double alternate rows in Mwala and Katangi during the 2022 short rains season.

Site and Variety	Number of branches plant-1				Plant height (cm)			
	Sole crop	Single row	Double row	Mean	Sole crop	Single row	Double row	Mean
Mwala								
N26	7.8 ± 0.29a	6.3 ± 0.18c	6.7 ± 0.27c	6.9 ± 0.25a	36.1 ± 0.59d	43.9 ± 0.62a	37.1 ± 0.33c	39.0 ± 1.24a
Biashara	7.1 ± 0.24b	5.8 ± 0.24d	6.4 ± 0.30c	6.4 ± 0.26b	33.9 ± 0.28f	40.5 ± 1.03b	35.1 ± 0.13e	36.5 ± 0.44b
Karembo	6.2 ± 0.18c	5.2 ± 0.29e	5.8 ± 0.32d	5.7 ± 0.26c	29.8 ± 0.31h	35.1 ± 0.10e	33.9 ± 0.44f	32.9 ± 0.79c
KS20	5.3 ± 0.27e	4.4 ± 0.12g	4.9 ± 0.23f	4.9 ± 0.21d	28.8 ± 0.30i	31.5 ± 1.03g	31.4 ± 0.15g	30.6 ± 0.40d
Mean	6.6 ± 0.25A	5.4 ± 0.21B	6.0 ± 0.28B		32.2 ± 0.37A	37.8 ± 0.70C	34.4 ± 0.26B	
Katangi								
N26	7.3 ± 0.53a	5.8 ± 0.43b	6.6 ± 0.35a	6.6 ± 0.44a	36.1 ± 0.26c	45.5 ± 0.15a	38.8 ± 0.33b	40.1 ± 0.18a
Biashara	6.5 ± 0.26a	5.4 ± 0.38b	5.9 ± 0.15a	5.9 ± 0.26b	32.0 ± 0.28f	39.5 ± 1.03b	35.3 ± 0.13d	35.6 ± 0.35b
Karembo	5.4 ± 0.23b	4.5 ± 0.24b	5.0 ± 0.37b	5.0 ± 0.28c	29.1 ± 0.36g	35.1 ± 0.10d	32.9 ± 0.44e	32.4 ± 0.16c
KS20	5.0 ± 1.18b	4.1 ± 0.23c	4.6 ± 0.32c	4.6 ± 0.58d	25.8 ± 0.31h	31.5 ± 1.03f	29.1 ± 0.36g	28.8 ± 0.44d
Mean	6.1 ± 0.55A	5.0 ± 0.32B	5.5 ± 0.30B		30.8 ± 0.30A	37.9 ± 0.58C	34.0 ± 0.32B	

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different from each other by the Fisher's test at 5% probability.

Table 4. Crop growth rate (g m-2 day-1) between branching and podding and land equivalent ratios of four green gram varieties grown as sole crops and intercropped with sorghum in single and double alternate rows in Mwala and Katangi during the 2022 short rains season.

Site and Variety	Crop growth rate (g m-2 day-1)				Land equivalent ratios		
	Sole crop	Single row	Double row	Mean	Single row	Double row	Mean
Mwala							
N26	11.4 ± .95a	7.3 ± 0.78b	9.6 ± 0.98a	9.4 ± 1.24a	1.37 ± 0.16b	1.62 ± 0.13a	1.50 ± 0.15b
Biashara	9.1 ± 0.17a	5.7 ± 0.46b	9.0 ± 0.70a	7.9 ± 0.44b	1.35 ± 0.16b	1.67 ± 0.20a	1.51 ± 018b
Karembo	9.2 ± 1.13a	6.3 ± 0.05ab	8.8 ± 1.20a	8.1 ± 0.79b	1.67 ± 0.18a	1.68 ± 0.21a	1.68 ± 0.20a
KS20	6.9 ± 0.29b	5.1 ± 0.05ab	7.2 ± 0.86b	7.1 ± 0.40ab	1.23 ± 0.17c	1.68 ± 0.21a	1.46 ± 0.19b
Mean	9.2 ± 0.89A	6.1 ± 0.34C	8.7 ± 0.94B		1.40 ± 0.17B	1.66 ± 0.19A	
Katangi							
N26	6.6 ± 0.15a	3.5 ± 0.20c	4.8 ± 0.18b	5.0 ± 0.18a	1.33 ± .14cd	1.64 ± 0.15ab	1.49 ± 0.15a
Biashara	4.5 ± .61ab	2.7 ± 0.11c	3.9 ± 0.34b	3.7 ± 0.35b	1.38 ± 0.12c	1.73 ± 0.16a	1.56 ± 0.14a
Karembo	4.1 ± .39ab	2.5 ± 0.18c	3.7 ± 0.09c	3.4 ± 0.16c	1.36 ± 0.16c	1.69 ± 0.20ab	1.53 ± 0.18a
KS20	3.6 ± 0.68c	2.5 ± 0.16c	2.7 ± 0.49c	3.8 ± 0.44b	1.22 ± 0.18d	1.58 ± 014b	1.40 ± 0.16b
Mean	4.7 ± 0.46A	2.8 ± 0.16C	3.8 ± 0.28B		1.33 ±0.15B	1.66 ± 0.16A	

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different from each other by the Fisher's test at 5% probability.

In addition, the double-row arrangement demonstrated a superior land and equivalent ratio. A direct relationship between crop growth rate and yield implied that green gram varieties with enhanced biomass accumulation were more competitive in sorghum intercrop systems (Raza et al., 2023). Against this backdrop, the large canopy variety N26 out-yielded the short-statured varieties, for example, KS20 by 0.56 t ha-1. The observed yield improvement under double row compared with single row could be associated with enhanced light, water, and nutrient efficiency. In a soybean-wheat intercrop system, intercrops with wide strips outperformed narrow and medium strips as a result of higher nitrogen uptake which increased total leaf area and biomass accumulation (Raza et al., 2023).

Results revealed that intercrops with wide strips outperformed the narrow and medium strips when the objective was to obtain higher total leaf area, dry matter, nitrogen uptake, and grain yield on a given land area due to reduced interspecific competition between intercrops. Similar results were reported by Mulwa et al. (2023). The tall sorghum plants shaded the shorter green gram plants (KS20) which could have reduced leaf area impacting negatively on radiation interception thus affecting intercropping productivity. Plants under a single row were taller than sole crops and double rows. The significant

Table 5. Grain yield (t ha^{-1}), grain number m^{-2}, shoot biomass (t ha^{-1}), crop growth rate (CGR) (g m^{-2} day^{-1}), number of tillers m^{-2} and number of fertile tillers m^{-2} of sorghum grown as sole crop, single and double alternate rows in Mwala and Katangi during 2022 short rains season.

The site and crop arrangement	Grain yield (t ha^{-1})	Grain number m^{-2}	Biomass (t ha^{-1})	CGR (g m^{-2} day^{-1})	Tillers m^{-2}	Fertile tillers m^{-2}
Mwala						
Sole	3.2 ± 0.03a	5840 ± 188a	7.0 ± 0.30a	12.8 ± 0.19a	7.7 ± 0.33a	4.7 ± 0.10a
Single	2.1 ± 0.04c	3173 ± 116c	4.7 ± 0.32c	8.3 ± 0.22b	2.7 ± 0.36c	1.7 ± 0.21b
Double	2.7 ± 0.05b	4315 ± 117b	5.6 ± 0.34b	9.0 ± 0.16b	5.3 ± 0.37b	2.0 ± 0.36b
Mean	2.7 ± 0.04	4443 ± 140	5.8 ± 0.32	10.1 ± 0.19	5.2 ± 0.35	2.8 ± 0.22
Katangi						
Sole	2.1 ± 0.03a	3220 ± 113a	5.7 ± 0.24a	15.5 ± 0.62a	4.7 ± 0.58a	3.6 ± 0.10a
Single	1.3 ± 0.03c	1496 ± 29c	3.3 ± 0.20c	8.3 ± 0.18c	2.0 ± 0.26b	1.0 ± 0.22c
Double	1.7 ± 0.04b	2399 ± 65b	4.3 ± 0.16b	10.1 ± 0.30b	3.0 ± 0.26b	2.3 ± 0.33b
Mean	1.7 ± 0.03	2372 ± 69	4.4 ± 0.20	11.3 ± 0.37	3.2 ± 0.37	2.3 ± 0.22

Values are means ± standard error of the mean. Means followed by the same letter are not significantly different from each other by the Fisher's test at 5% probability.

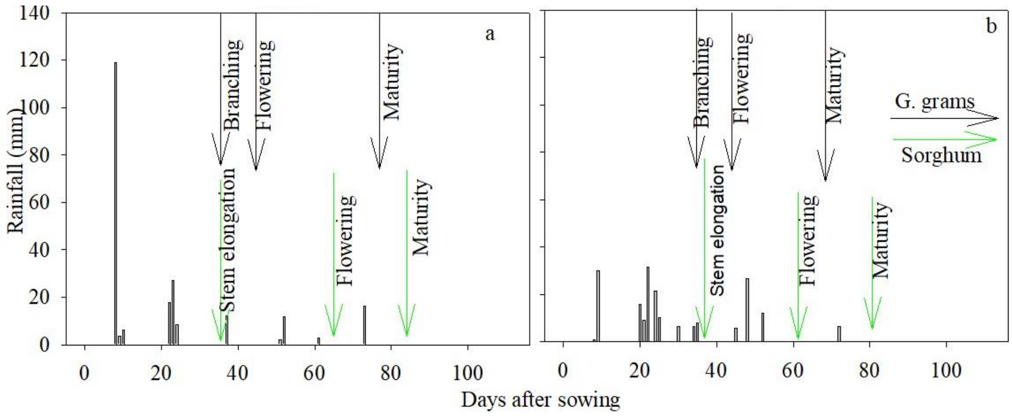

Figure 1. Daily rainfall (mm) during green gram and sorghum growing period in Mwala (a) and Katangi (b) during the 2022 short rains season.

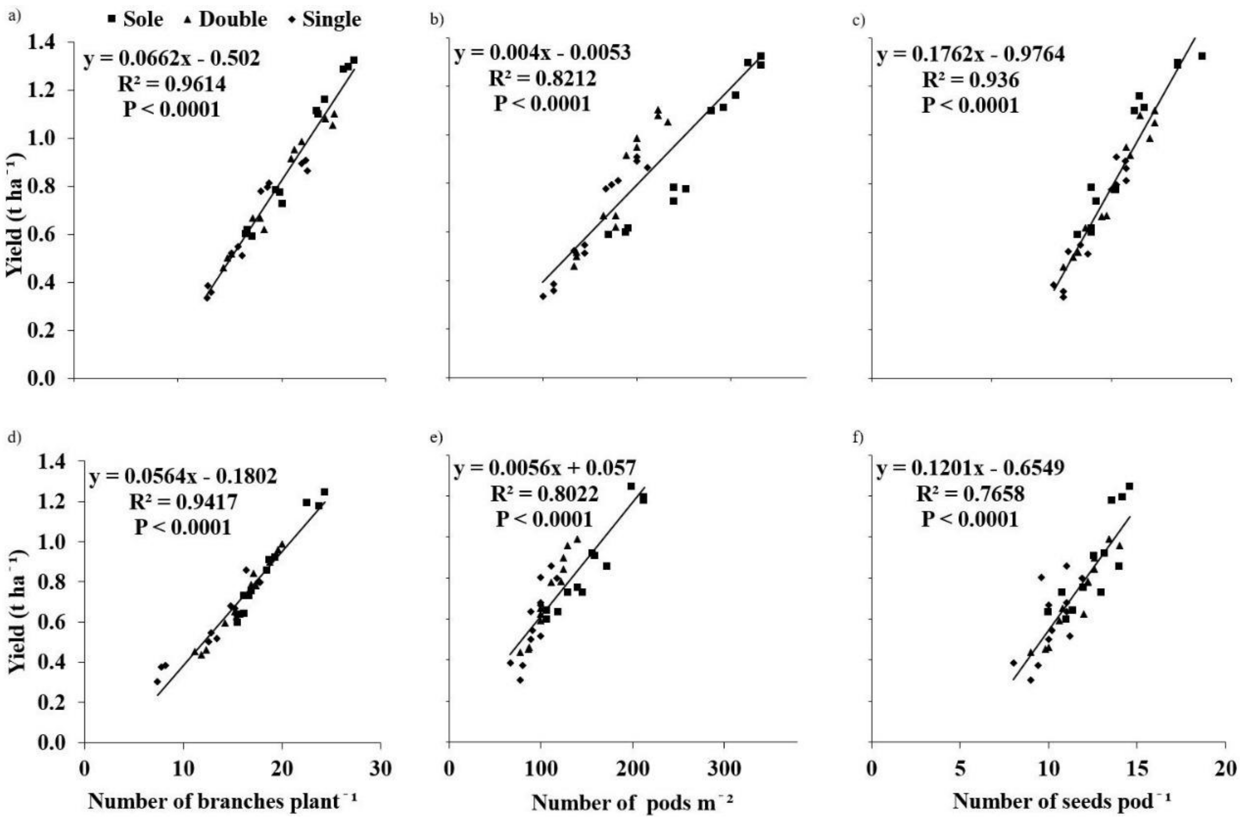

Figure 2. Correlation between green gram grain yield (t ha^{-1}) and number of branches $plant^{-1}$ (a), number of pods m^{-2} (b), and number of seeds pod^{-1} (c) in Mwala and correlation between green gram grain yield (t ha^{-1}) and number of branches $plant^{-1}$ (d), number of pods m^{-2} (e), and number of seeds pod^{-1} (f) in Katangi. Lines are least-square linear regressions. N = 36.

increase in plant height and crop growth rate could have been linked to increased competition for solar radiation which helped the plants to grow taller, and improved leaf area but reduced yield (Sowmya et al., 2023). Therefore, when selecting green gram varieties for intercropping, the traits to be focused on by intercrop breeders should be those related to radiation interception such as number of branches, plant height, and crop growth rate.

The land equivalent ratio (LER) was more than one unit, thus intercrops showed a greater yield advantage compared to the sole crop. The double row showed a maximum LER of 1.66 which indicated that 66 percent more land would be required by the sole green gram to produce an equivalent yield of this system. This resulted in more total biomass accumulation and yield compared with the single row. Variety N26 of green gram under double row arrangement is a promising agronomic strategy with a greater potential ability to improve green gram productivity and farmers' benefits in dryland areas of Kenya. However, although intercropping reduced green gram yield, the present results show that there is potential to exploit crop arrangement patterns and variety interactions to increase yields in drylands with low rainfall and poor soils. Nevertheless, future studies should focus on the optimum spacing that can reduce intercropping competition and improve yield performance.

Materials and methods

Plant materials

A locally adapted high-yielding short-maturity sorghum, variety Seredo which is able to survive in harsh conditions and tolerate birds was used as an intercrop (Okeyo et al., 2020). The four green gram varieties are of narrow phenology and comprise two old varieties (N26 and KS20) which were released in the 1990's and two new varieties (Biashara and Karembo) which were released in 2017 (Mulwa et al., 2023). The green gram varieties are early maturing, tolerant to aphids, resistant to powdery mildew, and high-yielding (Yumbya et al., 2024).

Experiment sites

Two field experiments were conducted during the 2022 short rains season in farmers' fields in Mwala which is located at 1°21′29′′S, 37°27′41′′E and 1252 m elevation, and in Katangi that is 1°40′13′′S, 37°68′18′′E, and 1051 m elevation, both in Machakos County of Kenya. The sites have two rainy seasons annually, which are distributed in a long rainy season from March to May and a short rainy season from October to December. Mwala site lies in the low midland agroclimatic zone (LM-3) where annual rainfall ranges between 600-700 mm, and the temperature range is 18-29 °C. Soils in this site are predominantly sandy clay with a pH of 5.7. Katangi site in the drier LM-4 zone with 17-35 °C temperature and 274 mm annual rainfall, while soils are well-drained red-brown to clay with pH 6 (Namoi et al., 2014).

Treatments

Treatments were three crop arrangement systems and four green gram varieties. The crop arrangement systems were one row of sorghum intercropped with one row of green gram (single row), two rows of sorghum intercropped with two rows of green gram (double row), and pure stands of green gram and sorghum used as control.

Experiment design and management

Treatments were placed in a randomized complete block design with a split-plot arrangement and replicated three times. Crop arrangement system formed the main plots while the subplots were assigned to the green gram variety. The land was ploughed to a fine tilth before the onset of rains. Plots measuring 11.5 m by 6 m were demarcated with 0.5 m space left between the treatment plots. In the sole crop plots, the green gram was sown at a spacing of 0.5 m x 0.15 (13 plants m^{-2}) while sorghum was sown at a spacing of 0.6 m x 0.2 m (8 plants m^{-2}). In the single row treatment, the distance between adjacent sorghum and green gram rows was 0.3 m while the distance between two adjacent sorghum and green gram plants was 0.2 m and 0.15 m respectively (11 green gram plants m^{-2} and 8 sorghum plants m^{-2}). For the double row, the row spacing between sorghum and green gram was 0.9 m, and the in-row spacing of sorghum and green gram plants was 0.2 m and 0.15 m respectively (11 green gram plants m^{-2} and 8 sorghum plants m^{-2}). Seeds were sown on the same day before the onset of the 2022 short rains.

Treatments in Mwala received 20 kg N ha^{-1}, 11 kg P $ha^{-1,}$ and 16 kg K ha^{-1} of farm yard manure and 45 kg N ha^{-1} and 115 kg P ha^{-1} basal fertilizer while Katangi plots received basal dose of 57.5 kg N ha^{-1} and 57.5 kg P ha^{-1} based on recommendations of initial soil analysis. Sorghum was top dressed with 39 kg N ha^{-1} in two doses at stem elongation and anthesis stages. Plots were kept weed free by manual weeding and regularly sprayed with insecticides, mostly against Fall armyworm (*Spodoptera frugiperda*) in sorghum and sucking bugs in green gram while mancozeb fungicide was used to control blight and powdery mildew in green gram.

Data collection

Rainfall data and soil sampling

During the crop growing period, rainfall data was obtained from meteorological stations located near the experimental sites. Soils were sampled at 0-30 cm depth and analyzed before sowing by measuring soil pH in $CaCl_2$, and organic carbon using the Walkley and Black wet oxidation method (Spertus, 2021) while total nitrogen was analyzed by the Kjeldahl method

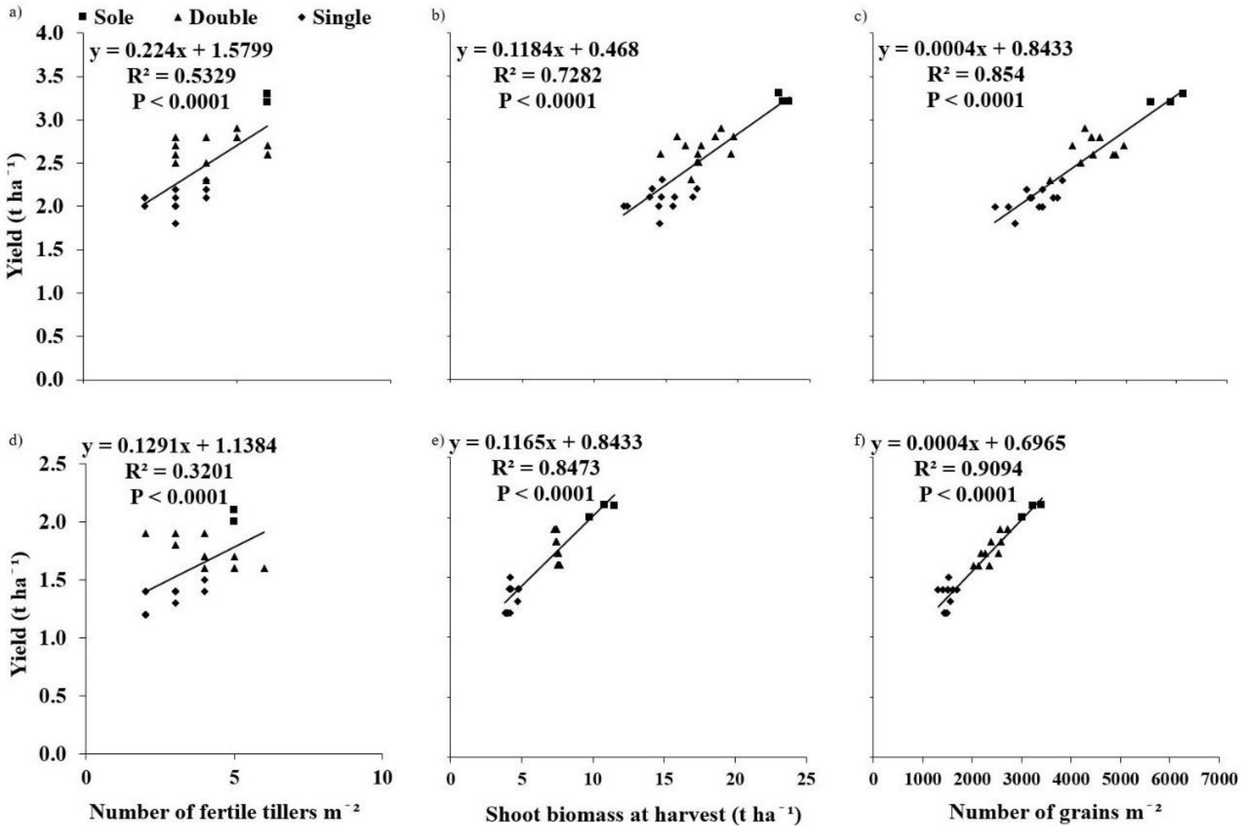

Figure 3. Correlation between sorghum grain yield (t ha^{-1}) and number of fertile tillers m^{-2} (a), shoot biomass at harvest (t ha^{-1}) (b), and number of grains m^{-2} (c) in Mwala and correlation between sorghum grain yield (t ha^{-1}) and number of fertile tillers m^{-2} (d), shoot biomass at harvest (t ha^{-1}) (e), and number of grains m^{-2} (f) in Katangi. Lines are least-square linear regressions. N = 27.

(Sáez-Plaza et al., 2013). Available soil phosphorus was evaluated by Olsens' method (De Silva et al., 2015) while the flame photometer determined potassium level (Potdar et al., 2021).

Green gram growth and yield

At physiological maturity, five plants per plot were randomly selected, and the numbers of primary branches of $plant^{-1}$ were counted. The plant height of five randomly sampled green gram plants in the middle of each plot were measured from the soil surface to the tip of the central leaf of the plants using a measuring tape.

At harvesting, five plants were sampled for the number of seeds pod^{-1}, number of pods $plant^{-1}$, and 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. While evaluating shoot biomass (t ha^{-1}), five plants were randomly cut at ground level in each plot at physiological maturity and then oven-dried at 62 ^{o}C to a constant weight.

Sorghum growth and yield

During the critical crop growth period (stem elongation-anthesis), five plants in the middle of the plot were gently uprooted, oven-dried to constant mass, and then biomass was evaluated. Crop growth rate (g m^{-2} day^{-1}) was determined by dividing biomass accumulated per unit time. The number of both fertile and infertile tillers was counted per plot at 90% physiological maturity and expressed per unit area.

Sorghum heads were harvested at maturity and yield components were determined from net plots. Seeds were removed from the heads, and total grain yield (t ha^{-1}) was obtained after drying the grains to about 12.5% water content, and number of grains m^{-2} was determined by getting the product of yield and weight $grain^{-1}$. To determine shoot biomass (t ha^{-1}), samples were oven-dried at 50 ^{o}C to a stable mass.

Computations

Crop growth rate (CGR) was calculated according to (Bybee-Finley & Ryan, 2018) as shown in Equation 1, while the land equivalent ratio, (Mir et al., 2016) was computed following Equation 2.

$$\text{CGR} = \frac{Biomass\ t2 - Biomass\ t1}{t2 - t1} \qquad (1)$$

t_1 is the time at the first observation and t_2 is the time of the second observation

LER = partial LER sorghum + partial LER green gram

$$LER = \left(\frac{Yab}{Yaa} + \frac{Yba}{Ybb}\right) \qquad (2)$$

where Yaa and Ybb are yields of sorghum and green gram as sole crops
Yab and Yba are yields of intercrop of sorghum and yields of green gram respectively.

Data analysis

Before statistical analyses, data was checked for normality using the Shapiro-Wilk test and then subjected to R software version 4.3.3.0 using analysis of variance to establish significant differences by Fisher's test at 5% probability. Standard errors were estimated and the values were reported with standard errors of mean (SEM). Relationships between parameters were explored using simple linear regression.

Conclusions

Present results showed that different green gram-sorghum arrangements affected crop growth and yield. Land equivalent ratios demonstrated that intercropping is advantageous to sole cropping, and double-row intercropping was superior to single-row. Green gram variety N26 outperformed the other varieties, irrespective of the crop arrangement. These provide insights into understanding interspecific interactions between green gram and sorghum, which are important food and cash crops for dry areas of southeastern Kenya. As farmers seek to intensify cereal-legume crop systems, weather, and non-competitive plant configurations are desired.

Acknowledgments

We extend appreciation to farmers in Mwala and Katangi sites who provided their farms for the experiments.

Author Contributions: This work was carried out in collaboration of all authors. Author BY designed the study, carried out the experiments, collected, analyzed the data and wrote the first draft of the manuscript under the supervision of authors OK and JK. The published version was read and approved by all authors.

Conflicts of Interest: There are no conflicts of interest in this work.

Data Availability Statement: Supplementary material related to this work can be provided upon request from the corresponding author.

References

Abbas RN, Arshad MA, Iqbal A, Iqbal MA, Imran M, Raza A, Chen J, Alyemeni MN, Hefft DI (2021) Weeds spectrum, productivity and land-use efficiency in maize-gram intercropping systems under semi-arid environment. Agron J. 2021(11): 1615.

Baker C, Modi AT, Nciizah AD (2021) Sweet sorghum (*Sorghum bicolor*) performance in a legume intercropping system under weed interference. Agron J. 11(5): 877.

Baxevanos D, Tsialtas IT, Vlachostergios DN, Hadjigeorgiou I (2017) Cultivar competitiveness in pea-oat intercrops under Mediterranean conditions. Field Crops Res. 214: 94–103.

Bremer E, Ellert BH, Pauly D, Greer KJ (2024) Variation in over-yielding of pulse-oilseed intercrops. Field Crops Res. 305: 109190.

Bybee-Finley KA, Ryan MR (2018) Advancing intercropping research and practices in industrialized agricultural landscapes. Agr (Switzerland). 8(80): 1–24.

De Silva CS, Koralage ISA, Weerasinghe P, Silva NRN (2015) The determination of available phosphorus in soil: A quick and simple method. OUSL Journal. 8(1): 1-10.

Demie DT, Döring TF, Finckh MR, van der Werf W, Enjalbert J and Seidel SJ (2022) Mixture × genotype effects in cereal-legume intercropping. Front. Plant Sci. 13: 1-17.

Ewansiha SU, Chiezey UF, Law-Ogbomo KE (2018) Yield and yield components of intercropped dual-purpose lablab and cowpea with maize of contrasting maturities. J Pure Appl Sci. 10(2): 177–183.

Feng L, Yang W, Tang H, Huang G, Wang S (2022) Bandwidth row ratio configuration affects interspecific effects and land productivity in maize–soybean intercropping system. Agron. (2022) 12: 3095.

Gao J, Lei M, Yang L, Wang P, Tao H, Huang S (2021) Reduced row spacing improved yield by optimizing root distribution in maize. Eur J Agron. 127(2021): 126291.

Hailu G, Niassy S, Zeyaur KR, Ochatum N, Subramanian S (2018). Maize–legume intercropping and push-pull for management of fall armyworm, stem borers, and Striga in Uganda. Agron J. 110(6): 2513–2522.

Hailu H, Geremu T (2021) Irrigation and drainage systems engineering effect of sorghum-legume intercropping patterns on selected soil chemical properties and yield of sorghum at midland areas of west Hararghe zone of Oromia regional state, eastern Ethiopia. Irrig Drain Sys Eng. 10(5): 1–8.

Hakim RO, Kinama JM, Kitonyo OM, Cheminingw`a GN (2022) Effect of tillage method and mulch application on growth and yield of green gram in semi-arid Kenya. Adv Agr. (2022): 1-11.

Karimi R, Nair R, Ledesma D, Mutisya D, Muthoni L (2019) Performance and participatory evaluation of green gram genotypes in the semi-arid environments of Eastern Kenya. E Afr Agr Forestry J. 83(2): 119–136.

Layek J, Das A, Mitran T, Nath C, Meena RS, Yadav GS, Shivakumar BG, Kumar S (2018) Cereal-legume intercropping: An option for improving productivity and sustaining soil health. In Meena RS (ed) Legumes for soil health and sustainable management, Spring Nature-Singapore. 11: 349-378.

Li S, van der Werf W, Zhu J, Guo Y, Li B, Ma Y, Evers J B (2021) Estimating the contribution of plant traits to light partitioning in simultaneous maize-soybean intercropping. J Exp Bot 72(10): 3630–3646.

Maclaren C, Waswa W, Tijjani K, Claessens L, Vanlauwe B, Storkey J, Mead A, Sch C (2023) Predicting intercrop competition, facilitation, and productivity from simple functional traits. Field Crop Res. 297:108926.

Mir F, Shahriari M, Rastine E, Zoraghi Z (2016) Influence of intercropping on soil conservation, forage quality and control of the pest. Int J Mult Res Dev. 3(1): 379–383.

Mugo JW, Opijah FJ, Ngaina J, Karanja F, Mburu M (2020) Suitability of green gram production in Kenya under present and future climate scenarios using bias-corrected cordex RCA4 Models. Agr Sci. 11(10): 882–896.

Mulwa GK, Kitonyo OM, Nderitu JH (2023) Earliness and crop morphological traits modulate field pest infestation in green gram. J Econ Entomol. (205):1-11.

Namoi NL, Onwonga RN, Karuku GN, Onyango CM, Kathumo VM (2014) Influence of selected ecological farming practices on soil moisture retention and yield of sorghum (*Sorghum bicolor* (L.) Moench) and cassava (*Manihot esculanta* Crantz) in semi-arid Yatta Sub-County, Kenya. J Agr Sci. 6(9): 214–231.

Okeyo SO, Ndirangu SN, Isaboke HN, Njeru LK (2020) Determinants of sorghum productivity among small-scale farmers in Siaya County, Kenya. Afr J Agr Res. 16(5): 722–731.

Potdar RP, Shirolkar MM, Verma AJ, More PS, Kulkarni A (2021) Determination of soil nutrients (NPK) using optical methods: A mini-review. J Plant Nutr. 44(12): 1826–1839.

Raza MA, Din AMU, Zhiqi W, Gul H, Ur Rehman S, Bukhari B, Haider I, Rahman MHU, Liang X, Luo S, El Sabagh A, Qin R, Zhongming M (2023) Spatial differences influence nitrogen uptake, grain yield, and land-use advantage of wheat/soybean relay intercropping systems. Scientific Reports, 13(1), 1–15.

Sáez-Plaza P, Navas MJ, Wybraniec S, Michałowski T, Asuero AG (2013) An Overview of the Kjeldahl method of nitrogen determination. Part II. Sample preparation, working scale, instrumental finish, and quality control. Cr Rev Anal Chem. 43(4): 224–272.

Sija P, Sugito Y, Suryanto A, Hariyono D (2020) Radiation use efficiency of maize (*Zea mays* L.) on different varieties and intercropping with mung bean in the rainy season. J Agr Sci. 42(3): 462–471.

Simon-Miquel G, Reckling M, Plaza-Bonilla D (2024) Maximising soybean productivity with late maturity groups in Mediterranean irrigated systems. Field Crop Res. 307: 109274.

Sowmya K, Bindhu JS, Pillai PS, Jacob D, Gladis R (2023) Productivity and profitability of green gram [*Vigna radiata* (L.) Wilczek] under the system of crop intensification. Ag Sci Dir. (2023): 50–53.

Spertus JV (2021) Optimal sampling and assay for estimating soil organic carbon. J Soil Sci. 11(02): 93–121.

Sun Z, Su C, Yun J, Jiang Q, Wang L, Wang Y, Cao D, Zhao F, Zhao Q, Zhang M, Zhou B, Zhang L, Kong F, Liu B, Tong Y, Li X (2019) Genetic improvement of the shoot architecture and yield in soya bean plants via the manipulation of GmmiR156b. Plant Biotechnol J. (2019) 17: 50–62.

Tang X, Zhang C, Yu Y (2020) Intercropping legumes and cereals increases phosphorus use efficiency: A meta-analysis. Plant Soil. 111(4): 4768.

Temeche D, Getachew E, Hailu G, Abebe A (2022) Effect of sorghum-mung bean intercropping on sorghum-based cropping system in the lowlands of North Shewa, Ethiopia. Adv Agr. 2022(1): 1–7.

Wambua JM, Ngigi M, Lutta M (2017) Yields of green grams and pigeon peas under smallholder conditions in Machakos County, Kenya. E Afr Agr Forestry J. 82(2–4): 91–117.

Wang S, Chen G, Zang H, Yang Y, Zeng Z, Hu Y (2021) Sowing ratio determines forage yields and economic benefits of oat and common vetch intercropping. Agron J. (2021): 1-11.

Yumbya BM, Kitonyo OM, Kinama JM (2024) Green gram-sorghum intercropping: Effects on crop microclimate, competition, resource use efficiency and yield in Southeastern, Kenya. International Journal of Environment and Climate Change. 14(12): 549–565.