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Yield and yield components responses to plant density in cowpea grown in two savannah agro-ecologies in Nigeria

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Abstract

Gap-filling is used to mitigate yield losses in different legumes. There is scanty information on this mechanism of yield compensation in the cowpea [*Vigna unguiculata* (L.) Walp]. This study investigated responses of yield and yield components to plant density in some accessions of cowpea at Minjibir and Shika locations. The randomized complete block design, in a split-plot arrangement in three replicates, was used. The main plots consisted of four plant densities, while the sub-plots consisted of six cowpea accessions. Results showed that plant density and environment affected yield and yield components. Total grain yield increased as plant density increased at both locations and was highest in the accession DANILA (1793.3 kg ha^{-1}) at 99,999 plant ha^{-1} and lowest in the accession IT98K-205-8 (1100 kg ha^{-1}) at 33,333 plants ha^{-1}. Pod yield was positively correlated with total grain yield at Minjibir (0.267*) and Shika (0.917**) and when data were combined (0.990**). Shelling percentage was negatively correlated with total grain yield when data were combined (−0.610**). Significant positive correlation between total grain yield and 100-seed weight as well as biological yield was observed at Shika. Harvest index was positively correlated with total grain yield (0.407**) at Minjibir. The study concludes that erect accessions (IT93K-452-1 and IT98K-205-8) and semi-erect accessions (IT99K-573-1-1 and IT08K-150-27) could be adopted for cultivation at 133,333 plants ha^{-1}, while prostrate accessions (IT89KD-288 and DANILA) could be cultivated at 99,999 plants ha^{-1} at Minjibir. The accessions IT93K-452-1, IT98K-205-8, IT99K-573-1-1, and IT08K-150-27 could be cultivated at Shika, irrespective of plant density.

Abbreviation: IITA, International Institute of Tropical Agriculture.

Plain Language Summary
The ability of a crop to maintain or increase yield under low plant density is referred to as yield compensation. There is limited study on yield compensation in the cowpea. This study investigated the responses of yield and yield components to plant density in cowpea in two savannah agro-ecologies in northern Nigeria. At 133,333 plants ha^{-1}, semi-erect and erect accessions produced high yield in the Sudan savannah. Prostrate accessions performed well at 99,999 plants ha^{-1} at Minjibir location. Accessions IT93K-452-1, IT98K-205-8, IT99K-573-1-1, and IT08K-150-27 could be cultivated at the Shika location irrespective of plant density. Environment and accession determine the plant density to adopt in the cultivation of cowpea in northern Nigeria.

1 | INTRODUCTION

Cowpea [*Vigna unguiculata* (L.) Walp] is a staple legume, which is consumed by millions of people. It has a high potential for food and nutritional security in sub-Saharan Africa; it is produced for grain, immature green pods, fresh leaves, or fodder due to its nutritional composition (Boukar et al., 2015; Gerrano et al., 2015; Gerrano et al., 2017; Omoigui et al., 2020). Cowpea can be determinate or indeterminate in growth habit and can either be prostrate, spreading, climbing, bushy, semi-erect, or erect in architecture.

Cowpea production has gained global attention over the years, particularly in the African continent, which is known to be one of the largest producing hubs of cowpea worldwide (Kebede, 2020). Nigeria and Republic of Niger are reported to be the largest producing countries in the sub-Saharan Africa (Kebede & Bekeko, 2020). The two countries account for about 80% of the cowpea production in West Africa (Aboki & Yuguda, 2013; Boukar et al., 2019; FAOSTAT, 2020; Kebede & Bekeko, 2020). The International Institute of Tropical Agriculture (IITA) has made significant advances in improving the productivity of cowpea in sub-Saharan Africa (Boukar et al., 2019). Boukar et al. (2019) also noted that several varieties have been developed, which combine canopy architecture, different maturity periods, and resistance to diseases, insect pests, and parasitic weeds, as well as good agronomic traits.

Cowpea is one of the most preferred crops and a valuable component in the farming systems of resource-poor rural households in sub-Saharan Africa (Molosiwa et al., 2016). Liu et al. (2008) and Yusuf et al. (2017) noted that yield has been and remains the trait of greatest emphasis by breeders, as it has the greatest impact on farmers' income. Yield losses in cowpea are associated with poor soil fertility, the use of unimproved varieties or landraces, poor agronomic practices, drought, and other abiotic and biotic stresses. These losses can be mitigated through the use of yield compensation to bridge the gap in cowpea productivity.

Yield compensation is defined as the ability of the plant grown under low plant density to produce equal or higher yields when compared with those grown under optimum density. The establishment of an appropriate mechanism of yield compensation could provide insights into the management and phenotypic improvement of different crops (Ball et al., 2000; Liu et al., 2010). Ndiaga (2001) reported that some crops produced higher yields with closer spacing than with wider spacing. However, at very high plant density, the yield per hectare begins to decrease due to decrease in seed weight arising from competition for resources. On the other hand, low plant density has been reported in other crops to result in higher yields than closer spacing. This has been attributed to less competition amongst the plants for light, nutrients, water, and other resources. The minimum plant density at which there is higher or lower yield has not been explicitly demonstrated in the cowpea, and especially the newly developed varieties (Odesina, 2024).

Ndiaga (2001) reported that most cowpea cultivars used in breeding programs are cultivated at low plant densities compared to the recommended row spacing, with remarkable impact on yield. Kamara et al. (2016) noted that the yield of cowpea in the Nigerian savannah was low despite the adoption of improved varieties. Results of field experiments have shown that the recommended density of 133,333 plants ha^{-1} adopted by farmers was not optimum for cowpea productivity; it has, therefore, been suggested that smallholder farmers could increase grain and fodder yields at a plant density of 266,666 plants ha^{-1} (Kamara et al., 2016), even though this might not be applicable in all cases, as high population density could result in decreased yield or yield components (Nur Arina et al., 2021).

Yield components are yield-contributing attributes that sum up to the yield value per unit area (Kozak & Mądry, 2006). They are individual plant parts contributing to yield based on their number, size, and weight. Selection indices such as yield and one, or more, morphological characters, which contribute to yield formation, are considered to increase the inherent yielding ability of cowpea. Adewale et al. (2010) noted that yield improvement of cultivars has been achieved through careful selection of yield components. The evaluation of the yield components allows for clarification on how variations resulting from genetic, environmental, and management practices affect variation in crop yields. In breeding for increase in yield, breeders need a good knowledge of the nature and level of genetic factors that regulate characters that contribute to yield (Edematie et al., 2021). Yield components include pod length, pod width, number of pods, shelling percentage, number of seeds per pod, and average seed weight (Odesina, 2024). Nwofia (2012) noted that pod length and pod width are important components in vegetable cowpea, as they are known to influence pod yield and grain yield. In many countries, pod length is an important attribute that influences consumer acceptability of vegetable cowpea and is used as a selection index in the breeding program. A higher shelling percentage indicates that a greater proportion of the weight of pods is comprised of seeds, which directly translates to increased seed yield. This relationship is observed across various crops like maize and peanut (Keno et al., 2024). A higher shelling percentage means more seeds are produced for the same amount of pod weight, directly contributing to a higher seed yield. This is because more of the plant's resources are allocated to seed production rather than pod development or other non-seed components. Shelling percentage is influenced by factors such as genotype, environment, and management practices like fertilizer application, planting density, and other agronomic practices (Keno et al., 2024).

Grain yield in the cowpea has been reported to be positively correlated with pod length (Udensi et al., 2011; Manggoel et al., 2012). Kamara et al. (2016) reported that grain yield increased as the seed number per pod and 100-seed weight increased but that the effect of seed size on grain yield was not significant. The number of pods, seed number per pod, and 100-seed weight have been reported as major yield-contributing traits in the cowpea (Adewale et al., 2010; Brolmann & Stoffella, 1986; Odesina, 2024). These components are also affected by plant population and can operate in complex ways to affect yield compensation. Understanding the trends in the variation of yield components and the relationship among the components based on genetics, physiology, and development may be helpful in modifying the agronomic practices to optimize yield (Odesina, 2024).

Harvest index has also been reported as a major factor that influences crop yield. It is defined as the total seed weight expressed as a percentage of the total plant weight or biological yield; or the ratio of dry seed weight to the total crop dry weight; or the ratio of economically important portion of the yield (e.g., grain) to the total biological yield; or the weight of the above-ground portion at the time of harvest (Harper & Ogden, 1970; Kozlowski & Ziólko, 1988; Okelana & Adedipe, 1982). Harvest index is also defined as the fraction of the total dry matter that is partitioned to the harvestable plant parts or the ratio of yield to the above-ground biomass (Donald & Hamblin, 1976; Forbes & Watson, 1992). Harvest index is considered as an important selection index in crop breeding programs because it gives insight to yield efficiency and resource allocation potentials of crop varieties (Giridhar et al., 2020).

Core Ideas

- Yield compensation defines the ability of a crop to increase productivity when plants grown under low plant density produce equal or higher yields when compared with those grown under optimum density.
- There is limited study on yield compensation mechanism in newly developed varieties of the cowpea.
- At 133,333 plants ha^{-1}, semi-erect accessions (IT99K-573-1-1 and IT08K-150-27) and erect accessions (IT93K-452-1 and IT98K-205-8) of cowpea produced high yield in the Sudan savannah.
- Irrespective of plant density, the accessions IT93K-452-1-1, IT98K-205-8, IT99K-573-1-1, and IT08K-150-27 could be considered for cultivation in the Northern Guinea Savannah agro-ecology.

Studies have shown the importance of plant population suitable for optimum yield in improved crop varieties. Seran and Brintha (2010) and Nur Arina et al. (2021) noted that excessive plant population might result in low yield due to overcrowding and competition for limited resources, and suggested a reduction in the number of seedlings in order to optimize yield. In soybean [*Glycine max* (L.) Merr], studies have been carried out to determine if yield compensation resulting from low plant population could be achieved through increasing plant density, yield components (Ball et al., 2000), or the use of improved varieties (Pepper & Walker, 1988). Studies have been carried out in major crops such as sorghum [*Sorghum bicolor* (L.) Moench] (Ball et al., 2000) and black gram [*Vigna mungo* (L.) Hepper] (Biswas et al., 2002). Not much has been reported for the cowpea. Therefore, this study was aimed to investigate the mechanism of yield compensation in the cowpea, with particular emphasis on responses of yield and yield components to plant density and environment in two agro-ecologies in northern Nigeria.

TABLE 1 Physico-chemical properties of the top soil used for the experiment.

Soil properties	Minjibir	Shika
Sand (%)	70.00	32.00
Clay (%)	21.00	23.00
Silt (%)	9.00	45.00
pH (H_2O 1:1)	5.50	6.30
Organic carbon (%)	0.30	0.60
Total N (%)	0.02	0.05
Mehlich P (ppm)	9.00	12.80
Ca ($cmolkg^{-1}$)	1.00	2.16
Mg ($cmolkg^{-1}$)	0.25	0.83
K ($cmolkg^{-1}$)	0.30	0.42
Na ($cmolkg^{-1}$)	0.07	0.06

Source: International Institute of Tropical Agriculture (IITA) Analytical Services Laboratory (ASL), Ibadan.

2 | MATERIALS AND METHODS

2.1 | Experimental site

The experiment was carried out in 2020 at two locations, namely the experimental station of the IITA, Shika, Zaria (11˚11′ N, 7˚38′ E; 686 m above sea level) in the northern Guinea Savannah, and the research farm of the IITA, Minjibir (12˚42′ N, 8˚39′ E; 509 m above sea level) in the Sudan Savannah in Kano State, Nigeria.

2.2 | Soil sampling and analysis

Soil samples were collected from the topsoil from six different spots at the experimental site at a depth of 0–20 and 20–50 cm. These were composited and analyzed in the Analysis Services Laboratory of the IITA, Ibadan, Nigeria. The results of the soil analysis are as shown in Table 1.

2.3 | Meteorological data

Meteorological data were collected from the weather stations situated at the IITA experimental stations at Minjibir and Shika (Table 2).

2.4 | Planting materials

The six cowpea accessions used in this study were sourced from the Germplasm Unit of IITA, Kano station. The agronomic characteristics of the accessions are as shown in Table 3.

TABLE 2 Meteorological data collected in 2020 from Minjibir and Shika research stations.

		Location	
Weather reports	Month	Minjibir	Shika
Solar radiation ($MJ/m^2/day$)	August	15.76	15.22
	September	17.24	19.02
	October	18.41	22.10
	November	18.12	20.12
	December	18.37	19.31
Minimum relative humidity (%)	August	54.38	70.70
	September	48.02	70.99
	October	26.28	44.19
	November	12.38	23.93
	December	9.03	18.37
Maximum relative humidity (%)	August	94.96	98.66
	September	95.53	98.62
	October	87.42	92.03
	November	72.48	64.60
	December	66.97	51.12
Minimum temperature (˚C)	August	22.00	19.79
	September	22.41	19.76
	October	20.74	18.91
	November	16.47	16.52
	December	11.47	15.78
Maximum temperature (˚C)	August	29.74	26.50
	September	31.91	29.61
	October	34.66	32.02
	November	31.49	31.49
	December	32.70	32.56
Rainfall (mm)	August	8.57	5.56
	September	5.64	26.45
	October	0.52	2.85
	November	0.00	0.03
	December	0.00	0.00

Source: International Institute of Tropical Agriculture, Minjibir and Shika sub-station.

2.5 | Experimental layout, planting, and management

The randomized complete block design in a split-plot arrangement with three replicates was used. The recommended optimum density of 133,333 plants ha^{-1}, alongside three lower densities representing 75% (99,999 plants ha^{-1}), 50% (66,666 plants ha^{-1}), and 25% (33,333 plants ha^{-1}) of the optimum level, were used in this study. The main plot consisted of four plant densities (33,333 plant ha^{-1}; 66,666 plants ha^{-1}; 99,999 plants ha^{-1} and 133,333 plants ha^{-1}). The subplots consisted of six cowpea accessions, namely

TABLE 3 Agronomic characteristics of cowpea accessions used in the experiment.

Accession	Original name	National code	Growth pattern	Growth habit	Maturity period
SAMPEA-8	IT93K-452-1	NGVU-05-23	Determinate	Erect	Early maturing
SAMPEA-14	IT99K-573-1-1	NGVU-11-30	Semi-determinate	Semi-erect	Medium maturing
SAMPEA-11	IT89KD-288	NGVU-09-26	Indeterminate	Prostrate	Late maturing
_	IT98K-205-8	_	Determinate	Semi-erect	Early maturing
_	IT08K-150-27	_	Semi-determinate	Erect	Medium maturing
_	DANILA	_	Indeterminate	Prostrate	Late maturing

Source: Seed Bank, International Institute of Tropical Agriculture, Kano Station.

IT89KD-288, IT93K-452-1, IT99K-573-1-1, IT98K-205-8, IT08K-150-27, and DANILA.

The field was disc-harrowed and ridged before planting. The subplots measured 3 × 4 m, consisting of four rows each with inter- and intra-row spacing of 75 and 20 cm, respectively. The seeds were cleaned to avoid mechanical mixtures and were treated with 250 g of Apron Star [Thiamethoxam (200 g/kg) + metalaxyl-M (200 g/kg) + difenoconazole (20 g/kg)] to protect them from soil-borne pathogens. Three seeds per hill were sown by hand on August 17 and August 21, 2020, at Minjibir and Shika locations, respectively. The seedlings were thinned down to one per hill at 2 weeks after sowing (2 WAS).

A starter dose of NPK 15:15:15 was applied at 2 WAS at the rate of 14.25 kg ha^{-1}. Cypermethrin [cyano-(3-phenoxyphenyl)methyl)3-(2,2-dichloroethenyl)-2,2-dimethycylopropane-1-carboxylate] was applied at the rate of 120 µL ha^{-1} to control insect pests. Ampligo (chlorantraniliprole [10%] + lambda-cyhalothrin [5%] Zc), manufactured by Syngenta Crop Protection AG, Switzerland, was applied at the rate of 100 mL ha^{-1}, after the emergence of flowers, to control damage by the pod borer, Maruca (*Maruca vitrata*).

2.6 | Phenotyping

Field observation and data collection were commenced at 2 WAS using the two middle rows in each plot for sampling. The pods were harvested at 106 and 120 days after sowing at Shika and Minjibir locations, respectively. All the pods harvested from each plot were weighed. The weight was converted to the equivalent in kilograms per hectare before the statistical analysis.

Shelling percentage is the ratio of seed weight to pod weight. It was computed as the ratio of the shelling weight to the pod weight and multiplied by 100 (Sakariyawo et al., 2017) as follows:

$$\text{Shelling percentage}\ (\%) = \frac{\text{Shelling weight}\ (\text{kg})}{\text{Pod weight}\ (\text{kg})} \times 100$$

A seed-counting machine (Dimo's S-JR Automatic Seed Counter, Dimo's Labtronics) was used to count 100 seeds from each plot. The seeds were weighed using the Camry ZE11 digital weighing balance.

The biological yield was computed by weighing the biomass at harvest from each plot. The weight was extrapolated to the equivalent in kg ha^{-1} before the statistical analysis. Harvest index was computed as the ratio of grain yield to biological yield (Amanullah & Inamullah, 2016) as follows:

$$\text{Harvest index}\ (\%) = \frac{\text{Grain yield}\ \left(\text{kg ha}^{-1}\right)}{\text{Biological yield}\ \left(\text{kg ha}^{-1}\right)} \times 100$$

The pods were dried for 2 days after harvest and then threshed. The seeds were then dried in the midday sun for 4 h for 6 days. The seeds were weighed, and the weight was extrapolated to kg ha^{-1}, using the following formula (Toungos et al., 2019):

$$\text{Grain yield}\ \left(\text{kg ha}^{-1}\right) = \frac{\text{Grain yield}\ (\text{kg})}{\text{Plot size}\ (\text{m}) \times \text{net row}\ (\text{m})} \times 10,000\ \left(\text{m}^2\right)$$

Total grain yield was computed at 12% moisture content, which is the safe storage moisture content of the cowpea.

2.7 | Data analysis

Data collected from both locations were subjected to two-way analysis of variance tests separately and then combined, using the R Core Team (version 4.1.0; 2021). The plant density and cowpea accessions were considered as factors in determining the mean square and the *F*-test. The means were separated using the Duncan's new multiple-range test at 5% level of portability. Correlation coefficient was computed using the R-programming software (version 4.1.0) to determine the relationship between yield and yield components.

TABLE 4 Main effects of plant density and cowpea accession on pod yield and 100-seed weight at Minjibir and Shika.

Treatments	Pod yield (kg ha^{-1})			100-seed weight (g)		
	Minjibir	Shika	Pooled	Minjibir	Shika	Pooled
Density (plants ha^{-1})						
33,333	1883.98b	527.87b	1205.93b	16.22a	19.22a	18.15a
66,666	1888.52b	579.17b	1233.84b	16.32a	18.92a	17.63a
99,999	2136.11a	750.18a	1443.15a	16.81a	18.60a	17.67a
133,333	2156.39a	781.67a	1469.03a	16.97a	18.72a	17.78a
Accession						
IT89KD-288	1834.72c	724.17a	1279.44b	17.34b	20.57b	18.96b
IT93K-452-1	1870.14bc	706.94a	1288.54b	15.03c	15.87c	15.45c
IT99K-573-1-1	2000.14abc	700.97a	1350.56ab	18.08b	19.61b	18.85b
IT98K-205-8	2035.69abc	695.83a	1365.76ab	15.14b	16.25c	15.70c
IT08K-150-27	2118.75ab	807.49a	1463.13a	20.10a	24.45a	22.28a
DANILA	2238.06a	322.91b	1280.49b	14.70c	16.50c	15.60c
Level of significance						
DEN	***	***	***	ns	ns	ns
ACS	***	***	*	***	***	***
EVR			***			***
Interactions						
DEN × ACS	ns	ns	ns	ns	ns	ns
DEN × EVR			ns			ns
ACS × EVR			**			ns
ACS × DEN × EVR			***			ns
CV (%)	15.20	27.32	18.86	13.8	17.8	17.2

Note: Means followed by the same letter(s) within the same column are not significantly different at 5% level of probability.
Abbreviations: ACS, accession; CV, coefficient of variability; DEN, density; EVR, environment; ns, not significant.
***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

3 | RESULTS

3.1 | Pod yield

Table 4 shows the main effects of plant density and accession on pod yield and 100-seed weight at Minjibir and Shika locations. At the Minjibir location, pod yield increased with increasing plant density, ranging from 1883.98 kg ha^{-1} at 33,333 plants ha^{-1} to 2156.39 kg ha^{-1} at 133,333 plants ha^{-1}. Pod yield was highest in the accession DANILA (2238.06 ha^{-1}) and lowest in the accession IT89KD-288 (1834.72 kg ha^{-1}). At the Shika location, pod yield also increased with increasing plant density, from 527.87 kg ha^{-1} at 33,333 plants ha^{-1} to 781.67 kg ha^{-1} at 133,333 plants ha^{-1}. Pod yield was highest in the accession IT08K-150-27 (807.49 kg ha^{-1}) and lowest in the accession DANILA with a pod yield value of 322.91 kg ha^{-1} (Table 4). The result of the combined analysis showed that pod yield also increased as plant density increased, ranging from 1205.93 kg ha^{-1} at 33,333 plants ha^{-1} to 1469.03 kg ha^{-1} at 133,333 plants ha^{-1}. The highest pod yield of 1463.13 kg ha^{-1} was observed in the accession IT08K-150-27 while the lowest (1279.44 kg ha^{-1}) was observed in the accession IT89KD-288. The pod yield was generally higher at Minjibir than at the Shika location (Table 4).

TABLE 5 Interaction effects of accession and environment on pod yield (kg ha^{-1}).

Accession	Minjibir	Shika
IT89KD-288	1834.72c	724.17d
IT93K-452-1	1870.14c	706.94d
IT99K-573-1-1	2000.14bc	700.97d
IT98K-205-8	2035.69abc	695.83d
IT08K-150-27	2118.75ab	807.50d
DANILA	2238.06a	322.92e
LSD (0.05)	204.59	

Note: Means followed by the same the letter(s) within the same column are not significantly different at 5% level of probability.
Abbreviation: LSD, least significant difference.

The interaction of accession and environment on pod yield was significant (Table 5). The highest pod yield of 2238.06 kg ha^{-1} was observed in the accession DANILA when it was planted at the Minjibir location but lowest in the same accession DANILA (322.92 kg ha^{-1}) when it was planted at the Shika location (Table 5).

3.2 | 100-seed weight

At the Minjibir location, the 100-seed weight was statistically similar across the plant densities. The 100-seed weight was significantly higher in the accession IT08K-150-27 (20.10 g) than in the other accessions (Table 4). At the Shika location, the 100-seed weight was statistically similar across the plant densities. The 100-seed weight was also significantly higher ($p < 0.001$) in the accession IT08K-150-27 (24.45 g) than in the other accessions. Unlike the pod yield, the 100-seed weight was generally higher at Shika than at the Minjibir location (Table 4). The results of the combined analysis showed that the 100-seed weight was similar across the plant densities. The 100-seed weight was highest in the accession IT08K-150-27 (22.28 g) and lowest in the accession IT93K-452-1 (15.45 g).

3.3 | Shelling percentage

Table 6 shows the main effects of plant density and accession on shelling percentage and biological yield at Minjibir and Shika locations. At the Minjibir location, shelling percentage was statistically similar across the plant densities. It was significantly higher in the accession IT08K-150-27 (35.94%) than in the other accessions. At the Shika location, the shelling percentage was also similar across the plant densities but differed significantly amongst the cowpea accessions, with the highest value (43.27%) observed in the accession DANILA and the lowest (36.74%) in the accession IT99K-573-1-1. The shelling percentage was generally higher at Shika than at the Minjibir location. The results of the combined analysis showed that shelling percentage was statistically similar irrespective of the plant density or cowpea accession (Table 6).

3.4 | Biological yield

At the Minjibir location, the biological yield was highest (2925.46 kg ha^{-1}) at 133,333 plants ha^{-1} and lowest (1832.87 kg ha^{-1}) at 33,333 plants ha^{-1}. The biological yield ranged from 3162.50 kg ha^{-1} in the accession IT08K-150-27 to 1898.61 kg ha^{-1} in the accession DANILA. At the Shika location, the biological yield varied from 497.22 kg ha^{-1} at 33,333 plants ha^{-1} to 773.15 kg ha^{-1} at 133,333 plants ha^{-1}. The biological yield was highest in the accession IT08K-150-27 (852.77 kg ha^{-1}) and lowest (272.22 kg ha^{-1}) in the accession DANILA at the Shika location. The biological yield was generally higher at Minjibir than at the Shika location. The results of the combined analysis showed that the biological yield differed significantly with plant density and cowpea accession (Table 6).

3.5 | Harvest index

At the Minjibir location, a significantly lower harvest index (54%) was observed at 133,333 plants ha^{-1} than at the other plant densities (Table 7). The harvest index was highest in the accession DANILA and lowest in the accession IT08K-150-27 with values of 92% and 47%, respectively (Table 7). At the Shika location, the lowest harvest index of 58% was observed at 133,333 plants ha^{-1} compared to the other planting densities. Harvest index was highest in the accession IT89KD-288 (94%) and lowest in the accession IT08K-150-27 (61%). Results of the combined analysis showed that harvest index decreased with increasing plant density. The highest harvest index was observed in the accession DANILA (81%), while the lowest (46%) was observed in the accession IT08K-150-27 (Table 7). Harvest index was generally higher at Shika than at the Minjibir location.

3.6 | Total grain yield

At the Minjibir location, the total grain yield increased with increasing plant density from 1323.43 kg ha^{-1} at 33,333 plant ha^{-1} to 1494.8 kg ha^{-1} at 133,333 plant ha^{-1}. Total grain yield was highest in the accession DANILA and lowest in the accession IT89KD-288 with yield values of 1597.36 and 1270 kg ha^{-1}, respectively (Table 7). Like Minjibir, the total grain yield at the Shika location increased as the plant density increased. Total grain yield was highest in the accession IT08K-150-27 and lowest in the accession DANILA with values of 512.92 and 174.4 kg ha^{-1}, respectively. The results of the combined analysis showed that total grain yield increased with increasing plant density, ranging from 819.6 to 972.2 kg ha^{-1} at 33,333 and 133,333 plants ha^{-1}, respectively. Total grain yield was generally higher at Minjibir than at the Shika location (Table 7).

The interaction of plant density and accession on total grain yield at the Minjibir location was significant. The highest total grain yield of 1793.3 kg ha^{-1} was observed in the accession DANILA at 99,999 plants ha^{-1}, while the lowest (1058.9 kg ha^{-1}) was observed in the accession IT08K-150-27 at 66,666 plants ha^{-1} (Table 8). Also, the interaction of accession and environment on total grain yield was significant (Table 9). The highest total grain yield of 1597.36 kg ha^{-1} was observed when the accession DANILA was planted at the Minjibir

TABLE 6 Main effects of plant density and accession on shelling percentage and biological yield at Minjibir and Shika.

Treatments	Shelling percentage (%)		Pooled	Biological yield (kg ha^{-1})		Pooled
	Minjibir	Shika		Minjibir	Shika	
Density (plants ha^{-1})						
33,333	32.98a	39.53a	36.30a	1832.87c	497.22b	1165.05c
66,666	33.96a	39.64a	36.93a	2235.09bc	531.48b	1383.29b
99,999	33.30a	40.08a	36.70a	2663.42ab	648.15ab	1655.79a
133,333	34.96a	41.15a	37.42a	2925.46a	773.15a	1849.31a
Accession						
IT89KD-288	33.76b	39.15ab	36.45a	2488.19b	525.00c	1506.60b
IT93K-452-1	32.17d	42.47a	37.32a	2386.11b	655.56bc	1520.83b
IT99K-573-1-1	33.93b	36.74b	35.34a	2384.72b	759.72b	1572.22b
IT98K-205-8	33.29bc	40.37ab	36.83a	2165.14b	609.72bc	1387.43b
IT08K-150-27	35.94a	38.59ab	37.27a	3162.50a	852.77a	2007.64a
DANILA	32.35 cd	43.27a	37.81a	1898.61b	272.22d	1085.42c
Level of significance						
DEN	ns	ns	ns	***	***	***
ACS	***	*	ns	***	***	***
EVR			***			***
Interactions						
DEN × ACS	ns	ns	ns	ns	ns	ns
DEN × EVR			ns			ns
ACS × EVR			ns			ns
ACS × DEN × EVR			ns			ns
CV (%)	6.13	14.1	14.5	32.3	52.9	71.52

Note: Means followed by the same letter(s) within the same column are not significantly different at 5% level of probability.
Abbreviations: ACS, accession; CV, coefficient of variability; DEN, density; EVR, environment; ns, not significant.
***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

location. The lowest grain yield of 174.4 kg ha^{-1} was observed when the same accession, DANILA, was planted at the Shika location.

3.7 | Correlation of yield components with total grain yield

At Minjibir and Shika locations, the pod yield was positively correlated with total grain yield. A similar trend was observed when the data were combined. Shelling percentage was negatively correlated with total grain yield at Minjibir and Shika locations as well as when the data were combined. The 100-seed weight was positively and significantly correlated with total grain yield at the Shika location (Table 10). Biological yield and total grain yield were positively and significantly correlated at Shika and in the combined analysis. The harvest index was positively and significantly correlated with total grain yield at the Minjibir location (Table 10).

4 | DISCUSSION AND CONCLUSION

The differences in pod yield and 100-seed weight may be attributed to genotype and environment. Zhao et al. (2017) and Bakal et al. (2020) reported that pod yield increased with decreasing plant density; in other words, the number of plants that compete for available nutrients and other resources decreased as the plant density decreased. In this study, however, pod yield increased with increasing plant density. These differences could have been due to genotypic differences, growth habit, and architectural types. Bakal et al. (2020) observed that cowpea varieties with prostrate growth habit produced pods, which were not as heavy as those produced by the erect or semi-erect types. This could be due to mutual shading, for which reason photosynthesis no longer exceeds respiration in older leaves, which then cease to be net producers of dry matter (Namo, 2005). Therefore, the assimilates available for pod development and grain-filling in prostrate varieties are reduced. The number and size of the pods have been reported to contribute to the final grain yield (Kamara

TABLE 7 Main effects of plant density and accession on harvest index and grain yield at Minjibir and Shika.

	Harvest index (%)			Grain yield (kg ha^{-1})		
Treatments	**Minjibir**	**Shika**	**Pooled**	**Minjibir**	**Shika**	**Pooled**
Density (plants ha^{-1})						
33,333	79.00a	71.00a	65.00a	1323.43b	315.83b	819.63b
66,666	60.00b	75.00a	56.00b	1297.13b	342.13b	819.63b
99,999	60.00b	77.00a	55.00b	1494.26a	438.52a	966.39a
133,333	54.00b	58.00b	50.00b	1494.82a	449.63a	972.22a
Accession						
IT89KD-288	55.00bc	94.00a	50.00bc	1270.00b	424.17b	847.08a
IT93K-452-1	57.00bc	62.00b	51.00b	1338.89b	375.42b	857.15a
IT99K-573-1-1	61.00b	65.00b	53.00b	1380.69b	438.47ab	909.58a
IT98K-205-8	68.00b	68.00b	57.00b	1426.39ab	393.75b	910.07a
IT08K-150-27	47.00c	61.00b	46.00c	1401.11b	512.92a	957.01a
DANILA	92.00a	70.00b	81.00a	1597.36a	174.44c	885.90a
Level of significance						
DEN	***	ns	**	*	***	***
ACS	***	*	***	*	***	ns
EVR			***			***
Interactions						
DEN × ACS	ns	ns	ns	*	ns	ns
DEN × EVR			ns			ns
ACS × EVR			ns			***
ACS × DEN × EVR			ns			ns
CV (%)	36.5	36.6	37.0	20.7	42.5	62.7

Note: Means followed by the same letter(s) within the same column are not significantly different at 5% level of probability.
Abbreviations: ACS, accession; CV, coefficient of variability; DEN, density; EVR, environment; ns, not significant.
***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

TABLE 8 Interaction effects of accession and plant density on grain yield (kg ha^{-1}) at Minjibir.

	Density (plants ha^{-1})			
Accession	**33,333**	**66,666**	**99,999**	**133,333**
IT89KD-288	1323.9cdefg	1245.0defg	1259.4defg	1251.7defg
IT93K-452-1	1301.7cdefg	1186.7efg	1587.2abcd	1280.0cdefg
IT99K-573-1-1	1434.4abcdefg	1115.0fg	1372.8bcdefg	1600.6abcd
IT98K-205-8	1100.0 g	1513.3abcde	1377.2bcdefg	1715.0ab
IT08K-150-27	1340.0bcdefg	1058.9 g	1575.6abcd	1630.0abcd
DANILA	1440.6abcdefg	1663.9abc	1793.3a	1491.7abcdef
LSD (0.05)	388.28			

Note: Means followed by the same the letter(s) within the same column are not significantly different at 5% level of probability.

et al., 2016). Medium-maturing varieties of cowpea have been reported to produce a higher number of pods and pod yield (Kamara et al., 2016). Differences in pod yield could also be attributed to the phenological differences in the accessions studied. Late-maturing accessions had a longer period of production and partitioning of photosynthates from the source to the sink (Ahmed & Abdelrhim, 2010; Kamara et al., 2016).

Shelling percentage is believed to have a positive and significant effect on seed yield. A higher shelling percentage indicates that a greater proportion of pod weight is comprised of seeds, which directly translates to increased seed yield. This relationship has been reported in different crops like maize [*Zea mays* (L.)] and peanut [*Arachis hypogaea* (L.)] (Keno et al., 2024). In this study, shelling percentage was generally

TABLE 9 Interaction effects of accession and environment on grain yield (kg ha^{-1}).

Accession	Location	
	Minjibir	Shika
IT89KD-288	1270.00c	424.17de
IT93K-452-1	1338.89bc	375.42e
IT99K-573-1-1	1380.69bc	438.47de
IT98K-205-8	1426.38b	393.75e
IT08K-150-27	1401.11b	512.92d
DANILA	1597.36a	174.44f
LSD (0.05)	117.88	

Note: Means followed by the same the letter(s) within the same column are not significantly different at 5% level of probability.

TABLE 10 Correlation coefficients of yield components with total grain yield at Minjibir and Shika.

Traits	Minjibir	Shika	Pooled
Pod yield	0.267*	0.917**	0.990**
Shelling percentage	−0.462**	−0.232*	−0.610**
100-seed weight	0.002ns	0.405**	0.052ns
Biological yield	0.199ns	0.755**	0.810**
Harvest index	0.407**	−0.007ns	−0.029ns

Abbreviation: ns, not significant.
$^{**}p \leq 0.001$; $^{*}p \leq 0.05$;

higher at the Minjibir than at the Shika location, and this was reflected in the total grain yield, which was also higher at the Minjibir than at the Shika location. Bakal et al. (2020) reported that an increase in plant density resulted in increased seed yield.

The result of the correlation analysis showed that shelling percentage was negatively correlated with grain yield at both locations and in the combined analysis. This implies that accessions with higher shelling percentage had lower grain yields and vice versa. This is contrary to the findings reported for other crops, indicating that more of the resources produced by the cowpea accessions (especially the indeterminate types) used in this study could have been allocated to pod development or other non-seed components. The interaction of accession and environment on pod yield in this study showed that the cowpea accessions responded differently to plant density in the different environments.

A proportion of the total dry matter produced by a crop is partitioned to the sink (the grains in legumes and corn); in other words, yield is a function of the total dry matter produced by a crop. Therefore, the higher the biological yield, the higher the amount of photosynthates available to be translocated to the grain during the grain-filling period. Bakal et al. (2020) noted that biological yield increased with increasing plant density. Kamara et al. (2014) reported a similar finding in the soybean. In this study, biological yield was positively correlated with the total grain yield.

Harvest index is believed to be influenced by many factors among which is the partitioning of assimilates within a plant. The dry matter partitioning is in turn determined by the change from vegetative to the reproductive growth in most crops. In indeterminate flowering crops like soybean, tomato, and cotton, a proportion of dry matter produced after flowering is used to produce new leaves rather than to fill reproductive sinks (Ashley, 1972; Ismail & Khalifa, 1987). Spitters (1983) observed that yield/biomass ratio did not remain constant but varied with plant density and that harvest index decreased as plant density increased. This was evident in this study, indicating that harvest index decreased as plant density increased, especially in indeterminate accessions where the assimilates produced were partitioned to newly formed leaves.

In this study, the planting of cowpea accessions at lower densities resulted in higher harvest index at both Minjibir and Shika locations, which is in line with the findings of Giridhar et al. (2020), who suggested a lower plant density to attain a higher harvest index in the cowpea. The highest harvest index observed in the cowpea accessions IT89KD-288 and DANILA suggests that the rate of translocation of assimilates from the source to the sink was more efficient in the prostrate accessions. Samarrai et al. (1983) noted that harvest index could be considered as a promising yield-selection criterion. Siddique et al. (1987) suggested that kernel weight should be used as a selection criterion for early identification of productive mutants in wheat (*Triticum aestivum* L.). Grain yield is a function of several factors, while the biological yield is a function of another set of factors. Both the grain yield and the biological yield, which determine the harvest index, may vary with environment, management practices, pests, diseases, and ergonomic conditions (Ismail, 1993). This has been demonstrated in the present study. DeLougherty and Crookston (1979) identified the population density as a major factor influencing the harvest index.

The increase in total grain yield with increasing plant density in this study is in line with the findings of Biswas et al. (2002) in the black gram, Kamara et al. (2014) in soybean, and Bakal et al. (2020) in the peanut. Kamara et al. (2016) reported that the photosynthetic rate increased with increasing plant density and the intercepted photosynthetically active radiation (IPAR). Kamara et al. (2016) also noted that increasing plant density resulted in increasing biological efficiency and the total grain yield. The same trend was observed in this study.

The interactions of accession and environment as well as accession and plant density on total grain yield indicate that the cowpea accessions responded differently to the plant density at the two locations. Chen et al. (2017) and Iseki et al. (2023) also noted that cowpea accessions responded differently to plant densities at different locations. The yield differentials observed at Minjibir and Shika locations could be partly attributed to the incidence of leaf scab disease (*Sphaceloma* spp.) at the Shika location, which affected the photosynthetic leaf area.

This study was aimed at identifying the mechanism of yield compensation in some accessions of cowpea at different environments. The results of the study have shown that plant density and environment affect yield and yield components in the cowpea. The study showed that for optimum grain yield in the cowpea, different accessions should be cultivated at different locations and at different plant densities. At the Minjibir location, the erect accessions (IT93K-452-1 and IT98K-205-8) and semi-erect accessions (IT99K-573-1-1 and IT08K-150-27) could be cultivated at 133,333 plants ha^{-1}. The prostrate accessions (IT89KD-288 and DANILA) could be cultivated at 99,999 plants ha^{-1}. At the Shika location, the erect and semi-erect accessions performed better than the prostrate types irrespective of the plant density. Therefore, the accessions IT93K-452-1-1, IT98K-205-8, IT99K-573-1-1, and IT08K-150-27 could be considered for cultivation at the Shika location.

AUTHOR CONTRIBUTIONS

Timothy Aku Otsanjugu Namo: Conceptualization; funding acquisition; investigation; supervision; validation; writing—original draft; writing—review and editing. **Gideon Oluwaseye Oyebode**: Data curation; project administration. **Ifeoluwa Simeon Odesina**: Data curation; formal analysis; methodology; project administration; software; visualization; writing—review and editing. **Patrick Obia Ongom**: Data curation; formal analysis; methodology; software; visualization. **Ousmane Boukar**: Conceptualization; investigation; supervision; validation. **Tersur Theophilus Akpensuen**: Funding acquisition; project administration. **Grace Obaiya Utoblo**: Formal analysis; software.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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