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Response of Sorghum (*Sorghum bicolor* L. Moench) to Varying Plant Spacing under BRIS Soil Conditions

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ABSTRACT

Global agriculture faces increasing pressure to sustain food production amid soil degradation, water scarcity, and climate change. Sorghum (*Sorghum bicolor* L. Moench), a stress-tolerant cereal, offers great potential for cultivation on marginal soils such as BRIS (Beach Ridges Interspersed with Swales) soils, which are sandy, acidic, and low in fertility. This study evaluated the effect of within-row plant spacing on sorghum growth and yield performance under BRIS soil conditions at the MARDI Bachok Research Station. The experiment employed a Randomized Complete Block Design (RCBD) with four spacing treatments (10, 15, 20, and 25 cm within rows) replicated five times. Results showed that plant spacing had a significant influence on several growth and yield parameters. Stem diameter increased significantly with wider spacing, while plant height and leaf number were not affected. Among yield components, 1000-grain weight, panicle weight per plant, and grain weight per plot were significantly influenced by spacing ($p < 0.05$). The 15 cm spacing (J2) produced the highest grain yield (4466.6 g plot^{-1}) due to a favourable balance between plant competition and resource availability. Closer spacing (10 cm) caused intense competition, reducing grain size, whereas wider spacing (25 cm) reduced total yield per area. These findings indicate that moderate within-row spacing (15–20 cm) is most effective for optimizes sorghum growth and yield under BRIS soil conditions. The results provide practical recommendations for enhancing sorghum productivity and land-use efficiency on marginal coastal soils.

Keywords: Sorghum; *Sorghum bicolor*; BRIS Soil; Plant Spacing; Planting Density; Agronomic Traits; Plant Height; Stem Diameter; Number of Leaves; Root-Shoot Ratio; Yield; Yield Components.

1. Introduction

Global agriculture is under growing pressure to meet rising food demands while coping with environmental constraints such as declining soil fertility, water scarcity, and the impacts of climate change. These challenges are particularly acute in developing regions, where large areas of land are categorized as marginal due to poor soil quality and limited natural fertility. Enhancing agricultural productivity on such lands has become a key priority in achieving sustainable food security. In this context, the cultivation of stress-tolerant crops and the development of site-specific agronomic practices offer promising solutions. One crop that holds considerable potential for these marginal conditions is sorghum (*Sorghum bicolor* L. Moench), a cereal known for its exceptional adaptability and resilience.

Sorghum is widely cultivated in arid and semi-arid regions of Africa, Asia, and Latin America (Proietti et al., 2015). It is a C4 plant, which contributes to its high water-use efficiency and heat tolerance. These physiological traits enable sorghum to thrive where other cereal crops may fail, particularly in areas with limited rainfall and low soil fertility. In addition to its use as a staple food in many parts of the world, sorghum serves as livestock feed, forage, and a raw material for biofuel production, making it an important multipurpose crop in both subsistence and commercial farming systems (Reddy et al., 2009; FAO, 2021).

Despite its adaptability, sorghum yield is strongly influenced by management practices, particularly plant density and spacing. Plant spacing affects key aspects of crop performance, including light interception, canopy structure, root development, and inter-plant competition for water and nutrients. Consequently, optimizing plant spacing is critical to maximizing sorghum productivity, especially in resource-limited environments. Several studies have examined the impact of plant spacing on sorghum growth and yield, with findings showing that denser planting may increase biomass and suppress weeds but can also intensify intra-specific competition, leading to smaller panicles and lower grain yield per plant (Maman et al., 2004; Rao et al., 2013). Conversely, wider spacing may improve individual plant performance but reduce overall yield per unit area. These findings suggest that the ideal spacing is context-dependent and influenced by soil type, climate, and crop variety.

One particularly challenging soil type for crop production is BRIS (Beach Ridges Interspersed with Swales) soil. Found predominantly in coastal regions of Southeast Asia, BRIS soils are highly sandy, acidic, and characterized by low organic matter, poor water-holding capacity, and rapid nutrient leaching (Roslan et al., 2011). These conditions severely limit crop growth unless proper management practices are applied. Although sorghum has shown potential for cultivation on marginal soils, including sandy and drought-prone areas, there is a gap on its performance in BRIS soil, particularly concerning plant spacing. Most available agronomic recommendations are derived from studies conducted in loamy or clay-rich soils and are therefore not directly applicable to BRIS conditions.

1.1. Study Objectives

1. To evaluate the response of sorghum to varying plant spacing under BRIS soil conditions.
2. To assess the impact of different spacing regimes on growth parameters.
3. To study the effect of different plant spacing on biomass yield of sorghum.
4. To evaluate the effect of different plant spacing on yield components and productivity of sorghum.
5. To identify spacing strategies that optimize sorghum performance in terms of both plant health and land-use efficiency in nutrient-poor, sandy soils.

░ 2. Materials and Methods

2.1. Site description and land preparation

The field trial was conducted at the Malaysian Agricultural Research and Development Institute (MARDI), Bachok Research Station (5.97838° N, 102.42751° E). The site is characterized by BRIS (Beach Ridges Interspersed with Swales) soil, which is sandy, acidic, and nutrient poor. Prior to planting, the plot was mechanically tilled using a rotavator to a depth of approximately 15–20 cm to break up soil clods and improve soil aeration. Organic chicken manure was incorporated into the soil at a rate of 5 t/ha, five days before sowing, to improve soil fertility. The manure was uniformly broadcast and incorporated during final tillage.

2.2. Experimental design

The experiment was conducted using a Randomized Complete Block Design (RCBD) with five replications to account for field variability. The treatment factors were inter-row plant spacing at four levels: J1 (10 cm), J2 (15 cm), J3 (20 cm), and J4 (25 cm). The between-row spacing was fixed at 45 cm, and each plot measured 5 m × 5 m

(25 m²). The corresponding plant populations for each treatment were 222,222 plants/ha (J1), 148,148 plants/ha (J2), 111,111 plants/ha (J3), and 88,889 plants/ha (J4).

2.3. Seed sowing and thinning

Sorghum seeds were sown manually at a depth of 1 cm, with two seeds per planting hole. After 14 days, thinning was performed to leave one healthy seedling per hole, ensuring uniform plant density. The seeding process followed standard sowing practices for field crops.

2.4. Irrigation

Irrigation was provided using an overhead sprinkler system, scheduled twice daily (morning and evening) to maintain optimum soil moisture, particularly crucial for BRIS soils. Irrigation amounts were adjusted according to weather conditions to avoid water stress and leaching.

2.5. Fertilizer application

Fertilization was carried out in three stages. The basal application was performed on the day of planting, where NPK Green 15:15:15 was applied at a rate of 320–800 g per plot, depending on plant density, to provide balanced macronutrients. At 30 days after planting (DAP), topdressing was conducted using urea (46% N) at a rate of 2 g per plant to support vegetative growth. The final stage involved foliar fertilization at 45 DAP using Vitagrow foliar fertilizer applied at 200 ml/ha (or 0.5 ml/plot) diluted in 18 L of water, using a calibrated backpack sprayer. The foliar application was carried out early in the morning to enhance nutrient absorption and minimize evaporation. All fertilization activities adhered to standard safety and application procedures as recommended by the manufacturer.

2.6. Weed, pest, and disease management

Weeds were removed manually at regular intervals using hoes and hand tools to avoid competition for nutrients and light. Pest and disease control was carried out based on visual scouting. When thresholds were exceeded, recommended chemical pesticides and fungicides were applied.

2.7. Harvesting

At 110 days after planting, sorghum plants were manually harvested at physiological maturity using secateurs. The panicles were detached and placed in a drying room for five days until a moisture content of approximately 12% was achieved, as verified with a grain moisture meter. Once dried, the grains were separated from the panicles and thoroughly cleaned to remove chaff and other impurities before subsequent measurements and analyses.

2.8. Data collection

2.8.1. Plant growth

Plant growth parameters were assessed at 60 days after planting (DAP). Plant height was measured from the soil surface to the tip of the highest leaf or panicle, and stem diameter was recorded 5 cm above the soil surface using a digital vernier calliper. The number of fully expanded green leaves was manually counted, excluding senescent ones. A total of six plants per plot were sampled for all vegetative growth measurements, including root-to-shoot ratio determination. For root-to-shoot analysis, the same six plants were uprooted, washed, and oven-dried at 60°C for three days before dry weights were recorded and the ratio calculated.

2.8.2. Yield and Yield Components

Six plants were randomly selected from each plot for all yield component measurements, including panicle length, panicle weight, grain number per plant, and 1,000-grain weight. Panicle length was measured from the base, where it emerged from the last leaf sheath to the tip using a measuring tape. Each dried panicle was then weighed individually using a digital weighing scale to obtain panicle weight. The number of grains per plant was determined by manually threshing the panicle from each sampled plant, and the total grain count was recorded using an automated seed counter. A random subsample of 1,000 cleaned grains from each plot was used to determine the 1,000-grain weight.

Grain yield per plot was not determined from the six sampled plants. Instead, grain yield was estimated from all plants harvested within a designated 4 m × 4 m crop-cutting area. All plants within this area were manually harvested to represent the overall yield performance. After drying, the panicles were manually threshed, cleaned, and weighed using an analytical balance. Grain yield was calculated based on the total grain weight obtained from the crop-cutting area, adjusted for planting density.

2.8.3. Statistical analysis

All collected data were subjected to analysis of variance (ANOVA) using SAS software. Normality of residuals and homogeneity of variance were checked to ensure ANOVA assumptions were met. Treatment means were compared using the Least Significant Difference (LSD) test at $p < 0.05$, following the procedures described by FAO (1995) and Gomez and Gomez (1984).

3. Results and Discussion

3.1. Effect of varying plant spacing to the plant growth

The effects of within-row plant spacing on sorghum plant height, stem diameter, and number of leaves are presented in Table 1. Analysis revealed that plant spacing significantly influenced stem diameter, while plant height and number of leaves were not significantly affected.

Table 1. ANOVA of plant growth parameters of sorghum in response to plant spacing

Source	df	Sum of Squares	Mean Square	F	Sig.
Plant height (cm)					
Treatments (Plant spacing)	3	178	59.3333333	0.49	0.6942
Rep	4	707.35625	176.8390625	1.47	0.2724
Error	12	1446.09375	120.507813		
Total	19	2331.45			

Stem diameter (mm)					
Treatments (Plant spacing)	3	51.943015	17.31433833	8.32	0.0029
Rep	4	6.30772	1.57693	0.76	0.5721
Error	12	24.96996	2.08083		
Total	19	83.220695			
Number of leaves/plants					
Treatments (Plant spacing)	3	0.15	0.05	0.07	0.9769
Rep	4	1.7	0.425	0.56	0.6958
Error	12	9.1	0.75833333		
Total	19	10.95			
Root: Shoot ratio					
Treatments (Plant spacing)	3	0.00861255	0.00287085	2.1	0.1535
Rep	4	0.0045283	0.00113207	0.83	0.5319
Error	12	0.0163917	0.00136598		
Total	19	0.02953255			

Plant height ranged from 219.35 cm in J1 (10 cm) to 227.55 cm in J4 (25 cm), with differences statistically non-significant (Table 2). This stability in height suggests that sorghum's vertical growth is predominantly under genetic control, with minimal environmental modulation from plant spacing under the prevailing conditions. Similar results were observed by Gebrelibanos et al. (2019) and Ali et al. (2018), who reported that plant height in sorghum is relatively insensitive to moderate variations in spacing when grown under favorable temperature and adequate soil moisture conditions. The slightly taller plants in the wider spacing treatments (J3 and J4) may be attributed to reduced inter-plant competition for light, water, and nutrients, which can allow plants to express their full elongation potential. In dense stands, plants sometimes elongate more due to light competition (shade avoidance response), but in this study, the absence of significant differences suggests that the LAI (leaf area index) was not high enough to trigger a strong shade avoidance effect.

Table 2. Effect of within-row spacing on plant height, stem diameter, number of leaves, and root: shoot ratio of sorghum cultivated in BRIS soil

Treatment (Within-row plant spacing)	Plant height (cm)	Stem diameter (mm)	Number of leaves	Root: Shoot Ratio/plant
J1 (10 cm)	219.35a	20.06c	5a	0.284b
J2 (15 cm)	223.15a	21.91bc	5a	0.300ab
J3 (20 cm)	221.75a	24.36a	5a	0.338a
J4 (25 cm)	227.55a	23.31ab	5a	0.321ab

Stem diameter was significantly affected by spacing, with the thickest stems recorded in J3 (20 cm, 24.36 mm) and the thinnest in J1 (10 cm, 20.06 mm) (Table 2). This trend indicates that wider spacing allows plants to accumulate more assimilates in structural tissues due to greater resource availability per plant. Thicker stems are particularly important for sorghum grown in open-field conditions, as they provide improved mechanical strength and reduce susceptibility to lodging. Lodging problem is a major issue in tall sorghum varieties under high wind or heavy grain loads (Kebede et al., 2020). The improvement in stem girth under moderate spacing has also been linked to improved vascular development, which facilitates efficient transport of water and nutrients to the developing panicle (Olaniyan & Lucas, 2019). This suggests that a balance between plant density and stem robustness should be considered in production systems, especially under BRIS soil conditions where nutrient and water availability are limiting factors.

The number of leaves per plant remained constant at five across all treatments. This finding supports earlier reports by Tesfaye et al. (2021) that leaf initiation in sorghum is largely determined genetically and is less influenced by plant spacing or moderate environmental variation. However, while the number of leaves was unaffected, spacing can still influence leaf size, thickness, and angle, which are known to affect canopy photosynthesis and light distribution within the crop stand (Amanullah et al., 2017). Under wider spacing, leaves often exhibit a more horizontal orientation, increasing light interception by the lower canopy layers and potentially improving photosynthetic efficiency.

Meanwhile, Table 2 also shows that the root-to-shoot ratio was significantly higher in J3 (0.338), followed by J4 (0.321), and lowest in J1 (0.284). A higher root-to-shoot ratio typically indicates greater root development relative to shoot biomass. This finding suggests that wider spacing facilitated more extensive root growth, which is crucial in soils with limited fertility, such as BRIS soils, where nutrient and water uptake can be limiting factors. Marschner et al. (1996) emphasized that a higher root-to-shoot ratio benefits plants in nutrient-poor soils, as larger root systems improve water and nutrients acquisition. Thus, the results from J3 support the idea that wider spacing promotes better root system development, enhancing the plant's ability to adapt to challenging soil conditions.

From a physiological standpoint, the non-significant effect of spacing on plant height and leaf number indicates that sorghum plants in this trial had sufficient access to light and resources to maintain typical vegetative development across spacing treatments. However, the significant increase in stem diameter at moderate spacing suggests that intra-specific competition had a measurable impact on biomass partitioning. In closely spaced stands (J1), competition for nutrients in BRIS soils, which are inherently low in organic matter and have a low cation exchange capacity, may have diverted assimilates toward height growth at the expense of stem thickening.

The implications for management are clear, while plant height and leaf number may not be strongly influenced by spacing within the tested range, stem robustness can be significantly improved by using moderate spacing (20–25 cm). This could have downstream benefits for grain yield stability, especially in regions prone to strong winds or heavy rains during the grain-filling stage. Moreover, the stronger stems in wider spacing treatments may also support better translocation of assimilates to the panicle, which could partly explain the higher panicle weight observed in the yield component analysis for these treatments.

Overall, the results suggest that while vegetative traits like plant height and leaf number are relatively stable across spacings, structural traits such as stem diameter are highly responsive and should be considered in plant density recommendations. Balancing stem strength with plant population will be crucial in optimizing both yield potential and crop resilience under the challenging conditions of BRIS soils.

3.2. Effect of varying plant spacing to the yield and yield component

The analysis of variance (ANOVA) revealed that plant spacing had a significant effect on several key agronomic traits of sorghum (Table 3). Specifically, the 1000-grain weight (p = 0.0008), panicle weight per plant (p = 0.0353), and grain weight per plot (p = 0.0079) were significantly influenced by plant spacing, indicating that optimal spacing can enhance grain development and overall yield. In contrast, grain number per plant and panicle length were not significantly affected (p = 0.2709 and p = 0.2527, respectively), suggesting that these traits are less responsive to variations in plant density. Further results related to these parameters are discussed below.

Table 3. ANOVA of agronomic traits and yield of sorghum in response to plant spacing

Source	**df**	**Sum of Squares**	**Mean Square**	**F**	**Sig.**
Panicle weight/plant (g)					
Treatments (Plant spacing)	3	8.47384	2.82461	2.25	0.0353
Rep	4	21.06412	5.26603	4.19	0.137
Error	12	15.08376	1.25698		
Total	19	44.62172			
Panicle length (cm)					
Treatments (Plant spacing)	3	12.04582	4.01527	1.55	0.2527
Rep	4	5.29723	1.32431	0.51	0.729
Error	12	31.10153	2.59179		
Total	19	48.44458			
Number of grain/plants					
Treatments (Plant spacing)	3	891132.55	297044	1.48	0.2709
Rep	4	373438.3	93359.6	0.46	0.7613
Error	12	2416603.7	201384		
Total	19	3681174.6			
1000-grain weight (g)					
Treatments (Plant spacing)	3	367.73844	122.579	11.49	0.0008
Rep	4	27.50325	6.87581	0.64	0.6413
Error	12	128.04251	10.6702		
Total	19	523.2842			
Grain weight/plot (g)					
Treatments (Plant spacing)	3	5886427.4	1962142	6.37	0.0079
Rep	4	3285628.2	821407	2.67	0.084
Error	12	3693583.4	307799		
Total	19	12865639			

Panicle weight per plant ranged from 12.50 g in J1 (10 cm) to 14.30 g in J3 (20 cm) (Figure 1). The higher panicle weight in moderately spaced treatments (J2 and J3) may be attributed to reduced intra-specific competition, which enhances light interception per plant, photosynthetic efficiency, and nutrient uptake (Gebrelibanos et al., 2019). Under close spacing (J1), competition for limited soil nutrients and light under BRIS soil conditions, which are inherently low in fertility and water-holding capacity, likely restricted assimilate supply to the developing panicles. Conversely, at excessively wide spacing (J4, 25 cm), the reduced number of plants per unit area can limit total dry matter accumulation, as fewer plants intercept solar radiation, resulting in lower total grain production despite higher individual plant resource availability (Mahama et al., 2022).

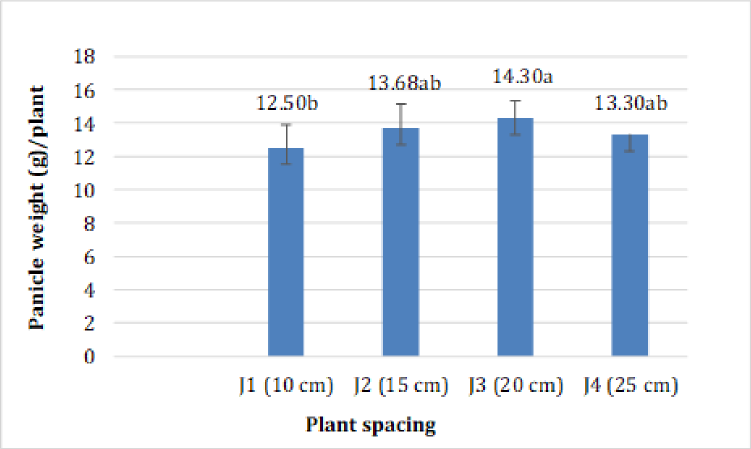

Figure 1. Effect of panicle weight per plant at different within-row plant spacing. Mean values with different letters are significantly different by LSD ($p < 0.05$).

Panicle length values, ranging from 29.05 cm (J1) to 31.10 cm (J4), were statistically similar across treatments (Figure 2). This observation supports earlier reports that panicle length is more genetically regulated than environmentally driven, except under extreme stress conditions (Ali et al., 2018). Since BRIS soil conditions are characterized by low water-holding capacity, the absence of severe drought during the critical reproductive stage may have minimized environmental effects on panicle elongation.

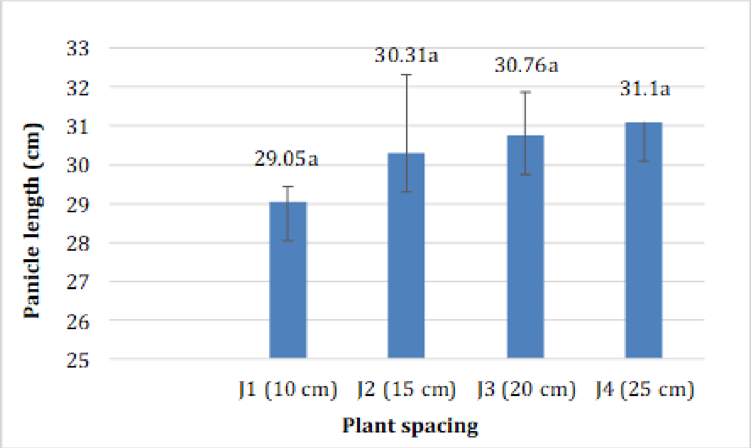

Figure 2. Effect of panicle length at different within-row plant spacing. Mean values with different letters are significantly different by LSD ($p < 0.05$).

The number of grains per plant was highest in J2 (2888 grains) and lowest in J4 (2351 grains), although the differences were not statistically significant (Figure 3). This trend suggests that intermediate spacing (15 cm) could optimize the balance between resource capture and plant population, allowing for better pollination and floret retention. Similar trends were reported by Amanullah et al. (2017), who observed that moderate plant density improved the number of grains per plant in cereals by reducing inter-plant shading during anthesis, which is critical for sorghum fertility.

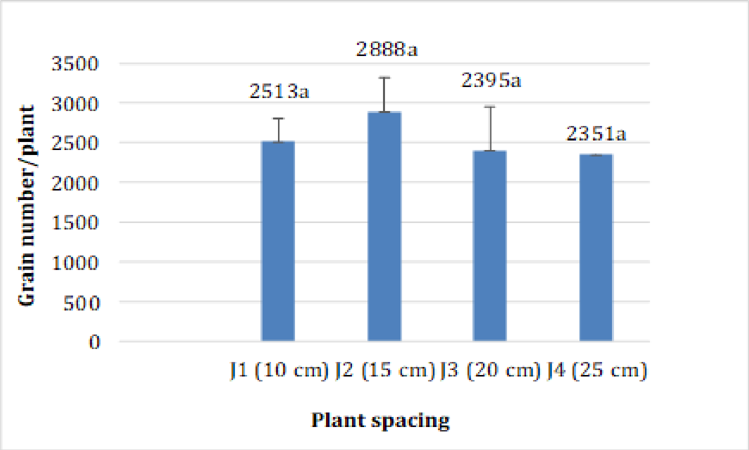

Figure 3. Effect of grain number per plant at different within-row plant spacing. Mean values with different letters are significantly different by LSD ($p < 0.05$).

Thousand-grain weight showed a clear and significant response to plant spacing. The heaviest grains were recorded in J2 (44.90 g), followed by J4 (39.12 g) and J3 (37.79 g), with J1 producing the lightest grains (32.86 g) (Figure 4). Grain weight is largely determined during the grain-filling stage, which is highly sensitive to assimilate supply (Kebede et al., 2019). The heavier grains in J2 may be explained by its optimal plant population density, which likely allowed sufficient photosynthate allocation to each kernel while still maintaining high total yield. The low 1000-grain weight in J1 suggests that excessive plant competition in close spacing can limit carbohydrate supply to individual grains, leading to shrivelling or incomplete filling.

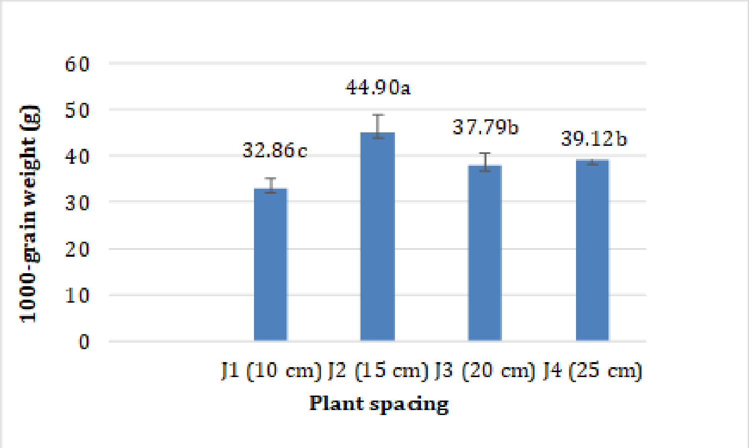

Figure 4. Effect of 1000-grain weight per plant at different within-row plant spacing. Mean values with different letters are significantly different by LSD ($p < 0.05$).

Grain yield per plot was maximized at J2 (4466.6 g), followed by J1 (4031.6 g) (Figure 5). Despite J3 having the highest panicle weight per plant, its lower plant population reduced total yield per plot. Likewise, J4 had the lowest yield (3154.0 g), demonstrating the yield penalty associated with overly wide spacing. This supports the classic agronomic principle that grain yield is a product of yield components (grain number × grain weight) and plant density (Donald, 1963). The interaction between plant density and resource competition plays a decisive role in final yield, with an optimum spacing point where the balance between individual plant performance and total plant population is achieved (Olaniyan & Lucas, 2019).

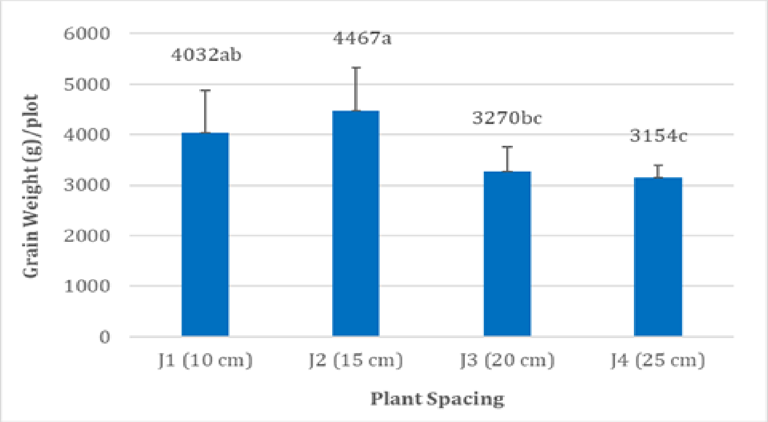

Figure 5. Effect of grain weight at different within-row plant spacing. Mean values with different letters are significantly different by LSD ($p < 0.05$).

From a physiological perspective, the superior performance of J2 in grain weight per plot can be attributed to more efficient light interception throughout the canopy, better leaf area index (LAI), and higher radiation use efficiency (RUE) without inducing excessive self-shading. Moderate spacing also facilitates better root proliferation, which is particularly important in BRIS soils with low nutrient-holding capacity, enabling plants to exploit the available moisture and nutrients more effectively (Tesfaye et al., 2021).

These findings align with earlier research showing that plant spacing adjustments are a cost-effective agronomic practice to enhance yield potential without additional inputs, especially under marginal soil conditions (Amanullah et al., 2017; Mahama et al., 2022). Importantly, the results highlight that optimum spacing recommendations for sorghum must consider not only plant architecture and environmental conditions but also soil fertility and moisture-holding characteristics.

In summary, the results of this study demonstrate that a within-row spacing of 15 cm (J2) achieved the most favorable balance between individual plant performance and plant population per unit area, leading to the highest grain yield under BRIS soil conditions. Wider spacing reduced overall yield due to fewer plants, while closer spacing reduced grain weight due to intense competition. This suggests that under nutrient-poor sandy soils, intermediate plant spacing can maximize yield potential.

4. Conclusion

The study demonstrates that plant spacing significantly affects grain weight, grain number, and panicle characteristics. The 15 cm spacing (J2) proved to be the most effective, balancing yield and grain quality.

Moderate plant spacing (15–20 cm) is recommended to optimize sorghum production, as excessive plant density (J1) can reduce individual grain size, while overly wide spacing (J4) can lower total grain number. Based on the findings of this study, several areas require further investigation to strengthen understanding and improve sorghum production management. The following future research recommendations are proposed:

1) Examine the interaction between plant spacing and fertilizer rates.
2) Test plant spacing across different locations and soil types.
3) Evaluate varietal responses of sorghum to different spacing distances.
4) Assess the effects of plant spacing on pest and disease incidence.
5) Investigate spacing performance under abiotic stresses such as drought and salinity.

Declarations

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Competing Interests Statement

The authors have declared that no competing financial, professional or personal interests exist.

Consent for publication

All the authors contributed to the manuscript and consented to the publication of this research work.

Availability of data and material

Supplementary information is available from the authors upon reasonable request.

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