Phyton-
International Journal of
Experimental Botany

Tech Science Press

DOI: 10.32604/phyton.2024.048770

Check for updates

ARTICLE

Sorghum Productivity and Its Farming Feasibility in Dryland Agriculture: Genotypic and Planting Distance Insights

Kristamtini[1], Sugeng Widodo[2], Heni Purwaningsih[3], Arlyna Budi Pustika[1], Setyorini Widyayanti[1], Arif Muazam[1], Arini Putri Hanifa[1,*], Joko Triastono[2], Dewi Sahara[2], Heni Sulistyawati Purwaning Rahayu[2], Pandu Laksono[2], Diah Arina Fahmi[2], Sutardi[1], Joko Pramono[4] and Rachmiwati Yusuf[1]

[1]Research Center for Food Crops, National Research and Innovation Agency, Jl. Raya Bogor-Jakarta, Cibinong Bogor, 16911, Indonesia

[2]Research Center for Behavioral and Circular Economics, National Research and Innovation Agency, Jl. Jend. Gatot Subroto No. 10, Jakarta, 12710, Indonesia

[3]Research Center for Food Technology and Processing, National Research and Innovation Agency, Jl. Jogja-Wonosari Km 31.5 Gading, Playen, Gunungkidul, Yogyakarta, 5586, Indonesia

[4]Research Center for Horticultural and Estate Crops, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor, Cibinong, Kabupaten Bogor, 16915, Indonesia

[*]Corresponding Author: Arini Putri Hanifa. Email: arin010@brin.go.id

Received: 18 December 2023 Accepted: 08 April 2024 Published: 28 May 2024

ABSTRACT

Sorghum (*Sorghum bicolor* L. Moench) is an essential food crop for more than 750 million people in tropical and sub-tropical dry climates of Africa, India, and Latin America. The domestic sorghum market in Indonesia is still limited to the eastern region (East Nusa Tenggara, West Nusa Tenggara, Java, and South Sulawesi). Therefore, it is crucial to carry out sorghum research on drylands. This research aimed to investigate the effect of sorghum genotype and planting distance and their interaction toward growth and sorghum's productivity in the Gunungkidul dryland, Yogyakarta, Indonesia. In addition, the farm business analysis, including the feasibility of sorghum farming, was also examined. The research used a randomized complete block design (RCBD), arranged in a 5 × 4 factorial with 3 replicates. The first treatment consisted of 5 varieties (2 high-yielding varieties (Bioguma 1 and Kawali) and 3 local sorghum varieties (Plonco, Ketan Merah, and Hitam Wareng)). The second treatment consisted of 4 levels of planting distance, namely 50 × 20 cm, 60 × 20 cm, 70 × 15 cm, and 70 × 20 × 20 cm. Analysis of variance was used to analyze the data, where Duncan's multiple range test (DMRT) was used *post hoc*. Plant height, panicle height, panicle width, panicle weight, stover weight, grains weight/plot, and productivity were significantly affected by sorghum varieties ($p < 0.05$). However, there was no significant effect from the planting distance treatment and no interaction between planting distance and varietal treatments. Ketan Merah had the highest height, panicle length, and panicle width, while Bioguma 1 had the highest stover weight, panicle weight, grain weight/plot, and productivity. There was a significant linear regression equation, i.e., productivity = 0.0054–0.0003 panicle height + 0.4163 grains weight/plot. Our findings on farm business analysis suggested that four out of five tested sorghum varieties were feasible to grow, except for the Ketan Merah variety. The most economically profitable sorghum variety to grow in Gunungkidul dryland was Bioguma 1.

KEYWORDS

Sorghum; dryland agriculture; planting space; variety; local; Gunungkidul

1 Introduction

Sorghum (*Sorghum bicolor* L. Moench) is an essential food containing nutrition consumed in Africa, Asia, Australia, and Central America and is an animal feed [1,2]. In Africa, sorghum seeds are consumed as processed bread, porridge, drinks, popcorn, and chips [3]. In India, sorghum flour is made into chapati bread, a staple food for rural communities. In Indonesia, sorghum is the third major cereal crop after rice and corn. The use of sorghum as food has significantly decreased due to the affordable price of rice and rice sufficiency [4]. One of the strategies to improve global food security is by increasing dryland cereals' productivity [5]. Known to have tolerance to water scarcity [6] and decent yield [7], sorghum significantly contributes to food production in the dryland area of Indonesia [8].

The higher usage of sorghum as a food ingredient in high-income countries occurs due to its ability to reduce inflammation and cholesterol [9,10]. Sorghum seeds are rich in bioactive compounds, and the popularity of sorghum as breakfast cereals, drinks, and other products indicates the potential for higher future consumption in many countries, including the United States [11], Brazil [12], South Africa [13], and Kenya [14].

The data on the sorghum market in Indonesia is very limited, though sorghum holds much potential due to agroecosystem suitability. The domestic sorghum market in Indonesia is still restricted to the eastern region (East and West Nusa Tenggara, Java, and some in South Sulawesi). Under the global climate change conditions, sorghum will become a prominent crop commodity as a food and industrial crop [15,16]. Global climate change creates a more challenging situation for crop farming in drylands due to the risk of drought. Moreover, the rainfall is generally low and not well distributed. Sorghum, a crop that can withstand drought and thrive in low-quality land, is a crucial commodity offering an alternative food source and revenue for small-scale farmers. Additionally, it comes with marketing guarantees [17].

Row spacing and plant populations can significantly impact sorghum producers' net revenue [18]. Enhancing our comprehension of sorghum's response to different cultivation management methods will help reduce the gap in crop production and guarantee food security, particularly in arid and semi-arid areas [19].

Genotype selection is essential in ensuring the productivity of sorghum plants. The use of new high-yielding varieties of sorghum threatens the existence of local sorghum. Local sorghum as food and animal feed has been known for generations; its existence needs to be preserved, and its potential development needs to be explored. Some local sorghum varieties of Gunungkidul, Yogyakarta, Indonesia, such as Hitam Wareng, Ketan Merah, and Plonco, are still cultivated. Sorghum varieties with wide-ranging adaptability can consistently be productive across environments. Detailed knowledge about the performance of different cultivars in specific locations is crucial for enhancing sorghum productivity in various ecological contexts [19].

The productivity increase in dryland cropping can be attributed to advancements in breeding (variety), agronomic management (planting area), cropping system, and their interrelationships. Sorghum exhibits diverse responses across different environments because of the interaction between genetic features (such as maturity, tillering, and stay-green) and agronomic practices [20]. The stay-green (SG) trait in sorghum allows crop plants to continue to photosynthesize and have green leaves after anthesis for extended periods, particularly when subjected to heat stress and drought. As a result, SG plants yield more than non-SG plants since they take longer to fill their grains. It is necessary to comprehend how combining hybrid features and agronomic management techniques enhances crop output in diverse situations. To improve crop productivity in more favorable conditions, it is essential to increase the density of plants [20,21]. In addition, making the rows bigger, and lowering the number of plants per area may shift the water use from the growth phase to the reproductive stage. Nevertheless, this approach may result in a lower crop yield when there is plenty of rain [22,23].

The productivity (yield) of sorghum is greatly influenced by planting space and population. Plant density, or the distance between rows of plants, greatly affects sorghum grain yields. Field crops like maize yield better as plant density increases [24]. Producers can enhance sorghum yield by acquiring knowledge about the most effective spacing and understanding the impact of growing conditions and varieties. The ideal plant densities for grain sorghum vary across different regions. Prior studies have shown a positive correlation between plant populations and grain yield, meaning that as the number of plants increases, the amount of grain produced also increases [25–27]. The space between crop rows can also affect the crop yield [27–30]. Research on planting distance response against sorghum varieties has been conducted in China [19] and the Texas Coastal Bend Region [18]. In contrast, research on the interaction between sorghum genotype and planting distance in the dryland of Gunungkidul, Yogyakarta, Indonesia, has never been conducted.

This study aimed to determine: i) the response of sorghum genotype, planting distance, and their interaction on sorghum growth and productivity; and ii) the feasibility of sorghum farming in the dryland of Gunungkidul, Yogyakarta, Indonesia.

2 Methods

2.1 Research Sites and Dates

The study was conducted in the dryland of Gunungkidul, Yogyakarta, Indonesia, and at an altitude of 104 m a.s.l (−7°58′27″(N) and 110°34′7″(E)). The soil type in the study area was Vertisols or Grumosol type 2:1, montmorillonite mineral type. Sorghum planting was carried out on June 13, 2023, with harvest time on September 06, 2023. The total monthly rainfall from May–October 2023 was 169.5 mm (Figs. 1 and 2).

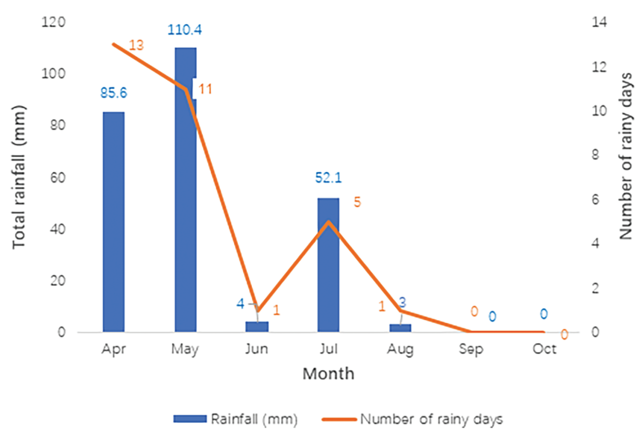

Figure 1: Monthly rainfall and number of rainy days during the study in 2023

2.2 Research Design

The study used a randomized complete block design with three replicates. The experiment was arranged in a factorial design. The first factor consisted of 5 varieties: 2 high-yielding varieties (Bioguma 1/V1 and Kawali/V2) and 3 local sorghums (Plonco/V3, Ketan Merah/V4, and Hitam Wareng/V5). The second factor consisted of 4 planting distances (PD), i.e., PD1 (50 × 20 cm), PD2 (60 × 20 cm), PD3 (70 × 15 cm), PD4 (70 × 20 × 20 cm/double row). The dose of fertilizer was 2,000 kg ha^{-1} of organic fertilizer, 326 kg ha^{-1} N, 33.3 kg ha^{-1} K_2O, and 49 kg ha^{-1} P_2O_5. The double-row planting distance of 70 × 20 × 20 cm is illustrated in Fig. 3.

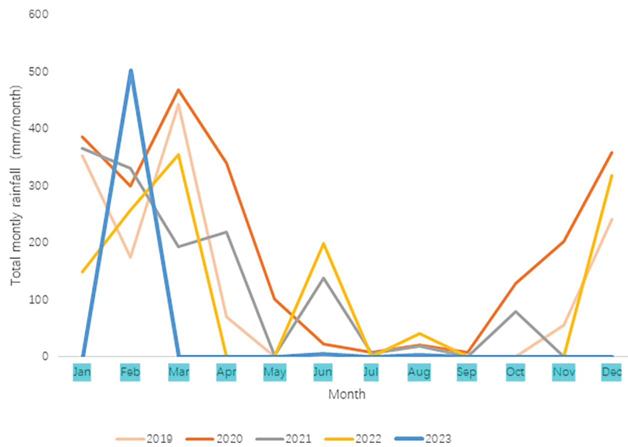

Figure 2: Total monthly rainfall from 2019 to 2023 at the study site

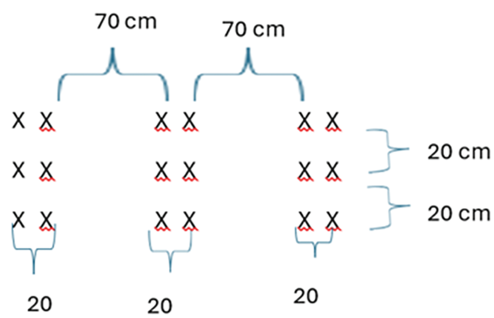

Figure 3: Schematic diagram of the experiment design: double row planting distance of 70 × 20 × 20 cm. X represents the plants

2.3 Data Collection

Plant height, panicle height, width panicle, stover weight, grain weight/plot, and productivity were collected from five plant samples per plot. The measurement of observed parameters was carried out as follows:

- Plant height (cm) was measured from the plant's above-ground part to the panicle tip of the main stem at harvest time. Plant height was calculated as an average of five random samples.
- Panicle length (cm) was measured from the panicle base to the panicle tip using five random sample plants. Observations were made at harvest time.
- Panicle width (cm) was measured from panicles in their natural position at their widest spot. The measurement was from five random sample plants. Observations were made at harvest time.
- Panicle weight (g) was measured by weighing the weight of panicles per plant taken from five random samples. Observations were made at harvest time.
- Stover weight (kg) was measured by weighing the remains of unharvested parts of the plant, such as leaves, stems, and roots, taken from five random samples per plot. Observations were made at harvest time.
- Sorghum grain weight/plot (kg) was measured by weighing the weight of grains per plot during harvest time.
- Productivity (ton ha^{-1}) was calculated by converting the grain weight/plot to area units per hectare. Observations were made at harvest time.

Production costs, revenue, and income were collected for the sorghum farm business analysis.

2.4 Data Analysis

2.4.1 The Effect of Variety and Planting Distance on Sorghum Growth, Productivity and their Interaction

PROC GLM with SAS (SAS Institute, Inc., Cary, NC, USA) and a model statement suitable for a factorial design were used to analyze the collected data. Means of the collected data were analyzed using analysis of variance, followed by Duncan's multiple range test (DMRT) as *post hoc* analysis, where $p < 0.05$ was considered statistically significant.

2.4.2 Correlation and Regression

Correlation analysis was carried out to determine the relationship between the observed parameters. Regression analysis was done to estimate and assess the strength of the relationship between the dependent variable and one or more independent variables. Correlation and regression analysis were undertaken if the assumptions of homogeneity of variety and normality of error were fulfilled.

2.4.3 Sorghum Farm Business Analysis

Farming business analysis was performed in this research by calculating the production costs, revenue, and income. Total cost is the sum of all fixed and variable (non-fixed) costs incurred during production. The production cost of the farming business was calculated using the following formula [31]:

$$\mathbf{TC} = \mathbf{FC} + \mathbf{VC}$$

where TC, FC, and VC were total cost (USD), fixed cost (USD), and variable cost (USD), respectively.

Gross income or total revenue was defined as all earnings from the farming business during a period calculated from the sale proceeds or restatement measured in USD. Gross income or total revenue was calculated using the following formula:

$$\mathbf{TR} = \mathbf{Y}.\,\mathbf{Py}$$

where TR, Y, and Py were total revenue (USD), total production (kg), and price (USD/kg), respectively.

Business income was considered as the total revenue earned from a business minus all expenses incurred during a period.

$$\boldsymbol{\pi} = \mathbf{TR} - \mathbf{TC}$$

where $\boldsymbol{\pi}$ and TC were net income (USD) and total cost (USD), respectively.

The feasibility of sorghum cultivation was determined using R/C ratio analysis. This ratio was obtained from the following formula [32]:

$$\mathrm{R/C\ Ratio} = \mathrm{Total\ Cost} / \mathrm{Total\ Income}$$

If R/C > 1, the farming business was considered financially profitable. Meanwhile, if R/C = 1, the farming business was considered at the break-event poin. In contrast, if R/C < 1, the farming business was considered financially not profitable.

3 Result

3.1 The Effect of Variety and Planting Distance on Sorghum Growth, Productivity and Their Interaction

The effect of varietal treatment (V) on sorghum was significant for all parameters ($p < 0.05$). However, there was no significant difference in each treatment of planting distance (PD) and the interaction between sorghum varieties and planting distance (Table 1).

Table 1: The effect of varieties (V) and planting distance (PD) treatments on the observed parameters

Parameter	Source of variance			
	Variety (V)		Planting distance (PD)	VxPD
df	**4**		**3**	**12**
Plant height (cm)	F value	30.98	0.49	0.62
	p-value	0.0001*	0.6912	0.8121
Panicle length (cm)	F value	34.43	0.37	0.81
	p-value	0.0001*	0.7756	0.6401
Panicle width (cm)	F value	9.84	0.91	0.24
	p-value	0.0001*	0.4471	0.7968
Stover weight (kg)	F value	13.81	1.46	1.20
	p-value	0.0001*	0.2413	0.3215
Panicle weight (g)	F value	11.77	0.62	0.55
	p-value	0.0001*	0.6044	0.8695
Grain weight/plot (kg $plot^{-1}$)	F value	8.37	0.98	0.61
	p-value	0.0001*	0.4146	0.8231
Productivity (ton ha^{-1})	F value	8.39	0.97	0.61
	p-value	0.0001*	0.4147	0.8242

Note: * Significant at $p < 0.05$.

Fig. 4 shows that the highest plant height, panicle length, and panicle width are found in the Ketan Merah variety. It is a local sorghum of the study site (Gunungkidul) with a tall stature; the panicle shape is curved and has no compact panicles (Fig. 5). Unlike Ketan Merah, Bioguma 1 had a compact panicle. It was suggested that the compact panicle and ideal harvest index (the ratio of harvested grain weight per total of stover and grain) contributed to the high mean values of stover weight, panicle weight, grain weight/plot, and productivity (Fig. 4).

3.2 Correlation and Regression

The correlation was analyzed to determine the relationship between the observed parameters. Regression analysis was aimed to estimate and assess the strength of the relationship between the dependent variable and one or more independent variables. Correlation analysis was carried out since the assumption of homogeneity of variety and normality of error were fulfilled (Fig. 6).

The *p*-value of the regression model was less than 0.01, showing significance on the observed parameters, which indicates that the model was fit (appropriate). This result aligns with the *t*-test for panicle height and weight grains/plot parameters ($p < 0.01$). Thus, the obtained regression equation was as follows:

$$\text{Productivity} = 0.0054 - 0.0003 \text{ panicle height} + 0.4163 \text{ grains weight/plot}$$

Adj R-Sq (corrected R^2) of 1.00 indicates that 100% of the variability of productivity can be explained by panicle height (negative) and grains weight/plot through linear relationships. A scatter plot diagram between productivity and grains weight/plot is presented in Fig. 7.

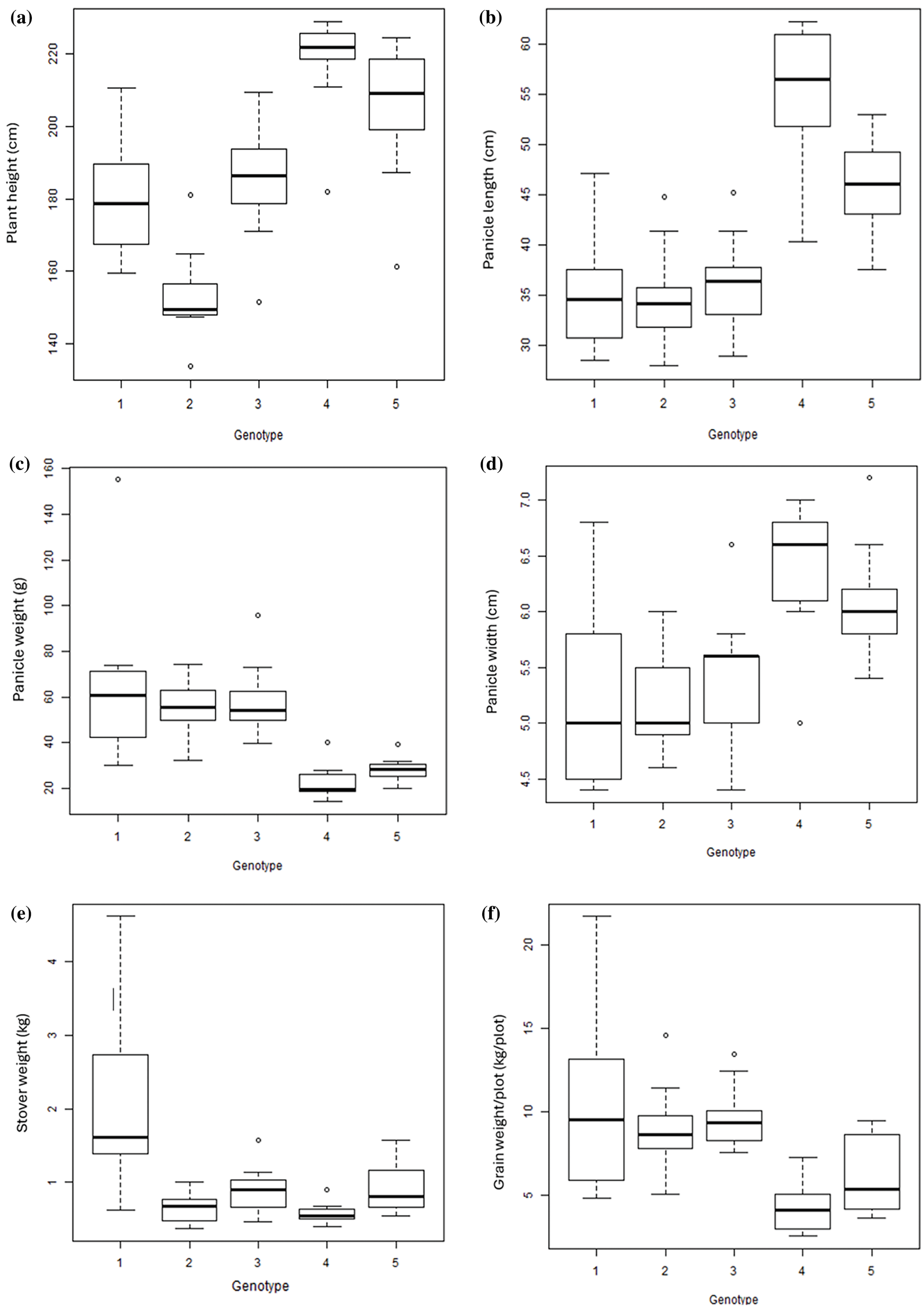

Figure 4: (Continued)

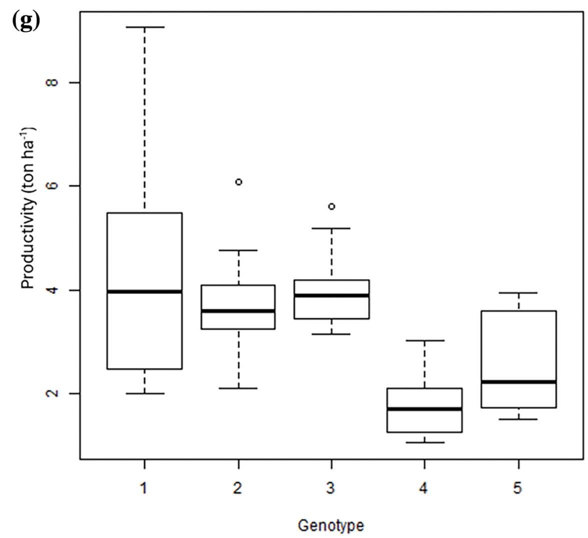

Figure 4: Box plots of data distribution among five sorghum varieties (1: Bioguma 1; 2: Kawali; 3: Plonco; 4: Ketan Merah; 5: Hitam Wareng). Plant height (a), Panicle length (b), Panicle width (c), Panicle weight (d), Stover weight (e), Grains weight (f), and Productivity (g) are the observed parameters

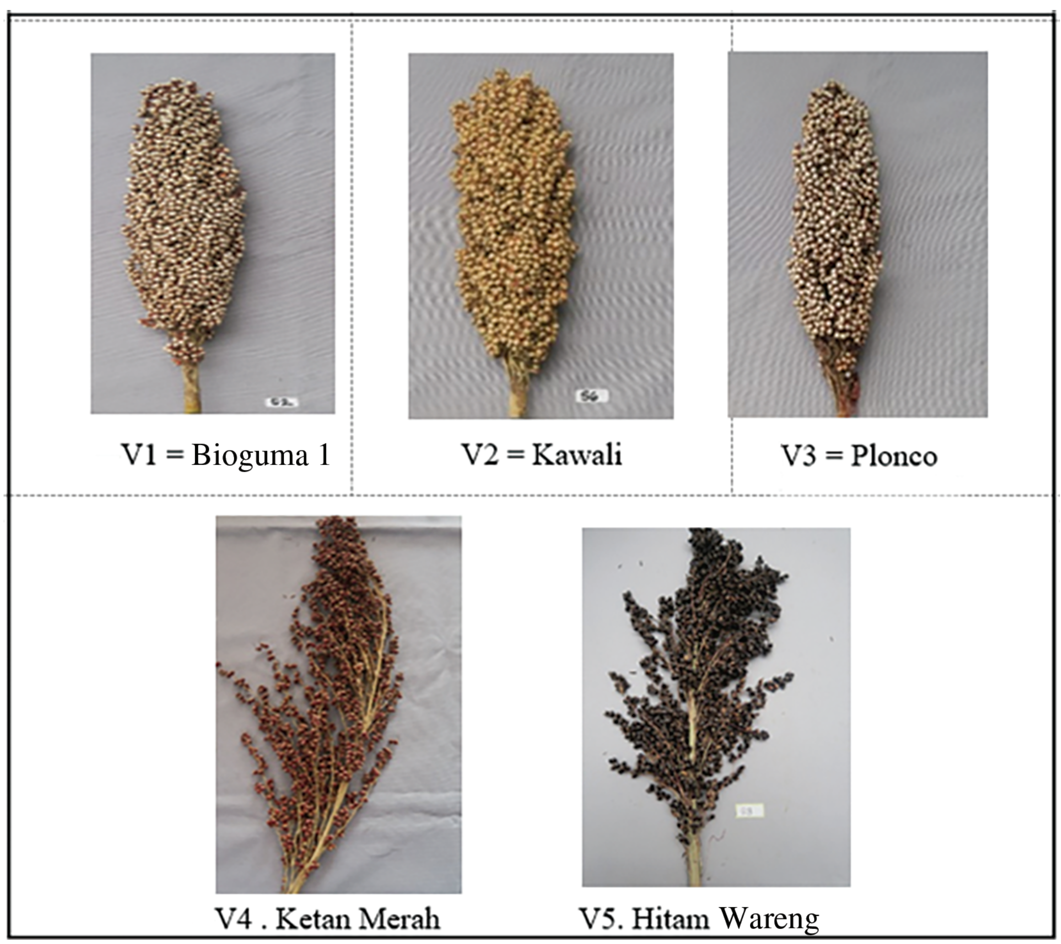

Figure 5: Panicle shape of five sorghum varieties

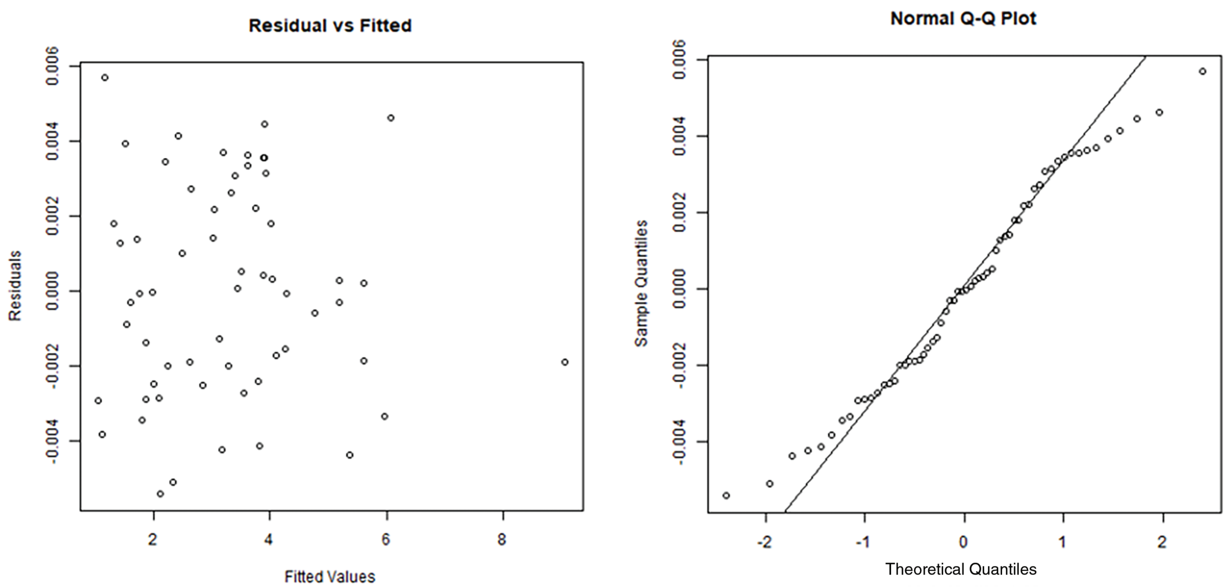

Figure 6: Assumption of homogeneity of variety and normality of error

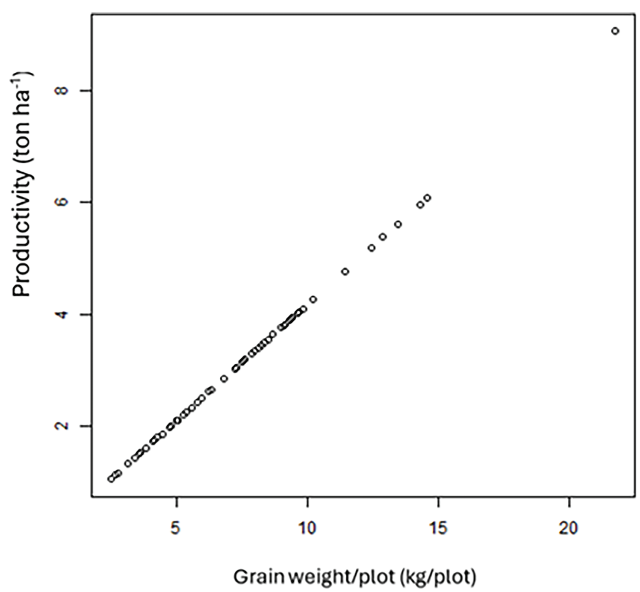

Figure 7: A significant and positive correlation between productivity and grain weight

3.3 Sorghum Farming Business Analysis

The results of the sorghum farming analysis showed that the superior variety Bioguma was the best variety for cultivation in the dryland of Gunungkidul (Table 2). Though the price of Bioguma seed was significantly higher than the other varieties, its production volume and selling price were the highest. The highest R/C ratio was achieved by Bioguma (2.56), followed by Plonco, Kawali, and Hitam Wareng. This finding is quite interesting since Plonco, a local variety, can outperform Kawali, a superior variety. However, planting Ketan Merah was not feasible due to the low R/C ratio (<1).

Table 2: Farming analysis of sorghum in dryland at Gunungkidul, Yogyakarta, in 2023

Item	Sorghum variety				
	Bioguma (USD)	Kawali (USD)	Plonco (USD)	Ketan Merah (USD)	Hitam Wareng (USD)
Seed (10 kg ha^{-1})	31.53	11.35	11.35	11.35	11.35
Fertilizer					
*Urea (125 kg ha^{-1} = 326 kg ha^{-1} N)	31.53	31.53	31.53	31.53	31.53
*Phonska (150 kg ha^{-1} = 49 kg ha^{-1} P_2O_5)	47.30	47.30	47.30	47.30	47.30
*KCl 20 (kg ha^{-1} = 33.3 kg ha^{-1} K_2O)	21.95	21.95	21.95	21.95	21.95
Pesticide (6 bottles)	22.7	22.7	22.7	22.7	22.7
Labor cost (soil tillage-harvest)	504.51	504.51	504.51	504.51	504.51
Watering cost	25.23	25.23	25.23	25.23	25.23
Seed processing cost	50.45	50.45	50.45	50.45	50.45
The total cost of production	**735.2**	**735.2**	**735.2**	**735.2**	**735.2**
Production (kg)	4,270	3,710	3,980	1,780	2,540
Price USD kg^{-1}	0.44	0.38	0.38	0.38	0.38
Revenue	**1,884.97**	**1,403.8**	**1,505.96**	**673.52**	**961.09**
Net income	**1,149.78**	**688.78**	**790.94**	**41.50**	**246.03**
R/C	**2.56**	**1.96**	**2.11**	**0.94**	**1.34**

Note: Exchange rate 1 USD = IDR 15,857.

4 Discussion

The only treatment that significantly affects the result of this study is sorghum varieties, which are likely related to their attributes in response to the dryland condition. Local varieties are known to be adaptive in site specifics. However, the common constraint of the local variety is the low yield attribute. The low yield can result from the inefficient photosynthate partition or low harvest index.

Our finding demonstrated that the Ketan Merah had the highest values of plant height, panicle length, and panicle width. Though it had the highest width of panicle size, the grain weight and productivity were low.

Early maturation, resistance to pests and diseases, and high production are the most important considerations in cultivating a variety. The results of this study showed that the highest yield was found in Bioguma 1 (V1), as evidenced by the panicle weight, stover weight, grains weight/plot, and productivity. However, the productivity of Bioguma 1 is still far from its official varietal description (7-ton ha^{-1} under optimal conditions). In contrast to the ideal growth condition, this study was conducted on dryland with low rainfall. The cultivation of sorghum is predominantly found in arid locations that require short-lived cultivars to thrive in a restricted water supply. Sorghum's ability to thrive on infertile terrain and its capacity to provide a substantial harvest made it a fundamental food source for African and Asian residents in subtropical and semi-arid areas [33].

In addition to the short lifespan, the basis for selecting sorghum varieties is their suitability for high-density planting. Cultivating sorghum plants with short planting distances (high density) is one of the efforts to increase crop yield. When Missouri's number of plants per hectare went from 73,600 to

147,300, the sorghum yield went up from 6.3 to 7.3 kg ha^{-1}. Similarly, increasing the number of sorghum plants from 24,000 to 96,000 plants ha^{-1} in some places in Kansas led to a 14% rise in yield. However, no increase in crop output was observed in other cases [34].

This study demonstrated that planting distance treatment had no significant effect on all parameters. The insignificant effect of planting distance is likely due to water scarcity during plant growth. The amount of rainfall during the study was 169.5 mm, with 18 rainy days (Fig. 1). Moreover, El Nino's impact during 2023 significantly reduced the annual monthly rainfall, as seen in Fig. 2.

Sorghum cultivation in South Africa occurs across various soil types. It is subject to varying levels of rainfall, ranging from roughly 400 mm in the arid western regions to about 800 mm in the more humid eastern areas [35]. In line with the study's results, an increased plant density did not provide higher sorghum grain production, particularly when irrigation was limited [36]. The ideal planting density for maximizing grain output varies and is influenced mainly by soil moisture levels and the maturity of the crop variety [37,38]. Varieties with a high planting density tolerance often respond more to densification. However, the growth circumstances can also influence the response [39]. Reducing row spacing or using a wide-narrow row pattern in field-grown cereal crops, like maize, can improve solar absorption, resulting in increased accumulation of dry matter and higher grain yield [40,41]. Compared to wide row spacing, narrow row spacing reached a 3%–14% sorghum yield increase [42]. However, other studies suggested that when compared with equal-row planting, the wide-narrow row pattern was ineffective in increasing sorghum yield [23,43]. Proximity between plants leads to inhibited growth and decreased production, a prevalent occurrence in maize cultivation [44,45]. According to [19], planting in the late-maturing zones during spring revealed that using the wide-narrow row pattern decreased sorghum production across different planting densities. This drop in yield could be attributed to the insufficient precipitation accumulation during the initial growth stage of sorghum. Prolonged exposure to sunlight can lead to soil dehydration [46], resulting in early drought and decreased sorghum yield [47]. The research results of [48] showed that sorghum planting distance affected the dry matter production; a shorter planting distance (25 × 25 cm) gave a higher yield compared to a wider planting distance (25 × 40 cm). Dense planting distances enable the utilization of sunlight, water, and nutrients and support plant growth and development, resulting in increased yield [49,50]. Many factors affect how much dry matter sorghum trees make, but the main ones are genetic and environmental factors [51].

According to farm business analysis, sorghum production costs were obtained by summing the total expenses incurred during the production process, namely fixed and variable costs. The variable costs in this study consisted of seeds, fertilizers, pesticides, and labor, while the fixed costs in this study were not considered. This approach is consistent with a study by [52], which reported that fixed costs are negligible in small-farmer subsistence farming ventures. The results showed that the production costs of Kawali, Plonco, Ketan Merah, and Hitam Wareng were equal. Meanwhile, Bioguma had the highest production cost compared to others.

Revenue from the sorghum farm business was obtained by multiplying the production by the sale price. The production of all five sorghum varieties showed that Bioguma had the highest yield compared to the other four varieties. Production in this study was calculated from the weight of sorghum seeds produced. The sale price of four varieties was the same, which was USD 0.38, while Bioguma's price was USD 0.44. Hence, Bioguma obtained the highest revenue.

The net income of sorghum cultivation was obtained from the total receipts minus the expenses incurred. The calculation results showed that the Bioguma variety produced the highest income (USD 1,149.78), followed by Kawali, Plonco, Hitam Wareng, and Ketan Merah. As indicated by the Ketan Merah farm business analysis, the loss suggested that the income was not worth the cost of expenditure. This is due to the low sales price of Ketan Merah compared to other varieties.

The R/C ratio indicates the feasibility of sorghum farming by comparing the total cost of production with the revenue. The ideal R/C ratio is more than 1. The results showed the feasibility of planting four varieties: Bioguma 1, Kawali, Plonco, and Hitam Wareng. In contrast, Ketan Merah was considered to be unviable because the R/C value was less than 1.

5 Conclusion

The effect of varietal sorghum treatment on all parameters was significant ($p < 0.05$), but the planting space treatment did not affect the parameters. Furthermore, no interaction between the two treatments was identified. The greatest values of plant height, panicle length, and panicle width were achieved by the Ketan Merah. Meanwhile, the highest stover weight, grain weight/plot, and productivity were acquired by Bioguma 1. The calculated linear regression equation was productivity = 0.0054–0.0003 panicle height + 0.4163 grain weight/plot. Our findings demonstrated the feasibility of sorghum farming by using Bioguma 1, Kawali, Plonco, and Hitam Wareng. On the other hand, we found that the Ketan Merah was not feasible for sorghum farming. Researchers are encouraged to conduct further studies under different ecological conditions to determine the yield stability of selected sorghum varieties.

Acknowledgement: This work was supported by the Indonesia Research and Innovation Agency and Gunung Kidul Agency for Regional Development. The authors also thank all participants of this study for their valuable input.

Funding Statement: This work was funded by the Indonesia Research and Innovation Agency and Gunung Kidul Agency for Regional Development.

Author Contributions: Conceptualization: Kristamtini, Sugeng Widodo, Heni Purwaningsih, Arlyna Budi Pustika, Setyorini Widyayanti, Arif Muazam, Arini Putri Hanifa, Joko Triastono, Dewi Sahara, Heni Sulistyawati Purwaning Rahayu, Pandu Laksono, Diah Arina Fahmi, Sutardi, Joko Pramono, Rachmiwati Yusuf; Methodology: Kristamtini, Sugeng Widodo, Heni Purwaningsih, Arlyna Budi Pustika, Setyorini Widyayanti, Arif Muazam, Arini Putri Hanifa, Joko Triastono, Dewi Sahara, Heni Sulistyawati Purwaning Rahayu, Pandu Laksono, Diah Arina Fahmi, Sutardi, Joko Pramono, Rachmiwati Yusuf; Software: Kristamtini, Sugeng Widodo, Heni Purwaningsih, Arlyna Budi Pustika, Setyorini Widyayanti, Arif Muazam, Arini Putri Hanifa, Joko Triastono, Dewi Sahara, Heni Sulistyawati Purwaning Rahayu, Pandu Laksono, Diah Arina Fahmi, Sutardi, Joko Pramono, Rachmiwati Yusuf; Validation: Kristamtini, Sugeng Widodo, Heni Purwaningsih, Arlyna Budi Pustika, Setyorini Widyayanti, Arif Muazam, Arini Putri Hanifa, Joko Triastono, Dewi Sahara, Heni Sulistyawati Purwaning Rahayu, Pandu Laksono, Diah Arina Fahmi, Sutardi, Joko Pramono, Rachmiwati Yusuf; Investigation: Kristamtini, Sugeng Widodo, Heni Purwaningsih, Arlyna Budi Pustika, Setyorini Widyayanti, Arif Muazam, Arini Putri Hanifa, Joko Triastono, Dewi Sahara, Heni Sulistyawati Purwaning Rahayu, Pandu Laksono, Diah Arina Fahmi, Sutardi, Joko Pramono, Rachmiwati Yusuf; Data curation: Kristamtini, Arlyna Budi Pustika, Setyorini Widyayanti, Arif Muazam; Writing—original draft preparation: Kristamtini, Sugeng Widodo; Writing—review and editing: Kristamtini, Sugeng Widodo, Heni Purwaningsih, Arlyna Budi Pustika, Setyorini Widyayanti, Arif Muazam, Arini Putri Hanifa, Joko Triastono, Dewi Sahara, Heni Sulistyawati Purwaning Rahayu, Pandu Laksono, Diah Arina Fahmi, Sutardi, Joko Pramono, Rachmiwati Yusuf; Visualization: Kristamtini, Sugeng Widodo, Heni Purwaningsih, Arlyna Budi Pustika, Setyorini Widyayanti, Arif Muazam, Arini Putri Hanifa, Joko Triastono, Dewi Sahara, Heni Sulistyawati Purwaning Rahayu, Pandu Laksono, Diah Arina Fahmi, Sutardi, Joko Pramono, Rachmiwati Yusuf; Supervision: Kristamtini, Sugeng Widodo, Heni Purwaningsih, Arini Putri Hanifa, Joko Triastono, Dewi Sahara, Heni Sulistyawati Purwaning Rahayu, Pandu Laksono, Diah Arina Fahmi, Sutardi, Joko Pramono, Rachmiwati Yusuf.

Availability of Data and Materials: Data are available based on request to the corresponding author.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

References

1. Mejia D, Lewis B. Sorghum: Post-harvest operations. Natural Resources Institute (NRI), Food Security Department; 1999. Available from: https://www.cd3wdproject.org/INPHO/COMPEND/TEXT/CH07.HTM. [Accessed 2024].
2. Ramatoulaye F, Mady C, Fallou S. Production and use sorghum: a literature review. J Nutr Health Food Sci. 2016;4:1–4.
3. Dicko MH, Gruppen H, Traore AS, van Berkel WJH, Voragen AG. Evaluation of the effect of germination on phenolic compounds and antioxidant activities in sorghum varieties. J Agric Food Chem. 2005;53(7):2581–8. doi:10.1021/jf0501847.
4. Suarni, Firmansyah IU. Structure, nutrient composition, and processing technology of sorghum. In: Sumarno, Damardjati Dj S, Syam M, Hermanto, editors. Sorghum: Technological innovation and development. Jakarta: IAARD Press; 2013. p. 260–79 (In Bahasa Indonesia).
5. Stewart BA, Lal R. Increasing world average yields of cereal crops: it's all about water. In: Sparks DI, editor. Advances in agronomy. Cambridge: Academic Press; 2018. vol. 151, p. 1–44. doi:10.1016/bs.agron.2018.05.001.
6. Blum A. Sorghum physiology. In: Nguyen HT, Blum A, editors. Physiology and biotechnology integration for plant breeding. Boca Raton, FL: CRC Press; 2004.
7. Potgieter AB, Lobell DB, Hammer GL, Jordan DR, Davis P, Brider J. Yield trends under varying environmental conditions for sorghum and wheat across Australia. Agric For Meteorol. 2016;228:276–85. doi:10.1016/j.agrformet.2016.07.004.
8. Clarke SJ, McLean J, George-Jaeggli B, McLean C, de Voil P, Eyre JX, et al. Understanding the diversity in yield potential and stability among commercial sorghum hybrids can inform crop designs. Field Crops Res. 2019;230:84–97. doi:10.1016/j.fcr.2018.10.010.
9. Althwab S, Carr TP, Weller CL, Dweikat IM, Schlegel V. Advances in grain sorghum and its co-products as a human health-promoting dietary system. Food Res Int. 2015;77(1):349–59. doi:10.1016/j.foodres.2015.08.011.
10. Vanamala JKP, Massey AR, Pinnamaneni SR, Redivari L, Reardon KF. Grain and sweet sorghum (*Sorghum bicolor* L. Moench) is a novel source of bioactive compounds for human health. Crit Rev Food Sci Nutr. 2018;58:2867–81. doi:10.1080/10408398.2017.1344186.
11. Poquette NM, Gu X, Lee SO. Grain sorghum muffin reduces glucose and insulin responses in men. Food Funct. 2014;5:894–9. doi:10.1039/C3FO60432B.
12. Anunciação PC, Cardoso LM, Gomes JVP, Della Lucia CM, Carvalho CWP, Galdeano MC, et al. Comparing sorghum and wheat whole grain breakfast cereals: sensorial acceptance and bioactive compound content. Food Chem. 2017;221:984–9. doi:10.1016/j.foodchem.2016.11.065.
13. Adeyanju AA, Kruger J, Taylor JR, Duodu KG. Effects of different souring methods on the protein quality and iron and zinc bioaccessibilities of nonalcoholic beverages from sorghum and amaranth. Int J Food Sci Tech. 2019;54:798–809. doi:10.1111/ijfs.2019.54.issue-3.
14. de Groote H, Mugalavai V, Ferruzzi M, Onkware A, Ayua E, Duodu KG, et al. Consumer acceptance and willingness to pay for instant cereal products with food-to-food fortification in Eldoret. Kenya Food Nutr Bull. 2020;41:224–43. doi:10.1177/0379572119876848.
15. Hariprasanna K, Rakshit S. Economic importance of sorghum. Sor Gen. 2017;78(3):1–25. doi:10.1007/978-3-319-47789-3_1.
16. Chapke RR, Tonapi VA. Adoption and Socio-economic benefits of improved post-rainy sorghum production technology. Agric Res. 2019;8:270–8. doi:10.1007/s40003-018-0359-x.

17. Ogeto RM, Cheruiyot E, Mshenga P, Onyari CN. Sorghum production for food security: a socioeconomic analysis of sorghum production in Nakuru County. Kenya Afr J Agric Res. 2013;8:6055–67.
18. Fernandez CJ, Fromme DD, Grichar WJ. Grain sorghum response to row spacing and plant populations in the Texas coastal bend region. Int J Agron. 2012;2012(3):1–6. doi:10.1155/2012/238634.
19. Yan P, Song YH, Zhang KY, Zhang F, Tang YJ, Zhao XN, et al. Interaction of genotype-ecological type-plant spacing configuration in sorghum [*Sorghum bicolor* (L.) Moench] in China. Front Plant Sci. 2023;13:1076854. doi:10.3389/fpls.2022.1076854.
20. Hammer GL, McLean G, Chapman S, Zheng B, Doherty A, Harrison MT, et al. Crop design for specific adaptation in variable dry land production environments. Crop Pasture Sci. 2014;65(7):614–26. doi:10.1071/CP14088.
21. Jordan D, Hunt C, Cruickshank A, Borrell A, Henzell R. The relationship between the stay-green trait and grain yield in elite sorghum hybrids grown in a range of environments. Crop Sci. 2012;52(3):1153–61. doi:10.2135/cropsci2011.06.0326.
22. Steiner J. Dryland grain sorghum water use, light interception, and growth responses to planting geometry. Agron J. 1986;78(4):720–6. doi:10.2134/agronj1986.00021962007800040032x.
23. Steiner J. Radiation balance of dryland grain sorghum as affected by planting geometry. Agron J. 1987;79(2): 259–65. doi:10.2134/agronj1987.00021962007900020017x.
24. Liu GZ, Liu WM, Hou P, Ming B, Yang YS, Guo XX, et al. Reducing maize yield gap by matching plant density and solar radiation. J Integr Agric. 2021;20(2):363–70. doi:10.1016/S2095-3119(20)63363-9.
25. Jones OR, Johnson GL. Row width and plant density effects on Texas High Plains sorghum. J Prod Agri. 1991;4:613–21. doi:10.2134/jpa1991.0613.
26. Conley SP, Stevens WG, Dunn DD. Grain sorghum response to row spacing, plant density, and planter skips. Crop Manag. 2005;4(1):1–8. doi:10.1094/CM-2005-0718-01-RS.
27. Staggenborg SA. Grain sorghum response to row spacings and seeding rates in Kansas. J Prod Agri. 1999;12: 390–5. doi:10.2134/jpa1999.0390.
28. Besler BA, Grichar WJ, Senseman SA, Lemon RG, Baughman TA. Effects of row pattern configurations and reduced (1/2x) and full rates (1x) of imazapic and diclosulam for control of yellow nutsedge (*Cyperus esculentus*) in peanut. Weed Technol. 2008;22:558–62. doi:10.1614/WT-08-030.1.
29. Limon-Ortega A, Mason SC, Martin AR. Production practices improve grain sorghum and pearl millet competitiveness with weeds. Agron J. 1998;90:227–32. doi:10.2134/agronj1998.00021962009000020020x.
30. Bryant HH, Touchton JT, Moore DP. Narrow rows and early planting produce top grain sorghum yields. Highlights Agric Res Al., Ag Exp Sta. 1986;33:5.
31. Manono R, Ruauw E, Tarore MLG. Break even point (BEP) analysis of tomato farming business in Taraitak I village, Langowan district, Minahasa district. Agri–Sosio Ekonomi Unsrat. 2021;5:85–92.
32. Priatmojo B, Adnyana MO, Wardana IP, Sembiring H. Financial and technical feasibility of jajar legowo super planting pattern in sumatra rice production center. J Penelitian Pertanian Tan Pangan. 2019;3:9–15.
33. Hariprasanna K, Rakshit S. Economic importance of sorghum. In: Rakshit S, Wang YH, editors. The sorghum genome. Cham: Springer International Publishing; 2016. p. 1–25.
34. Pidaran K. Effect of planting geometry, hybrid maturity, and population density on yield and yield components in sorghum (Master Thesis). Kansas State University: USA; 2012.
35. Mashao J, Prinshloo T. Sorghum Production. Available from: https://www.arc.agric.za/arcgci/Fact%20Sheets%20Library/Sorghum%20Production.pdf. [Accessed 2023].
36. Berenguer MJ, Faci JM. Sorghum (*Sorghum bicolor* L. Moench) yield compensation processes under different plant densities and variable water supply. Eur J Agronomy. 2001;15(1):43–55. doi:10.1016/S1161-0301(01)00095-8.
37. Abunyewa AA, Ferguson RB, Wortmann CS, Lyon DJ, Mason SC, Klein RN. Skip-row and plant population effects on sorghum grain yield. Agron J. 2010;102(1):296–302. doi:10.2134/agronj2009.0040.

38. Adam M, Mac Carthy DS, Traore P, Nenkam A, Freduah B, Ly M, et al. Which is more important to sorghum production systems in the sudano-sahelian zone of West Africa: climate change or improved management practices? Agric Syst. 2020;185:10292020. doi:10.1016/j.agsy.2020.102920.
39. Baumhardt RL, Howell TA. Seeding practices, cultivar maturity, and irrigation effects on simulated grain sorghum yield. Agron J. 2006;98(3):462–70. doi:10.2134/agronj2005.0156.
40. Bernhard BJ, Below FE. Plant population and row spacing effects on corn: phenotypic traits of positive yield-responsive hybrids. Agron J. 2020;112(4):1589–600. doi:10.1002/agj2.20206.
41. Bernhard BJ, Below FE. Plant population and row spacing effects on corn: plant growth, phenology, and grain yield. Agron J. 2020;112(4):2456–65. doi:10.1002/agj2.20245.
42. Maiga A. Effects of planting practices and nitrogen management on grain sorghum production. Acta Zool Litu. 2012;15(4):361–9. doi:10.1080/13921657.2005.10512702.
43. Sanabria R, Stone JF. Weeks. Stomatal response to high evaporative demand in irrigated grain sorghum in narrow and wide row spacing. Agron J. 1995;87:1010–7. doi:10.2134/agronj1995.00021962008700050040x.
44. Sarlangue T, Andrade FH, Calvino PA, Purcell LC. Why do maize hybrids respond differently to variations in plant density? Agron J. 2007;99(4):984–91. doi:10.2134/agronj2006.0205.
45. Ruffo ML, Gentry LF, Henninger AS, Seebauer JR, Below FE. Evaluating management factor contributions to reduce corn yield gaps. Agron J. 2015;107(2):495–505. doi:10.2134/agronj14.0355.
46. Kugedera AT, Mandumbu R, Nyamadzawo G. Rainwater harvesting and *Leucaena leucocephala* biomass rates effects on soil moisture, water use efficiency and *Sorghum bicolor* [(L.) moench] productivity in a semiarid area in Zimbabwe. J Sci Food Agric. 2022;102(14):6443–53. doi:10.1002/jsfa.12011.
47. Yang XL, Wang GY, Chen YQ, Chen YQ, Pacenka S, Steenhuis TS, et al. Reduced groundwater use and increased grain production by optimized irrigation scheduling in winter wheat-summer maize double cropping system–a 16-year field study in North China plain. Field Crops Res. 2022;275:10836464. doi:10.1016/j.fcr.2021.108364.
48. Hajar, Abdullah L, Diapari. The effect of plant spacing on the growth of several hybrid sorghum varieties as a feed source. J Trop Livest Sci Technol. 2019;6:283–7.
49. Febriyono R, Eko YS, Suprapto A. Increased yield of land kale (*Ipomoea reptans* L.) through spacing treatment and number of plants per hole. J Trop Subtrop Agri Sci. 2017;2:22–7.
50. Solichatun, Anggarwula E, Mudyantini N. The effect of water availability on growth and saponin content of Talinum paniculatum Gaertn. Biofarm J Nat Prod Biochem. 2005;3:47–51. doi:10.13057/biofar/f030203.
51. Kurniawan W. The Potential of Numbu sorghum, Cty-33, and BMR as feed at several levels of manure in ultisol sedimentation soil (Master Thesis). IPB University: Bogor Indonesia; 2014 (In Bahasa Indonesia).
52. Abbeam GD, Bosiako JA, Ehiakpor DS, Mabe FN. Adoption of improved maize variety among farm households in the northern region of Ghana. Cogent Econom Finan. 2017;5:1–14.