Phyton-
International Journal of
Experimental Botany

Tech Science Press

DOI: 10.32604/phyton.2024.048339

ARTICLE

# Optimizing Sorghum Productivity Using Balanced Fertilizers on Dryland

**Samijan Samijan, Endah Nurwahyuni, Sri Minarsih*, Agus Supriyo, Sodiq Jauhari, Yulis Hindarwati, Meinarti Norma Setiapermas, Raden Heru Praptana, Endah Winarni and Vina Eka Aristya**

Research Center for Food Crops, Research Organization for Agriculture and Food, National Research and Innovation Agency (BRIN), Cibinong Science Center, Jl. Raya Jakarta-Bogor Km. 46, Bogor, 16911, Indonesia

*Corresponding Author: Sri Minarsih. Email: srim011@brin.go.id

Received: 05 December 2023 Accepted: 24 May 2024 Published: 30 July 2024

## ABSTRACT

Sorghum is the fifth most required cereal crop globally. *Sorghum bicolor* has the advantage of being adaptive to both lowland and dryland, with drought-tolerant and wide adaptability. The low nutrient availability in dryland requires additional effective fertilizers to increase sorghum productivity. The research aimed to assess the application of organic, inorganic, and biofertilizers for sorghum productivity on dryland. Research in Central Java, Indonesia as dryland sorghum areas, from November 2022 to February 2023. The experiment cooperates with the farmers in a split-plot design, the main plot was two varieties and subplots of four fertilizers. The enhanced sorghum yield (21.38%–36.06%) with combined fertilizer was greater than the existing fertilization. Nutrient control does not rely on inorganic fertilizers but also on applying biofertilizers. The sorghum farming economic value farming indicated that combinations of fertilizer treatments and varieties provide benefits of USD 929.81–1955.81 with a revenue-cost ratio (R/C) value >1. Sorghum is an essential food commodity that faces the threat of the global crisis and an unfavorable environment. This study indicated balanced fertilizers could provide sufficient nutrients to the soil and increase nutrient absorption availability for sorghum growth and productivity. Balanced fertilization increases the uptake of N, P, and K nutrients correlates with an increase in yield of 21.38%–36.06%.

## KEYWORDS

Biofertilizer; dryland adaptability; economic value; sorghum; potential yield

## 1 Introduction

Sorghum is an adaptable and versatile grain crop of significant importance in global agriculture. *Sorghum bicolor* remarkable resilience and ability to thrive under various environmental conditions have earned it a reputation as a crucial staple crop in numerous regions worldwide [1]. Sorghum is a widely cultivated cereal grain crop in the *Poaceae* family. It is known for its resilience and ability to adapt to diverse environmental conditions, making it a crucial staple crop in many world regions [2].

Sorghum is a plant with drought tolerance and is well-adapted to dryland conditions. Sorghum can grow in zones with limited water availability, infertile, and poor soil conditions. Sorghum is suitable for cultivation in marginal and semi-arid regions [3]. Sorghum efficiency in high water use produces a higher biomass than in other plants. Concerning soil fertility, sorghum is tolerant of limited nutrients, optimal for plant development and growth, and related to the morphology of sorghum roots that can reach nutrients [4].

Dryland is characterized by dry climatic conditions, high temperature and evaporation, low soil moisture, and limited water resources. A dryland is an area that experiences significant water shortages or does not have access to adequate water to support optimal plant growth. Drought can be caused by low rainfall, high evaporation, or a combination of both. In addition, dryland has a lower level of susceptibility to certain diseases and pests. The dryland disadvantages include lower plant productivity, a high risk of drought, and limitations in crops that can be grown on these lands [1].

Soil factors that affect the quality and productivity of dryland include limited groundwater which is one of the main limiting factors in dryland to support plant growth. Soil drought can limit plant access to water needed for photosynthesis and growth. The generally low soil organic matter content was caused by less-than-ideal soil structure, water-holding capacity, and soil fertility [5].

Soil erosion was also a common problem in dryland due to sparse vegetation, high rainfall, and vulnerable topographical conditions. Soil erosion can remove fertile soil layers and reduce the land's ability to hold water. Lack of certain nutrients, such as nitrogen, phosphorus, and potassium in dryland could cause nutrient deficiency and limit plant growth and production on the land [6].

Scarcity of soil moisture and decreased dryland fertility contribute to reduced crop productivity. Dryland tends to have a relatively good level of suitability for sorghum plants. Sorghum is a drought-tolerant plant with solid roots that can grow well in areas with limited water supply. This plant is also tolerant of high temperatures and has lower water requirements [7].

In dryland areas with specific soil properties, proper fertilization is crucial for achieving optimal growth and maximizing yields of sorghum crops. The soil properties characteristic of environments, including clay texture, slightly acidic pH, low organic nitrogen, phosphorus, potassium, carbon, exchangeable cations, and moderate cation exchange capacity, present challenges for nutrient availability and uptake by sorghum. To address these challenges and ensure successful sorghum cultivation, combining organic, inorganic, and biofertilizers can enhance soil fertility, improve nutrient uptake efficiency, and promote sustainable agricultural practices.

In the context of dryland agriculture, sorghum's unique traits shine particularly brightly. With its inherent drought tolerance and robust root system, sorghum can flourish even in areas with limited water resources. Furthermore, this crop demonstrates impressive heat resistance and relatively low water demands, making it an ideal candidate for cultivation in dry and arid regions [7].

The success of sorghum cultivation in dryland areas is intricately tied to the provision of proper fertilization. Addressing these challenges and ensuring the viability of sorghum cultivation demands a holistic approach involving the application of organic, inorganic, and biofertilizers. An integrated approach has a pivotal role in enhancing soil fertility, optimizing nutrient uptake efficiency, and fostering sustainable agricultural practices.

In the pursuit of balanced and sustainable fertilization practices, the use of inorganic fertilizers is targeted at rectifying nutrient imbalances and bolstering the ability of sorghum to absorb nutrients. Furthermore, the integration of biofertilizers, composed of beneficial microorganisms, such as Rhizobium and Azotobacter, can significantly reduce reliance on synthetic nitrogen fertilizers by facilitating the conversion of atmospheric nitrogen into forms usable by plants. Incorporating biofertilizers into the soil environment fosters beneficial microbial activity, enhancing sorghum plants' nutrient status and overall health [8].

Biofertilizers maintain soil ecosystems' long-term health and sustainability. By harnessing the power of nitrogen fixation, mobilization of macronutrients and micronutrients, and converting insoluble phosphorus into plant-accessible forms, biofertilizers contribute to enhanced plant growth and yield. Integration of biological and chemical fertilizers not only amplifies both the quantity and quality of crop yield but also offers a more environmentally responsible approach [9].

Proper fertilization practices are crucial in achieving optimal growth and maximizing sorghum yields in marginal dryland. The environments necessitate a comprehensive approach that includes the application of organic, inorganic, and biofertilizers. These fertilizers enhance soil fertility, improve nutrient availability, and promote sustainable agricultural practices [10].

Organic fertilizers from plant or animal sources offer numerous benefits for sorghum production in dryland areas. By incorporating organic fertilizers into the soil, the organic carbon content can be increased, leading to enhanced nutrient retention, water-holding capacity, and overall soil fertility. Organic fertilizers also foster the growth of beneficial microorganisms in the soil, contribute to nutrient cycling, and improve nutrient availability to sorghum. Inorganic fertilizers provide essential macronutrients and micronutrients in readily available forms.

The nutritional needs of plants that only come from inorganic fertilizers will worsen soil health, pollute the environment, and increase production costs. Using only organic fertilizers will challenge the nutritional plants' needs in large quantities [11]. In pursuing optimal agricultural production while upholding environmental integrity, the research aims to explore the synergistic effects of organic, inorganic, and biofertilizers on sorghum productivity in dryland conditions. By enhancing nutrient availability, fostering sustainable practices, and increasing sorghum yields, this research seeks to substantially contribute, to addressing food security and advancing agricultural sustainability.

Integrated fertilization using organic, inorganic fertilizers, and biofertilizers can produce plants optimally production without polluting the environment. Increasing sorghum productivity in dryland was expected to significantly contribute to meeting the community's food needs. The study aimed to assess the application of organic, inorganic, and biofertilizers for sorghum productivity on dryland.

## 2 Materials and Methods

### *2.1 Sites and Time Studies*

Research in Tegalsari, Kandeman, Batang, Central Java, Indonesia (Latitude −6.924822° and Longitude 109.753282°), at an altitude of 14.26 m above sea level. The study site availability of dryland potential for sorghum development which was quite extensive and the presence of existing farmers who developed sorghum plants. The program implemented in November 2022 to February 2023, cooperated with the farmers who were members of the sorghum production business group. This study was conducted in one season based on consistent climatic characteristics from the last 20 years with adjustments to existing cropping patterns.

### *2.2 Experimental Design and Procedures*

The study was a split-plot design. The first factor includes 2 varieties (Bioguma and Numbu) as the main plot and the second factor was 4 fertilizers applied (existing, balanced, 50% balanced, and biofertilizers) as subplots. Each treatment was repeated three times. Sorghum was planted in a 75 $m^2$ area for each treatment (Table 1). Sorghum was planted with 2 seeds per hole, with a spacing of 70 × 20, resulting in a population of about 950 plants per plot or 128,000 plants/ha.

Data collected were soil, climates, cropping patterns, nutrient uptake, sorghum performance, and yield components. The climatic data of the study site from POWER [12]. Soil properties were taken from composite soil in a 20 cm layer using a drill and hoe by systematic methods (diagonal and zig-zag random) from 10 individual sample points. Soil specimens were put together in a bucket, and then 0.5–1.0 kg was taken from the field. Soil samples were picked up before planting and in the generative phase (before harvest). Soil data comprise physical parameters (structure, texture) and chemicals (pH, C-organic, N-total, P total and available, K total and available, Cation Exchange Capacity Fe, Mn, Zn) in the AIAT Central Java laboratory.

**Table 1:** Combination of sorghum varieties and fertilization types

| Fertilization | Variety | |
|---|---|---|
| | Bioguma (A) | Numbu (B) |
| Existing (organic 1600 kg/ha + carbontilizer 300 kg/ha) (F0) | AF0 | BF0 |
| Balanced (organic 1600 kg/ha + NPK 300 kg/ha + urea 200 kg/ha) (F1) | AF1 | BF1 |
| 50% balanced (organic 1600 kg/ha + NPK 150 kg/ha + urea 100 kg/ha + carbontilizer 300 kg/ha) (F2) | AF2 | BF2 |
| Organic 1600 kg/ha + biofertilizer 4.1 kg/ha (F3) | AF3 | BF3 |

Note: NPK content of 15% N, 15% $P_2O_5$, 15% $K_2O$.

The nutrient organic fertilizer content was known by analysis of water content using the gravimetric method, pH using the electrometric method, C-organic using the Walkey & Black method, N-total using the Kjeldahl method, $P_2O_5$, and $K_2O$ analysis using $HNO_3$ and $HClO_4$ wet ashing [13]. NPK nutrient uptake analyzed from leaf samples was taken from the third leaf under the flag leaf for each plot treatment. The 12-leaf stover was grabbed in the primordia phase of the plant before flowering for analysis in the laboratory to know nutrient absorption [14].

Sorghum performance, i.e., plant growth (plant height, number of leaves, number of internodes, stem diameter, stover wet weight) and leaf samples for nutrient absorption purposes. Morphological observations according to the plant phases (at 22, 36, and 55 days after planting/DAP). Observation of sorghum yield components at harvest were panicles' wet weight, panicles' dry weight, and yield. The harvest was made by tiling when the panicles were ripe with the size of tiled plots (2.00 m × 1.80 m), the stems cleared, and the panicles dried to a 14% moisture content. The yield component was taken from 12 sample plants per treatment plot [15].

### *2.3 Data Analysis*

The collected data were tabulated and analyzed for a variance to examine significant differences between the main and sub-treatments and their interactions with observed sorghum growth and yield variables. Analyzed data for variance if there were significant differences between treatments followed by the Duncan Multiple Range Test (5%). The data were also analyzed in a comparative descriptive manner. Statistical analysis tools published by IRRI STAR [16] for data analysis.

### *2.4 Sorghum Farming Economic Value*

The economic value of sorghum farming on dryland was assessed through income, revenue-cost ratio (R/C), and break-even point (BEP) analysis. The input-output data includes the costs of production inputs quantity, the quantity, and production value. Income was calculated using a model [17]:

$$\text{Net Income} = \text{Gross Income} - \text{Total Cost} \tag{1}$$

R/C was calculated using a formula [18]:

$$R/C = \text{Gross Income}/\text{Total Cost} \tag{2}$$

The break-even point was that revenue equals the total cost of production inputs, or the value of benefits equals zero. There were two types of BEP for production (BEP-Y) and BEP for prices (BEP-P). Production

BEP was the minimum amount of output required to cover production costs, calculated using the equation model [19]:

$$BEP - Y = \text{Total Cost}/\text{Price of the Output} \quad (3)$$

$$BEP - P = \text{Total Cost}/\text{Total Production} \quad (4)$$

## 3 Results

### 3.1 Climate Facts

The climate facts in the study site from POWER [12] indicated monthly rainfall from November 2022 to February 2023 was 226.79 up to 752.84 mm. The monthly average was 524.03 mm, with the average number of rainy days being 16 days. The humidity at the harvest (February 2023) was 88.34%. Based on observations of climate data, the trend of climate conditions at the time of the study was consistent with the distribution of multi-year climate patterns (2000–2022) (Fig. 1).

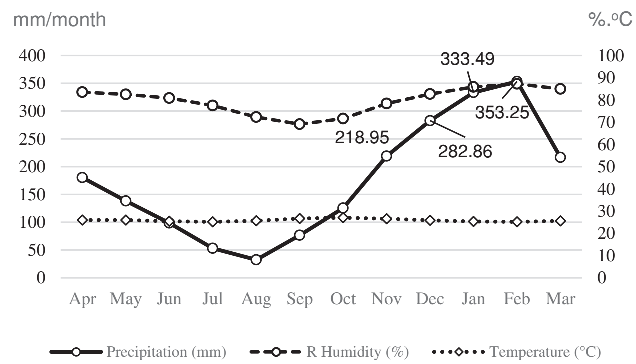


**Figure 1:** Multi-year climate data at the study site (2000–2022)

### 3.2 Soil Properties

The soil type in the study zone was Inceptisols (*Typic Dystrudepts*) with a clay texture and subangular blocky soil structure. The soil was composed of sand (4.53%), silt (13.98%), and clay (81.49%). Soil pH was classified as acid (<5.5), high potential P elements, low potential K, low CEC (<16), and cations (K, Na, Ca, and Mg) exchanged entirely at very low to low status (Table 2).

**Table 2:** Soil properties

| Element | Unit | Before treatment | Status | After treatment | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | AF0 | AF1 | AF2 | AF3 | BF0 | BF1 | BF2 | BF3 |
| Texture | | | | | | | | | | | |
| Sand | % | 4.53 | | | | | | | | | |
| Silt | % | 13.98 | | | | | | | | | |
| Clay | % | 81.49 | | | | | | | | | |
| pH $H_2O$ | – | 5.46 | Acid | 5.19 | 5.60 | 5.75 | 5.72 | 5.53 | 5.24 | 5.27 | 5.41 |
| C-organic | % | 0.98 | Very low | 0.78 | 0.87 | 0.60 | 0.77 | 0.92 | 1.18 | 1.41 | 0.99 |
| N-Kjeldahl | % | 0.15 | Low | 0.15 | 0.17 | 0.13 | 0.17 | 0.17 | 0.20 | 0.22 | 0.20 |

(Continued)

**Table 2 (continued)**

| Element | Unit | Before treatment | Status | After treatment | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | AF0 | AF1 | AF2 | AF3 | BF0 | BF1 | BF2 | BF3 |
| $P_2O_5$ Olsen | ppm | | Very low | | 7.95 | 4.02 | 1.62 | 2.02 | | | |
| $P_2O_5$ Bray | ppm | 4.23 | Very low | 0.76 | | | | | 2.89 | 3.64 | 2.81 |
| $P_2O_5$ HCl 25% | mg/100 g | 59.19 | High | | | | | | | | |
| $K_2O$ HCl 25% | mg/100 g | 7.32 | Low | | | | | | | | |
| Cation exchange capacity | cmol (+)/kg | 13.01 | Low | 13.28 | 13.29 | 11.89 | 13.05 | 13.97 | 13.75 | 14.76 | 13.02 |
| Exchangeable cation | | | | | | | | | | | |
| K | cmol (+)/kg | 0.19 | Very low | 0.14 | 0.13 | 0.12 | 0.20 | 0.21 | 0.19 | 0.21 | 0.18 |
| Na | cmol (+)/kg | 0.13 | Low | 0.05 | 0.03 | 0.05 | 0.05 | 0.03 | 0.05 | 0.05 | 0.05 |
| Ca | cmol (+)/kg | 4.77 | Low | 4.80 | 5.03 | 5.05 | 5.21 | 4.80 | 4.87 | 5.17 | 4.46 |
| Mg | cmol (+)/kg | 1.74 | Very low | 1.42 | 1.29 | 1.20 | 1.32 | 1.29 | 1.33 | 1.48 | 1.43 |

After fertilizer treatment, the highest pH in 50% balanced (AF2) soil was 5.75, an increase from the initial soil (5.46), although the pH was still relatively low (acid). Balanced fertilization application (BF1) has a pH lower (5.24) than the initial soil pH (5.46). Generally, the fertilizer added during one growing season does not significantly affect the soil pH from its initial status. Furthermore, the C-organic content, N-total, and CEC showed that different varieties give distinct responses from the initial soil. The 50% balanced (BF2) gave a higher value (1.41%, 0.22%, 14.76 cmol (+)/kg) than the initial soil treatment. Meanwhile, 50% balanced (AF2) has the lowest (0.60%, 0.13%, 11.89 cmol (+)/kg). Fertilizers can only be used to meet the needs of nutrient availability during one growing season and are not available as a soil enhancer to improve the physical and biological soil properties (Table 2).

### *3.3 Cropping Pattern*

The agricultural system in the study area was classified as less intensive. The cropping pattern on dryland in a year at the research zone only developed a few plants. Climatic conditions strongly influenced variations in cropping patterns. The dominant cropping pattern was maize or peanuts in rotation with peanuts or maize. Some farmers only grow cassava in monoculture. Sorghum farming in the study site was classified as less intensive. Sorghum was usually planted in October–November or the beginning of the rainy season and then rotated with ratoon sorghum or peanuts (Fig. 2).

### *3.4 Nutrients Uptake*

Nutrient uptake is a process by which plants absorb nutrients from the soil through the roots for growth, development, and production. The optimum value nutrient uptake of N (2.5%–4.5%), P (0.2%–0.5%), and K

(1.5%–3.5%) were still normal conditions in the range of nutrient adequacy limits. Organic plus 100% inorganic fertilizer (AF1 and BF1) indicated higher nutrient uptake compared to organic fertilizer plus 50% inorganic (AF2 and BF2). The treatments that only rely on organic fertilizers in one season tend to have the lowest NPK nutrient uptake. It was due to differences in the use of organic and inorganic fertilizers. The higher fertilizer showed the capacity supply of nutrient absorption available in the soil (Fig. 3).

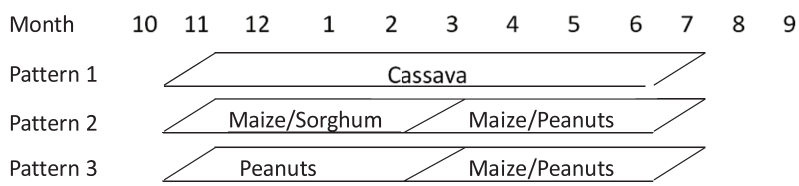


**Figure 2:** Cropping pattern

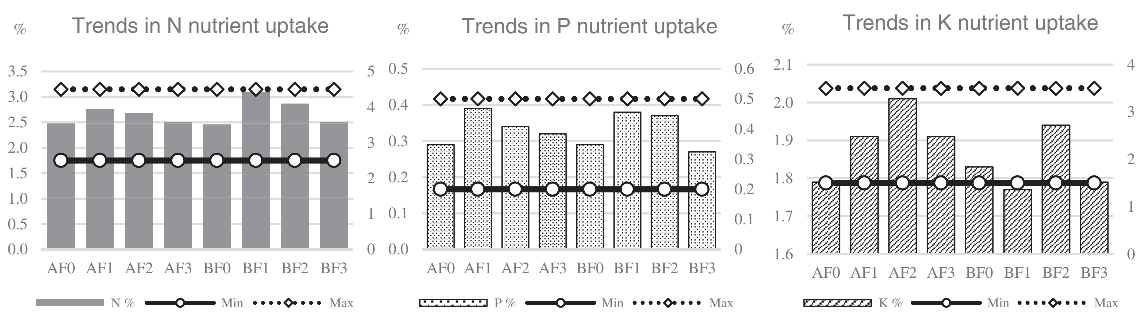


**Figure 3:** Sorghum nutrient uptake

### *3.5 Sorghum Performance*

The study results indicated no interaction between four fertilization and two sorghum varieties on growth parameters. Sorghum varieties did not significantly affect the measured sorghum growth ($p$-value > 0.05). Significant differences were seen in the variable plant height and number of leaves (36 and 50 DAP), number of internodes, and stem diameter due to the influence of fertilization. Fertilization showed a significant effect on stem diameter. Organic plus inorganic fertilizers of 300 kg NPK/ha and 200 kg urea/ha (F1) resulted in the largest stem diameter of 1.59 cm and the highest stover wet weight (474.61 g) compared to other treatments (Table 3).

**Table 3:** Sorghum vegetative performance

| Fertilization | Plant height (cm) | | Number of leaves | | Number of internodes | Stem diameter (cm) | Stover wet weight (g) |
|---|---|---|---|---|---|---|---|
| | 36 DAP | 50 DAP | 36 DAP | 50 DAP | | | |
| F0 | 100.99 b | 167.46 b | 5.76 b | 7.61 b | 10.76 b | 1.36 b | 376.56 b |
| F1 | 117.32 a | 211.29 a | 6.40 a | 8.85 a | 11.17 a | 1.59 a | 474.61 a |
| F2 | 114.24 a | 194.56 a | 5.85 b | 8.69 a | 11.36 a | 1.49 ab | 457.51 a |
| F3 | 101.81 b | 170.89 b | 5.64 b | 7.75 b | 11.03 ab | 1.47 ab | 449.04 a |
| StdDev | 10.45 | 23.80 | 0.53 | 0.75 | 0.41 | 0.13 | 63.07 |

(Continued)

**Table 3 (continued)**

| Fertilization | Plant height (cm) | | Number of leaves | | Number of internodes | Stem diameter (cm) | Stover wet weight (g) |
|---|---|---|---|---|---|---|---|
| | 36 DAP | 50 DAP | 36 DAP | 50 DAP | | | |
| Variety (V) | 0.73 | 0.89 | 0.32 | 0.79 | 0.61 | 0.50 | |
| Fertilization (F) | 0.01** | 0.00** | 0.02* | 0.00** | 0.01** | 0.02* | |
| V × F | 0.67 | 0.81 | 0.42 | 0.39 | 0.06 | 0.63 | |

Note: Significant differences between fertilization were indicated by different letters; * = significant (Alpha 0.05), ** = very significant (Alpha 0.01).

### *3.6 Sorghum Yield*

Balanced fertilization, with half fertilization, 100% dose, combining organic fertilizers and biofertilizers significantly increased the panicles' wet weight, panicles' dry weight, and yield. The increase in panicle wet weight and panicle dry weight in treatments (F1–F3) ranged between 24.00%–27.45% and 21.30%–36.00% of the existing fertilization (F0). The yield increase was 21.38%–36.06% (Table 4).

**Table 4:** Effect of fertilization on the yields component

| Fertilization | Panicles' wet weight (t/ha) | Panicles' dry weight (t/ha) | Yield (t/ha) |
|---|---|---|---|
| F0 | 9.98 b | 6.36 b | 4.77 b |
| F1 | 12.45 a | 8.65 a | 6.49 a |
| F2 | 12.37 a | 8.36 a | 6.27 a |
| F3 | 12.72 a | 7.72 a | 5.79 a |
| CV (%) | 12.98 | 10.98 | 10.98 |

Note: Significant differences (Alpha 0.05) were indicated by different letters.

Bioguma showed superiority compared to Numbu. Bioguma has panicles' wet weight and panicles' dry weight was 27.0% and 27.4% higher than the Numbu, respectively. The yield of Bioguma (6.53 t/ha) was 26.4% higher than Numbu (5.13 t/ha) (Table 5).

**Table 5:** Effect of varieties on the yield's component

| Variety | Panicles' wet weight (t/ha) | Panicles' dry weight (t/ha) | Yield (t/ha) |
|---|---|---|---|
| Numbu | 10.66 a | 6.84 b | 5.13 b |
| Bioguma | 13.11 b | 8.71a | 6.53a |

Note: Significant differences (Alpha 0.05) were indicated by different letters.

The applied fertilization packages from the application of organic 1600 kg/ha, NPK 300 kg/ha, and urea 200 kg/ha gave different responses between Numbu and Bioguma to soil nutrient status. The treatment of organic plus 100% inorganic fertilizer showed the highest results. The increase in sorghum yields sequentially to a lower level occurred in organic plus 50% inorganic, and then in the treatment of organic fertilizer plus biofertilizer. Optimal plant nutrient uptake conditions in line with fertilizer treatments affect sorghum productivity on relatively poor soil nutrients (Fig. 4).

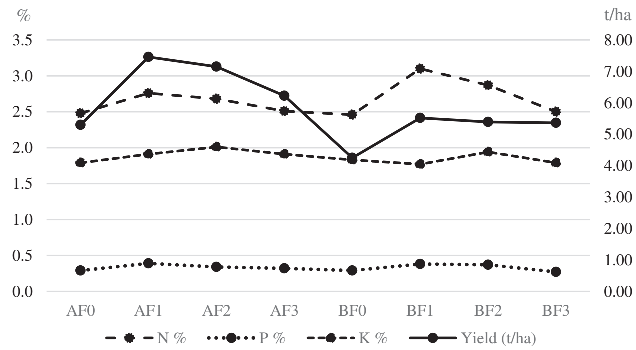


**Figure 4:** Trends in nutrient uptake and sorghum productivity

### *3.7 Sorghum Farming Economic Value*

Cost variables used to determine the sorghum farming profitability include seeds, fertilizers (inorganic, organic, carbontilizer, manure, and biofertilizers), pesticides (insecticides, fungicides, and herbicides), labor (production, harvesting, and processing), transportation (production process and transportation costs), and land taxes. The selling price used was the selling price of sorghum at harvest. The cost variable that differentiates between treatments is the fertilizer used. The results indicated that all combinations of fertilizer treatments and sorghum varieties provide benefits of between USD 930.61 and 1957.82 with an R/C value >1 (Table 6).

**Table 6:** The economic value of sorghum farming with four fertilizer combinations

| Treatment | Yield (kg/ha) | Price (USD/kg) | Cost (USD/ha) | Revenue (USD/ha) | Profit (USD/ha) | R/C | BEP-Y | BEP-P |
|---|---|---|---|---|---|---|---|---|
| AF0 | 5300 | 0.402 | 787.623 | 2131.790 | 1,344.17 | 2.70 | 1,958.17 | 0.149 |
| AF1 | 7460 | 0.402 | 1063.825 | 3000.595 | 1,936.77 | 2.82 | 2,644.85 | 0.143 |
| AF2 | 7150 | 0.402 | 1067.948 | 2875.906 | 1,807.96 | 2.69 | 2,655.10 | 0.149 |
| AF3 | 6230 | 0.402 | 548.039 | 2505.859 | 1,957.82 | 4.57 | 1,362.52 | 0.088 |
| BF0 | 4250 | 0.402 | 778.841 | 1709.454 | 930.61 | 2.19 | 1,936.33 | 0.183 |
| BF1 | 5520 | 0.402 | 1047.594 | 2220.280 | 1,172.69 | 2.12 | 2,604.50 | 0.190 |
| BF2 | 5390 | 0.402 | 1053.200 | 2167.990 | 1,114.79 | 2.06 | 2,618.44 | 0.195 |
| BF3 | 5360 | 0.402 | 540.808 | 2155.924 | 1,615.12 | 3.99 | 1,344.54 | 0.101 |

Note: Price (USD) Seed = 1.67/kg; Organic Fertilizer = 0.10/kg; NPK = 1.21/kg; Urea = 0.84/kg; Biofertilizer = 24.13/kg; Pesticide = 3.35/L; Labor = 5.03/man day; Transportation = 0.67/man day; Land Tax = 0.80/ha; Price at Harvest = 0.40/kg.

The highest gain was obtained in treatment organic plus biofertilizer (AF3) and the lowest in existing (BF0). All fertilization combinations in Bioguma (A) resulted in higher profits than the fertilizer mix in Numbu (B). All combinations of fertilizer and sorghum varieties increased by USD 613.65–684.50 compared to the existing fertilization (AF0 and BF0). Based on the BEP-Y and BEP-P values, sorghum farming on dryland treated with a combination of fertilizers with Bioguma (A) and Numbu (B) was considered feasible to develop at a selling price of USD 0.402 at harvest and productivity 4.25–7.46 t/ha (Table 6).

## 4 Discussion

### *4.1 Climate Facts*

Based on the climatic data during the planting period (November 2022 to February 2023), monthly rainfall ranges from 226.79 to 752.84 mm, with an average of 524.03 mm more than adequate for sorghum growth. Excessive rainfall can cause poor soil drainage and adversely affect plants. Fortunately, the possibility of poor soil drainage at the study site was overcome by a land slope of about 5%, allowing water to drain off the land.

The average number of rainy days during the study period of 16 days per month was a condition of regular and even rainfall to help maintain soil moisture levels and support optimal plant growth. Adequate spacing between rainy days allows the soil to absorb water effectively and reduces the risk of water stress or waterlogging.

The high rainfall at the study site figure exceeds the rainfall needed for sorghum growth. The conditions for growing sorghum were 50–100 mm/month rainfall and 2.0–2.5 months after planting. High rainfall causes leaching of the soil and is acidic. Climate change (rising temperatures and changing rainfall patterns) impacts agricultural activities [20].

Meanwhile, the air humidity recorded at harvest time was high (88.34%), affecting the sorghum growth and development. Although sorghum can tolerate a wide range of high humidity conditions and prolonged rainfall, it can increase the risk of fungal diseases, such as downy mildew and grain mildew.

Understanding sorghum response to climate change was necessary to formulate and disseminate adaptation strategies for smallholder farming systems to increase yields in water-limited environments. Climate change generally brings warmer, wetter seasons to the study area, and an increase in failures at the beginning of the rainy season harms yields.

Climate change also causes a shift in the rainy season beginning and a shift in the planting season. Crop management, the amount, and the rainfall distribution in the growing season influenced sorghum yield. Sorghum phenology was inversely comparable to changes in temperature, and yield was directly equivalent to rainfall [21].

Climate phenomena were influential and had an impact on the agricultural sector. Rainfall data was important for agricultural production and vegetation growth, which were related to environmental and ecological resources. The efforts to mitigate climate change using fertilizers and applying low-emission technologies. Sorghum cultivation was inseparable from climate, which was related to water availability and resistance to drought [22].

### *4.2 Soil Properties*

The soil texture at the research site was clay, indicating fine-textured soil with small particles. Clay soils have good water-holding capacity but may be prone to compaction and poor drainage. Soil pH characteristics showed no significant changes after four treatments. The pH ($H_2O$) of 5.19 to 5.72 suggests that the soil was slightly acidic. Sorghum typically prefers a pH of slightly acidic to neutral between 6.0 to 7.5. Soil pH level falls within an acceptable range for sorghum cultivation, but adjustments are needed to ensure optimal pH for nutrient availability.

Soil with a low pH can inhibit the transport of plant nutrients and reduce yield formation. Sorghum yield would decrease significantly if the soil pH $< 5.8$, and at a pH of 5.42 the yield decreased by 10%. The low soil pH obstructs nutrient transport for plant growth. Acid soils significantly affect sorghum development and inhibit growth [23].

The C-organic content measured before treatment was 0.98%. After treatment, it was 0.60%–1.41% indicating that soil organic carbon was in a low to very low state. Organic matter is beneficial for soil profitability because it repairs structure, moisture retention, and nutrient availability. The presence of organic matter indicates that the soil has a certain level of fertility, which can be beneficial for sorghum growth. However, the amount is still insufficient to support optimal production.

Organic fertilizers, derived from plant or animal sources, offer a plethora of benefits for sorghum production in dryland areas. The incorporation of organic fertilizers into the soil can lead to an increase in organic carbon content, thereby enhancing nutrient retention, water-holding capacity, and overall soil fertility. Additionally, these fertilizers promote the proliferation of beneficial microorganisms in the soil, contributing to nutrient cycling and augmenting nutrient availability for sorghum. Inorganic fertilizers also supply essential macronutrients and micronutrients in forms that are readily accessible to plants.

The addition of inorganic and organic fertilizers in the long term was needed to increase the effectiveness of improving soil nutrients. Insufficient inorganic fertilizers cause soil nutrient deficiencies. These deficiencies can obstruct plant growth and degrade its ability to absorb nutrients for optimal development [24].

Nitrogen is a crucial nutrient for plant growth and role in foliage development and overall plant productivity. The N-Kjeldahl value indicated the N content measured in the study zone soil was 0.15%. Nitrogen levels appear to be relatively low, and additional nitrogen fertilization is necessary to meet the needs of the sorghum.

Bray's and Olsen's $P_2O_5$ value was determined to be very low, while the HCl $P_2O_5$ value was very high. These represented the available P content in the soil. Phosphorus is essential for root development, flowering, and fertilization in plants. Phosphorus levels appear relatively low and P fertilization was required to meet sorghum phosphorus requirements.

The $K_2O$ HCl before treatment value was 7.32 mg/100 g and available K after treatment at 0.12 to 0.21 cmol (+)/kg, indicating the available K content was very low. Potassium is essential for physiological processes in plants, including absorption of water and nutrients, photosynthesis, and overall plant health. Potassium levels appear low, so additional P fertilization is required for optimal sorghum growth and productivity.

The soil CEC indicator of the ability of soil to provide plants with nutrients. CEC was measured before and after treatment and showed a moderate status below 16. A higher CEC indicates a greater soil nutrient holding capacity. The CEC value indicates that the soil has a moderate capacity to hold cations, which can be beneficial for the availability of nutrients for sorghum.

Biofertilizers are essential in maintaining long-term soil properties and sustainability by fixing nitrogen in the atmosphere, mobilizing macro-micronutrients, and converting insoluble P in the soil into available to plants. Biological fertilizers combined with chemical fertilizers significantly increase the quantity and quality of plants' characteristics [11]. Fertilizer adequacy was positively related to plant nutrient uptake. Fertilizer was given in sufficient quantities according to plant needs, and nutrient uptake by plants tends to increase. Optimal plant nutrient uptake positively affects increased productivity because plants can absorb nutrients properly and meet their needs [25].

### *4.3 Cropping Pattern*

Cropping pattern is a substantial factor put up to crop yields and food security at local and national scales. Cropping pattern is an important data input variable for many land surfaces and global climates [26]. Agriculture management in the study site was classified as less intensive. The cropping pattern on dryland in a year at the research site only grows a few plants, so efforts to intensify land use were needed.

Cropping patterns are associated with plant production and intensity of land use. Climatic conditions strongly influenced variations in cropping patterns. Changes in climate conditions require appropriate practices through cropping systems and the use of plant species, cultivation, and management in agricultural sustainability and production [27].

### *4.4 Nutrients Uptake*

Nutrient uptake is a crucial process for plant growth and development. The roots of plants play a vital role in absorbing nutrients and water from the soil. The roots of plants have fine hairs called root hairs that absorb nutrients and water from the soil for plant growth, development, and production. The root hairs are tiny projections on the root cells' surface and greatly increase the surface area available for nutrient absorption. The process involves active transport and passive diffusion, and nutrients move through the root cell membrane to the plant's vascular tissues (xylem and phloem) for distribution throughout the plant.

Active transport is an energy-dependent process that allows plants to take up nutrients against the concentration gradient. This mechanism enables the selective uptake of specific ions that are essential for plant growth, such as nitrate ($NO^{3-}$), phosphate ($PO^{4-}$), and potassium ($K^{+}$). The active transport process involves carrier proteins embedded in the root cell membranes, which facilitate the movement of ions into the root cells. Passive diffusion is a passive process driven by concentration gradients. It allows for the movement of nutrients from areas of higher concentration in the soil to lower concentration in the root cells. Passive diffusion mainly contributes to the uptake of oxygen ($O_2$) and carbon dioxide ($CO_2$), as well as some micronutrients like iron (Fe) and manganese (Mn).

The nutrient uptake efficiency can be influenced by the availability and concentration of soil nutrients, pH level, and root characteristics of the plant species. Organic and inorganic fertilizers can contribute to a better intensify in plant nutrient uptake.

The impact of organic and inorganic fertilizers increased sorghum uptake of nitrogen, phosphorus, and potassium. Organic fertilizers (compost or manure) provide slow-release nutrients and improve soil structure, thus promoting nutrient availability. Inorganic fertilizers, such as synthetic N, P, and K, supply readily available nutrients for immediate uptake by plants [28].

Biofertilizers and organic fertilizers positively impact plant nutrient uptake and are better than the use of only inorganic fertilizers. This condition proves that balanced fertilizers, accompanied by complementary organic and biofertilizers help reverse environmental degradation by providing nutrients to the soil, thus increasing crop yields.

The combination of biofertilizers and organic fertilizers has a positive impact on increased nutrient uptake. Biofertilizers have positively impacted nutrient uptake by promoting nutrient solubilization, mineralization, and fixation. Rhizobium and Azotobacter can convert atmospheric nitrogen into a form that plants can use. Mycorrhizae form symbiotic relationships with roots and facilitate nutrient uptake. Microorganisms break down complex organic compounds into simple forms, allowing plants to easily absorb nutrients [29].

Sorghum is well adapted to marginal soils, absorbs nutrients properly, avoids nutrient deficiency conditions, and possesses inherent mechanisms to acquire and utilize nutrients efficiently. Sorghum ensures their growth and development in nutrient-deficient environments. Sorghum's ability to optimize nutrient uptake can have significant implications for enhancing productivity and reducing the reliance on external nutrient inputs, thus promoting sustainable agriculture, particularly in areas with limited soil fertility.

A comprehensive approach that combines organic, inorganic, and biofertilizers is essential for sustaining soil health and fertility, while also mitigating the environmental impacts of excessive synthetic fertilizer use. The overreliance on inorganic fertilizers could degrade soil health, lead to environmental contamination, and escalate production costs. Conversely, sole reliance on organic fertilizers may struggle to meet the substantial nutritional demands of crops at scale [10].

The application of inorganic fertilizers is targeted to address nutrient imbalances and improve sorghum nutrient uptake. Biofertilizers are composed of beneficial microorganisms (Rhizobium and Azotobacter) that can fix atmospheric N and convert it into plant-available forms, thereby reducing the reliance on synthetic N fertilizers. The combined use of organic and inorganic fertilizers can be a good approach to deal with nutrient depletion and promote sustainable crop production as well as improve soil health [9].

### *4.5 Sorghum Performance*

The absence of difference between Bioguma and Numbu in response to fertilizers could be due to the similarity of genetic characteristics. Bioguma was an improvement from Numbu through an *in vitro* method and has identical plant height, number of leaves, and stem diameter. This resulting study indicated no significant interaction between varieties and fertilization dosages caused by the varieties that were relatively unresponsive to different types of fertilization.

Fertilizer improved growth characteristics, especially in plant height and stem diameter. The application of biofertilizer significantly increased the plant height and stem circumference of sorghum. Balanced fertilizers can increase the growth and sorghum yield as well as nutrient absorption in dryland. Plants with larger stem diameters allow for better growth, support plants strongly, and are resistant to falling, so their physiological functions run well. Stem diameter was related to K nutrients absorbed by plants. Potassium increases the levels of sclerenchyma in the stem, thickening the stem tissue and making plants stronger [30].

The effect of varying fertilization at each plant age can be caused by nutrient requirements at each growth phase, nutrient absorption efficiency, and the environment. At the time of the experiment, temperature, humidity, light, and rainfall were relatively optimal for growth, so they could not be considered differences.

Distinct nutrition requirements at each sorghum growth stage can cause nutritional effects. At the beginning of growth, plants need N, P, K, Ca, and Mg to stimulate vegetative growth and the formation of roots. In the juvenile phase, roots have not fully developed, so the ability to absorb nutrients is still limited. Nutrients P, K, Ca, Mg, and B were required for headway flower, fruit, and seed formation [31]. Roots develop and absorb nutrients more efficiently with age. Variations in the effect of fertilization at each plant age can also be affected by the type of fertilizer, dosage, method of application, and soil conditions.

Sorghum morphologically has a solid and deep root system, enabling it to absorb available water in the soil more efficiently. Sorghum leaves that were curled stiffly when dry can reduce water evaporation through the leaf surface. Physiologically, the sorghum's ability to regulate water use efficiently when drought occurs through closing stomata to reduce water evaporation through transpiration [32]. This supports sorghum adapt to a dry environment and sweltering temperatures.

This study's use of balanced fertilizers consisting of a combination of inorganic and organic increases the plant growth, panicle dry weight, and seed dry weight. This indicated that dryland at the experimental site needed a balanced manner, both organic and inorganic fertilizers. The application of organic and dose of NPK produced plant height and seed dry weight was significantly higher [33]. The NPK application in combination with organic fertilizer resulted in higher plant height and the number of leaves. Biofertilizers can also be used as an appropriate alternative to chemical fertilizers in sustainable agricultural systems [34].

### *4.6 Sorghum Yield*

Bioguma showed higher panicles' wet weight and panicles' dry weight compared to Numbu. The yield of Bioguma was 26.4% higher (6.53 t/ha) than that of Numbu (5.13 t/ha). In the study, the use of balanced fertilizers consisting of a combination of inorganic and organic in this study increased plant growth, panicle dry weight, and seed dry weight.

Dryland in the experimental site requires balanced fertilization with, both organic and inorganic fertilizers. Balamurugan et al. [33] reported that the application of 5 t/ha poultry manure at the dose of 125% NPK resulted in plant height (307.3 cm), dry stover production (19.64 kg/ha), grain yield (4.59 kg/ha) significantly higher than dry stover (15.71 kg/ha).

The interaction between biochar and the fertilizer combination was insignificant, but the mixture of biofertilizers and inorganic fertilizers significantly increased sorghum's productivity and brix value. The inorganic and biofertilizers were the best treatment for increasing the 1000 seeds' weight, yield, and crude sugar content [35].

Sorghum yields with the use of inputs combination of organic, inorganic, and biofertilizers give a better response compared to fertilization under existing conditions. They are choosing the proper planting time, bearing in mind that in dryland agroecosystems the availability of water in the early phases of sorghum plant growth also determines optimal sorghum growth and yield.

### *4.7 Sorghum Farming Economic Value*

The productivity of sorghum farming through the existing fertilization system (AF0 and BF0) was lower than the introduced fertilization treatment (AF1, AF2, AF3, BF1, BF2, and BF3), but it can provide benefits at favorable price conditions. This further emphasizes that sorghum farming requires lower production inputs than other cereal food crop commodities.

Sorghum cultivation is a profitable business, has better consumer preferences, and can be considered for a guaranteed minimum price for sorghum. Sorghum production was more profitable on marginal farms compared to small and medium-scale farms in Andhra Pradesh, India [36].

Sorghum production was profitable in Siaya, Kenya. The average gross margin sorghum was KSh. 4.29/ha [37]. The net income of sorghum farming in Kuje, Abuja, Nigeria, is USD 0.34 with a return on investment of 1.59, which shows that sorghum production is a profitable farming business [38]. Sorghum farming in the dryland of Wonogiri and Gunungkidul (Indonesia) provides a BCR value of >1 or a profit value greater than production costs [39].

The combination treatments of both types and doses of fertilizers proved to increase the productivity and profits of sorghum farming on dryland. Based on the level of importance, the eight main obstacles to sorghum production at the most important level were fertilizer costs, inadequate capital, labor costs, inadequate superior seeds, weed attacks, pests and diseases, storage facilities, and inadequate extension agents [40].

Input variables such as fertilizer, seeds, chemicals, labor, and input costs, significantly affect sorghum production. Fertilizer was one factor that significantly increased yields and profitability substantially during one growing season [41]. Manure was also highly recommended to increase soil fertility and optimize productivity. Organic manure amendments release completed nutrients, upgrade water-holding capacities for plant use, and give better plant production [42].

In Nigeria, 44.3% of farmers use inorganic fertilizers (NPK 20:10:10 compound fertilizer), and 35.3% of farmers use a mix of organic and inorganic fertilizers (manure and NPK 20:10:10) (35.3%). The farmers (9.0%) use manure and 11.3% farmers do not use fertilizer in sorghum production [43].

The combined treatment of manure and biological fertilizers (AF3 and BF3) provided higher benefits than the combined treatment of manure and chemical fertilizers (AF1, AF2, BF1, and BF2) for each variety. The addition of input costs for chemical fertilizers leads to reduced profits from the use of biological fertilizers. Increasing production based on the level of response to nitrogen and reducing transportation costs to secure inputs was an effective approach to increasing the profitability of using fertilizers for sorghum farmers.

Furthermore, Tugga et al. [40] stated that to increase profitability in sorghum production, it was necessary to reduce the cost of the main variable inputs with an average return on investment of USD 0.0027/ha. Farmers in Tamil Nadu, India, using inorganic fertilizers urea, single super-phosphate, and potash with a ratio of 32:16:16 kg/ha and 2 t/ha of manure can earn a net profit of USD 85.55/ha [44]. The maximum relative net return of 28,084.53 ETB ha-1 was found in the Melkam variety treated with NPK fertilizer in Tigray, Ethiopia [45].

The operating costs of planting high-yielding sorghum cultivars increased by 40% higher than planting local cultivars, but significant gains were obtained from increasing seed yields by 65% and net income by 72% [46]. It should be noted that the inorganic fertilizers used in the combined treatment of introduced fertilizers were non-subsidized fertilizers with prices almost three times the price of subsidized ones. This was in line with the development of sorghum in Mali, where sorghum producers do not receive a 50% fertilizer price subsidy annual fiscal savings from reducing subsidy requirements were USD 816.01, and reducing environmental impacts due to reduced chemical fertilizers consumption [47].

Based on the value of the benefits obtained for the sustainability and environmental conservation of land resources, the organic plus biofertilizer (AF3) treatment was recommended for the development of sorghum on dryland. Our limited research was just in one season in one site dryland, so further study could add multiseason in multisite to significant results about dynamic soil nutrients and microbial.

## 5 Conclusions

The fertilization treatment has no significant short-term impact on changes in soil characteristics. NPK nutrient uptake found in sorghum leaf tissue was within nutrient adequacy limits. Sorghum nutrient uptake has a positive effect on productivity. Bioguma was more suitable for dryland agroecosystems than Numbu. Bioguma indicated higher panicles' wet weight (24%) and panicles' dry weight (27.45%) compared to Numbu. Bioguma yield was 26.4% higher (6.53 t/ha) than Numbu (5.13 t/ha). The increase in growth (stover wet weight) was 19.2%–26.0%. Fertilization treatments (F1–F3) increase sorghum yield (21.4%–31.4%) over the existing fertilization (F0). The economic value of sorghum farming showed that combinations of fertilizer treatments and varieties provide benefits with an R/C value >1 and a profit of USD 930.61–1,957.82. Balanced fertilization (inorganic, organic, and biofertilizers) was needed to help the sorghum absorb nutrients, achieve optimal growth, and increase yield.

**Acknowledgement:** Thank you to our colleagues and reviewers who provided valuable suggestions for this publication.

**Funding Statement:** The study was funded by the Research Program from the Research Center for Food Crops, the Research Organization for Agriculture and Food, National Research and Innovation Agency (BRIN).

**Author Contributions:** All authors confirmed that they contributed to the study conception and design, data collection, analysis and interpretation of results, draft manuscript preparation, reviewed the results, and approved the final version of the manuscript.

**Availability of Data and Materials:** The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

**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. FAO. *Sorghum bicolor* L. Moench. Food and Agriculture Organization of the United Nations. Available from: http://www.fao.org/sorghum/en/. [Accessed 2023].
2. Erbetta E, Echarte L, Smachetti MES, Gabbanelli N, Echarte MM. Sorghum biomass yield and allocation as affected by the combination of photoperiod sensitivity, sweet-stalk, and brown midrib traits. Field Crops Res. 2024;305(4):109186. doi:10.1016/j.fcr.2023.109186.
3. Abdel-Ghany SE, Ullah F, Ben-Hur A, Reddy ASN. Transcriptome analysis of drought-resistant and drought-sensitive sorghum (*Sorghum bicolor*) genotypes in response to peg-induced drought stress. Int J Mol Sci. 2020;21(3):1–26. doi:10.3390/ijms21030772.
4. Sahib MR, Pervaiz ZH, Williams MA, Saleem M, DeBolt S. Rhizobacterial species richness improves sorghum growth and soil nutrient synergism in a nutrient-poor greenhouse soil. Sci Rep. 2020;10(1):1–13. doi:10.1038/s41598-020-72516-3.
5. Aristya VE, Samijan. Rice breeding breakthrough for rainfed fields. In: Rainfed rice field management, technology, and institutional. Surakarta: UNS Press; 2021. p. 245–65.
6. Brevik EC, Calzolari C, Miller A, Pereira P, Kabala C, Baumgarten A, et al. Soil mapping, classification, and pedologic modeling: history and future directions. Geoderma. 2015;264(9):256–74. doi:10.1016/j.geoderma.2015.05.017.
7. Ananda GKS, Myrans H, Norton SL, Gleadow R, Furtado A, Henry RJ. Wild sorghum as a promising resource for crop improvement. Front Plant Sci. 2020;11:1108. doi:10.3389/fpls.2020.01108.
8. Lone R, Hassan N, Bashir B, Rohela GK, Malla NA. Role of growth elicitors and microbes in stress management and sustainable production of Sorghum. Plant Stress. 2023;9(1):100179. doi:10.1016/j.stress.2023.100179.
9. Arefin MS, Islam MA, Rahman MM, Alim MA, Hassan S, Soliman MFK, et al. Integrated nutrient management improves productivity and quality of sugarcane (*Saccharum Officinarum* L.). Phyton-International Journal of Experimental Botany. 2022;91(2):439–69. doi:10.32604/phyton.2022.017359.
10. Samijan, Minarsih S, Jauhari S, Basuki S, Susila A, Nurwahyuni E, et al. Revitalizing sub-optimal drylands: exploring the role of biofertilizers. Open Agric. 2023;8(1):20220214. doi:10.1515/opag-2022-0214.
11. Akinseye FM, Birhanu BZ, Ajeigbe HA, Diancoumba M, Sanogo K, Tabo R. Impacts of fertilization management strategies on improved sorghums varieties in smallholder farming systems in Mali: productivity and profitability differences. Heliyon. 2023;9(3):1–13. doi:10.1016/j.heliyon.2023.e14497.
12. POWER. Pediction of worldwide energy resource data access viewer - NASA/ POWER CERES/MERRA2 native resolution monthly and annual. Dates (month/day/year): 04/01/2022 through 03/31/2023. Location: Latitude–6.9249 Longitude 109.7537. Available from: https://power.larc.nasa.gov/data-access-viewer/. [Accessed 2023].
13. AOAC (Association of Official Agriculture Chemists). Official methods of analysis of AOAC international. In: Horwitz W, editor. Agricultural chemicals, contaminants, drugs. 17th ed. MD, USA: AOAC International; 2002.
14. Havlin JL, Beaton JD, Tisdale SL, Nelson WL. Soil fertility and fertilizers: an introduction to nutrient management. 6th ed. Upper Saddle River, NJ: Prentice Hall; 2014.
15. UPOV. Sorghum guidelines for the conduct of tests for distinctness, uniformity, and stability. Geneva: International Union for the Protection of New Varieties of Plants; 2015.
16. Gulles AA, Bartolome V, Morantte R, Nora LA, Relente C, Talay D, et al. Data randomization and data analysis using STAR (statistical tool for agricultural research). Philipp J Crop Sci. 2014;39(1):137.
17. Dube AK, Ozkan B, Ayele A, Diriba I, Aliye A. Technical efficiency and profitability of potato production by smallholder farmers: the case of Dinsho District, Bale Zone of Ethiopia. J Dev Agric Econ. 2018;10(7):225–35. doi:10.5897/JDAE2017.0890.
18. Bonabana-Wabbi J, Mugonola B, Ajibo S, Kirinya J, Kato E, Kalibwani R, et al. Agricultural profitability and technical efficiency: the case of pineapple and potato in SW Uganda. Afr J Agric Resour Econ. 2017;8(3):145–59.

19. Abera S, Assaye A. Profitability analysis of rainfed upland rice production under smallholder farmers in Libokemkem District, North Western Ethiopia. Int J Agric Econ. 2021;6(3):111–5. doi:10.11648/j.ijae.20210603.13.
20. Bosire E, Karanja F, Ouma G, Gitau W. Assessment of climate change impact on sorghum production in Machakos County. Sustain Food Prod. 2018;3:25–45. doi:10.18052/www.scipress.com/SFP.3.25.
21. Sandeep VM, Rao VUM, Rao BB, Pramod VP, Chowdary PS, Kumar PV, et al. Impact of climate change on sorghum productivity in India and its adaptation strategies. J Agrometeorol. 2018;20(2):89–96. doi:10.54386/jam.v20i2.517.
22. Blackmore I, Rivera C, Waters WF, Iannotti L, Lesorogol C. The impact of seasonality and climate variability on livelihood security in the Ecuadorian Andes. Clim Risk Manag. 2021;32(2):100279. doi:10.1016/j.crm.2021.100279.
23. Zhou Z, Li Z, Zhang Z, You L, Xu L, Huang H, et al. Treatment of the saline-alkali soil with acidic corn stalk biochar and its effect on the sorghum yield in western Songnen Plain. Sci Total Environ. 2021;797:149190. doi:10.1016/j.scitotenv.2021.149190.
24. Fageria NK. The use of nutrients in crop plants. Boca Raton, FL: CRC Press, Taylor & Francis Group; 2019.
25. Marschner P. Marschner's mineral nutrition of higher plants. 3rd ed. Australia: Academic Press; 2011.
26. Aristya VE, Samijan S. The yield gap of maize under intensive cropping system in Central Java. Plan Trop. 2022;10(1):1–12. doi:10.18196/pt.v10i1.8789.
27. Mahlayeye M, Darvishzadeh R, Nelson A. Cropping patterns of annual crops: a remote sensing review. Remote Sens. 2022;14(10):2404. doi:10.3390/rs14102404.
28. Kunrath TR, Lemaire G, Teixeira E, Brown HE, Ciampitti IA, Sadras VO. Allometric relationships between nitrogen uptake and transpiration to untangle interactions between nitrogen supply and drought in maize and sorghum. Eur J Agron. 2020;120:126145. doi:10.1016/j.eja.2020.126145.
29. Zhang X, Bashir MA, Raza Q, Liu X, Luo J, Zhao Y, et al. Evaluating the effects of sustainable chemical and organic fertilizers with water saving practice on corn production and soil characteristics. Phyton-Int J Exp Bot. 2023;92(5):1349–60. doi:10.32604/phyton.2023.026952.
30. Kamdi PJ, Swain DK, Wani SP. Developing climate change agro-daptation strategies through field experiments and simulation analyses for sustainable sorghum production in semi-arid tropics of India. Agric Water Manage. 2023;286:108399. doi:10.1016/j.agwat.2023.108399.
31. Hacisalihoglu G, Armstrong PR. Flax and sorghum: multi-element contents and nutritional values within 210 varieties and potential selection for future climates to sustain food security. Plants. 2022;11(3):1–12. doi:10.3390/plants11030451.
32. Chen X, Wu Q, Gao Y, Zhang J, Wang Y, Zhang R, et al. The role of deep roots in sorghum yield production under drought conditions. Agronomy. 2020;10(4):611. doi:10.3390/agronomy10040611.
33. Balamurugan P, Hemalatha M, Joseph M, Prabina BJ. Influence of organic and inorganic fertilizer levels on growth and yield of dual purpose K12 sorghum (*Sorghum bicolor*) under irrigated condition. Int J Chem Stud. 2020;8(5):50–3. doi:10.22271/chemi.2020.v8.i5a.11005.
34. Nurlaily R, Samijan, Aristya VE, Lestari F. Effect of biofertilizer application on the population of nitrogen-fixing bacteria and yields of chili pepper at Temanggung, Central Java. In: Proceeding of the International Workshop and Seminar Innovation of Environmental-Friendly Agricultural Technology Supporting Sustainable Food Self-Sufficiency; 2019; Surakarta, Indonesia. p. 346–54. doi: 10.5281/zenodo.3345272.
35. Yang H, Zhang S, Hu J, Huang J, Ao Z, Wang X, et al. Influence of biochar produced from distiller grains on agronomic performances of sorghum (*Sorghum bicolor* L.) and greenhouse gas emissions from soil. Pedosphere. 2023. doi:10.1016/j.pedsph.2023.07.005.
36. Mouni M, Pritam BS. An economic analysis of the production of sorghum in the Kurnool district of Andhra Pradesh. J Pharmacogn Phytochem. 2022;11(1):6–8.
37. Kula OO, Nyangweso PM, Saina E. Socio-economic factors affecting the profitability of sorghum farming in Siaya County, Kenya. JEFA. 2022;6(2):69–83.

38. Idisi PO, Ebukiba ES, Ibeh HC. Profitability analysis of sorghum production in Kuje Area Council of Abuja, Nigeria. Eur Mod Stud J. 2019;3(2):10–6.
39. Widodo S, Triastono J, Sahara D, Pustika AB, Kristamtini, Purwaningsih H, et al. Economic value, farmers perception, and strategic development of sorghum in Central Java and Yogyakarta, Indonesia. Agriculture. 2023;13(3):516. doi:10.3390/agriculture13030516.
40. Tugga SE, Hassan AA, Ojeleye OA. Profitability analysis of sorghum small-scale farmers in selected local government areas of Gombe State, Nigeria. J Agripreneurship and Sustain Dev. 2023;6(1):47–55. doi:10.59331/jasd.v6i1.391.
41. Okot F, Laing M, Shimelis H, de Milliano WAJ. Diagnostic appraisal of the sorghum farming system and breeding priorities in Sierra Leone. Sustainability. 2022;14(12):7025. doi:10.3390/su14127025.
42. Atugwu AI, Chukwudi UP, Eze EI, Ugwu MO, Enyi JI. Growth and yield attributes of cowpea accessions grown under different soil amendments in a derived Savannah zone. AIMS Agric Food. 2023;8(4):932–43. doi:10.3934/agrfood.2023049.
43. Yahaya MA, Shimelis H, Nebie B, Ojiewo CO, Danso-Abbeam G. Sorghum production in Nigeria: opportunities, constraints, and recommendations. Acta Agric Scand Sect B. 2022;72(1):660–72.
44. Prabakar C, Peter YS. An economic analysis on the cultivation of Sorghum Wrt Dindigul District of Tamil Nadu. Plant Arch. 2020;(2):4972–6.
45. Weldegebriel R, Araya T, Egziabher YG. Effect of NPK and blended fertilizer application on Yield, Yield Component and its profitability of Sorghum (*Sorghum bicolor* (L.) Moench) varieties under rainfed condition in northwestern Tigray, Ethiopia. Int J Life Sci. 2018;6(1):60–8.
46. Rao BD, Mukherjee DN, Devi YL, Tonapi VA. An economic analysis of improved rabi sorghum cultivars in a rainfed situation of Maharashtra, India. Int J Curr Microbiol App Sci. 2017;4:7–15.
47. Miklyaev M, Schultz M, Awantang A, Laval M. Cost-benefit analysis of Mali's sorghum and millet value chains. 2017. Available from: https://cri-world.com/publications/qed_dp_300.pdf. [Accessed 2023].