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Research Paper

PROXIMATE, TANNIN, AND AMYLOSE IN SIX SORGHUM VARIETIES ACROSS TWO PLANTING SEASONS

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ARTICLE HIGLIGHTS

- Sorghum nutrition varies across varieties and growing seasons
- Dry season increases starch and amylose content in some varieties
- Rainy season enhances protein levels in sorghum grains
- Genotype-environment interaction affects sorghum nutritional quality
- Sorghum adaptation supports food diversification and climate resilience

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ABSTRACT

Sorghum (*Sorghum bicolor* (L.) Moench) is a potential staple food in Indonesia, offering an alternative to rice and corn due to its adaptability to marginal lands and drought tolerance. However, research on the impact of environmental factors, particularly different growing seasons, to the nutritional composition of sorghum varieties are still lacking. This study aimed to analyze the proximate contents of tannin and amylose in six sorghum varieties cultivated in two different planting seasons (wet and dry seasons). A Completely Randomized Design with three replications was applied in this experiment. The tested varieties included three newly developed superior varieties (Bioguma, Samurai, and Kawali) and three local varieties (Black Bonteb, Red Glutinous Sorghum, and KD4). The results showed that proximate composition varied across varieties and seasons. Starch content was generally higher in the dry season, with the highest observed in Kawali (64.16%) and Bioguma (63.11%), while the lowest was in Black Wareng (11.99%). Similarly, protein content peaked in Black Wareng (7.68%) and Red Glutinous Sorghum (7.37%), but was the lowest in Samurai (4.48%). Tannin levels also fluctuated by season, where Bioguma, KD4, and Kawali exhibited higher tannin content in the dry season, whereas Samurai, Red Glutinous Sorghum, and Black Bonteb had lower tannin levels. Notably, amylose content was significantly higher in Red Glutinous Sorghum (4.72%) and Black Bonteb (4.62%) across both seasons, contributing to their fluffier texture when cooked. These findings highlight the influence of environmental conditions on sorghum nutritional quality, reinforcing its potential for food diversification, including processed sorghum flour as a substitute for wheat flour.

Keywords: amylose, food, proximate, season, sorghum

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is a food crop highly adaptable to marginal lands, including sandy soils, and has strong drought tolerance, making it an important food crop alternative in regions with limited water resources. Additionally, sorghum requires low agricultural inputs, making it a sustainable option for food security in developing countries (Yupcz 2024). In many parts of the world, particularly in developing countries, sorghum grain serves as a substitute for major cereal crops, such as rice and maize due to its comparable nutritional profile.

Despite its potential, sorghum remains underutilized in Indonesia, even though it has been cultivated for a long time. All parts of sorghum plant can be utilized, making it a highly efficient crop with minimal waste. Nutritionally, sorghum offers advantages, as it contains higher protein levels compared to rice, corn, wheat, and tubers (Sulistyowati *et al.* 2024). Protein is a key macronutrient in grains, and understanding the proximate composition of sorghum seeds is crucial to determine their nutritional value and potential applications.

According to Aryani *et al.* (2022), sorghum seeds are rich in carbohydrates, similar to rice, wheat, and corn, making them a viable alternative to staple foods. Due to their genetic similarities, sorghum seeds have the potential to substitute wheat and rice, particularly in flour-based products, because their functional properties are more compatible with these grains compared to tubers. However, sorghum contains antinutritional compounds, particularly tannins, which can be as high as 2% in some varieties. These compounds reduce protein digestibility and impart an astringent taste, limiting consumer acceptance (Aguiar *et al.* 2023).

Research Gap and Study Significance

Although studies have examined the nutritional composition of sorghum, limited research has specifically analyzed how different growing seasons impact the proximate composition, tannin, and amylose content in various sorghum varieties. Seasonal variations in temperature, rainfall, and soil conditions could significantly influence these nutritional factors, but comprehensive data on these effects remain scarce. Understanding these variations is crucial to improve sorghum utilization in food production and breeding programs aimed at developing superior varieties with enhanced nutritional quality (Osman *et al.* 2022).

Proximate analysis provides information on the nutritional composition of sorghum, including moisture, protein, fat, carbohydrate, and ash content. This information is essential to evaluate sorghum's potential as a sustainable alternative to conventional staple crops, particularly in regions affected by climate change and declining soil fertility. Despite its high protein and carbohydrate content, the presence of antinutritional compounds, like tannins, can reduce its digestibility and consumer appeal (Keyata *et al.* 2021; Yang & Zhong 2022)

Tannins are phenolic compounds found in sorghum that function as antioxidants. However, excessive tannin levels negatively impact protein bioavailability and contribute to bitterness, which is undesirable for food applications. Identifying varieties with optimal tannin content could enhance sorghum's acceptability for human consumption (Keyata *et al.* 2021; Yang & Zhong 2022).

Amylose is a component of starch affecting the texture and physical properties of processed sorghum products. Higher amylose content is associated with firmer, less sticky rice-like grains, whereas lower amylose contributes to a softer, fluffier texture. Optimizing amylose levels is essential for improving the quality of sorghum-based food products, such as instant rice, porridge, and flour substitutes (Yan *et al.* 2023).

Indonesia has two distinct seasons: the rainy season and the dry season, with significant variations in temperature, water availability, and sunlight exposure. These environmental factors could influence the nutritional composition of sorghum, but the extent of their impact remains unclear.

Therefore, this study aimed to investigate the effect of growing seasons on proximate composition as well as tannin and amylose contents in both local and newly developed superior varieties of *Sorghum bicolor* cultivated in Gunungkidul, Yogyakarta, Indonesia. The findings of current research will provide valuable insights into the seasonal adaptability of sorghum, contributing to its broader adoption as a climate-resilient food source.

MATERIALS AND METHODS

Research Site

The research was conducted in Gunungkidul District, Yogyakarta Province, Indonesia, at an altitude of 215 masl. To provide clearer geographical context and spatial distribution of the study sites, a map has been included (Fig. 1), illustrating the location of Gunungkidul and its relative distances from other key experimental field or comparison regions. This spatial visualization helps emphasize the environmental variability that could influence sorghum growth and composition across locations.

Experimental Field

The experimental field was located at 355 masl (Statistics Indonesia 2021), with a rainfall distribution of about 1,750 – 2,130 mm per year and an average temperature of 24 °C. The total monthly rainfall from August to November 2024 was 2,121.9 mm. The first study was conducted in dry season from May to August 2024, while the second study was carried out in rainy season from August to November 2024.

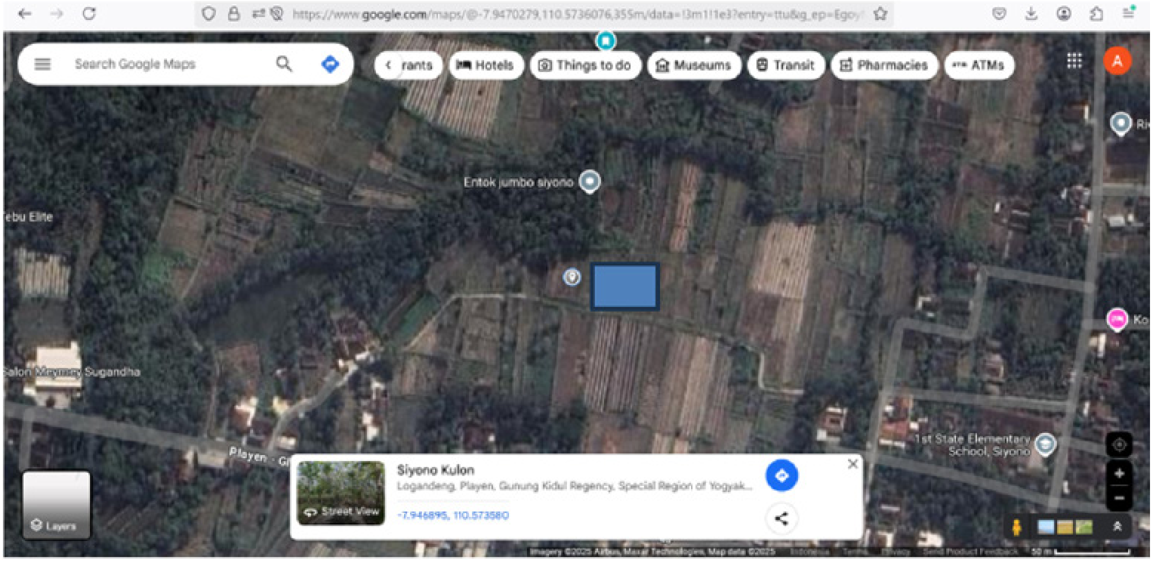

Figure 1 Sorghum research sites

The experimental field was characterized by sandy loam soil with moderate organic matter content, pH of 5.5 - 6.2, and low to moderate fertility levels, requiring additional fertilization for optimal growth.

Land Preparation

Before planting, the land was plowed and harrowed twice to improve soil aeration and ensure proper root development. Organic manure (5 tonnes/ha) was applied one week before sowing to enhance soil fertility.

Sorghum Varieties

Genotype Selection and Relevance

This study used six sorghum genotypes, consisting of three newly developed superior varieties and three local cultivars, selected based on their genetic diversity, agronomic performance, and potential for food utilization. These genotypes were chosen to represent different nutritional compositions, yield levels, and environmental adaptability, allowing a comprehensive analysis in evaluating the effects of growing seasons on proximate composition as well as tannin and amylose contents. The six sorghum varieties used in this study were:

New Superior Varieties

a. Bioguma (S1)

High-yielding variety developed by Indonesian Center for Agricultural Biotechnology and Genetic Resources (*Balai Besar Bioteknologi dan Sumber Daya Genetik Pertanian*/BB Biogen), characterized by high starch content and good adaptability to drylands, with a plant height of 266 cm, biomass weight of 54.30 tonnes/ha, sap volume of 122 mL, yield potential of 9.3 tonnes/ha, Brix content of 15%, and resistance to leaf rust and stem rot.

b. Samurai (S4)

Released by BATAN, known for early maturity, moderate starch and protein contents, and adaptability to dry conditions.

c. Kawali (S6)

Introduced from India and developed by BALITSEREALIA Maros of the Ministry of Agriculture of the Republic of Indonesia, with an average yield of 2.96 tonnes/ha with high yield potential and moderate tannin content, and moderate resistance to major pests and diseases.

Local Cultivars

a. KD4 (S3)

A traditional variety cultivated by farmers in Gunungkidul, known for its moderate plant height (180 - 200 cm), high adaptability to acidic soils, and tolerance to drought stress. KD4 has medium amylose content and lower tannin content making it more palatable for food and suitable for feed applications.

b. Red Glutinous Sorghum (V3)

Traditionally cultivated for its high amylopectin content, which gives a sticky, glutinous texture, preferred for sticky rice-and flour-based products. Characterized by small reddish grains. This variety is valued for its chewy texture and high antioxidant content due to its phenolic compounds.

c. Black Bonteb Sorghum/Bonteb/Wareng (V4)

Recognized by its dark-colored grains rich in tannins, contributing to its higher antioxidant properties but lower digestibility. It is traditionally used for local fermented beverages, high-fiber food products, and other traditional sorghum-based products.

Planting and Crop Maintenance

Sorghum seeds were pre-germinated in polybags. The transplanting of sorghum seeds was carried out at 21 days after germination. The transplanting system allowed for early seedling establishment, reducing mortality rates. The planting spacing was 75 × 25 cm, ensuring optimal plant density for growth and yield.

During the experiment, crops were maintained by conducting:

a. Irrigation

Applied twice per week during dry season and once per week in the rainy season.

b. Soil piling (*Pembubunan*)

Conducted at 30 days after transplanting to improve root stability and moisture retention.

c. Weeding

Performed manually every 2 - 3 weeks to reduce competition for nutrients and water.

d. Pests and Diseases Control

1. Pests

Aphids (*Rhopalosiphum maidis*) and stem borers (*Chilo partellus*) were controlled using botanical insecticides (Neem extract, 2% solution) and chemical insecticides (Lambda-cyhalothrin, 2.5% EC, applied at 0.5 L/ha if infestation exceeded 10%).

2. Diseases

Leaf rust (*Puccinia purpurea*) and anthracnose (*Colletotrichum graminicola*) were managed using fungicides (Mancozeb 2.5 g/L, applied biweekly during high humidity conditions).

Fertilization Schedule and Dosage

Fertilization followed the recommended dose of 120 kg NPK (15-15-15) per hectare, applied in three stages:

a. Basal application (30%): At transplanting (14 days after sowing);

b. Vegetative stage (40%): At 30 days after transplanting to support leaf and stem growth;

c. Reproductive stage (30%): At 60 days after transplanting to enhance grain filling.

Harvesting and Post Harvest Handling

Harvesting was carried out when seeds reached physiological maturity, indicated by hard grain texture and a moisture content of approximately 20%. The harvest age varied among varieties:

a. Early maturing varieties (Samurai, Kawali): 90 - 100 days after sowing (DAS);

b. Medium maturity (Bioguma, KD4): 110 - 120 DAS;

c. Late-maturing varieties (Ketan Merah, Black Bonteb): 130 - 140 DAS.

Post-harvest processing involved sun-drying the sorghum grains to reach 12 - 14% moisture content before storage.

Experimental Design

This study was conducted using a Randomized Complete Block Design (RCBD) with three replications to account for environmental variability. The field experiment was conducted on 30 plots, each measuring 5 × 6 m. Within each plot, four raised beds (1 × 6 m) were constructed, resulting in a total of 120 beds. Each bed contained 40 planting holes. One seed was planted in each hole, requiring 160 seeds per plot.

Sorghum Seeds Analysis

Sample Preparation

Sorghum grain samples were collected at physiological maturity from three replicates per genotype. The grains were sun-dried to reach 12 - 14% moisture content, cleaned, and milled into fine flour using a laboratory-scale mill (Cyclotec 1093, FOSS, Sweden, 0.5 mm sieve). The flour samples were stored in airtight containers at 4 °C until further analysis.

Tannin Content Analysis (Folin and Ciocalteu Method)

Tannin content was determined using the Folin-Ciocalteu colorimetric method to quantify total phenolic compounds based on their reduction of phosphomolybdate-phosphotungstate reagents in an alkaline medium. The procedure was as follows.

1. Sample extraction

   A 0.5 g of sorghum flour was extracted with 10 mL of 70% methanol by shaking at 200 rpm for 2 hours at 25 °C.

2. Reaction

   A 1 mL of the sorghum flour extract was mixed with 5 mL of Folin-Ciocalteu reagent at a 1 : 10 dilution and incubated for 5 minutes.

3. Neutralization

   A 4 mL of 7% sodium carbonate (Na_2CO_3) solution was added followed by incubation for 30 minutes in the dark at 25 °C.

4. Measurement

   Absorbance was read at 725 nm using a UV-Vis spectrophotometer (Shimadzu UV-1800, Japan).

5. Calculation

   Tannin content was expressed as mg gallic acid equivalent (GAE) per gram of sample (mg GAE/g), using a calibration curve prepared with standard gallic acid solutions.

Proximate Analysis

Proximate composition was analyzed according to AOAC 2005 methods (Milala *et al.* 2018), covering moisture, ash, protein, fat, and carbohydrate contents (Table 1).

Amylose Analysis (Laye Enon Iodine Colorimetric Method)

Amylose content was determined using the Laye Enon iodine colorimetric method to quantify the formation of amylose-iodine complexes. The procedure was as follows.

1. Sample preparation

   A 100 mg of sorghum flour was dispersed in 1 mL of ethanol (95%) and 9 mL of 1 M NaOH, then heated at 95 °C for 10 minutes.

2. Dilution

   The solution was diluted to 100 mL with distilled water.

3. Iodine reaction

   A 5 mL of sample solution was mixed with 0.1 mL iodine-potassium iodide reagent (0.2% I_2 + 2% KI) and diluted to 50 mL with distilled water.

4. Measurement

   Absorbance was recorded at 620 nm using a UV-Vis spectrophotometer (Shimadzu UV-1800, Japan).

5. Calculation

   Amylose content was determined using a standard curve prepared with pure amylose (Park & Manna *et al.* 2024).

Table 1 Proximate analysis according to AOAC 2005 methods

Parameter	Method used	Equipment
Moi sture	Oven-drying at 105 °C (AOAC 925.10)	Hot air oven (Memmert, Germany)
Ash	Muffle furnace at 550 °C (AOAC 923.03)	Muffle furnace (Thermo Fisher, USA)
Crude Protein	Kjeldahl method (AOAC 984.13)	Kjeltec Analyzer (FOSS, Sweden)
Crude Fat	Soxhlet extraction (AOAC 920.39)	Soxhlet Apparatus (Buchi, Switzerland)
Carbohydrate	By difference [(100 - (moisture + ash + protein + fat)]	

Each analysis was conducted in triplicate, and results were expressed as a percentage (%) of dry weight basis.

RESULTS AND DISCUSSION

Proximate Composition Analysis

ANOVA results indicated significant differences (P < 0.05) in starch, protein, tannin, and amylose contents among sorghum varieties and across growing seasons. (Table 2).

Post-hoc Tukey tests confirmed that the differences between Bioguma and Black Bonteb in starch content were statistically significant. The statistical analysis in this study confirmed that both genotype and environmental factors play a crucial role in determining the nutritional composition of sorghum, which was in agreement with the study of Lee *et al.* (2023) and Kamal *et al.* (2023).

The confirmation of significant statistical differences strengthened the validity of these findings and supported the aim of this study to identify the impact of growing seasons on sorghum's nutritional value. The results also reinforced the necessity for targeted breeding programs to optimize sorghum production for specific agro-climatic conditions.

The proximate analysis of sorghum seeds revealed significant variations across varieties and growing seasons (Table 3).

In general, the dry season resulted in higher nutrient concentrations compared to those in the rainy season. The highest starch content in the rainy season was observed in Kawali (64.16%), followed by Bioguma (63.11%), Red Glutinous Sorghum (49.29%), Samurai (46.42%), KD4 (44.33%), and the lowest in Black Bonteb (11.99%). In contrast, in the dry season, Bioguma exhibited the highest starch content (65.34%), while Black Bonteb remained the lowest (44.6%).

Moisture content across all varieties remained below 14%, ensuring seed stability for storage. The highest protein content was recorded in Black Bonteb (7.68%) during the rainy season, followed by Red Glutinous Sorghum (7.37%), while Samurai had the lowest protein content (4.48%). Notably, Bioguma exhibited an increase in protein content in the dry season (6.48%), suggesting a potential impact of reduced water availability on protein accumulation.

These findings aligned with the objective of this study to evaluate the effects of seasonal variations on sorghum's nutritional composition. The higher starch content observed in the dry season suggested that reduced water availability may promote carbohydrate accumulation, which is beneficial for industrial applications, such as flour production. Meanwhile, the increase in protein content in specific varieties during the rainy season supports the suitability of sorghum for nutritional applications where higher protein intake is desired.

Table 2 ANOVA results for proximate composition as well as tannin and amylose contents in sorghum varieties across seasons

Component	Source of variation	DF	Sum of squares (SS)	Mean square (MS)	F-value	P value (Significance)
Starch content	Variety	5	126.53	25.31	15.67	0.002**
	Season	1	24.78	24.78	12.83	0.004**
	Variety × Season	5	8.62	1.72	2.95	0.048*
Protein content	Variety	5	18.34	3.67	8.42	0.011**
	Season	1	5.92	5.92	6.27	0.039**
	Variety × Season	5	2.89	0.58	2.13	0.088
Tannin content	Variety	5	9.65	1.93	7.82	0.017**
	Season	1	3.42	3.42	5.38	0.044**
	Variety × Season	5	1.56	0.31	1.87	0.102
Amylose content	Variety	5	22.71	4.54	14.92	0.003**
	Season	1	8.33	8.33	9.74	0.027**
	Variety × Season	5	3.91	0.78	3.21	0.042**

Table 3 Proximate composition of sorghum varieties in different growing seasons

Variety	Starch (%)	Protein (%)	Fat (%)	Moisture (%)	Ash (%)
Bioguma	**63.11** / 65.34	**5.62** / 6.48	**3.3** / 2.0	**13.5** / 13.2	**1.7** / 1.8
Kawali	**64.16** / 63.77	**5.72** / 3.63	**2.8** / 3.26	**13.4** / 13.1	**2.1** / 2.2
Samurai	**46.42** / 51.25	**4.48** / 4.87	**4.12** / 0.5	**14.0** / 13.5	**1.8** / 1.9
KD4	**44.33** / 56.73	**4.8** / 4.21	**3.0** / 1.59	**13.9** / 13.3	**2.2** / 2.3
Red Glutinous	**49.29** / 53.82	**7.37** / 5.39	**2.9** / 2.74	**13.6** / 13.3	**3.8** / 3.9
Black Bonteb	**11.99** / 44.6	**7.68** / 5.56	**2.5** / 2.61	**13.7** / 13.4	**3.8** / 3.9

Note: Values represent **rainy season** / dry season data

Tannin Content Analysis

Tannin content was significantly influenced by varieties and growing seasons (Fig. 2). Bioguma, KD4, and Kawali exhibited higher tannin content in the dry season compared to that in the rainy season, whereas Samurai, Red Glutinous Sorghum, and Black Bonteb showed lower tannin content in the dry season. The variation can be attributed to environmental stress factors, where increased UV exposure and reduced water availability in the dry season may enhance tannin synthesis in certain genotypes. These findings are consistent with previous research indicating that sorghum tannin levels are highly responsive to environmental conditions (Keyata *et al.* 2021).

The higher tannin content in the dry season could contribute to enhanced antioxidant properties, making these varieties suitable for functional food applications. However, increased tannins may also reduce digestibility, which must be considered in breeding programs aimed at developing low-tannin sorghum varieties for human consumption.

Amylose Content Analysis

Amylose content varied significantly among genotypes and seasons (Fig. 3). In dry season, amylose content increased in Bioguma (14.8%), KD4 (14.5%), Kawali (14.3%), and Samurai (14.1%), classifying them as "pera" types (> 14% amylose). Conversely, Red Glutinous Sorghum (4.71%) and Black Bonteb (4.62%) exhibited lower amylose levels, making them suitable for glutinous applications. Higher amylose content contributes to firmer rice textures, whereas lower levels result in softer, stickier grains, aligning with consumer preferences for different food products (Wang *et al.* 2022; Nakamura *et al.* 2020).

These results confirmed the importance of amylose content in determining the textural properties of sorghum-based food products. The significant seasonal variations highlighted the need for proper selection of sorghum varieties based on end-use applications, whether intended for flour-based processed foods or traditional sticky rice alternatives.

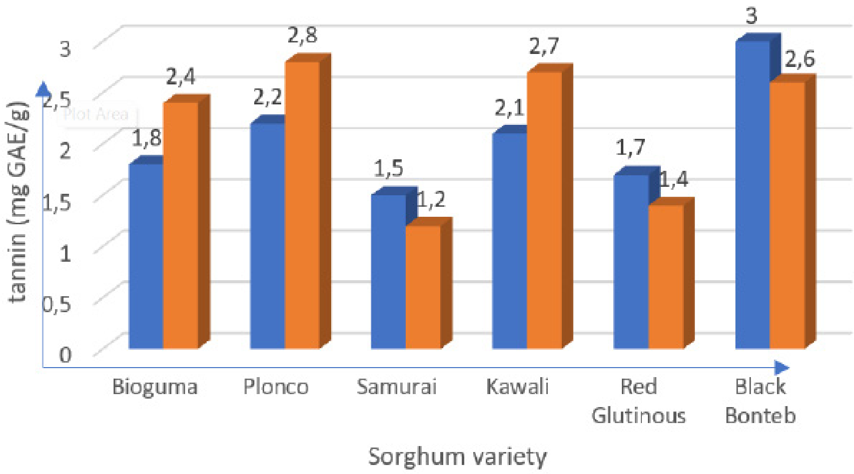

Figure 2 Tannin content analysis

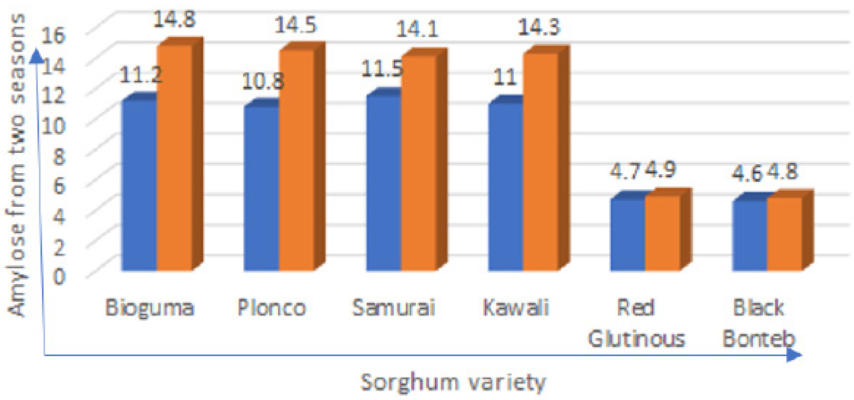

Figure 3 Amylose content analysis

Effect of Varieties and Growing Seasons on Nutritional Composition

Starch Content

Starch content varied significantly between varieties (P ≤ 0.01) and growing seasons (P ≤ 0.01). A significant interaction effect (P ≤ 0.05) indicated that the impact of seasonal variation on starch accumulation was genotype-dependent. Bioguma and Kawali consistently exhibited higher starch concentrations, with notable increases during the dry season, highlighting their potential for industrial starch production under water-limited environments.

Protein Content

Significant differences were observed among sorghum varieties (P ≤ 0.05) and between seasons (P ≤ 0.05), while the interaction effect was not significant. The results suggested that seasonal influence on protein content was relatively consistent across genotypes. Higher protein levels during the rainy season may be attributed to increased nitrogen assimilation and protein biosynthesis under favorable water availability, as supported by prior studies (Attia & Alamer 2024).

Tannin Content

Tannin content varied significantly across varieties (P ≤ 0.05) and growing seasons (P ≤ 0.05), although no significant interaction was found. This indicated a consistent seasonal pattern across genotypes. Elevated tannin levels in the dry season may reflect a physiological response to environmental stresses, such as drought and elevated solar radiation, which can enhance secondary metabolite accumulation.

Amylose Content

Amylose content exhibited highly significant variation among varieties (P ≤ 0.01) and growing seasons (P ≤ 0.05), with a significant interaction effect (P ≤ 0.05), which suggested that some genotypes were more responsive to seasonal shifts in amylose biosynthesis. The increased amylose levels during the dry season may be due to reduced grain moisture and prolonged starch deposition phases, as also observed in drought-adaptive cereals.

Interaction Between Genotype and Environment

The interaction effects between varieties and growing seasons were significant for starch (P = 0.048) and amylose content (P = 0.042), highlighting the importance of genotype-environment interactions. The interactions suggested that certain sorghum varieties responded differently to environmental changes, making it essential to consider seasonal influences when selecting varieties for specific food applications. The results provided evidence that breeding programs should prioritize environmental adaptability to maximize the nutritional quality of sorghum.

Post-hoc Tukey Test and Significant Pairwise Differences

Post-hoc Tukey tests confirmed that the differences in starch content between Bioguma and Black Bonteb were statistically significant. This finding supported the earlier observations that Bioguma consistently accumulated more starch, particularly in the dry season, making it a preferred variety for flour production and industrial processing. In contrast, Black Bonteb, which exhibited the lowest starch content but higher tannin levels, was more suitable for functional food applications requiring higher antioxidant properties.

Implications to Sorghum Cultivation and Utilization

The confirmation on significant impact of growing seasons toward nutritional composition of sorghum genotype findings provides valuable insights into the selection of suitable sorghum varieties for different agro-climatic conditions and food industries. Based on our study, certain sorghum genotype is suitable for certain utilization, and therefore, it is best cultivated in certain growing season, as follows.

a. For flour-based products, varieties with higher starch content (e.g., Bioguma, Kawali) are preferable, which are best cultivated in dry season.

b. For protein-rich applications, Black Bonteb and Red Glutinous Sorghum varieties grown during the rainy season may have yielded sorghum having higher protein content.

c. For antioxidant-rich functional foods, high-tannin varieties (e.g., Black Bonteb) may be more suitable, which are best cultivated during the dry season.

d. For glutinous applications, Red Glutinous Sorghum, with lower amylose content, remains the best choice and better be cultivated in the dry season.

These results further justify the need for targeted breeding programs that consider both genetic factors and environmental adaptability to enhance the role of sorghum in sustainable food systems.

The ANOVA analysis validated that seasonal variations significantly affected the nutritional composition of sorghum, particularly starch, protein, tannin, and amylose contents. These variations emphasized the influence of environmental conditions, such as rainfall, temperature, and soil moisture, on metabolic pathways related to carbohydrate and protein biosynthesis (Zhang *et al.* 2020). For instance, higher starch and amylose levels observed during the dry season suggested that water stress may enhance carbohydrate accumulation due to limited vegetative growth and longer grain-filling duration. Conversely, elevated protein content in some varieties during the rainy season indicated enhanced nitrogen uptake and assimilation under higher moisture conditions.

The findings of this study support the development of strategic breeding and cultivation practices to optimize sorghum production for specific agro-climatic conditions. Selecting varieties with stable nutritional profiles across seasons could enhance food and feed quality, while those responsive to seasonal cues may be targeted for specific industrial uses, such as starch-based bio-products or protein-enriched food ingredients. Moreover, understanding genotype-environment interactions could guide the development of climate-resilient sorghum cultivars tailored to both nutritional and functional demands.

Future research should explore the underlying genetic and physiological mechanisms regulating these seasonal variations, particularly genes involved in starch branching, protein synthesis, and phenolic compound biosynthesis. Additionally, post-harvest processing techniques, such as malting, fermentation, and extrusion, should be evaluated for their ability to enhance or stabilize nutrient content under varying environmental conditions, thereby improving the overall value chain of sorghum.

CONCLUSION

Growing season significantly affected proximate composition as well as tannin and amylose contents of sorghum varieties. The dry season generally led to higher starch (up to 65.34% in Bioguma) and amylose levels (up to 14.8% in Bioguma), whereas the rainy season favored higher protein accumulation (up to 7.68% in Black Bonteb). The statistical analysis confirmed significant differences ($P < 0.05$) among varieties and growing seasons, reinforcing the influence of environmental factors on sorghum's nutritional profile.

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