






Plant Growth, Nitrogen Content, Nitrogen Uptake, and Seed Quality in Six Bambara Groundnut (*Vigna subterranea* (L.) Verdc) Landraces

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Abstract

Bambara groundnut (*Vigna subterranea* (L.) Verdc) is recognized for its nutritional benefits and ability to improve soil fertility through nitrogen fixation. This study evaluated growth performance, nitrogen dynamics, and seed quality across six landraces: Tasikmalaya, Sukabumi, Sumedang, Small Sumedang, Bogor, and Gresik. The experiment was conducted at IPB University's Sawah Baru experimental field from July 2022 to March 2023. The experiment used a randomized complete block design with four replications. The measured variables were petiole length, number of petioles, number of leaves, leaf greenness, plant dry weight, nitrogen content, nitrogen uptake in roots, petioles, leaves, and pods, protein content in pods, and seed quality. Results showed significant variation among landraces. Gresik exhibited superior vegetative growth and dry biomass, while Tasikmalaya had the highest pod nitrogen (4.58%) and protein content (28.03%), indicating efficient nitrogen assimilation. Nitrogen analysis revealed distinct uptake patterns across landraces, particularly with Gresik, where a rapid increase in nitrogen suggests that this landrace is well-suited to environments where nitrogen is efficiently fixed and mobilized toward reproductive growth. Sukabumi and Bogor showed the highest germination rates (94%), and Bogor and Gresik had the highest vigor indices (76% and 72%). Overall, Gresik is recommended for balanced performance in growth and seed vigor, while Tasikmalaya is optimal for protein yield and nitrogen use efficiency.

Keywords: biomass accumulation, landrace variability, nitrogen assimilation, protein content, vigor index

Introduction

Bambara groundnut (*Vigna subterranea* (L.) Verdc.) has received more attention in crop science recently than other underutilized crops due to its agronomic and nutritional features (Boulay et al., 2020). Bambara groundnut is measured as a balanced diet because of the high percentage of carbohydrates (55-77%), protein (17-25%), fat (1.4-12%), fiber (5.0-12%), minerals (potassium, phosphorus, magnesium, iron, zinc) and vitamins (vitamin B, E, and antioxidant) (Musah et al., 2021).

Bambara groundnut is an important legume indigenous to Africa, has high nutritional value, and the ability to grow in low-input agricultural systems. One of its key features is its ability to fix atmospheric nitrogen, which can enhance soil fertility and reduce the need for synthetic fertilizers (Musa and Singh, 2019; Majola et al., 2021). Bambara groundnut has symbiotic relationships with nitrogen-fixing bacteria, which enable it to convert atmospheric nitrogen into forms usable by plants. This process enriches the soil with nitrogen, benefiting subsequent crops in rotation systems. The nitrogen-fixing ability of Bambara groundnut not only supports its growth but also contributes to the nitrogen economy of the cropping system. This makes Bambara groundnut a valuable crop for sustainable agriculture, especially in regions with low soil fertility (Musa and Singh, 2019).

Nitrogen is considered an essential element for the growth and improvement of crops. Nitrogen is a critical component of amino acids, which are the building blocks of proteins. Proteins serve as structural support, biochemical catalysts, hormones, enzymes, building blocks, and initiators of cellular death (Jain et al., 2022). Nitrogen is a key element in the synthesis of chlorophyll, the pigment responsible

for photosynthesis. Adequate nitrogen is essential for efficient photosynthesis and energy production, which are vital for plant growth (Marschner, 2017). Nitrogen affects plant growth by influencing leaf expansion, biomass accumulation, and overall plant development. Nitrogen deficiency can lead to reduced growth, leaf chlorosis, and low crop yields (Leghari et al., 2016). The uptake pattern of nitrogen during plant growth is a crucial aspect of nutrient management, as it directly influences plant development, yield, and overall productivity. Nitrogen is a vital macronutrient, primarily acquired by plants as nitrate (NO_3^-) or ammonium (NH_4^+), and its availability significantly impacts various physiological and developmental processes (Luo et al., 2020). Different stages of plant growth exhibit varying nitrogen demands, which can be maximized through carefully timed nitrogen applications.

It is essential to recognize that the interaction between nitrogen availability and plant physiological responses is a complex phenomenon. Plants have evolved sophisticated mechanisms for nitrogen sensing and uptake, regulated by signal transduction pathways that adjust to the fluctuations in nitrogen sources available within the soil environment (O'Brien et al., 2016; Krouk, 2016). For example, nitrate transporters facilitate the movement of nitrates from the soil into plant roots, activating signaling pathways that stimulate growth and development (O'Brien et al., 2016). Nitrogen uptake during plant growth is a dynamic process influenced by the available nitrogen sources, plant developmental stages, and external management practices.

Research indicates that Bambara groundnut accumulates nitrogen in various parts of the plant, including leaves, stems, roots, and seeds. The nitrogen content varies among different landraces and environmental conditions. A previous study shows that nitrogen fixation and uptake efficiency can significantly impact the growth and yield of Bambara groundnut (Majola et al., 2021). This research aimed to examine plant growth, nitrogen content, nitrogen uptake, and seed quality in six Bambara groundnut landraces.

Materials and Methods

The research was conducted at the Sawah Baru experimental field, testing laboratory, and seed storage and quality testing laboratory of the Department of Agronomy and Horticulture, IPB University, from July 2022 to March 2023.

The experiment employed a one-factor randomized complete block design, using landraces from Tasikmalaya, Sukabumi, Sumedang, Small Sumedang, Bogor, and Gresik, with four replications. Tillage was performed 14 days before planting. A 500-gram soil sample was composited from five points taken diagonally at a depth of 20 cm, after which samples were taken for soil analysis. Soil analysis was conducted before and after planting. Chicken manure was applied at a dose of 2 tons.ha⁻¹, and dolomite lime ($\text{CaMg}(\text{CO}_3)_2$) 500 kg.ha⁻¹ was added before planting. Seeds were planted in a 169 m² area with a total of 24 plots using a 60 cm x 25 cm plant spacing (Suryati et al., 2019). Each plot consisted of approximately 1127 plants. Inorganic fertilizers were applied at planting time through the furrows next to the plant rows, with a dose of urea at 50 kg.ha⁻¹, SP-36 100 kg.ha⁻¹, and KCl 75 kg.ha⁻¹ (Fitriesta et al., 2016; Sari et al., 2021). The number and length (cm) of petioles, and the number of trifoliolate leaves were observed from 14 days after planting (DAP) until the plants entered the generative stage (35 DAP). Canopy diameter (cm) was observed from 49 to 70 DAP with an interval of 7 days. The level of leaf greenness was observed from 21 to 70 DAP with an interval of 7 days using a SPAD 502 Chlorophyll Meter. The observations were conducted on five sample plants in each experimental plot. The plant's dry weight was observed from 21 to 112 DAP. The plants were pulled out from their roots, one plant per experimental plot, and then cleaned off the attached soil. Cleaned plants were then separated into parts (roots, stems, leaves, and pods), and each part of the plant was placed into an envelope and dried in the oven at 60°C for 3 days. The measurement of nitrogen content of roots, leaves, petioles, and pods was taken from 0.5–1.0 g of dried samples. Measurement of nitrogen content using the Kjeldahl method (Arena et al., 2020). Nutrient uptake analysis was conducted using data obtained from nitrogen content and the destructive dry weight of each plant organ. Nitrogen uptake was measured by the following equation (Black, 1965):

$$\text{Nitrogen uptake} = (\text{dry weight} \times \text{nitrogen content})$$

Protein content was determined using the Kjeldahl method. Measurement of pod protein content was carried out at harvest. Protein measurements were taken on the seed and shells, and sample preparation was carried out using the same method as the nitrogen content analysis.

Seed quality tests were conducted by planting seeds in 25 cm x 20 cm plastic boxes using sand as a medium. Each treatment was repeated three times, consisting of 50 seeds. Seed quality observation includes germination percentage and vigor index

variables. Germination percentage was calculated based on the percentages of normal seedlings (NS) in the first count (NS I; 5 DAP) and final count (NS II; 10 DAP) (ISTA, 2018). The vigor index was calculated based on the percentage of normal seedlings in the first count (NS I; 5 DAP). The germination percentage and vigor index were calculated using the following equation:

$$\text{Germination percentage (\%)} = \frac{\text{Number of NS I} + \text{Number of NS II}}{\text{Total seeds germinated}} \times 100\%$$

$$\text{Vigor index (\%)} = \frac{\text{Number of NS I}}{\text{Total seeds germinated}} \times 100\%$$

The data were analyzed using analysis of variance (ANOVA) at an α level of 5%. Treatment with a significant effect was further analyzed with DMRT at $\alpha = 5\%$.

Results and Discussion

Soil Properties and Climate Conditions at the Experimental Site

The soil properties before planting showed that the soil pH was 5.53 (slightly acid), the content of C-organic was 1.51% (medium), N-total was 0.26% (medium), total P_2O_5 was 188.75 mg.100 g⁻¹ (very high), and total K_2O was 27.85 mg.100 g⁻¹ (medium). After planting, several changes were observed; the soil pH (H_2O) increased to 6.33, indicating a shift towards a more neutral pH, which can enhance nutrient availability and microbial activity beneficial to plant growth. Studies indicated that a shift towards a neutral pH can facilitate better nutrient solubility and microbial activity, which are beneficial to plant growth (Rolbiecki et al., 2021; Bista et al., 2019). C-organic content increased to 2.35%, suggesting an increase in organic matter, possibly due to the decomposition of plant residues or organic amendments during the planting cycle. This phenomenon is supported by findings that increased organic matter has a positive influence on soil structure and fertility (Salahin et al., 2021; Qian et al., 2023). The total nitrogen (N-Total) content showed a slight increase from 0.26% to 0.27%, which, although minimal, reflects improvement in soil fertility and nitrogen retention. Literature suggests that the

management of nitrogen, particularly through organic inputs, significantly affects soil nitrogen dynamics and can enhance overall nitrogen retention in agricultural soils (Cui et al., 2019; Wang et al., 2018). A study has also demonstrated that nitrogen fertilization correlates with biomass production, which in turn influences nitrogen retention, thereby enhancing the soil fertility potential (Kong et al., 2022). However, the phosphorus (P_2O_5) content decreased from 188.75 mg.100 g⁻¹ to 155.83 mg.100 g⁻¹, possibly due to plant uptake or leaching during the growing period. It aligns with findings by Płaza and Rzażewska (2022) that nitrogen application can lead to alterations in phosphorus dynamics, showcasing the complexities surrounding nutrient interactions within soils. Such nutrient management practices are crucial, as they significantly influence soil fertility outcomes and crop performance. In contrast, the potassium content (K_2O) increased significantly from 27.85 mg.100 g⁻¹ to 38.96 mg.100 g⁻¹ (Table 1). Previous studies have consistently demonstrated that proper nutrient management, including potassium, is crucial for optimal plant growth and yield, as potassium plays a vital role in various physiological processes of plants (Filho et al., 2020; Qu et al., 2023). Thus, the combination of these nutrient dynamics illustrates a complex interaction that enhances agricultural productivity and soil health. The rainfall during the experiment averaged 230.62 mm per month. The average temperature was 25.7°C with a relative humidity of 75.2%. The data was collected from the Dramaga Climatology Station accessed through <https://data.bmkg.go.id/>. These parameters affected soil properties, plant physiological processes, and overall crop performance. It also allows comparison with other agroecological zones and enhances the credibility of the research findings.

Plant Growth

The growth and development of vegetative organs characterize the vegetative phase. The duration of this phase varies depending on the type of plant and the environment. Bambara groundnut is an indeterminate plant; vegetative growth proceeds even though it has entered the generative phase. Vegetative growth variables are presented in Table 2.

Table 1. Soil properties before and after planting

Parameters	Before planting	After planting
pH H_2O	5.53	6.33
C-organic (%)	1.51	2.35
N-Total (%)	0.26	0.27
P_2O_5 (mg.100 g ⁻¹)	188.75	155.83
K_2O (mg.100 g ⁻¹)	27.85	38.96

The length of the petiole at 21 to 42 DAP showed significantly different results. In general, the Sumedang landrace had the highest petiole height, while the Gresik landrace had the lowest. However, at the 49 DAP, petiole heights across the landraces were relatively similar, with values ranging from 21.7 cm (Gresik) to 25.2 cm (Sumedang). This aligns with the findings of Muhammad et al. (2023), who noted substantial morphological variations among landraces, emphasizing that specific traits, including plant height and petiole length, are significant factors influencing crop performance. These variations in morphological traits can be attributed to genetic diversity among the landraces, a theme echoed in various studies exploring the adaptability of Bambara groundnut in diverse environments, including research on the impact of environmental factors and genetic traits on crop performance (Mubaiwa et al.,

2018). The number of petioles tended to increase with plant age, but different landraces exhibited varying growth patterns. At the maximum vegetative phase (49 DAP), the Gresik landrace reached the highest count of 57.8 petioles. This suggests that the Gresik landrace is more prolific in terms of branching, possibly due to environmental conditions that support more vegetative growth. Such prolific branching is supported by findings from Uba et al. (2023) and Khan et al. (2020), suggesting that genotypes exhibiting higher branching density are associated with specific environmental adaptations that enhance their survival and productivity. The leaf number trend showed an apparent increase as the plants matured, with the most significant growth occurring at 49 DAP across all landraces. Gresik landrace showed a high number of 52.8 leaves.

Table 2. Vegetative growth of six Bambara groundnut landraces

Time (DAP)	Landraces					
	Tasikmalaya	Sukabumi	Sumedang	Small Sumedang	Bogor	Gresik
Length of petioles (cm)						
21	15.8ab	16.8ab	18.0a	18.0a	14.3b	13.5b
28	19.1a	19.4a	19.3a	18.3ab	16.2bc	14.2c
35	20.8a	20.4a	21.8a	20.6a	17.3b	17.7b
42	21.6ab	21.7ab	23.0a	21.2ab	22.1ab	19.0b
49	23.3a	23.5a	25.2a	23.1a	22.5a	21.7a
Number of petioles						
21	9.5a	9.3a	8.0a	7.3a	7.3a	9.0a
28	13.5a	13.5a	12.8a	11.8a	11.8a	14.3a
35	17.0ab	20.0ab	19.5ab	17.0ab	16.8b	23.0a
42	23.3c	32.5abc	32.8abc	28.0bc	36.8ab	40.8a
49	28.0c	41.8b	40.3b	31.3c	41.5b	57.8a
Number of leaves						
21	5.0b	6.3a	6.0ab	6.0ab	5.3ab	6.0ab
28	9.3a	10.8a	10.0a	10.0a	9.6a	11.3a
35	14.5a	16.0a	15.3a	16.0a	15.0a	19.0a
42	23.8a	26.0a	25.0a	24.8a	33.0a	32.5a
49	30.3c	36.5bc	33.3bc	34.5bc	47.8ab	52.8a
Canopy diameter (cm)						
35	42.2a	44.0a	45.8a	42.0a	42.8a	40.8a
42	45.1ab	47.4ab	50.4a	45.6ab	41.8b	46.5ab
49	50.0a	55.5a	55.5a	44.9a	53.0a	54.8a
56	52.8ab	51.9ab	50.2ab	46.5b	60.0a	59.2a
63	56.5ab	53.7b	51.0b	50.7b	65.5a	59.9ab
70	69.1ab	57.1abc	53.3c	57.0bc	65.1abc	70.7a

Notes: Values followed by different letters in the same row indicate significant differences based on the 5% DMRT.

Canopy diameter of all six landraces showed significantly different results from 8 weeks to 10 weeks. Ikenganyia et al. (2017) stated that agricultural practices, particularly spacing and nutrient treatment, can significantly affect the vegetative development of Bambara groundnut. Bambara groundnut can be classified into three growth types based on canopy diameter, including bunch (canopy diameter <40 cm), semi-bunch (canopy diameter 40-80 cm), and spreading or open (canopy diameter >80 cm) (Ezedinma and Maneke, 1985). Throughout the observation period, all landraces had canopy diameters ranging from 52.1 cm to 70.7 cm. Thus, they were classified as semi-bunch type. Research has shown that the semi-bunch type allows Bambara groundnut to maximize sunlight capture and nutrient uptake, resulting in increased yield potential under optimal conditions (Makanda et al., 2010). This growth form has been linked to longer pod filling periods, suggesting that cultivars showcasing this trait might be superior, especially in diverse agricultural environments (Makanda et al., 2010). Such findings suggest that selection for traits associated with the semi-bunch growth type can improve yield performance, particularly in off-season production scenarios, thereby enhancing food security in semi-arid regions (Mubaiwa et al., 2018).

Leaf greenness is an indicator of leaf chlorophyll content. Measurement of leaf greenness was carried out up to 70 DAP. The leaf greenness of six Bambara groundnut landraces until the end of observation is presented in Table 3. The results showed that the level of leaf greenness in the six landraces was not significantly different except at 28 and 35 DAP. The highest level of leaf greenness at 28 DAP was achieved by the Sumedang, Small Sumedang, Tasikmalaya, and Gresik landraces with values ranging from 38.87 to 40.45. At 35 DAP, the highest leaf greenness was produced from the Sumedang landrace (42.12). Plants

with higher chlorophyll concentrations can absorb more light, which indicates photosynthetic efficiency. Plants with chlorophyll deficiency exhibit reduced photosynthetic activity, as the role of chlorophyll is crucial for optimal photosynthesis (Wang et al., 2022). Studies have shown that increased nitrogen supply leads to higher chlorophyll content in leaves (Bassi et al., 2018). Nitrogen is a core component of chlorophyll molecules, which means its availability directly influences chlorophyll synthesis and, consequently, photosynthetic efficiency.

Dry weight is a result of the photosynthesis process, where the plant converts sunlight into chemical energy stored in the form of organic compounds. The dry weight of each plant organ is presented in Figure 1. Each landrace demonstrates varying patterns of dry weight accumulation in different plant parts. Gresik consistently exhibited high dry weights across all plant parts, particularly in the petiole, leaf, and pod, indicating robust growth associated with its efficient photosynthetic capacity. Adequate light availability is crucial for photosynthesis, which directly impacts biomass accumulation. A study documenting the positive relationship between light availability and biomass of legumes highlights the role of environmental factors in enhancing the growth performance of crops such as Bambara groundnut (Ikenganyia et al., 2017). Furthermore, sufficient nitrogen levels enhance chlorophyll production, improving photosynthetic efficacy and explaining the higher dry weights observed in the Gresik landrace (Khansa et al., 2022). Small Sumedang has almost the same dry weight as Gresik in roots, petioles, and pods, especially at the end of the observation. Bogor has a more gradual increase in dry weight, with later peaks, indicating slower but steady growth. This aligns with observations from studies on phenotypic variations in Bambara groundnut, where different genotypes show varying growth rates due to their genetic makeup and

Table 3. Leaf greenness of six Bambara groundnut landraces

Time (DAP)	Landraces					
	Tasikmalaya	Sukabumi	Sumedang	Small Sumedang	Bogor	Gresik
21	43.57a	39.60a	36.32a	44.30a	37.67a	37.07a
28	39.20a	38.07ab	40.45a	38.50a	36.05b	38.87a
35	39.67b	39.30b	42.12a	39.67b	38.82b	39.35b
42	41.40a	40.90a	43.97a	42.57a	42.80a	42.62a
49	41.85a	41.42a	41.60a	42.32a	43.17a	43.62a
56	40.11a	39.06a	41.33a	40.18a	39.53a	40.75a
63	45.92a	45.22a	45.42a	40.86a	41.53a	42.05a
70	48.41a	48.91a	48.21a	45.97a	47.69a	45.56a

Notes: Values followed by different letters in the same row indicate significant differences based on the 5% DMRT.

environmental adaptability (Temegne et al., 2020). Such insights suggest that slower initial growth in some landraces may confer resilience, offering long-term advantages. Tasikmalaya and Sukabumi both exhibit steady increases in dry weight, with slight differences in the timing of peaks, indicating that these landraces reach their full potential earlier in the growing cycle. The graphs indicated that Small Sumedang and Gresik exhibit more efficient biomass accumulation across different plant parts. Dry weight is a crucial measurement for assessing biomass accumulation in plants and other organisms. Dry weight represents the amount of organic matter present after removing water content, providing a standardized way to compare biomass across different samples and growth stages.

Nitrogen Content and Nitrogen Uptake Pattern

The pattern of nitrogen content in roots, petioles, leaves, and pods is presented in Figure 2. All landraces showed an increase in nitrogen content in the roots (Figure 2.a) at the beginning of growth. The nitrogen level increased during the vegetative phase (until 42-56 DAP), and then it slowly decreased until harvest time (112 DAP). The nitrogen content in the Bambara roots during the growth period ranged from 1.16% to 3.00%. This pattern is understandable because, in the early to mid-vegetative phase, plants actively form root tissues and fix nitrogen. The same pattern was shown in the leaves and petioles. At the beginning of the growth phase, nitrogen is needed to support vegetative growth. At the generative phase, the nitrogen content in the leaves tends to decrease.

Nitrogen content in petioles was 0.574%-4.059% (Figure 2.b) and leaves 2.286%-5.770% (Figure 2.c). While 2.5% to 5.0% is a broad guideline, some studies suggest that legumes can exhibit high nitrogen use efficiency (NUE) even with slightly lower leaf nitrogen concentrations (Del Pozo et al., 2000). Accurate assessments of nitrogen in leaves have shown that concentrations can vary significantly, with values often reported to be 2.5% - 5.0%, depending on nitrogen fertilization practices and the plant's developmental stage (Sánchez-Navarro et al., 2020). Wang et al. (2016) discusses that nitrogen accumulation in seeds largely depends on the remobilization of nitrogen from vegetative parts, particularly during the grain-filling stage in legumes, such as soybean. This suggests that leaf nitrogen is crucial during this stage, as it is linked to the final yield of legumes due to its role in supplying the necessary nitrogen for seed development. The highest nitrogen levels are observed in the pods. After establishing vegetative growth, the plant likely shifts more nitrogen toward reproductive structures. The pods began to form at 70 DAP except in Gresik and Sumedang landraces (77 DAP). At 112 DAP, nitrogen content in the pods ranged from 3.80% to 4.58%, where the highest was obtained from the Tasikmalaya landrace and the lowest from the Sumedang landrace (Figure 2.d). The nitrogen content in legume species varies from approximately 2% to over 6% of their dry matter (Agele et al., 2017; Ishikawa et al., 2020).

Studying the nitrogen uptake pattern of each plant organ provides insight into how nitrogen is distributed and utilized throughout the plant for various functions

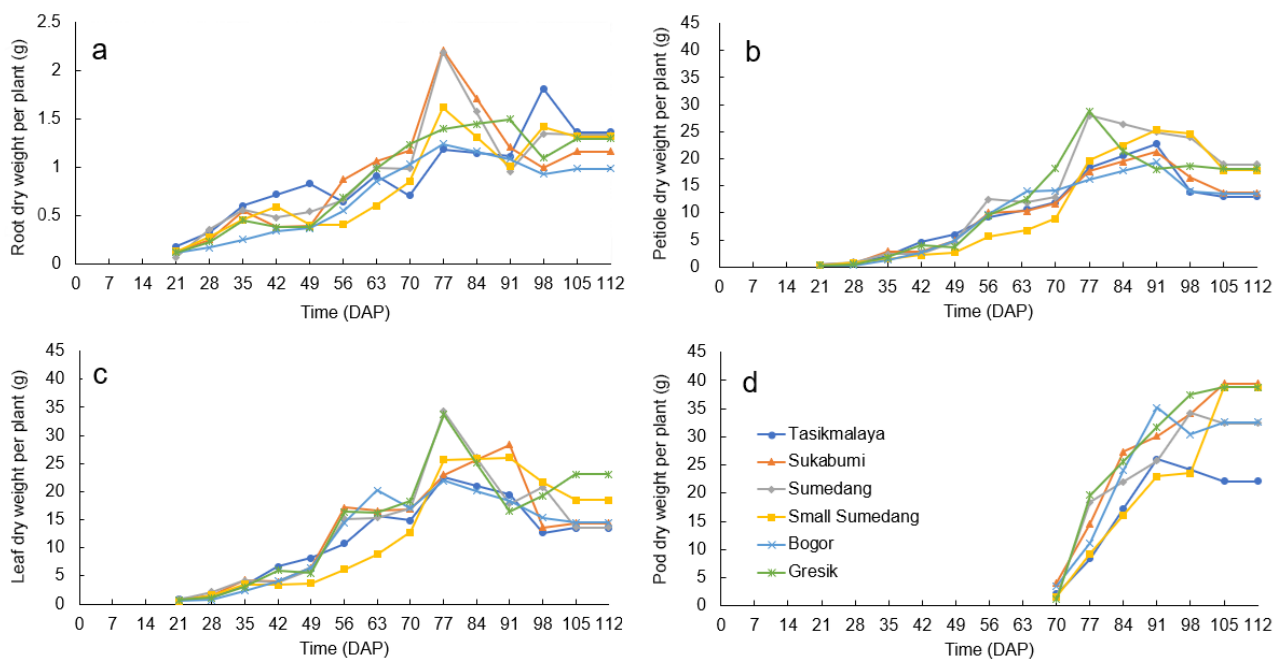


Figure 1. The dry weight of root (a), petiole (b), leaf (c), and pod (d) in six Bambara groundnut landraces

such as growth, development, and reproduction. Each organ (roots, stems, leaves, flowers, etc.) has specific roles in nitrogen assimilation and transport. These patterns explained that pods were more efficient at nitrogen uptake and how nitrogen was allocated to different tissues. The pattern of nitrogen uptake in roots, petioles, leaves, and pods in six Bambara groundnut landraces is presented in Figure 3.

Nitrogen uptake patterns in Bambara groundnut focus on the early vegetative growth phase. During

the reproductive phase, the plant diverts most of the nitrogen into pods. Gresik landrace showed significant nitrogen uptake values around 70 DAP in root and petiole (0.0282 g per plant and 0.2652 g per plant), and 84 DAP in leaves (0.9269 g per plant), indicating high nitrogen fixation and allocation to reproductive structures. The Sukabumi and Small Sumedang showed a moderate increase, peaking around 70 DAP, suggesting that these landraces also perform well in nitrogen uptake, though not as efficiently as Gresik. Tasikmalaya and Bogor landraces followed

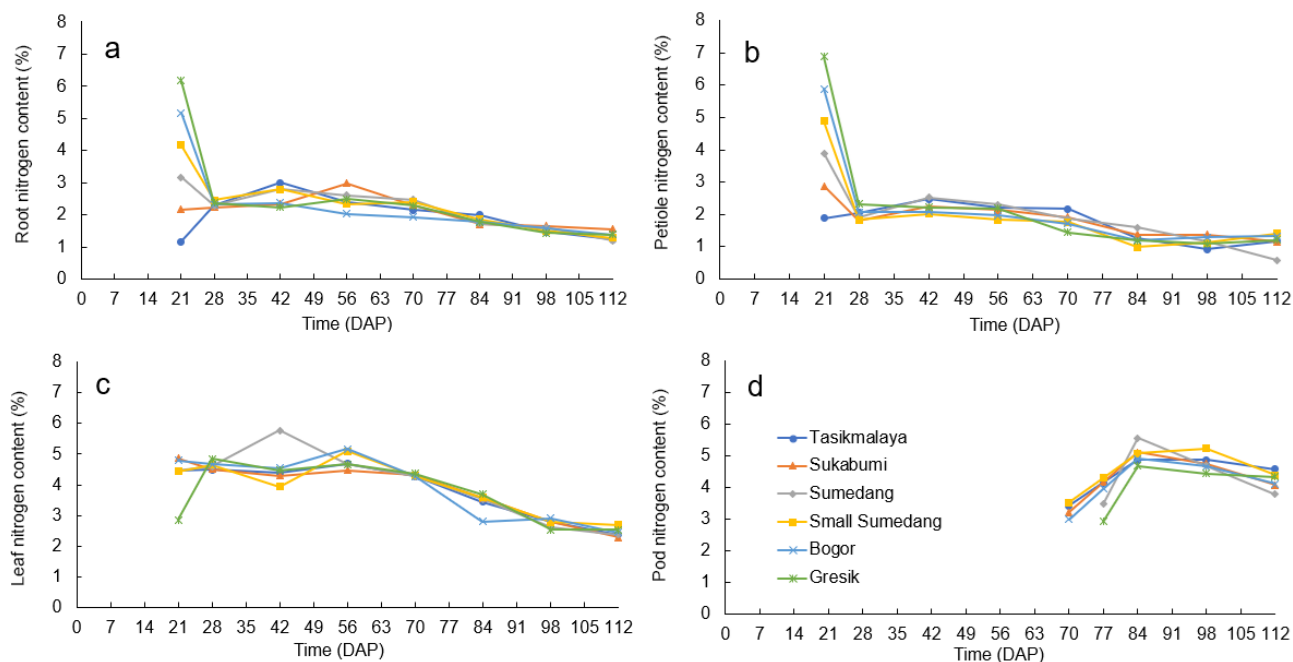


Figure 2. Nitrogen content patterns in root (a), petiole (b), leaf (c), and pod (d)

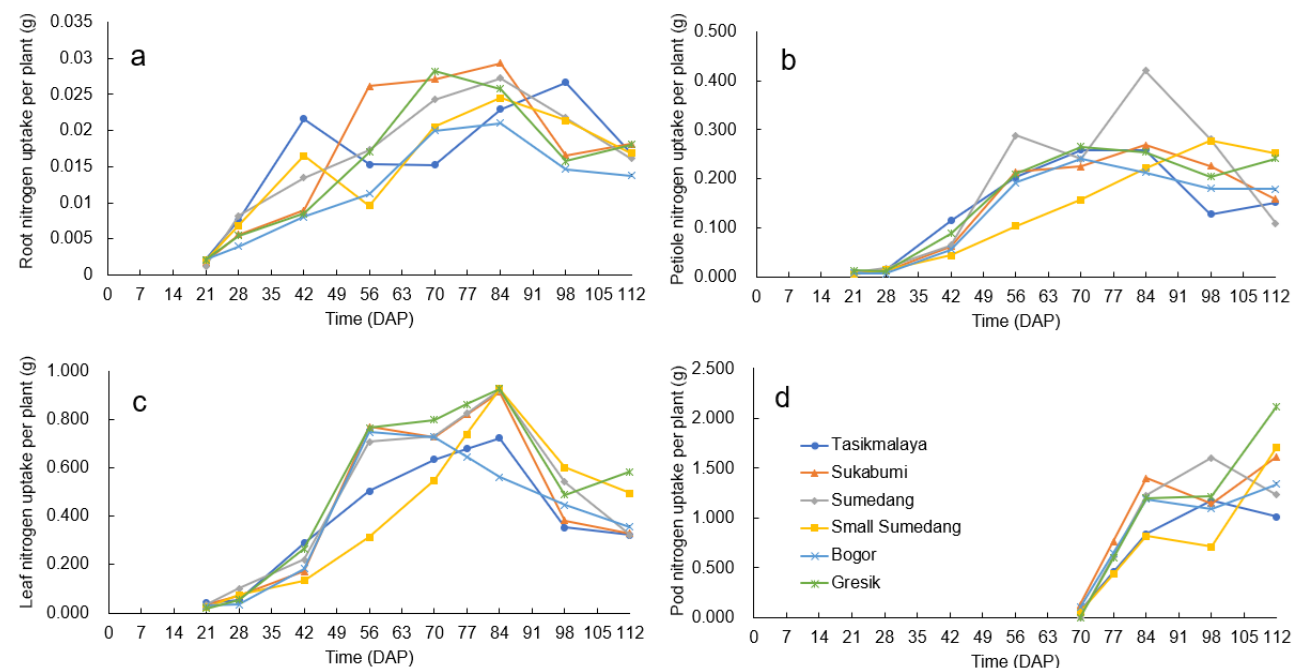


Figure 3. Nitrogen uptake patterns in root (a), petiole (b), leaf (c), and pod (d)

a more gradual nitrogen accumulation pattern, with nitrogen content peaking later in the growth stages, indicating slower but steady nutrient uptake and assimilation.

The patterns observed reflect the varying nitrogen fixation efficiencies of each landrace. Gresik emerges as the most efficient in nitrogen utilization, particularly in pod development, which is essential for yield and seed quality. The rapid increase in nitrogen in Gresik suggests that this landrace is well-suited to environments where nitrogen is efficiently fixed and mobilized for reproductive growth. The Bogor landrace, although not as fast in nitrogen accumulation as Gresik, still exhibits a consistent and steady rise in nitrogen content, which may indicate a more balanced distribution of nitrogen between vegetative and reproductive growth phases. The Sukabumi and Small Sumedang exhibit nitrogen accumulation patterns that suggest they may perform well in nitrogen-rich environments, but have slightly less efficient nitrogen fixation compared to Gresik. The Tasikmalaya landrace, with its slower rate of nitrogen uptake, may require more time to accumulate nitrogen, which could affect its overall yield potential; however, it still demonstrates effective nitrogen use during the later stages of development. These differences highlight the importance of nitrogen

efficiency in determining the growth and productivity of Bambara groundnuts under diverse environmental conditions.

Nitrogen plays a crucial role in synthesizing amino acids, which are essential components of proteins. Protein storage in leguminous plants is found in pod structures. The results showed that the protein content in seeds of six Bambara groundnut landraces ranged from 17.43% to 20.10% in seed and 5.68% to 10.05% in shell (Figure 4). The Tasikmalaya landrace has the highest seed protein content (20.10%), while the Gresik landrace has the lowest (17.43%). Studies have reported protein content ranges in Bambara groundnut seeds from approximately 14% to as high as 28% (Arise et al., 2015; Adegbanke et al., 2019; Traoré-Barro et al., 2023). Protein in seeds serves to provide nitrogen, carbon, and sulfur for the development of seeds during germination (Liu et al., 2022; Baud and Lepiniec, 2010). Proteins are the main reserves that are often mobilized and used during the germination of legume species (Zhao et al., 2018). During germination, proteolytic enzymes break down storage proteins, thereby increasing protein digestibility and the availability of free amino acids, which are essential for seedling development (Bera et al., 2023).

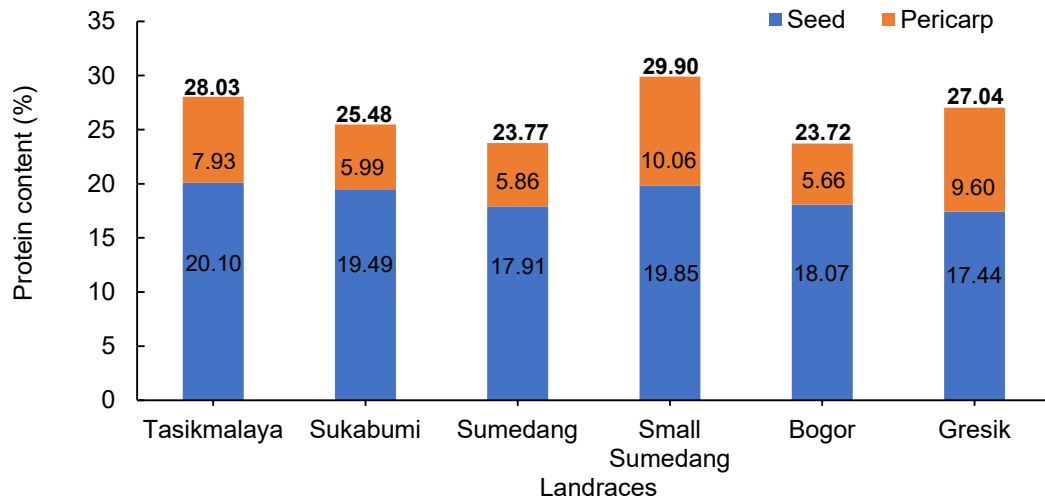


Figure 4. Protein content in the pods of six Bambara groundnut landraces

Table 4. Seed quality variables in six Bambara groundnut landraces

Variable	Landraces					
	Tasikmalaya	Sukabumi	Sumedang	Small Sumedang	Bogor	Gresik
Germination percentage (%)	89.25ab	94.00a	88.00bc	82.75c	94.00a	85.25bc
Vigor index (%)	50.00c	51.25c	58.75bc	62.00b	76.00a	72.00a

Notes: Values followed by different letters in the same row indicate significant differences based on the 5% DMRT test; seed moisture content during testing ranged from 11.05 to 12.52%.

Gresik landrace has a relatively higher protein content in the shell (9.60%) compared to other landraces. The shell of legumes often contains a small amount of nutrients, primarily fibers and sometimes small amounts of protein. Research has shown that peanut shells contain crude protein, typically estimated to range between 2% and 6% of their dry weight (Killı and Beycioğlu, 2022). This protein, though less bioavailable than that found in the seed, may still contribute to the overall amino acid profile. The shell or pericarp plays a crucial role in the translocation and storage of nutrients required for seed development, protecting the developing seed, and influencing the seed's ability to withstand environmental stresses (Olusola et al., 2023).

Seed Quality

The seed quality of six varieties of Bambara groundnut was observed based on the characteristics of the vigor index and germination percentage (Table 4). The vigor index of Bogor (76%) and Gresik (72%) landraces showed the highest results compared to other landraces. Kunene et al. (2022) demonstrate that high-vigor Bambara groundnut seeds can germinate under stress conditions, indicating potential resilience in adverse environmental situations, such as drought. The Sukabumi and Bogor landraces had the highest germination percentage (94%) while Small Sumedang had the lowest (82.75%). In general, the germination percentage of all landraces was high (>80%). According to Muhammad et al. (2023), among the examined landraces of Bambara groundnut, germination percentages have been observed to vary, typically ranging from 50% to 85% under optimal conditions.

Bambara groundnut landraces show variation in morphological and agronomic traits. Numerous studies have documented wide-ranging variability in several characteristics, including biomass accumulation, seed coat color, pod and seed weight, and emergence time among different landraces (Mohammed et al., 2024). The results showed that the Gresik landrace had a relatively higher number of petioles and leaves, as well as a heavier dry mass compared to others. The Tasikmalaya landrace had the lowest number of petioles and leaves, but it had the highest protein and nitrogen content in pods. It indicates that the Tasikmalaya landrace is more efficient in N assimilation.

Conclusions

Gresik landrace showed superior growth characteristics, marked by the number of petioles,

number of leaves, canopy width, dry weight of all organs, and higher nitrogen uptake compared to other landraces. On the other hand, Tasikmalaya landrace, although it had the lowest number of leaves and petioles, showed the highest nitrogen (N) and protein content in pods. It indicates that the Tasikmalaya landrace is the most efficient in N assimilation. While efficient N assimilation is important for protein synthesis and seed quality, it does not always equate to the highest total biomass or yield. Sukabumi and Bogor landraces had the highest germination capacity (94%) while Small Sumedang had the lowest (82.75%). The highest vigor index was obtained from the Bogor and Gresik landraces, respectively reaching 76% and 72%. Thus, for balanced performance across yield, growth, and seedling vigor, the Gresik landrace is the best choice; for protein content or nitrogen use efficiency, Tasikmalaya is the best.

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