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Agromorphological Characterization and Comparative Productivity of 14 Ecotypes of Bambara Groundnut (*Vigna subterranea* L., Verdc.) Under No-Input Farming Conditions in the District of Abidjan (Côte d'Ivoire)

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Abstract **Original Research Article**

The Bambara groundnut (*Vigna subterranea* L., Verdc.) is a legume belonging to the Fabaceae family and ranks third in terms of production and consumption after peanuts and cowpeas. However, its cultivation is largely neglected and underexploited. Yet its seeds are high in calories and rich in minerals, vitamins, and protein. In Côte d'Ivoire, Bambara groundnut is grown only in the north and center of the country. The main objective of this study was to contribute to food security by evaluating the agronomic performance of 14 Bambara groundnut ecotypes without the use of inputs or phytosanitary products in the autonomous district of Abidjan in southern Côte d'Ivoire. A trial was therefore set up on the experimental plot of the Plant Physiology and Pathology Teaching and Research Unit of Félix Houphouët-Boigny University. Plant growth parameters were assessed at 30 and 45 days after sowing, and yield parameters were assessed at harvest. The results showed variability between ecotypes. The average emergence rate ranged from 31.25% to 83.33%, with the highest performance observed in ecotypes 1 and 2. Plant growth was steady, with average heights ranging from 16.64 to 23.25 cm at 30 DAS and from 22.61 to 26.50 cm at 45 DAS. The highest plant height values were observed in ecotype 2. From a phenological perspective, ecotype 2 was the earliest, initiating flowering at 29 DAS and reaching 50% flowering at 32.33 DAS. Yield parameters also showed significant differences. The average number of pods per plant varied between 22.67 and 64.89. Ecotype 7 had the highest number of pods. The weight of 100 seeds ranged from 41.88 to 66.70 g, with maximum values obtained using ecotypes ECO 1, ECO 5, ECO 8, ECO 9, and ECO 12. All of the ecotypes tested showed an ability to adapt to the soil and climate conditions of southern Côte d'Ivoire.
Keywords: *Vigna subterranea*, Bambara groundnut, fungal genus, seeds, symptoms.

INTRODUCTION

Bambara groundnut (*Vigna subterranea* L., Verdc.) is a legume belonging to the Fabaceae family. It is one of the neglected and underutilized plant species that have been cultivated for thousands of years and contribute to food security in developing countries (Mkandawire, 2007). This plant is valued for its high-calorie seeds, rich in minerals, vitamins, and proteins (Minka and Bruneteau, 2000). Bambara groundnut is a hardy crop, capable of tolerating drought and producing on poor soils where other crops such as beans or peanuts are less suitable (Basu *et al.,* 2007). In general, the seeds are harvested before they are fully ripe and consumed after cooking, sold at markets, or dried for later use as seed, consumption, or commercialization. These food practices show the socio-economic importance of Bambara groundnut for local communities. Furthermore, interest in its production is growing. Global production in 2022 was estimated at 246,511.3 tons, all of which came from Africa, with the main producing countries in West Africa being Niger, Burkina Faso, Togo, and Mali (FAOSTAT, 2024). In Côte d'Ivoire, although this crop is neglected and little data is available on its production, it is grown in the north of the country, often in association with peanuts. Thus, grain legumes such as Bambara groundnut play a crucial role in food and nutritional security, particularly in the current context of climate change (Gbaguidi *et al.,* 2015). Despite its many advantages, Bambara groundnut remains an underutilized crop and one of the most neglected by scientific research (Makanda *et al.,* 2009; Berchie *et al.,* 2012). Today's farmers must contend with climatic constraints, increased demand linked to population growth, changing agri-food needs, biotic pressures on crops, and the preservation of environmental health. In this context, it is essential to promote some of the 5,000 neglected or underutilized plant species known for their resilience and low dependence on inputs. Bambara groundnut is distinguished by its productivity per hectare, which can reach an optimal yield of 4 t/ha (Brink *et al.,* 2000). This hardy crop also requires little fertilizer and appears to be less affected by diseases and pests than cowpeas or peanuts, although certain diseases and pests can cause significant losses (Brink *et al.,* 2000). Selecting resistant genotypes is the best strategy for limiting such damage. The most productive varieties of Bambara groundnut, both agronomically and phytosanitarily, could thus be a strategic tool for combating food insecurity while limiting the use of phytosanitary products and chemical inputs. In Côte d'Ivoire, research on Bambara groundnut remains limited, with the exception of a few studies on its phytotechnology and the diversity of local morphotypes (Djè *et al.,* 2005; Touré *et al.,* 2013). It is therefore essential to identify the most productive ecotypes that are tolerant to fungal diseases. This study was initiated in this context, with a view to contributing to food security by evaluating the agronomic performance of 14 Bambara groundnut ecotypes without the use of inputs or phytosanitary products in the autonomous district of Abidjan in southern Côte d'Ivoire.

I. Presentation of the study area

The trial was conducted at the experimental site of the Plant Physiology and Pathology Teaching and Research Unit of the UFR Biosciences. This site is located within the grounds of Félix HOUPHOUËT-BOIGNY University in the municipality of Cocody, with the following geographical coordinates: 4°10 and 5°30 north latitude and 3°50 and 4°10 west longitude (Ehoussou, 2004). The municipality of Cocody is bordered to the north by the municipality of Abobo, to the west by the municipalities of Adjamé and Plateau, to the east by the municipality of Bingerville, and to the south by the Ébrié lagoon (**Figure 1**).

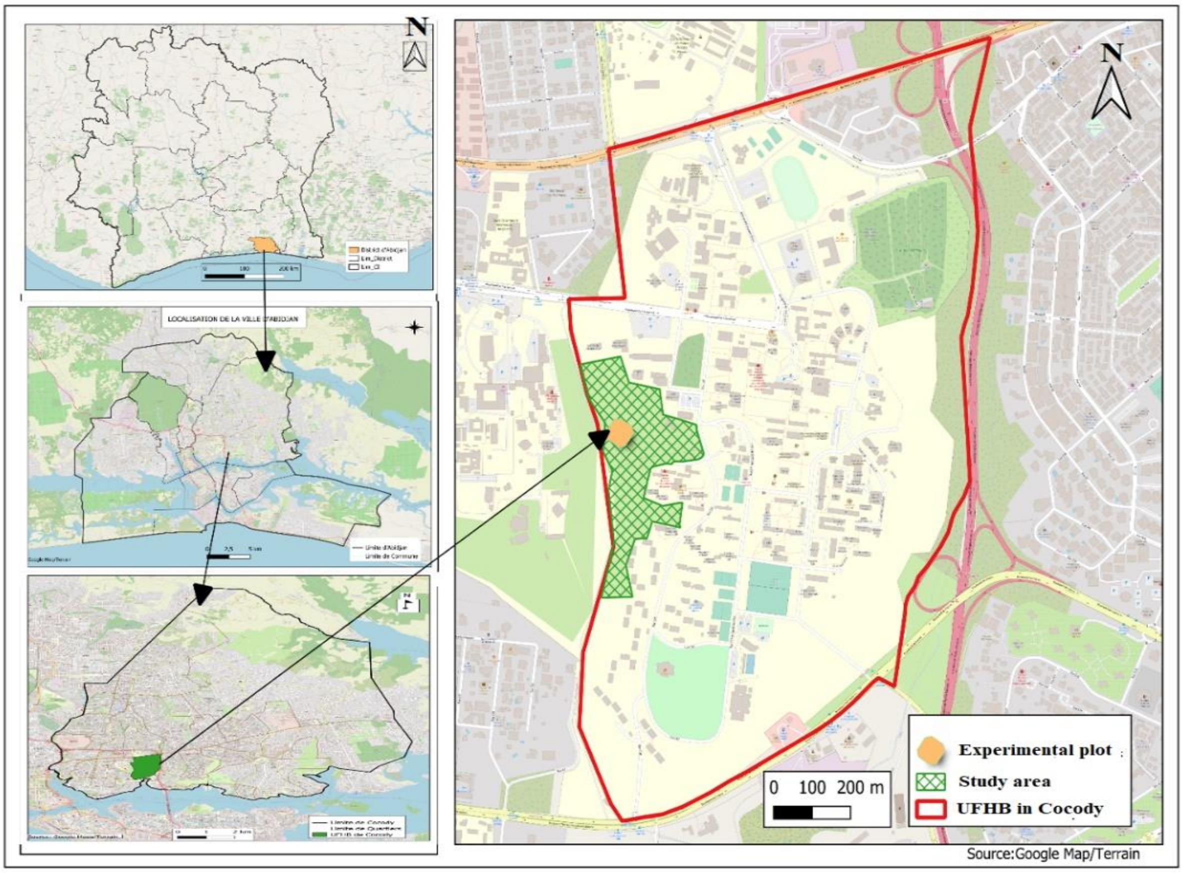

Figure 1: Map showing the study area for the trial under natural infestation conditions (Tuo *et al.,* 2023)

II. MATERIALS AND METHODS

II.1. Plant material

The plant material used in this study consisted mainly of seeds from different Bambara groundnut ecotypes taken from stocks stored in warehouses at the Korhogo grain market. These seeds were sorted according to color and the distribution of different traits on their surface and grouped into 14 morphotypes or ecotypes (**Figure 2**). The morphological characteristics of these different ecotypes are listed in Table 1. These seeds were used for testing under cultivation conditions without inputs. A total of 14 Bambara groundnut ecotypes were used (**Figure 2**).

Figure 2: Bambara groundnut ecotypes used in the study

Table 1: Phenotypic characteristics of seeds from the Bambara groundnut ecotypes used

Ecotypes	Characteristics
ECO 1	Dark red.
ECO 2	Black. Less appreciated.
ECO 3	Yellow integument covered with tiny gray dots at the base and black eye.
ECO 4	Yellow integument striped with brown bands from one end of the longitudinal axis to the other.
ECO 5	Yellow integument with dense brown stripes running from one end of the longitudinal axis to the other. Grey spot around the eye.
ECO 6	Yellow integument with stripes and a lower density of brown bands from one end of the longitudinal axis to the other.
ECO 7	Yellow integument with dark brown stripes running from one end of the longitudinal axis to the other.
ECO 8	Yellow integument with very dense brown stripes at each end of the longitudinal axis, without fusion of the two opposite stripes.
ECO 9	Yellow integument with dense brown stripes at each end of the longitudinal axis, without fusion of the two opposite stripes.
ECO 10	Yellow skin with black stripes. Gray spot around the eye.
ECO 11	Yellow integument with gray spot around the eye.
ECO 12	Yellow integument with much less dense brown stripes at each end of the longitudinal axis, without fusion of the two opposite stripes.
ECO 13	Yellow integument with brown stripes less dense than Eco 12 at each end of the longitudinal axis, with no fusion of the two opposite stripes.
ECO 14	Yellow integument with brown stripes less dense than Eco 13 at each end of the longitudinal axis, with no fusion of the two opposite stripes.

II.2. METHODS

II.2.1. Collection and preparation of Bambara groundnut seeds

The Bambara groundnut (*Vigna subterranea* L., Verdc.) seeds used in this study were collected at the Korhogo grain market, an area representative of traditional production in northern Côte d'Ivoire. After collection, all plant material was aggregated into a composite sample to ensure optimal representativeness of the available batch. Homogenization was carried out in accordance with the recommendations of the International Seed Testing Association (ISTA, 2023) by repeated manual mixing until a uniform batch was obtained. The composite sample was then reduced using the successive division method prescribed by ISTA to obtain three independent subsamples of equivalent masses for physical purity analysis.

II.2.2. Analysis of the physical purity of Bambara groundnut seeds

Purity was assessed in accordance with the International Rules for Seed Testing (FAO, 2010; ISTA, 2024). For each subsample, physiologically intact seeds that were morphologically consistent with the species were classified as pure seeds. The criteria for conformity included structural integrity, regular morphology (size, shape), absence of mechanical damage, and an external appearance free of contamination or biological alterations. Conversely, units with insect damage (perforations, erosion), abnormal reduction in size, inert matter, or visible signs of fungal contamination were classified as impure. The masses of the pure and impure fractions were determined using a precision electronic balance (± 0.001 g). The physical purity rate was then calculated using the following formula:

$$\textbf{Purity rate}\ (\%) = \frac{\textbf{Mass of pure seeds}}{\textbf{Total mass of the sample}}\ \textbf{x 100}$$

II.2.3. Setting up the field trial under cultivation conditions without inputs

II.2.3.1. Preparing the land for the trial

The experimental site was cleared and deeply plowed using a machete and a dagger. Before sowing, stakes were set out using ropes and wooden stakes. After plowing and staking, sowing was carried out after rainfall at a rate of 2 seeds per hole and at a depth of 3 cm in order to increase the germination rate and facilitate the emergence of the plants. No basal fertilizer was applied during or after plowing. Sowing was carried out on July 20, 2023 and repeated on March 15, 2024. Two weeks (14 days) after sowing, thinning to one plant per hole was carried out, and ungerminated holes were resown.

II.2.3.2. Test setup

For this test, the experimental design used was a completely randomized block design with three (3) replicates (3 blocks). The factor studied was the Bambara groundnut ecotype, with 14 treatments ranging from ecotype 1 to ecotype 14. These ecotypes were coded (ECO 1, ECO 2, ECO 3, ECO 4, ECO 5, ECO 6, ECO 7, ECO 8, ECO 9, ECO 10, ECO 11, ECO 12, ECO 13, and ECO 14). The experimental unit was the Bambara groundnut plant. Each block was subdivided into 14 micro-plots to which the Bambara groundnut ecotypes (Modalities) were assigned. The block was represented by all 14 Bambara groundnut ecotypes (modalities). Each micro-plot carried a Bambara groundnut ecotype represented by two rows of 8 plants each, giving 16 plants (**Figure 3**). The distance between the holes was 0.50 m, and the distance between the rows of the same ecotype was also 0.5 m. Each block or repetition contained 224 Bambara groundnut plants for 672 plants for the entire trial. The planting density was therefore 40,000 Bambara groundnut plants per hectare for each ecotype. The total area of the trial, including aisles and borders, was estimated at 360 m² (**Figure 3**).

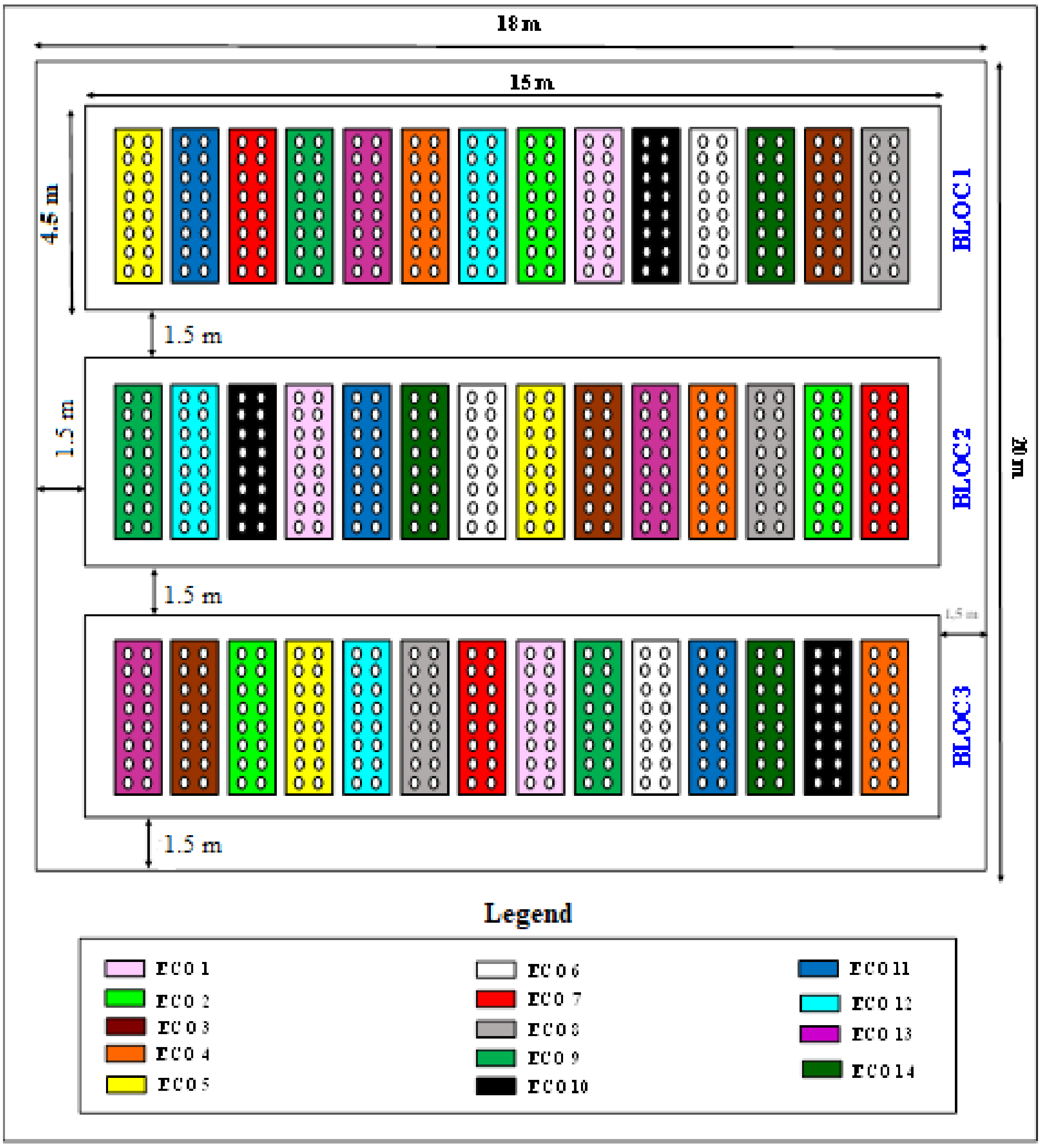

Figure 3: Experimental design

II.2.3.3. Maintenance and monitoring of the experimental plot

The experimental plot was maintained manually by systematic weeding with a hoe when necessary. A total of four (4) weeding operations were carried out during the trial. No fertilization was applied to the crop from the beginning to the end of the experiment. The plants were monitored every 2 days by visual observation to detect any anomalies.

II.2.4. Data collection from trials under no-input farming conditions

Data collection focused on six Bambara groundnut plants per ecotype and per repetition. Plant height measurements were taken 30 and 45 days after sowing (DAS). Yield parameters were assessed at harvest. Observations also focused on phenological dates (date of first appearance of flowering and date of 50% flowering) and plant health parameters (observation and description of symptoms, incidence of fungal diseases, and mortality rate).

II.2.4.1. Evaluation of the germination rate

The germination rate of the plants was evaluated on the 14th day after sowing (DAS) by counting the number of germinated seeds. The germination rate, expressed as a percentage, was calculated by dividing the number of germinated seeds by the total number of seeds sown using the following formula:

$$\textbf{Germination rate } (\%) = \frac{\Sigma ni}{N} \times 100$$

With:
Ni: Number of pots where germination occurred and
N: Total number of pots sown

II.2.4.2. Assessment of Bambara groundnut plant height

The height of Bambara groundnut plants (Hp) expressed in centimeters (cm) was assessed using a tape measure on the 30th and 45th days after sowing (DAS) from ground level (at the base of the plant) to the highest point, including the terminal leaflet. The average height was determined by ecotype using the following formula:

$$\textbf{Average height (cm)} = \frac{\Sigma Hi}{Nt}$$

Where,
Hi: Height of each plant by ecotype,
Nt: Total number of plants of the ecotype.

II.2.4.3. Assessment of the phenological stages of Bambara groundnut ecotypes

The phenological stages of the different Bambara groundnut (*Vigna subterranea* L., Verdc.) ecotypes were characterized through visual observations. The date of appearance of the first flower and the date corresponding to 50% flowering within the same ecotype were recorded on observation sheets. These data were used to establish detailed phenological profiles for each ecotype. Records were made at regular intervals of two (02) days to ensure the temporal accuracy of the observations.

II.2.4.4. Evaluation of yield parameters for Bambara groundnut ecotypes

The various Bambara groundnut ecotypes were harvested four months after sowing, and the following yield parameters were evaluated: number of pods per plant, number of seeds, and weight of 100 seeds expressed in grams.

II.2.5. Statistical analysis of data

All collected data were entered, and graphical representations were developed using Microsoft Excel 2021 spreadsheet software. For each parameter evaluated, a one-way analysis of variance was performed using Statistica 12.5 software. When significant differences between means were observed, the Student-Newman-Keuls test was applied to perform a multiple comparison of means at a significance level of 5%. In addition, a principal component analysis (PCA) was performed to explore the multidimensional relationships between the variables, followed by an ascending hierarchical classification (AHC) to identify natural groupings of data using the XLSTAT 2021 software.

III. RESULTS AND DISCUSSION

III.1. Results

III.1.1. Physical purity rates of Bambara groundnut seeds

The evaluation of the three subsamples revealed significant variability in physical purity rates, with levels that were generally insufficient in relation to international standards applicable to high-quality seed production. The measured rates ranged from 66.85% to 81.25%, with an average of 75.30% (**Figure 4**). According to the requirements of the International Seed Testing Association, a physical purity rate of at least 98% is the minimum acceptable threshold for small-seed legumes, a standard that the samples studied failed to meet.

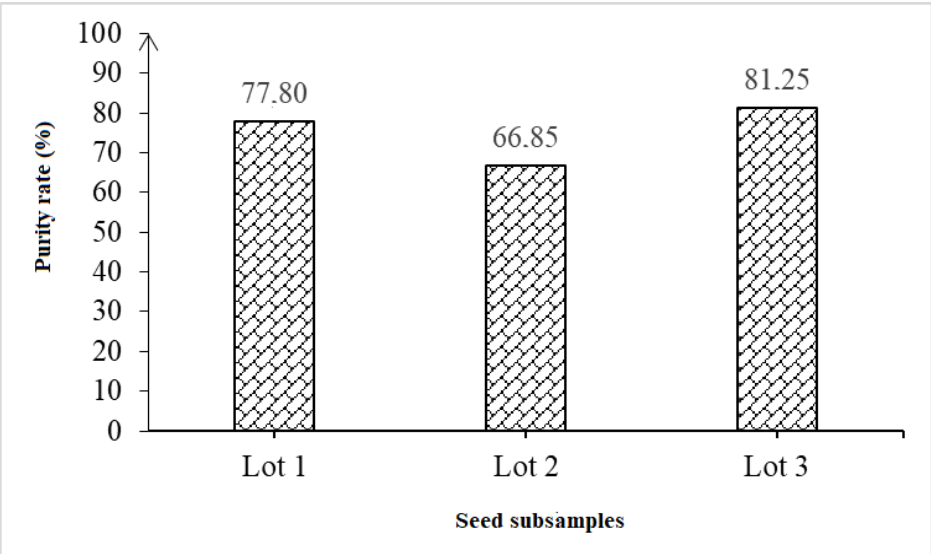

Figure 4: Physical purity rate of the Bambara groundnut samples analyzed.

III.1.1. Average germination rate of different Bambara groundnut ecotypes

The average germination rate of seeds from different Bambara groundnut ecotypes 14 days after sowing is shown in **Figure 5**. This average seed germination rate for the different Bambara groundnut ecotypes ranged from 31.25% to 83.33%, with an average of 46.88% below 50%. Analysis of variance of the average seedling emergence rate showed a significant difference ($p < 0.05$) between the Bambara groundnut ecotypes. The best average germination rates (77.08% and 83.33%) were obtained using ecotypes ECO 1 and ECO 2, respectively. The lowest average germination rates (31.25%) were observed in ecotypes ECO 5 and ECO 8.

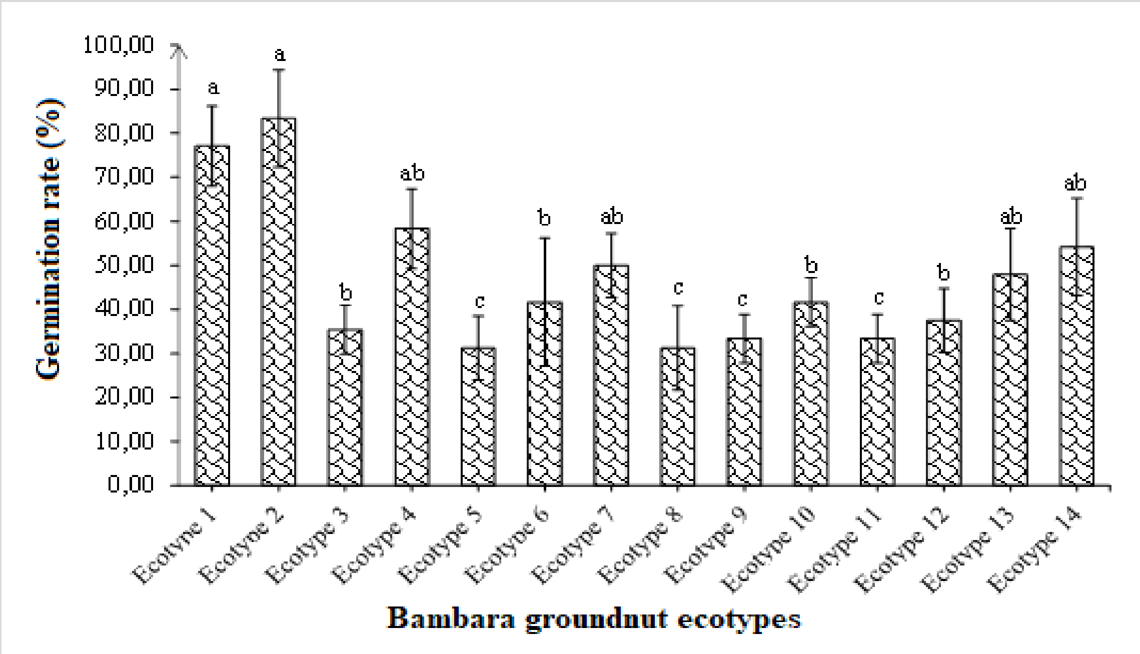

Figure 5: Germination rates of the different Bambara groundnut ecotypes used Histograms with the same letters are statistically identical at the threshold (α= 0.05) according to the Newman-Keuls test.

III.1.2. Plant height and phenological stages of different Bambara groundnut ecotypes

The results relating to changes in the average plant height and phenological stages of the different Bambara groundnut ecotypes are shown in **Table 2**. Analysis of variance showed a significant difference between the Bambara groundnut ecotypes ($p < 0.05$) according to the Newman-Keuls test at the 5% threshold. Analysis of the results from day 30 to day 45 shows steady growth of Bambara groundnut plants over time. The average plant height on day 30 after sowing (30 DAS) ranged from 16.64 to 23.25 cm, with an average of 19.20 cm for all Bambara groundnut ecotypes. The highest average plant height (23.25 cm) was observed in ecotype 2 (ECO 2). In contrast, the lowest average plant height (16.64 cm) was obtained using plants of ecotype 10 (ECO 10). The average height of the plants on the 45th day after sowing (45 DAS) ranged from 22.61 to 26.50 cm, with an average of 24.35 cm for all ecotypes. The best plant heights (26.50 cm) were observed in ecotype 2 (ECO 2), whereas the lowest plant heights (22.61 cm) were noted in ecotype 10 (ECO 10). The phenological stages studied (time to first flowering and time to 50% flowering) varied between 29.00 and 42.33 DAS for an average of 38.17 DAS and between 32.33 and 47.00 DAS with an average of 43.88 DAS. Ecotype 2 (ECO 2) was the first to have the first flowers at 29.00 DAS and the first to reach 50% flowering after 32.33 DAS. On the other hand, ecotypes ECO 1, ECO 3, ECO 6, ECO 10, ECO 12, and ECO 14 were the last to have the first flowers at 42.33, 40.67, and 40.00 DAS, respectively.

Table 2: Average plant height and phenological dates for different Bambara groundnut ecotypes

Ecotypes	Plant height (cm)		Phenological stages (j)	
	30 DAS	45 DAS	Time to first flowering	50% flowering time
ECO 1	20.25 ± 0.78 **b**	25.50 ± 0.82 **ab**	42.33 ± 2.67 **a**	45.00 ± 0.00 **a**
ECO 2	23.25 ± 0.86 **a**	26.50 ± 0.89 **a**	29.00 ± 1.00 **b**	32.33 ± 2.33 **b**
ECO 3	19.75 ± 0.63 **b**	24.94 ± 0.77 **ab**	40.67 ± 4.33 **a**	46.67 ± 1.67 **a**
ECO 4	18.56 ± 0.65 **bc**	24.52 ± 0.82 **ab**	37.33 ± 4.33 **ab**	45.00 ± 0.00 **a**
ECO 5	18.94 ± 0.39 **bc**	24.79 ± 0.56 **ab**	37.33 ± 4.33 **ab**	42.33 ± 2.67 **a**
ECO 6	17.30 ± 0.61 **c**	23.53 ± 0.59 **ab**	40.00 ± 5.00 **a**	47.00 ± 2.08 **a**
ECO 7	19.31 ± 0.60 **bc**	22.83 ± 0.55 **b**	35.67 ± 4.70 **ab**	44.33 ± 3.67 **a**
ECO 8	20.78 ± 0.62 **b**	23.36 ± 0.45 ab	37.33 ± 4.33 **ab**	43.33 ± 3.28 **a**
ECO 9	18.85 ± 0.59 **bc**	24.14 ± 0.92 **ab**	37.33 ± 4.33 **ab**	44.00 ± 3.79 **a**
ECO 10	16.64 ± 0.82 **d**	22.61 ± 0.89 **b**	40.67 ± 4.33 **a**	44.00 ± 3.79 **a**
ECO 11	18.00 ± 0.79 **bc**	24.72 ± 0.87 **ab**	39.33 ± 4.70 **ab**	45.00 ± 0.00 **a**
ECO 12	18.34 ± 0.66 **bc**	24.76 ± 0.74 **ab**	40.00 ± 5.00 **a**	46.00 ± 1.00 **a**
ECO 13	19.61 ± 0.77 **bc**	24.44 ± 1.01 **ab**	37.33 ± 4.33 **ab**	45.00 ± 0.00 **a**
ECO 14	19.22 ± 0.54 **bc**	24.31 ± 0.83 **ab**	40.00 ± 5.00 **a**	44.33 ± 0.67 **a**
Average	**19.20 ± 0.20**	**24.35 ± 0.21**	**38.17 ± 1.07**	**43.88 ± 0.74**
Coefficient of variation (%)	**16.65**	**13.88**	**18.11**	**10.88**
Probability (p)	**< 0.001**	**0.032**	**0.028**	**0.026**

In the same column, values with the same letters are statistically equal at the threshold (α= 0.05) according to the Newman-Keuls test.

III.1.3. Yield parameters of Bambara groundnut ecotypes

The results of the yield parameters of Bambara groundnut ecotypes (number of pods and weight of 100 seeds) are recorded in **Table 3**. Analysis of variance showed a highly significant difference for these evaluated parameters (p < 0.001). Thus, the average number of pods at harvest varied between 22.67 and 64.89 pods, with an average of 31.26 pods per plant. Ecotypes 5, 11, and 14 (ECO 5, ECO 11, and ECO 14) had the lowest number of pods at harvest, with 22.67 and 22.89 pods, respectively. The highest number of pods at harvest (64.89 pods) was obtained using ecotype 7 (ECO 7). The average weight of 100 seeds ranged from 41.88 to 66.70 g, with an average weight of 57.22 g. The best weights per 100 seeds (66.70; 64.88; 65.17; 64.62 and 65.48 g) were obtained with ecotypes ECO 1, ECO 5, ECO 8, ECO 9, and ECO 12, respectively.

Table 3: Yield parameters of the Bambara groundnut ecotypes used

Ecotypes	Number of pods	Weight of 100 seeds (g)
ECO 1	33.78 ± 2.02 **c**	66.70 ± 0.50 **a**
ECO 2	43.28 ± 1.16 **b**	48.92 ± 0.83 **f**
ECO 3	27.83 ± 1,01 **d**	51.86 ± 0.63 **ef**
ECO 4	23.28 ± 0.82 **de**	55.48 ± 0.72 **e**
ECO 5	22.67 ± 0.86 **e**	64.88 ± 1.67 **a**
ECO 6	24.72 ± 0.77 **de**	62.61 ± 0.67 **b**
ECO 7	64.89 ± 1.37 **a**	44.29 ± 0.42 **g**
ECO 8	42.00 ± 1.44 **b**	65.17 ± 1.10 **a**
ECO 9	26.11 ± 1.24 **de**	64.62 ± 0.43 **a**
ECO 10	35.22 ± 1.47 **c**	52.92 ± 0.82 **ef**
ECO 11	22.67 ± 1.02 **e**	41.88 ± 0.56 **g**
ECO 12	23.44 ± 0.63 **de**	65.48 ± 2.91 **a**
ECO 13	24.83 ± 0.63 **de**	57.15 ± 2.56 **d**
ECO 14	22.89 ± 0.42 **e**	59.08 ± 0.57 **c**
Average	**31.26 ± 0,79**	**57.22 ± 1.28**
Coefficient of variation (%)	**40.05**	**14.46**
Probability (p)	**< 0.001**	**< 0.001**

In the same column, values with the same letters are statistically equal at the threshold (α= 0.05) according to the Newman-Keuls test.

III.1.4. Multivariate analysis and structuring of Bambara groundnut ecotypes

III.1.4.1. Principal component analysis (PCA) of Bambara groundnut ecotypes

Figure 6 illustrates a PCA biplot based on a set of ecotypes described by several agronomic traits. The first two axes (F1 and F2) resulting from this PCA explain 71.16% of the total variance (46.27% and

24.89%, respectively), reflecting a strong capacity for structuring the morphophenological continuum. The first axis reflects a phenological and reproductive gradient dominated mainly by the emergence rate, flowering time, and 100-grain weight. It contrasts early-maturing, low-yielding ecotypes with late-maturing genotypes characterized by high seed mass and high pod production potential. The second axis reflects a gradient of initial vegetative vigor, structured by emergence rate and plant height at 45 days after sowing, thus discriminating between ecotypes with rapid establishment and early growth. The distribution of genotypes in the factorial plane highlights three contrasting groups: a lower left group (e.g., ECO 7) combining earliness and good pod production ; a central group on the right composed of intermediate ecotypes (ECO 1, ECO 3, ECO 6, ECO 8, ECO 9, ECO 10, ECO 11, and ECO 12), correlated with flowering variables and seed weight ; and an upper left group (ECO 2, ECO 4) strongly linked to uniform emergence and high juvenile vigor. The orientation and geometry of the vectors confirm several structuring correlations, notably the consistency between flowering variables, the positive relationship between 100-grain weight and late maturity, the partial dissociation between fruiting (number of pods) and flowering, and the coupling between emergence rate and initial growth.

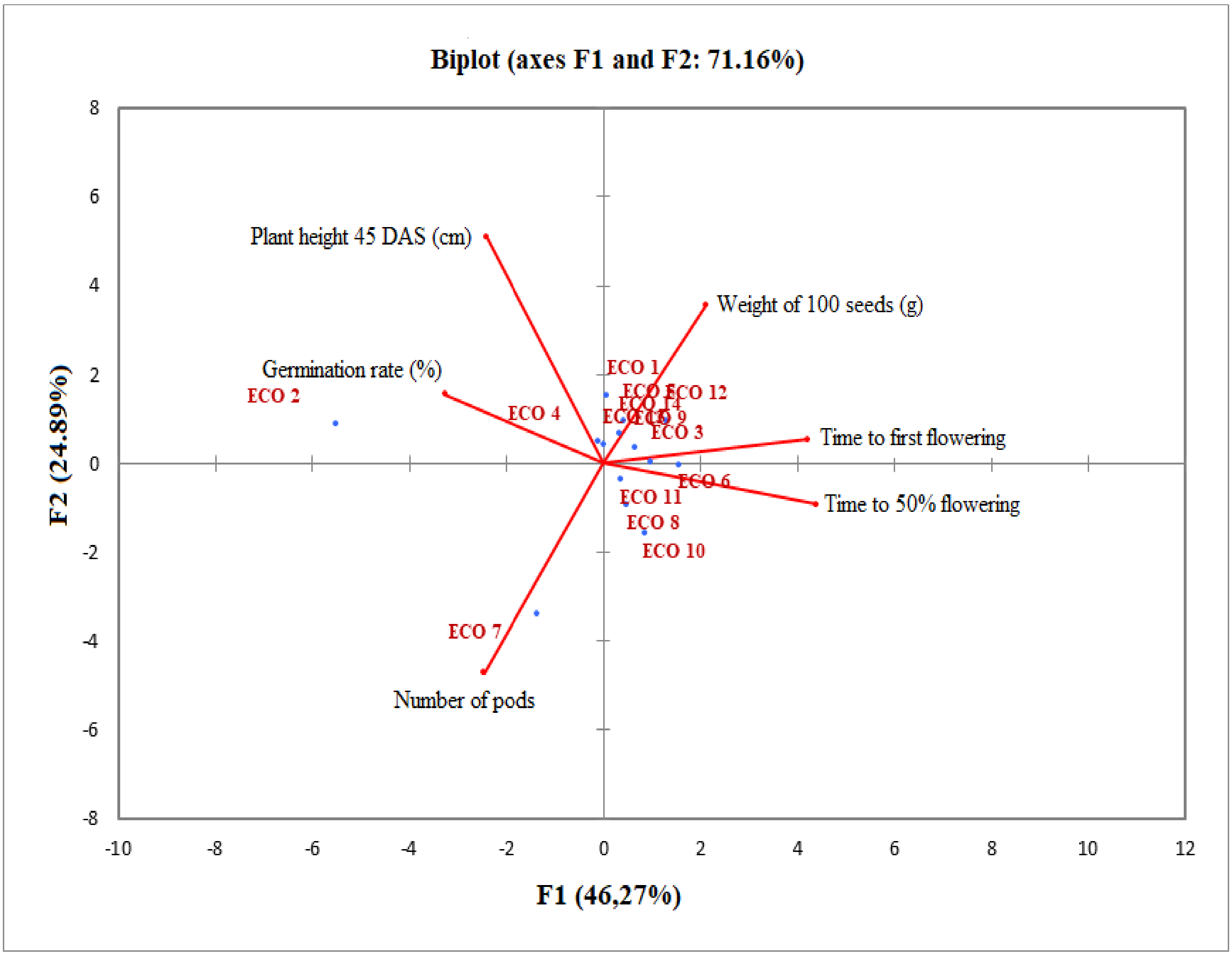

Fig. 6. Biplot of axes F1 and F2 from the principal component analysis showing the projection of the studied Bambara groundnut ecotypes and their agromorphological characteristics

III.1.4.2. Structuring of Bambara groundnut ecotypes using ascending hierarchical classification

The ascending hierarchical classification (AHC) based on the agromorphological variables studied revealed homogeneous groups of Bambara groundnut ecotypes. The dendrogram shown in **Figure 7** was developed using the dissimilarity coefficients calculated between the different Bambara groundnut ecotypes. The y-axis reflects the degree of dissimilarity between ecotypes, whereas the x-axis lists all ecotypes analyzed (ECO 1 to ECO 14). The ascending hierarchical analysis identified three main clusters at a dissimilarity threshold of 1050, indicated by the dotted line. Group 1 includes ecotypes ECO 10, ECO 3, ECO 11, ECO 8, ECO 6, ECO 5, and ECO 9, which are characterized by good emergence but average pod productivity. Ecotypes ECO 1, ECO 14, ECO 4, and ECO 13 form group 2. These ecotypes perform best in terms of emergence rate and number of pods. Group 3 consists of the low-performing ecotypes ECO 2 and ECO 7, characterized by poor emergence and limited pod yield. These results reveal a clear structure in the Bambara groundnut ecotype population, mainly based on the emergence rate and pod yield.

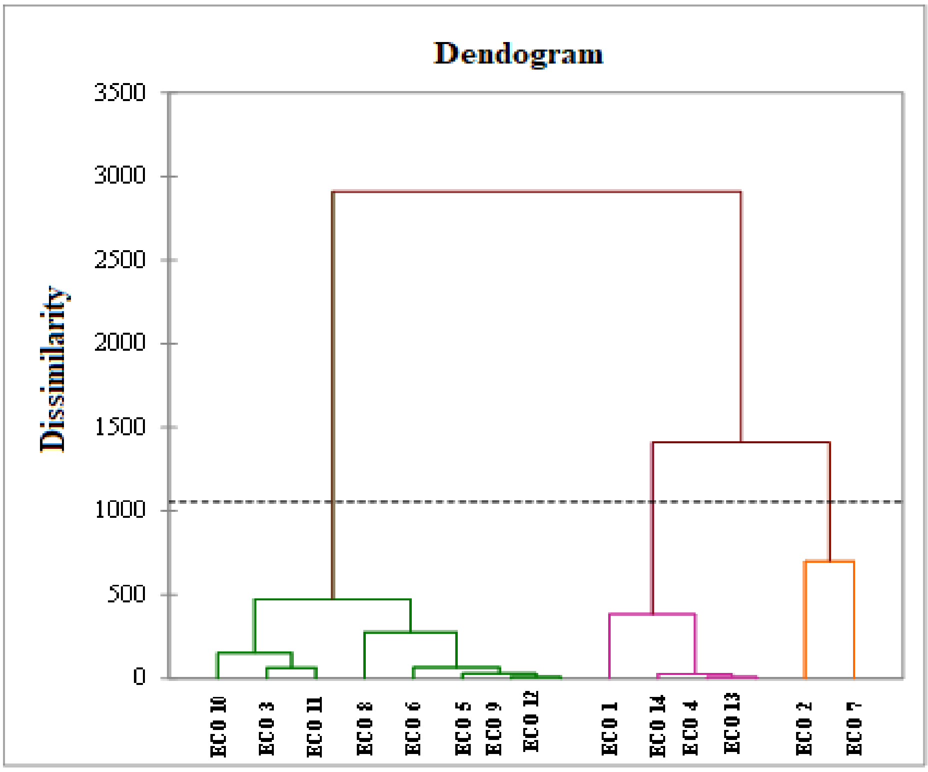

Fig. 7: Dendrogram resulting from the ascending hierarchical classification of Bambara groundnut ecotypes based on the variables studied

III.2. DISCUSSION

Analysis of the three subsamples revealed low and highly heterogeneous physical purity rates, ranging from 66.85% to 81.25%, with an average of 75.30%. These values are well below the minimum ISTA standards, which recommend a physical purity of 98% or higher for small seed legumes. Such noncompliance reflects structural dysfunctions in local production and marketing channels, marked by poor sorting, deficient quality control, and inadequate post-harvest management. The high proportion of perforated, atrophied, or contaminated seeds illustrates the poor quality of handling and storage operations. Insect damage, by altering the integrity of the seed coat, compromises imbibition, germination, and protection against opportunistic infections (Martín *et al.,* 2022; Almogdad *et al.,* 2023). The systematic presence of fungus-infected seeds also suggests the existence of a primary inoculum that could compromise crop establishment (Martín *et al.,* 2022; Dell'Olmo *et al.,* 2023). In West Africa, where Bambara groundnut yields remain historically low, the availability of high-quality seeds is a major determinant of productivity. Seeds sourced from informal channels, particularly local markets, do not meet the minimum requirements for seed use due to a lack of certification, limited sorting capacity, inadequate storage conditions, and rudimentary phytosanitary controls. Similar trends have been reported by Sperling *et al.,* (2020) and Majola *et al.,* (2021), who document the recurring weakness of physical purity and germination vigor in informal seed sectors in sub-Saharan Africa. The agronomic evaluation of the 14 Bambara groundnut ecotypes studied without inputs showed marked inter-genotypic variability. The emergence rates obtained (31.25–83.33%, average: 46.88%) indicate low physiological vigor, lower than the observations of Diagara *et al.*, (2022) in Niger (56.56.78–99.96 This reduced performance is probably due to the initial germination quality, the absence of pre-treatments to break dormancy (Coulibaly *et al.,* 2019; Zerome *et al.,* 2019), and fungal contamination that alters crop value (Dabiré *et al.,* 2023). Vegetative growth (16.64-23.25 cm at 30 DAS; 22.61-26.50 cm at 45 DAS) also shows significant differentiation, with ecotype 2 exhibiting greater vigor, consistent with the observations of Ndiang *et al.,* (2012). These differences probably reflect genotypic, nutritional, or radiation interception capacity differences (Touré *et al.,* 2013). Phenologically, ecotype 2 is distinguished by significantly earlier flowering. Early flowering is a strategic selection criterion in environments subject to water or heat stress (Diagara *et al.,* 2022) and strongly influences varietal adaptation (Dimakatso, 2006; Harouna *et al.,* 2018) and yield (Makanda *et al.,* 2009; Onwubiko *et al.,* 2011). The yield components confirm these contrasts. The number of pods per plant (22.67–64.89; mean: 31.26), with remarkable performance by ecotype 7, greatly exceeds the values reported by Edjé and Sesay (2004), Touré *et* *al.* (2013), and Diagara *et al.,* (2022), suggesting combined effects of genetic material and agroecological conditions. The weight of 100 seeds (41.88–66.70 g; average: 57.22 g) indicates significant phenotypic variability, attributable to genetic heterogeneity (Diagara *et al.,* 2002) and environmental factors such as photoperiod, temperature, and humidity (Collinson *et al.,* 1996; Bonny and Yao 2011.

Principal Component Analysis (PCA) highlights a robust structuring of ecotypes: the first two axes explain 71.16% of the total variance, consistent with the patterns described in other underutilized legumes with moderate diversity but organized in functional gradients (Adelabu and Franke, 2023 Mabhaudhi *et al.,* 2022). Axis 1, dominated by reproductive traits (100-seed weight, flowering precocity, number of pods), reflects an evolutionary compromise between rapid maturation and yield, a classic phenomenon for self-pollinating species subject to farmer selection (Kamenya *et al.,* 2021; Gómez-Fernández and Milla 2022). The association between late maturity and seed size corroborates work on grain filling duration in tropical legumes (Farooq *et al.,* 2018; Saied *et al.,* 2023). Axis 2, structured by juvenile vigor and emergence, refers to mechanisms of adaptation to edaphic and water stress (Mabhaudhi *et al.,* 2022). The spatial distribution of individuals distinguishes three contrasting phenotypic groups: very early ecotypes with low fruiting, adapted to short cycles; intermediate polyvalent genotypes; and vigorous ecotypes with high emergence, relevant for degraded environments (Sidibé *et al.,* 2020). The relationships between biplot variables are consistent with recent genetic results on cowpea and Bambara groundnut (Varshney *et al.,* 2021; Paliwal *et al.,* 2021). Ascending Hierarchical Classification (AHC) confirms three consistent clusters, including a highly differentiated group suggesting the presence of atypical genotypes carrying rare alleles, as already observed in other neglected legumes (Tadele, 2019; Jamnadass *et al.,* 2021). The ACP–CAH convergence highlights the robustness of the traits measured to capture intraspecific variability. It also suggests that the observed structure reflects distinct eco-geographical origins, divergent trajectories of farmer selection, or agroclimatic specializations similar to those described for fonio, cowpea, and Bambara groundnut (Sidibé *et al.,* 2020; Adelabu and Franke, 2023). These results provide a solid methodological foundation for guiding participatory selection, identifying elite genotypes, and conducting targeted molecular characterizations, in line with the integrative approaches recommended for the valorization of underutilized crops in West Africa (Varshney *et al.,* 2021; McMullin *et al.,* 2021).

CONCLUSION

The agronomic evaluation of 14 Bambara groundnut ecotypes grown under no-input conditions in the autonomous district of Abidjan in southern Côte d'Ivoire revealed significant variability between the morphotypes studied. Germination rates showed notable differences, with ecotypes 1 and 2 exhibiting better germination capacity. Analysis of vegetative growth highlighted the superiority of ecotype 2, which had the tallest plants at 30 and 45 days after sowing, as well as marked precocity in the onset of flowering and 50% flowering stage. Yield parameters also revealed significant heterogeneity. Ecotype 7 stood out with the highest number of pods per plant (64.89). In terms of seed biomass, several ecotypes (ECO 1, ECO 5, ECO 8, ECO 9, and ECO 12) recorded the highest 100-seed weights. These performances confirm the Bambara groundnut ability to adapt to the soil and climate conditions of southern Côte d'Ivoire, despite the absence of inputs and fertilizers. Overall, the results highlight the existence of promising genotypes that can be used in variety improvement programs or recommended to producers depending on the desired

Objectives: Earliness (ECO 2), high pod production (ECO 7), or seed weight quality (ECO 1, ECO 5, ECO 8, ECO 9, ECO 12). Further evaluation in other agro-ecological zones would confirm the stability of these agronomic performances.

Author Contributions

Seydou Tuo : Study design, scientific coordination, overall supervision of the work, organization of data collection, analysis and interpretation of results, drafting and critical review of the manuscript ; **Souleymane Sanogo :** Contribution to the implementation of the agronomic trial, monitoring of field experiments, data collection and processing, and participation in the drafting of the manuscript ; **Dramane Koné :** Methodological support, participation in data collection, preliminary statistical analyses, and technical revision of the manuscript ; **Kouamé Wilfried Davy Toto :** Advanced statistical analysis (ANOVA, PCA, CAH), production of figures and tables, participation in the interpretation of results, and writing ; **N'Doua Bertrand Guinagui :** Contribution to the implementation of the experimental setup, phenological and agronomic observations, and verification of data consistency ; **Barakissa Bamba :** Support for the identification and morphological characterization of ecotypes, participation in scientific discussion, and critical review ; **Daouda Koné :** Scientific and methodological supervision, validation of the various stages of the experimental protocol, review, and final approval of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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