

Identification of High-Yielding and Stables Genotypes of Millet (*Pennisetum glaucum* (L.) R. Br.) under Cultivation Conditions in the Savannah District of Northern Côte d'Ivoire

Tâh Valentin Félix N'guettia¹, Laopé Ambroise Casimir Siéné¹,
Ghislain Kanfany², Mariame Condé¹, Aya Kan Marie Louise Kouamé¹

¹Department of Plant Biology-Pedagogical and Research Unit of Plant Physiology, Training and Research Unit of Biological Sciences, Peleforo GON COULIBALY University, Korhogo, Côte d'Ivoire (BP 1328 Korhogo / www.univ-pgc.edu.ci)

²Department of Plant Production and Agronomy, Faculty of Agronomic Sciences, Aquaculture and Food Technologies (S2ATA), Gaston Berger University, B.P. 234, Saint Louis, Senegal

Corresponding Author: Tâh Valentin Félix N'guettia

DOI: <https://doi.org/10.52403/ijrr.20251147>

ABSTRACT

In Côte d'Ivoire, millet production remains low and highly variable due to the use of local seed varieties that are low-yielding and unsuited to the current climate variability. It therefore seems necessary in this context to identify accessions with high yield potential that are stable in production areas. To this end, a multi-location experiment was conducted over two agricultural seasons (2023 and 2024) in three localities in the Savannah district, namely Korhogo, Ferkessédougou, and Tengréla. One hundred and seventeen millet accessions, including twenty-five improved introduced varieties and ninety-two local varieties, were evaluated in an Alpha-lattice design with three blocks. Combined analysis of variance (AMMI) was used to estimate the effects of genotypes (G), environments (E), and their interaction (G×E). The GGE-biplot approach was then used to analyze the performance and stability of the accessions. Ecovalence was calculated to confirm the results obtained by GGE (Genotype + Genotype x Environment), identifying stable genotypes and the most discriminating environments. The results showed that all the variables

studied were significantly influenced by the environment (49.569%), genotypes (30.622%) and their interaction (17.624%). A strong influence of the environment was observed on the variables studied, as well as a significant G×E interaction, reflecting differentiated responses according to location. Three accessions (a160, a161, and a162) stood out for their high yields and stability in the different locations. In addition, the Ferkessédougou area proved to be the most representative and discriminating, confirming its value as a reference site for millet variety evaluation programs. Accessions a160, a161, and a162 can be recommended to improve millet production and contribute to securing sustainable incomes for producers in the savannah district of northern Côte d'Ivoire.

Keywords: high-performing millet accessions, GGE, AMMI, genotype x environment interaction, stability, Côte d'Ivoire

INTRODUCTION

Cereals play a key role in cropping systems and food security worldwide (Slama *et al.*, 2005). In Africa, particularly in arid and semi-arid areas, food security depends

largely on traditional cereals, including millet (*Pennisetum glaucum* (L.) R. Br.). This cereal, which is very rich in nutrients, is particularly drought-tolerant and can grow on poor soils (Ndjeunga *et al.*, 2012). It is therefore an essential source of food and income for millions of rural households (FAO, 2023; Haussmann *et al.*, 2012). West Africa is both a center of genetic diversity for millet and a major global production area, which reinforces its strategic role in food security (Ouédraogo *et al.*, 2018; Bezançon and Pham, 2004). The ten leading African producers worldwide, in descending order, are Niger, Mali, Nigeria, Senegal, Ethiopia, Burkina Faso, Sudan, Chad, Tanzania, and Ghana. Together, these countries account for most of Africa's millet production (Amadou *et al.*, 2013). Côte d'Ivoire ranks around 25th in the world according to recent estimates (FAO, 2023).

In Côte d'Ivoire, millet is the third most consumed cereal after rice and corn. Its annual production is estimated at around 67.000 tons, while domestic demand is around 120.000 tons (CNRA, 2022). However, yields per hectare remain very low in rural areas, barely reaching 500 kg/ha (Beninga, 2007). In addition, this crop faces many constraints that hinder its development. On the one hand, it is gradually being abandoned in favor of crops considered more profitable, such as cotton, cashews, and corn (Akanvou *et al.*, 2012; Kouakou *et al.*, 2024; Siéné *et al.*, 2024a). On the other hand, it is affected by various constraints, including attacks by cattle, damage caused by birds, caterpillar infestation, the spread of diseases on ears of corn, and declining soil fertility (Siéné *et al.*, 2024a). Furthermore, the effects of climate change are exacerbating the situation through the variability of the rainy seasons, uncertainty in the onset of rains, and changes in sowing dates, which disrupts the cropping calendar and increases the risk of low yields (Béniga *et al.*, 2011; Boko *et al.*, 2016; Siéné *et al.*, 2024 b). This climatic constraint compromises yield stability and reinforces producers' lack of interest in this crop.

To overcome these limitations, it is essential to identify genotypes that are capable of performing well and adapting to different environments. To this end, multi-location trials are a fundamental step, as they allow the performance and stability of genotypes to be evaluated across multiple sites. These trials are essential for identifying genotypes that are both high-performing and stable, capable of adapting to local constraints and climatic variations (Crossa *et al.*, 2002; Yan *et al.*, 2007). The combined analysis of variation between genotypes, environments, and their interaction (GxE) is a crucial step in understanding the sources of variation in multi-location trials. It allows the quantification of the proportion of variation due to genotypes, environments, and interaction, which is essential for guiding selection decisions and identifying the genotypes best suited to specific conditions (Eberhart and Russell, 1966; Crossa, 1990). In this context, the analysis of genotype x environment (GxE) interaction is furthered using AMMI (Additive Main Effects and Multiplicative Interaction) and GGE (Genotype + Genotype x Environment) statistical models, which are widely used to identify high-performing and stable genotypes. Ecovalence is calculated to confirm the results obtained by GGE (Genotype + Genotype x Environment), identifying stable genotypes and the most discriminating environments (Yan *et al.*, 2000).

In Africa, several recent studies on millet have highlighted the effectiveness of these models for analyzing genotype x environment interactions in identifying high-performing and stable varieties. Among these studies are those by Kanfany *et al.* (2024) conducted in Senegal; those by Hailemariam and Adane (2021) conducted in Ethiopia; and the studies by Yadav *et al.* (2022) and Gangashetty *et al.* (2023) conducted jointly in Niger, Senegal, Nigeria, and Ghana. However, in Côte d'Ivoire, no similar study has yet been conducted on the genotype x environment interaction of millet, despite the importance of this crop in the

north of the country. Thus, the present study is part of this dynamic and aims to determine the performance of genotypes according to the environment. Specifically, it aims to (i) identify the most productive and stable accessions in the different study environments, (ii) evaluate the accessions based on the ideal genotype from one environment to another, and (iii) evaluate the environments based on the ideal environment.

MATERIALS & METHODS

Description of study areas

The Savannah district, located in northern Côte d'Ivoire, is subdivided into three administrative regions: Bagoué, Poro, and Tchologo, comprising a total of ten departments (Koffi, 2021). One department was selected in each of these regions for this study, conducted over two agricultural seasons (2023 and 2024), namely Tengréla in Bagoué, Korhogo in Poro, and Ferkessédougou in Tchologo (Figure 1). The climate in this area is characterized by two main seasons: a dry season from November

to May and a rainy season from June to October, with the wettest months being July, August, and September.

The town of Tengréla (latitude 10.4840°N, longitude -6.4090°W), located in the northwest of the Savannah district, receives an average of approximately 1080 mm of rainfall per year. However, the ferrallitic soils have a more pronounced gravelly horizon than in the other two areas (Ouattara *et al.*, 2016). The average temperature in Tengréla varies between 25°C and 36°C. Korhogo, located in the center of the district (latitude 9.4580°N, longitude -5.6290°W), is characterized by annual rainfall of between 1000 and 1600 mm and an average temperature ranging from 24°C to 36°C. The soils in this area are mainly ferralsols (Diomandé, 2022). Located in the east of the district, the locality of Ferkessédougou (latitude 9.5928°N, longitude -5.1945°W) has annual rainfall varying between 1000 and 1400 mm, with an average temperature between 28°C and 32°C. The ferrallitic soils are similar to those observed in Korhogo (Dédé *et al.*, 2020).

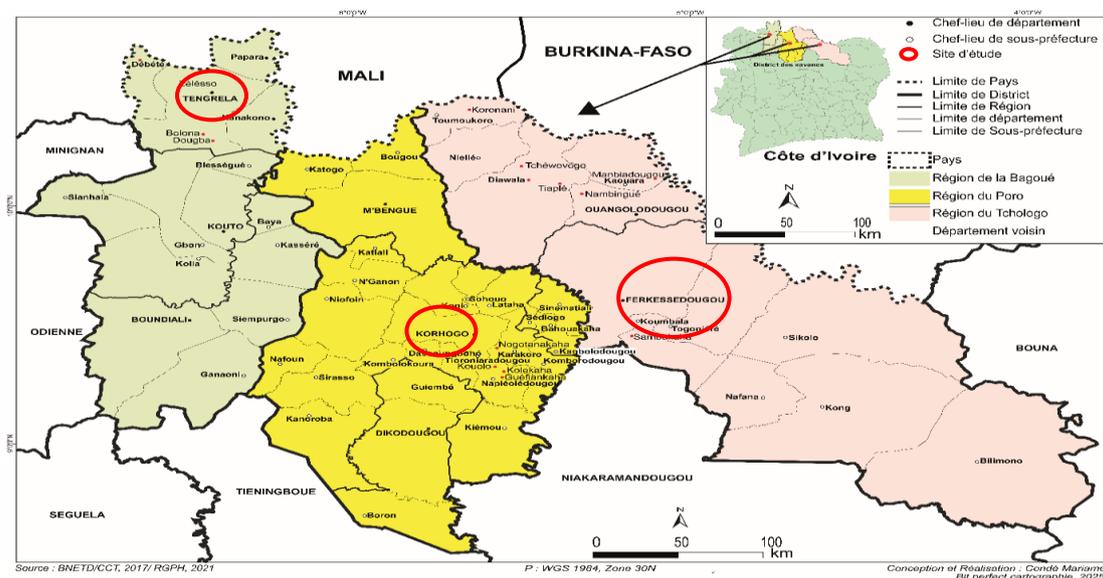


Figure 1: Map of study locations

Plant material

The plant material consists of 117 varieties of millet. Among these are 25 improved varieties, 15 of which originate from Burkina Faso and 10 from Senegal. The remaining 92

millet accessions were collected in the Savannah district of Côte d'Ivoire.

Experimental design and treatments studied

An Alpha-lattice experimental design with three replicates was set up to ensure good precision in the evaluation of the accessions. Each replicate was subdivided into three blocks, each comprising 39 elementary plots, for a total of 117 elementary plots per replicate. Each elementary plot, corresponding to a 10 m long seed row, represented a millet accession. They were spaced 0.75 m apart. Each row had 20 holes, spaced 0.5 m apart. The blocks were separated by a 1 m wide aisle to facilitate movement and maintenance of the plots. The total area of the experiment was 28.5 m x 32 m, or 912 m².

Conduct of the trial

Sowing was carried out by pinching seeds into the holes. Fifteen days after emergence, thinning was carried out to retain only three vigorous seedlings per hole, thus ensuring a uniform plant density. Subsequently, a first fertilizer application was made. This consisted of applying NPK fertilizer (15-15-15+6S+1B) at a dose of 4.46 g per hole. The fertilizer was applied using a measuring cap, at a distance of 5 cm from the plant. Then, 35 days after sowing, urea was incorporated into the soil at a dose of 7.86 g/plant hole, using two metering capsules, at a distance of 5 cm from the plant. Regular weeding was carried out throughout the vegetative phase to limit competition from weeds and promote good plant growth.

Observations and measurements

The observations and measurements concerned a set of parameters related to phenology, plant morphology, yield, and its components. Phenological observations were made daily on all plants in each elementary plot. For each plot, the date of flowering and grain maturity was considered effective when 50% of the plants had reached it. At maturity, agro-morphological parameters (plant height, number of tillers per clump, number of ears per clump) were measured from plants in 10 clumps per elementary plot.

At harvest, the number of ears was counted per yield square at maturity. The ears harvested per elementary plot were dried separately, then the weights and dimensions (length and diameter) of the ears were measured. Yield was determined in a 3.75 m² yield square, representing ten (10) hills per elementary plot located in the center of each elementary plot. Yield was calculated using the ratio of dry grain weight per yield square to the yield square area:

$$\text{Yield (t/ha)} = \left(\frac{\text{Dry weight of grain per yield square}}{\text{Yield square area}} \right) \times 0,01$$

The factor 0.01 converts g/m² to t/ha.

Statistical Analysis

Statistical analyses were conducted to evaluate the interaction between genotype and environment (G×E) and their respective effects on the agronomic performance of millet accessions. An analysis of variance (ANOVA) was first performed separately for each environment to evaluate the main effect of genotypes. Subsequently, a joint ANOVA was used to simultaneously analyze the effects of genotypes, environments, and their interactions on agromorphological traits. To explore the G×E interaction in depth, the AMMI (Additive Main Effects and Multiplicative Interaction) model was applied to grain yield data using the AMMI function of the Agricolae software package. The AMMI model was formulated as described by Gauch (2013). The stability of millet accessions was evaluated using the percentage of ecovalence stability according to the model of Wricke (1965). The most favorable environments were identified using the environmental index model proposed by Annicchiarico (1992). GGE biplot analysis was then used to visualize and interpret the G×E interaction through three essential representations: (1) the discriminatory power and representativeness of the tested environments, (2) the ranking of the tested genotypes across all environments, and (3) the ranking of the tested environments (Yan and Kang, 2003). All

statistical analyses were performed using R software, based on the Agricolae and metan packages (Olivoto and Lúcio, 2020).

RESULT

Combined analysis of variance of the agromorphological parameters of the evaluated millet accessions

The combined analysis of variance of the agromorphological parameters of the millet

accessions evaluated in the different environments is presented in Table 1.

The results reveal a highly significant effect ($p < 0.001$) of environments (E), genotypes (G), and their interaction (GxE) on all traits. These results indicate that the environments tested differ significantly from each other and that the accessions do not perform equally well in all environments.

Table 1: Mean squares of agromorphological parameters for millet accessions evaluated in six environments

Source de variation	Environment (E)	Rep(E)	Génotype (G)	Interaction (G*E)
Degree of freedom	5	12	116	580
% CTV	49.569	0.064	30.622	17.560
50% Flowering	5864.4**	454.6***	2113.1***	5 ***
Vegetative phase	5673.5**	603.6***	2154.3***	6 ***
Cycle duration	5344.2**	435.8***	2633.1***	5.6 ***
Number of ears/bunches	0.5497ns	0.1976ns	5.5307***	0.2485***
Total number of tillers/bunches	70.513**	440.43***	26.371***	1.692***
Plant height	41684 **	651***	1583***	547***
Ear length	234.08**	476.02***	43.12***	4.41***
Ear diameter	221.652**	28.307***	181.431***	16.434***
Total number of ears	51.11**	462.70***	1504.18***	2.98***
Weight of 1 ear	1819.05***	74.92***	424.71***	73.14***
Total weight of ears	1819905***	16045*	719023***	79372 ***
Weight of grains in 1 ear	1049.50***	35.33***	890.49***	46.08***
Total weight of grains	904701 ***	7126***	418967***	38060***
Yield	7.4119***	0.0507***	6.4572***	0.2707 ***

*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, ns: not significant, %CTV: percentage contribution to total variation

AMMI analysis of yield

The AMMI analysis of variance applied to the grain yield of the 117 millet accessions is presented in Table 2. The results revealed that all sources of variation (genotypes, environments, and interaction) are highly significant ($P < 0.001$). The environment contributed the largest share of the total variation with 49.569% of the sum of

squares, followed by the genotype x environment interaction (17.624%) and genotypes (30.622%). Furthermore, the effect of GEE was broken down into three principal interaction components (PIC). The first two PICs were significant and contributed to more than 80% of the total genotype-environment variation.

Table 2: Analysis of variance of additive main effects and multiplicative interactions for grain yield of 117 millet accessions

Source of variation	DF	S. S	M.S	Contribution to the sum of squares (%)	Pr(>F)
ENV	5	37.0595	7.4119	49.569	5.064e-08 ***
GEN	116	749.04	6.4572	30.622	0.0000 ***
ENV: GEN	580	155.79	0.2686	17.624	0.0000***
IPCA1	119	72.059	0.605	56.02	0.0000 ***
IPCA2	117	44.535	0.380	27.3	0.0000***
IPCA3	115	25.139	0.118	4.68	ns
RESIDUELS	1392	20.55	0.0148	2.185	-

*** Significant difference at $Pr < 0.001$; ENV: environment, REP: replication, GEN: genotypes/cultivars, PCA: principal component analysis of interaction, DF: degrees of freedom, SS: sum of squares, MS: mean square, ns: not significant

Identification of the most productive and stable accessions in different environments

The average performance and stability results for the six environments are presented in Table 3. These results allow the accessions to be ranked according to their productivity and stability. The stability of the accessions was assessed on the basis of ecovalence. In this study, accessions a160, a162, and a161 stood out for their high yields, ranging from 3.279 to 3.715 t/ha, with a stability percentage varying from 0.162 to 0.231. These accessions were considered stable. Several accessions, such as a141, a91, a94, a88, a142, a136, a126, a139, a124, a157, a140, a148, a127, a110, a85, a93, a125, a82, a112, a149, a150, a115, a111, a133, a144, a151, a123, and a152 showed average yields ranging from 1.004 to 1.577 t/ha, with a stability percentage ranging from 0.069 to 0.993. These accessions were considered. Another set of accessions, including a8, a5, a96, a83, a7, a6, a10, a58, a3, a14, a57, a1, a15, a56, a54, a121, a61, a147, a55, a62, a131, a145, a104, a108, a80, a103, a105, a146, a122, a98, a102, a116, a113, a89, a114, a156, a135, a120, a158, a155, a143, a90, a101, a107, a84, a86, a106, a134, a81, a118, a154, a92 was characterized by low yields, ranging from 0.0970 to 0.992 t/ha, with a stability percentage between 0.049 and 0.954. These accessions were considered stable. Accessions a87, a9, a109, a130, a132, a95, a159, a129, a74, a31, a16, a73, a137, a72, a128, a153, a79, a100, a69, a77, a4, a68, a70, a78, a63, a71, a13, a67, a75, a76, a2, a60, a53 had very low yields, ranging from 0.117 to 0.779 t/ha, with a high percentage of stability (1.016 - 7.747). They were classified as unstable. Another set of accessions, including a8, a5, a96, a83, a7, a6, a10, a58, a3, a14, a57, a1, a15, a56, a54, a121, a61, a147, a55, a62, a131, a145, a104, a108, a80, a103, a105, a146, a122, a98, a102, a116, a113, a89, a114, a156, a135, a120, a158, a155, a143, a90, a101, a107, a84, a86, a106,

a134, a81, a118, a154, a92 was characterized by low yields, ranging from 0.0970 to 0.992 t/ha, with a stability percentage between 0.049 and 0.954. These accessions were considered stable. Accessions a87, a9, a109, a130, a132, a95, a159, a129, a74, a31, a16, a73, a137, a72, a128, a153, a79, a100, a69, a77, a4, a68, a70, a78, a63, a71, a13, a67, a75, a76, a2, a60, a53 had very low yields, ranging from 0.117 to 0.779 t/ha, with a high percentage of stability (1.016 - 7.747). They were classified as unstable.

Based on the average data (Table 4), accessions a160, a162, and a161 stood out for their high yields (3.279 to 3.715 t/ha) combined with low eco-valence values (0.246 to 0.314%), reflecting high stability and good adaptation to environmental conditions. Accessions a148, a82, a142, a141, a125, a136, a91, a115, a94, a124, a139, a157, a110, a127, a112, a126, a133, a93, a140, a151, a152, a88, a144, a149, a123, a111, a85, a95, a153, a150 showed average yields (1.004 to 1.577 t/ha) with ecovalence values between 0.003 and 0.875%, indicating stable average performance depending on the environment. In addition, accessions a84, a122, a83, a90, a8, a137, a5, a7, a9, a86, a147, a6, a130, a10, a58, a96, a114, a135, a118, a128, a120, a14, a3, a121, a57, a1, a132, a13, a54, a131, a56, a63, a15, a158, a55, a145, a109, a155, a106, a108, a143, a146, a80, a104, a98, a103, a113, a89, a105, a116, a156, a159, a102, a107, a101, a100, a134, a81, a154 recorded relatively low yields (0.097 to 0.992 t/ha), but with good stability (0.017 to 0.979%). In contrast, accessions a129, a87, a61, a62, a16, a92, a4, a31, a74, a73, a72, a79, a69, a77, a68, a2, a70, a78, a71, a67, a75, a76, a60, and a53 had low yields (0.117 to 0.779 t/ha) with high ecovalence values (1.028 to 9.517%), reflecting instability in their performance depending on the environment. These accessions were not very productive and were sensitive to environmental variations.

Table 3: Average performance and stability of accessions in the six environments

Accessions	Yields (t/ha)	% Stability (Ecov perc)	Interpretations
a160- a162-a161	3.279 - 3.715	0.162 - 0.231	Stable
a141-a91-a94-a88-a142-a136-a126 -a139-a124-a157-a140-a148-a127-a110-a85-a93-a125-a82-a112-a149-a150-a115-a111-a133-a144-a151 a123-a152	1.004 - 1.577	0.069 - 0.993	Stable
a8-a5-a96-a83-a7-a6-a10-a58-a3-a14-a57-a1-a15-a56-a54-a121-a61-a147-a55-a62-a131-a145-a104-a108-a80-a103-a105-a146-a122 a98-a102 -a116-a113-a89-a114 -a156-a135-a120-a158-a155-a143-a90-a101-a107-a84-a86-a106-a134-a81-a118-a154-a92	0.0970-0.992	0.049 - 0.954	Stable
a87-a9-a109-a130-a132-a95-a159-a129-a74-a31-a16-a73-a137-a72 a128-a153-a79-a100-a69-a77-a4-a68-a70-a78-a63-a71-a13-a67-a75-a76-a2-a60 a53	0.117 - 0.779	1.016 - 7.747	Unstable

Table 4: Average performance and stability of accessions in the three environments

Accessions	Yields (t/ha)	% Stability (Ecov perc)	Interpretations
a160-a162-a161	3.279 - 3.715	0.246 - 0.314	Stable
a148-a82-a142-a141-a125-a136-a91-a115-a94-a124 -a139-a157-a110-a127-a112-a126-a133-a93-a140-a151-a152-a88-a144-a149-a123-a111-a85-a95-a153-a150	1.004 - 1.577	0.003 - 0.875	Stable
a84-a122-a83-a90-a8-a137-a5-a7-a9-a86-a147-a6-a130-a10-a58-a96-a114-a135-a118-a128-a120-a14-a3-a121-a57-a1-a132-a13-a54-a131- a56-a63-a15-a158-a55-a145-a109-a155-a106-a108-a143-a146-a80-a104-a98-a103-a113-a89-a105-a116-a156-a159-a102-a107-a101-a100- a134-a81-a154	0.0970 – 0.992	0.017 - 0.979	Stable
a129-a87-a61-a62-a16-a92-a4-a31 a74 -a73 -a72-a79-a69-a77-a68-a2 a70-a78-a71-a67-a75-a76-a60-a53	0.117 - 0.779	1.028 - 9.517	Instable

Evaluation of accessions based on the ideal accession from one environment to another

Accessions identified as ideal for valorization in the tested environments are illustrated in Figure 2. An ideal accession is characterized by high average grain yield and stability across different environments. In the biplot, it is located in the first concentric circle or close to the first concentric circle. Accessions considered desirable have satisfactory yields and are stable. They are positioned closer to the ideal accession. Conversely, undesirable accessions are characterized by marked instability across environments and appear further away from the first concentric circle, where the ideal accessions are located.

In this study, the biplot reveals that accessions a160, a161, and a162 represent the ideal accessions in all environments tested, as evidenced by their positions in the concentric circle. Accessions a141, a91, a94, a88, a142, a136, a126, a139, a124, a157, a140, a148, a127, a110, a85, a93, a125, a82, a112, a149, a150, a115, a111, a133, a144, a151, a123, and a152, located close to the latter, were classified as desirable accessions. On the other hand, the other accessions further from the center were considered undesirable due to their poor performance and instability depending on the environment (Figure 2A). Based on the average data, a160, a161, and a162 remain the ideal accessions. Accessions a148, a91, a94, a124, a126, a149, a123, a85, a82, a142, a141, a125, a136, a115, a139, a157, a110, a127, a112, a133, a140, a151, a152, a88, a144, a111, a95, a153, and a150 retained positions close to ideal and were classified as desirable. The other accessions, further from the center of the concentric circle, remain undesirable due to their instability and low average yields (Figure 2B).

Discriminating power and representativeness

The “discriminating power relative to representativeness” perspective allows the tested environments to be classified into three types. The main discriminating and representative parameters are determined by the length of the vector representing each environment and by the angle formed between

this vector and the average environment coordinate axis (AEC).

Environments with short vectors and large angles relative to the MCA axis are classified as type I. These environments provide little useful information about differences between accessions and are therefore not suitable for their evaluation. Type II environments, on the other hand, are characterized by long vectors and small angles relative to the AEC axis. They are therefore suitable for identifying accessions that are both stable and high-yielding. Type III environments have long vectors but large angles relative to the AEC axis. Like Type I environments, they are not very effective for evaluating genotypes.

Thus, the Ferké_23 environment has a long vector and a slightly smaller angle relative to the AEC axis than the other environments. It has therefore been classified as a type II environment. Type I environments include Ferké_23, Korhogo_24, Tengrela_23, and Tengrela_24. The Korhogo_23 environment was classified as a type III environment (Figure 3A). In addition, based on the average data, the Ferkessédougou environment showed good discrimination potential and good representativeness (Figure 3B).

Evaluation of environments based on the ideal environment

Figure 4 illustrates the GGE biplot centered on the ideal environment. An environment is considered ideal when it is located on or near the first concentric circle of the biplot. This environment is both representative and has the strongest discriminating power.

According to the GGE biplot analysis, the Ferké_23 and Ferké_24 environments stood out as the ideal environments among the six tested. The Korhogo_24 environment, close to this ideal point, was classified as a desirable environment. On the other hand, Korhogo_23, Tengrela_23, and Tengrela_24, which are significantly further away, were considered the least suitable environments (Figure 4A).

Analysis of the averages for the two years identified the Ferkessédougou environment as the ideal environment compared to the other environments (Figure 4B). The results in Tables 5 and 6 also confirm this observation.

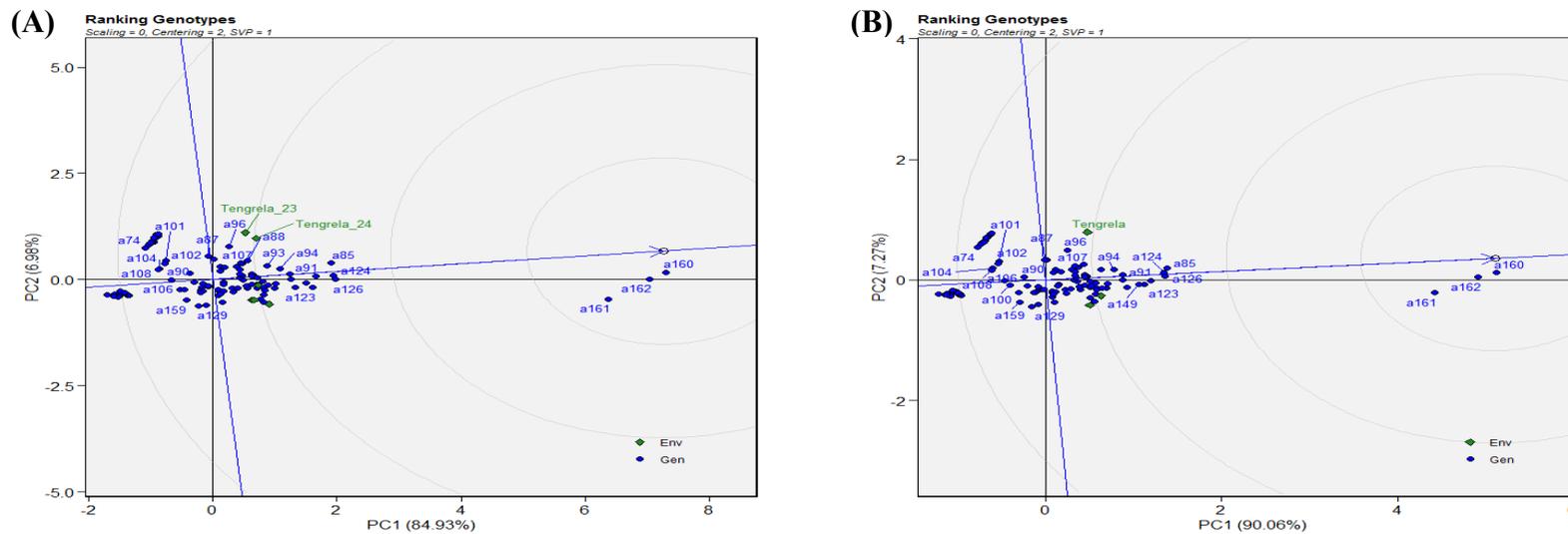


Figure 2: GGE biplot showing the ideal accession based on six environments (A) and two-year average data (B)

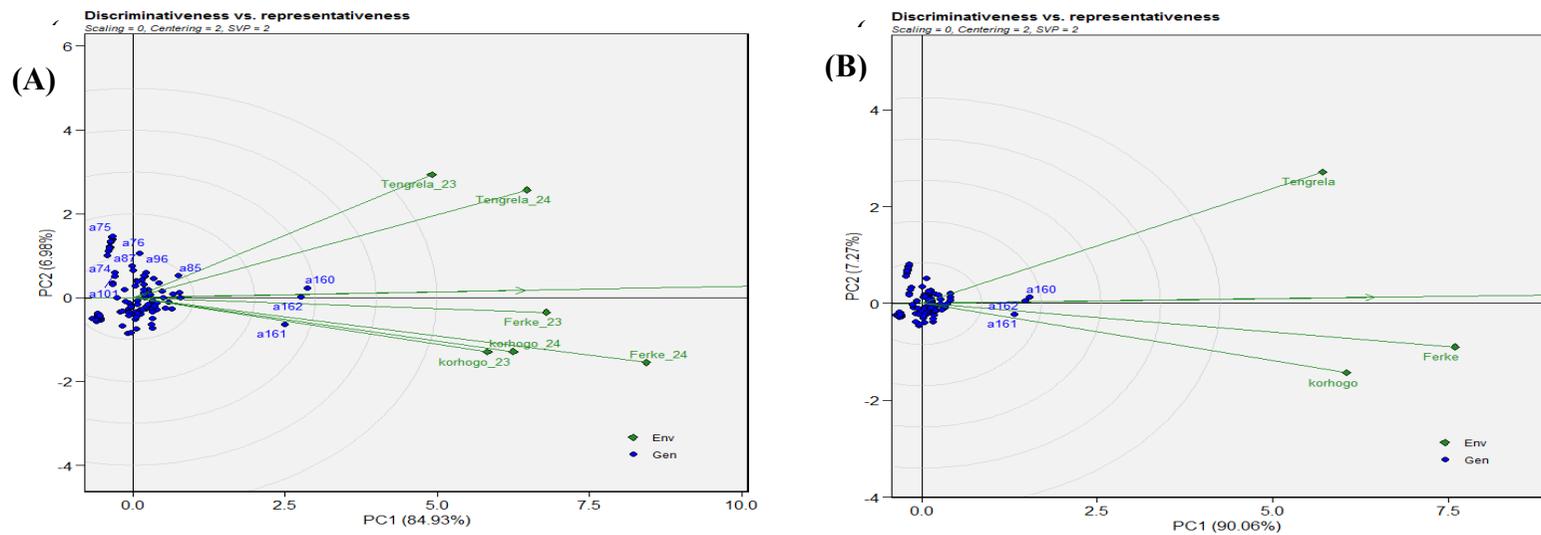


Figure 3: Biplot of discriminating power and representativeness based on six environments (A) and average data over two years (B)

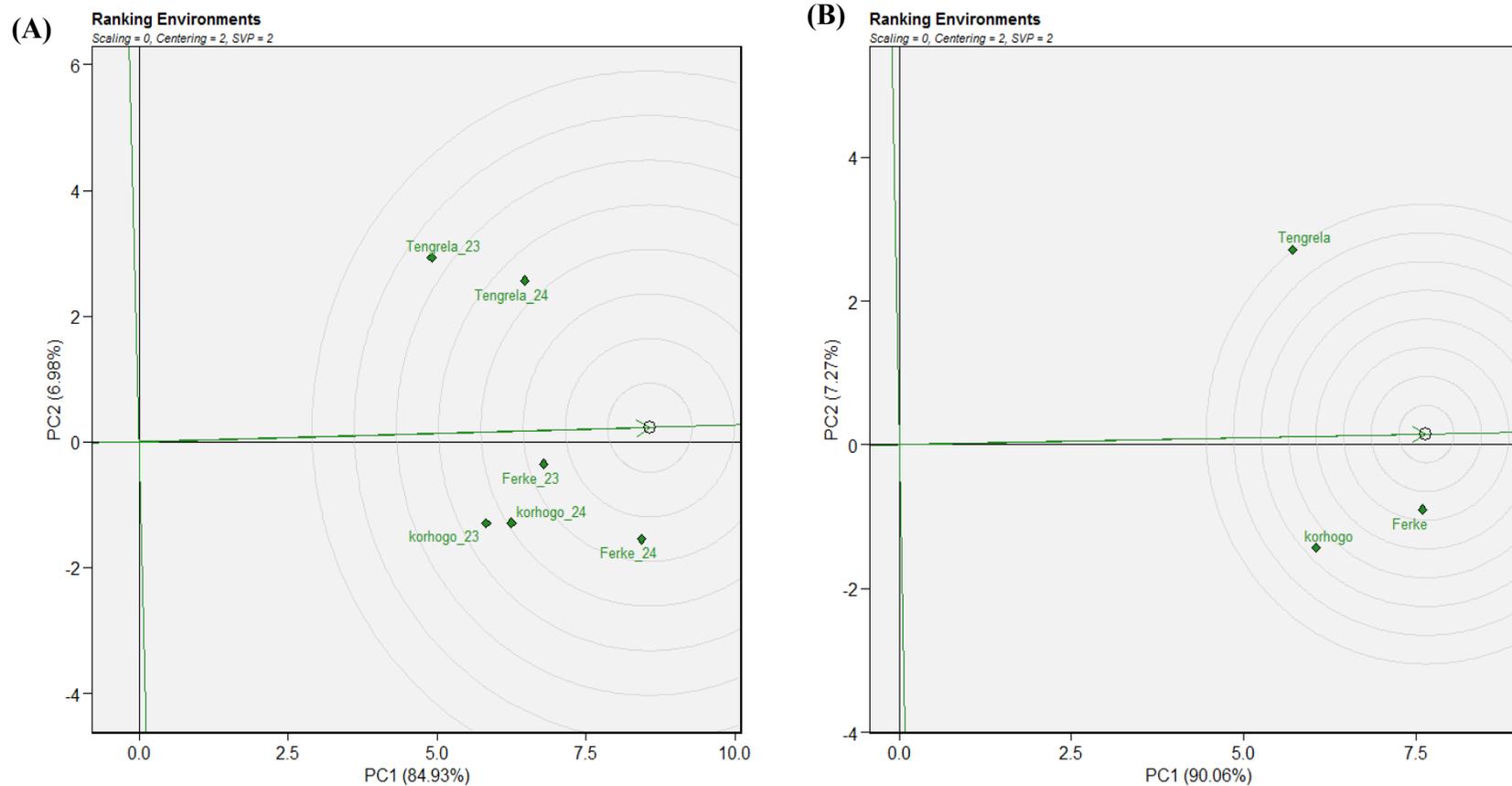


Figure 4: GGE biplot showing the ideal environment based on six environments (A) and two-year average data (B)

Table 5: Identification of the most favorable environments according to the environmental index model for the six environments

Environments	Yields	Index	Class
Ferke 23	0.860	0.0880	Favourable
Ferke 24	0.907	0.135	Favourable
Korhogo 23	0.747	-0.0248	unfavourable
Korhogo 24	0.685	-0.0869	unfavourable
Tengrela 23	0.680	-0.0914	unfavourable
Tengrela 24	0.730	-0.0197	unfavourable

Ferke: Ferkessédougou

Table 6: Identification of the most favorable environments according to the environmental index model for the average of the two years

Environments	Yields	Index	Class
Ferkessédougou	0.883	0.111	Favorable
Korhogo	0.716	-0.0559	unfavourable
Tengrela	0.705	-0.0555	unfavourable

DISCUSSION

The combined analysis of variance according to the AMMI model revealed that the effects of genotypes, environments, and their interaction (GxE) are highly significant for all the traits studied. This indicates that differences in environmental conditions (rainfall, temperature, soil fertility, etc.) between experimental sites alter the behaviour of accessions. Moreover, our results are consistent with those of Cooper *et al.* (2014), who showed that environmental conditions, particularly water availability and temperature, have a major influence on phenotypic expression and crop performance. Similarly, according to Amare (2019), the presence of a significant interaction between genotypes and environments reflects the difference in accession behaviour depending on the environment in which they are grown. Subsequently, AMMI analysis allowed the sum of squares of the G×E interaction to be broken down into two main interaction components (IPCA), both of which were significant. The results showed that the first axis (IPCA1) explains 56.02% of the interaction variance, while the second (IPCA2) explains 27.3%. According to Zobel *et al.* (1988), cited by Tewodros *et al.* (2021), these first two axes are generally sufficient to predict the performance of genotypes in different environments. In this study, based on average data, some stable accessions

showed high yields (3.279 - 3.715 t/ha), average (1.004 -1.577 t/ha) and low (0.0970 – 0.992 t/ha), while a few were unstable and unproductive (0.117 - 0.779 t/ha). The differences in responses observed between accessions could be explained mainly by the genetic characteristics specific to each accession, the specific environmental conditions of each site, and above all the genotype x environment (GxE) interaction, which is confirmed by our AMMI analysis results. Indeed, some accessions have genetic characteristics that enable them to adapt effectively to various environments, hence their high and stable yield (Badu-Apraku *et al.*, 2021). Consequently, an accession that performs well in one environment may have low productivity in another (Yan and Kang, 2003; Badu-Apraku *et al.*, 2021). Overall, these observations are consistent with the conclusions of Gauch (2013) and Amare (2019), according to which stability and performance result from a balance between genetic potential and compatibility with the environment. Complementarily, GGE analysis is a powerful statistical approach that allows simultaneous evaluation of the average performance and stability of genotypes across different environments. It integrates both genotype (G) and genotype x environment (GxE) interaction effects, making it an effective tool for identifying high-yielding, highly stable genotypes while highlighting the most discriminating

environments (Yan *et al.*, 2000; Gauch, 2006). Thus, according to Gauch *et al.* (2008), an ideal cultivar is one that lies within or near the first concentric circle of the GGE biplot. This genotype has both the highest grain yield and stability. In addition, desirable cultivars are close to this ideal cultivar and are characterized by average yield and acceptable stability. On the other hand, undesirable cultivars, located far from the center of the biplot, show high instability and low yields (Yan and Tinker, 2006). Based on the criteria proposed by Yan and Tinker (2006) and Gauch *et al.* (2008), the GGE analysis carried out in our study thus made it possible to distinguish three categories of accessions according to their position in the biplot. These include 3 ideal accessions, 30 desirable accessions, and 84 undesirable accessions. This classification clearly illustrates the ability of the GGE model to effectively discriminate genotypes according to their performance and stability. Furthermore, Gauch (2006) confirms that the GGE model is one of the most reliable tools for varietal selection, as it simultaneously integrates productivity and stability in a single interpretive graph. Similarly, Mohammadi and Amri (2008) add that ideal genotypes are the best candidates for selection, as the GGE method facilitates decision-making in varietal improvement programs. Furthermore, Yan *et al.* (2007) specify that these genotypes, thanks to their wide adaptation, are the best candidates for large-scale dissemination in different growing environments. However, Ceccarelli and Grando (2007) also emphasize the importance of conserving low-yield accessions, as they represent a valuable genetic reserve for strengthening crop resilience to climate change and future biotic pressures. Similarly, Gauch and Zobel (1997) point out that effective selection depends on the ability to identify genotypes whose response to environments is predictable and consistent, ensuring sustainable adaptation and consistent performance. With regard to environments, identifying an ideal environment is also an

essential step in analyzing genotype x environment interactions (GxE) interactions. According to Yan and Tinker (2006), an ideal environment is represented in the GGE biplot by a point located on or near the first concentric circle, indicating that it is both highly discriminating and representative of the average behaviour of genotypes. In other words, such an environment effectively distinguishes differences in performance between genotypes, while accurately reflecting their average performance across all tested environments. Furthermore, according to Gauch (2013), an environment that is both representative and discriminating allows for effective evaluation of genotype performance and stability, while saving time and effort. The ideal environment thus shows how genotypes generally behave in all test sites. In the context of this study, the Ferkessédougou environment was therefore identified as the ideal environment. Indeed, this site has a high discriminating capacity and represents the average response of accessions in a balanced manner, making it a reliable reference site for the evaluation of genotypes. Finally, the choice of an ideal environment is of major practical importance in multi-location trials. It provides researchers with a key site where the observed performances accurately reflect the general behaviour of genotypes, thus facilitating the selection of stable and high-performing varieties capable of maintaining good yields in various environments (Yan and Tinker, 2006).

CONCLUSION

The results of the combined ANOVA reveal a highly significant effect ($p < 0.001$) of environments (E), genotypes (G), and their interaction (GxE) on all the traits studied. Furthermore, the AMMI showed that the environment contributes most to the variation in grain yield (49.57%), followed by genotypes (30.62%) and the genotype x environment interaction (17.62%). Furthermore, based on average yields and eco-valency values, accessions a160, a161, and a162 stood out for their high yields

(3.279 to 3.715 t/ha) and stability, reflecting excellent adaptation to environmental variations. Conversely, some accessions showed low yields and high instability, indicating sensitivity to environmental fluctuations. In addition, the GGE biplot method showed that accessions a160, a161, and a162 were considered ideal compared to the other accessions. Across all three locations, the GGE method indicated that the Ferkessédougou location is considered the ideal environment. Consequently, this location can be considered an ideal place for various selection activities.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: No conflicts of interest declared.

REFERENCES

1. Annicchiarico, P. (1997). Joint Regression vs AMMI Analysis of Genotype-Environment Interactions for Cereals in Italy. *Euphytica*, (94), 53-62. <http://dx.doi.org/10.1023/A:1002954824178>
2. Akanvou, L., Akanvou, R., Kouakou C.K., N'Da HA. (2012). Evaluation of the agromorphological diversity of millet accessions [*Pennisetum glaucum* (L.) R. Br.] collected in Côte d'Ivoire. *Journal of Applied Biosciences*, (50), 3468–3477.
3. Al-Naggar, A. M. M., Abd El-Salam, R. M., Hovny, M. R. A., Yaseen, Y. S. (2018). Genotype × Environment Interaction and Stability of Sorghum bicolor Lines for Some Agronomic and Yield Traits in Egypt. *Asian Journal of Agricultural and Horticultural Research* 1(3): 1-14. DOI: 10.9734/AJAHR/2018/40985
4. Amare, S., Zigale, S., Adane, G. (2019). AMMI and GGE bipolt analysis of Genotype x Environment Interaction and Yield Stability of Pearl Millet Genotypes [*Pennisetum glaucum* (L.) R. Br.] in Moisture Stressed Areas of Ethiopia. *Acad. Res. J. Agri. Sci. Res.* 7(4): 190-201. DOI: 10.14662/ARJASR2019.038
5. Bezançon, G., Pham, J.L. (2004). Genetic resources of millets in West Africa: diversity, conservation, and utilization: proceedings of the workshop “Diversity, conservation, and utilization of millet genetic resources,” ICRISAT, Niamey (Niger). IRD. Colloques et séminaires, 56p.
6. Beninga, M. B. (2007). Genetics, improvement and extension of millet (*Pennisetum glaucum* (L.) R. Br.) in Côte d'Ivoire, Doctoral thesis, UFR Biosciences, University of Cocody, Abidjan, Côte d'Ivoire, 179p.
7. Blum, A. (2011). Plant Breeding for Water-Limited Environments. *Springer New York, NY*. <https://doi.org/10.1007/978-1-4419-7491-4>
8. Béninga, M.B., Sangaré, A., N'guettia, S.P.A., and Coulibaly, M.Y. (2011). Establishment of a collection of genetic resources of millet (*Pennisetum glaucum* (L.) R. Br.) in Côte d'Ivoire. *Agronomie Africaine*, 23(3): 193–204.
9. Boko, K.A.N.N., Cissé, G., Koné, B., Séri, D. (2016). Climate Variability and Environmental Change in Korhogo, Côte d'Ivoire: Myth or Reality? *European Scientific Journal*, 12(5), 158. <https://doi.org/10.19044/esj.2016.v12n5p158>
10. Badu-Apraku, B., Bankole, F.A., Fakorede, M.A.B., Ayinde, O., Ortega-Beltran, A. (2021). Genetic analysis of grain yield and resistance of extra-early-maturing maize inbreds to northern corn leaf blight. *Crop Science*;61:1864–1880. <https://doi.org/10.1002/csc2.20479>
11. CNRA. 2022. Annual Activity Report, 49p.
12. Crossa, J. (1990). Statistical Analyses of Multilocation Trials. *Advances in Agronomy*, (44), 55-85. [http://dx.doi.org/10.1016/S0065-2113\(08\)60818-4](http://dx.doi.org/10.1016/S0065-2113(08)60818-4)
13. Crossa, J.P.L., Yan, W. (2002). Biplots of linear-bilinear models for studying crossover genotype × environment interaction. *Crop Sci.*, 42:619–633.
14. Ceccarelli, S., Grando, S. (2007). Decentralized-Participatory Plant Breeding: An Example of Demand Driven Research. *Euphytica* 155(3):349-360. DOI: 10.1007/s10681-006-9336-8
15. Cruz, J.F., Béavogui, F., Dramé, D. (2011). Fonio, an African cereal. Versailles, France: Éditions Quæ; Wageningen, Netherlands: CTA; Gembloux, Belgium: Presses agronomiques de Gembloux, doi.org/10.35690/978-2-7592-1040-4

16. Chenu, K., Cooper, M., Mathews, K. L., Dreccer, M. F., Chapman, S. C. (2011). Environment characterization as an aid to wheat improvement: interpreting genotype–environment interactions by modeling water-deficit patterns in North-Eastern Australia. *Journal of Experimental Botany*, 62(6), 1743–1755. doi:10.1093/jxb/erq459
17. Cooper, M., Messina, C. D., Podlich, D., Totir, L. R., Baumgarten, A., Hausmann, N.J., Wright, D., Graham, G. (2014). “Predicting the future of plant breeding: complementing empirical evaluation with genetic prediction,” *Crop and Pasture Science* 65(4), 311-336. <https://doi.org/10.1071/CP14007>
18. Dede, L.E., N'DA, H.A., Akanvou, L. (2020). Agromorphological and botanical diversity of 357 sorghum accessions (*Sorghum bicolor* (L) Moench) collected in Côte d'Ivoire. *Agronomie Africaine* 32(3): 297-308
19. Diomandé, I. (2002). Pesticides used in mango production. University Diploma in Technology (DUT) thesis, option: agropastoral management, University of Bouaké/URES of Korhogo, Côte d'Ivoire. 55p
20. Eberhart, S.A., Russell W.A. (1966). Stability parameters for comparing varieties. *Crop Sci.* 6:36–40
21. FAO. (2023). FAO Database. Agricultural Statistics. <http://faostat.fao.org>
22. Gauch, H.G., Zobel, R.W. (1997) Identifying Mega-Environments and Targeting Genotypes. *Crop Science*, (37), 311-326. <https://doi.org/10.2135/cropsci1997.0011183X003700020002x>
23. Gauch, H.G. (2006). Statistical Analysis of Yield Trials by AMMI and GGE. *Crop Science*, 46, 1488-1500. <https://doi.org/10.2135/cropsci2005.07-0193>
24. Gauch, H.G., Piepho, H., Annicchiarico, P. (2008). Statistical Analysis of Yield Trials by AMMI and GGE: Further Considerations. *Crop Science*, 48(3), 866-889 <https://doi.org/10.2135/cropsci2007.09.0513>
25. Gauch, H. G. (2013). A simple protocol for AMMI analysis of yield trials. *Crop Science*, 53(5), 1860–1869. <https://doi.org/10.2135/cropsci2013.04.0241>
26. Koffi, K.J.M. (2021). Estimation of the physiological maturity of mangoes and the yield of mango orchards (*Mangifera indica* L., ‘Kent’ variety) in northern Côte d'Ivoire: towards the establishment of a harvest prediction model. Doctoral thesis. Jean Lorougnon Guédé University of Daloa. p162
27. Kouakou, K.R., N'Da, H.A., N'Cho, A.L. (2024). Literature review of cereals grown and produced in northern Côte d'Ivoire: The case of corn (*Zea mays* L.), millet (*Pennisetum glaucum* (L.) R. Br.), and sorghum (*Sorghum bicolor* L. Moench). *Journal of Animal & Plant Sciences*, 60 (2): 11015-11034. DOI: https://doi.org/10.35759/JANmPISc_i.v60-2.2
28. Lakho, A. A., Shar, P. A., Soomro, A. A., Nawal, N., Mehran, A. C. (2025). Evaluating Genetic Variability in Sesame (*Sesamum indicum* L.) Genotypes for Yield and Oil Content. *Pakistan Journal of Agriculture*, 2(2): 43-49. DOI: <https://doi.org/10.38211/PJA.2025.02.91>
29. Mohammadi, R., Amri, A. (2008). Comparison of parametric and non-parametric methods for selecting stable and adapted durum wheat genotypes in variable environments. *Euphytica* 159 (3):419-432. DOI: 10.1007/s10681-007-9600-6
30. Ndjeunga, J., Hash, C.T., Faye, I., Sanogo M., Echekwu, C.A. (2012) Assessing the Effectiveness of Agricultural R&D in West Africa: Cases of Pearl Millet, Sorghum and Groundnut Crop Improvement Programs. Diffusion and Impact of Improved Varieties in Africa (DIIVA) Project, Objective 1 Report. ICRISAT, Niamey, Niger. 25p
31. Ouattara, D., Kouame D., Tiebre, S. M., Yao, J.C., N'GUESSAN, K.K. (2016). Plant biodiversity and use value in the Sudanian zone of Côte d'Ivoire. *Int. J. Biol. Chem. Sci.* 10(3): 1122-1138, DOI: <http://dx.doi.org/10.4314/ijbcs.v10i3.18>
32. Ouédraogo, A. (2018). Adaptation strategies of local populations to climate change in northern Burkina Faso: the case of Oula in the province of Yatenga, Single Doctoral Thesis in Geography, University of Ouagadougou I Pr Joseph Ki-Zerbo, Burkina Faso, 276 p
33. Olivoto, T., Lúcio, A.D. (2020). Metan: An R package for multi-environment trial analysis. *Methods Ecol Evol*, (11):783–789. <https://doi.org/10.1111/2041-210X.13384>
34. Pasteur, J.L., Libéra, A., Sakiroglu, M. (2021). Perennial Medicago show signatures of parallel adaptation to climate and soil in

- highly conserved genes. *Molecular Ecology*, 30(18):4448-4465 DOI: 10.1111/moi.c.16061
35. Slama, A., Ben, Salem, M., Zid, E. (2005). Cereals in Tunisia: production, effects of drought, and resistance mechanisms. *Science and Global Change/Drought*, 16(3):225-229.
36. Siene, L.A.C., Conde, M., Bayala, R., Kouadio, A.F.B., N'guettia, T.V.F. (2024a). Ethnobotanical investigation and socio-cultural characteristics of millet (*Pennisetum glaucum* (L.) R. Br.) in the savannah district of northern Côte d'Ivoire. *International Journal of Innovation and Applied Studies*, 43(2), 503-512.
37. Siene, L.A.C., Conde M., N'guettia T.V.F., KOUADIO A.F.B., BAYALA R. (2024b). Characterization of millet-based cropping systems (*Pennisetum glaucum* (L.) R. Br.) in the savanna district of northern Côte d'Ivoire. *Int. J. Biol. Chem. Sci.* 18(4): 1343-1365, DOI: <https://dx.doi.org/10.4314/ijbcs.v18i4.11>
38. Tewodros, T., Kassahun, T., Gemechu, K., Tesfahun, A. (2021). Genotype by Environment Interactions and Yield of Sesame (*Sesamum indicum* L.) Varieties Across the Diverse Agro-ecologies of Ethiopia. *Ethiop. J. Agric. Sci.* 31(4), 1-17.
39. Wricke. (1965). Stability analysis based on Wricke's model.
40. Yan, W., Ma, M.S, Kang, B, Woods, S, Cornelius, P.L. (2007). GGE biplot vs. AMMI analysis of genotype-by-environment data. *Crop Sci.* (47), 643–653
41. Yan, W., Hunt, L., Sheng, Q., Szlavnics, Z. (2000). Cultivar evaluation and mega-environment investigation based on the GGE biplot. *Crop Sci.* 40(3) :597–605. <https://doi.org/10.2135/cropsci2000.403597x>
42. Yan, W., Kang, M. S. (2003). GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists. Boca Raton, FL: CRC Press. DOI: 10.1201/9781420040371.288p
43. Zakir, M. (2018). Review on Genotype X Environment Interaction in Plant Breeding and Agronomic Stability of Crops. *Journal of Biology*, 8 (12), 1-8
44. Zobel, R.W., Wright M.J., Gauch H.G. (1988) Statistical Analysis of a Yield Trial. *Agronomy Journal*, 80: 388-393. <http://dx.doi.org/10.2134/agronj1988>.
- How to cite this article: Tâh Valentin Félix N'guettia, Laopé Ambroise Casimir Siéné, Ghislain Kanfany, Mariame Condé, Aya Kan Marie Louise Kouamé. Identification of high-yielding and stables genotypes of millet (*Pennisetum glaucum* (L.) R. Br.) under cultivation conditions in the savannah district of Northern Côte d'Ivoire. *International Journal of Research and Review*. 2025; 12(11): 449-463. DOI: <https://doi.org/10.52403/ijrr.20251147>
