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OPTIMISATION OF MINERAL FERTILISATION AND PLANTING DENSITY FOR IMPROVING HYBRID MAIZE PRODUCTIVITY IN SENEGAL'S GROUNDNUT BASIN

OPTIMISATION DE LA FERTILISATION MINÉRALE ET DE LA DENSITÉ DE SEMIS POUR AMÉLIORER LA PRODUCTIVITÉ DU MAÏS HYBRIDE DANS LE BASSIN ARACHIDIER DU SÉNÉGAL

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ABSTRACT

Maize (*Zea mays* L.) is a major food security stable and cash crop in West Africa, particularly in Senegal, where it is a strategic crop in agricultural production. However, low soil fertility and climate variability severely limit maize productivity in the maize-groundnut intercropping system in the Groundnut Basin in Senegal. The objective of this study was to optimise the combined effects of mineral fertilisation and planting density on the productivity of hybrid maize in the maize-groundnut intercrop systems in the Groundnut Basin in Senegal. The trial was conducted at the Nioro Agricultural Research Station using a split-plot design with three replicates. Five mineral fertilisation treatments ranging from an unfertilised control to increasing rates of NPK (15-15-15) and urea assigned to main plots, and five planting density levels (53,333–133,333 plants ha^{-1}) assigned to subplots were evaluated. The experimental crop was a hybrid maize variety, known as Kabamanoj. Planting density had no significant influence on phenology ($P = 0.442$), collar diameter ($P = 0.18089$) or plant height ($P > 0.05$). However, aboveground dry matter and grain yields responded significantly ($P = 0.0493$ and $P = 0.0069$, respectively), with maximum values obtained with D3 (6.85 and 5.08 t ha^{-1}), compared to 4.71 t ha^{-1} and 3.98 t ha^{-1} for D1; representing gains of 45 and 28%, compared to the standard density D1. Application of mineral fertilisers at the rate of F2, F3 and F4, caused the earliest maize growth ($P = 0.028$) and best collar diameter ($P = 0.0016$). However, application of mineral fertiliser at the rate of F4, resulted in the highest maize grain yield of 5.56 t ha^{-1}; representing a 25% increase, compared to the control treatment, F1. Results also showed no significant ($P>0.05$) fertiliser application x planting density on grain yield. Thus, adopting an optimal density D3 (111,111 plants ha^{-1}), combined with mineral fertilisation F4, would contribute significantly to improving maize productivity in Groundnut -growing Basin of Senegal.

Key Words: Arachis hypogia, planting density, Senegal

RESUME

Le maïs (*Zea mays* L.) est une culture de base essentielle à la sécurité alimentaire et une culture de rente en Afrique de l'Ouest, notamment au Sénégal, où il constitue une culture stratégique dans la production agricole. Cependant, la faible fertilité des sols et la variabilité climatique limitent fortement la productivité du maïs, nécessitant l'optimisation de pratiques culturales adaptées aux variétés d'hybrides. Cette étude visait à évaluer les effets combinés de la densité de semis et la fertilisation minérale sur la productivité du maïs hybride. L'essai a été conduit durant la saison des pluies 2023 à la station de Nioro selon un dispositif en split-plot avec trois répétitions. Cinq traitements de fertilisation minérale, allant d'un témoin non fertilisé à des doses croissantes de NPK (15-15-15) et d'urée appliquées aux parcelles principales, ainsi que cinq niveaux de densité de plantation (53 333 à 133 333 plants ha^{-1}) appliqués aux sous-parcelles, ont été évalués. Le matériel végétal utilisé était une variété hybride de maïs (Kabamanoj). Les résultats ont montré que la densité de semis n'a pas influencé significativement la phénologie (P = 0,442), le diamètre au collet (P = 0,18089) et la hauteur des plantes (P> 0,05). Toutefois, les rendements en biomasse sèche et en grain ont varié significativement (P = 0,0493 et P = 0,006), avec des valeurs maximales obtenues avec D3 (6,85 t ha^{-1} et 5,08 t ha^{-1}), contre 4,71 t ha^{-1} et 3,98 t ha^{-1} pour D1, soit des gains de 45 % et 28 % par rapport à la densité vulgarisée D1. Concernant la fertilisation minérale, elle a significativement amélioré la précocité (P = 0,028) et le diamètre au collet (P = 0,0016). Le rendement en grain a été significativement influencé (P = 0,009), avec une valeur maximale observée avec F4 (5,56 t ha^{-1}) soit un gain de 25% par rapport à la fumure vulgarisée F1. Le rendement en biomasse n'était pas significatif (P = 0,078), bien que F2 ait présenté la valeur la plus élevée (6,59 t ha^{-1}) soit un accroissement de 27 % par rapport à F1. Les résultats ont montré aussi que la fertilisation minérale n'a pas été influencé par les densités de semis (P > 0,05 pour l'interaction densité x fertilisation). Ainsi, l'adoption d'une densité optimale D3 (111 111 plants ha^{-1}), associée à une fertilisation minérale F4, pourrait contribuer significativement à l'amélioration de la productivité du maïs dans le bassin arachidier.

Mots Clés : Arachis hypogia, densité semis, rendement, Sénégal.

INTRODUCTION

Maize (*Zea mays* L.) is a major food crop and one of the most important cereals for human and animal consumption worldwide (FAO, 2022). In sub-Saharan Africa (SSA), low maize productivity is attributed to gradual degradation of soil fertility and to low-intensity production systems (Saïdou *et al.,* 2012). In West Africa, it is one of the main cereals after millet and sorghum, due to its wide agroecological adaptability. However, despite the tendency of increase in level of production, output remains insufficient to meet growing food demand, leading to persistent dependence on imports in several countries (FAO, 2022; 2023).

In Senegal, maize ranks third among cereal crops in terms of area under cultivation and production, behind millet and rice (DAPSA, 2023). It accounts for around 15% of the national cereal area, with an estimated area of 276,668 ha, a production of 787,750 tonnes and an average yield of 2,847.3 kg ha^{-1} (DAPSA, 2023). Despite its strategic importance for food security, maize productivity remains low given the country's agroecological potential. In Senegal's Peanut Basin, agricultural production systems are severely constrained by progressive decline in soil fertility, irregular rainfall and increasing land use pressure; which significantly affect the performance of cereal crops (Bationo *et al*., 2004; Saïdou *et al.,* 2012). In this context, improving maize productivity relies on the adoption of appropriate farming techniques, including the use of improved varieties and the optimisation of agronomic practices (Taffouo *et al.,* 2008; Tollenaar and Lee, 2011).

Modern hybrids exhibit greater vigour and increased tolerance to high plant densities; allowing for better utilisation of available resources (Duvick, 2005; Tollenaar and Lee, 2011). Planting density is, therefore, a key determinant of yield, potentially leading to gains of 5-10% or more depending on agroecological conditions (Sangoi, 2001). However, its effectiveness depends heavily on nutrient quantity and availability; signalling a close interaction between planting density and mineral fertilisation as the opener to higher maize productivity. Optimum planting density can only be realised when accompanied by adequate mineral nutrition, to minimise inter-plant competition. Consequently, augmenting nutrient levels in the production system is an essential strategy for improving soil fertility, the effectiveness of which has been widely demonstrated in Senegal (FAO, 2015). From this standpoint, combined optimisation of plant density and fertilisation appears to be a key approach for the sustainable intensification of maize in the Peanut Belt. The objective of this study was to optimise the combined effects of mineral fertilisation and planting density on the productivity of hybrid maize in the maize-groundnut intercrop systems in the Groundnut Basin in Senegal.

MATERIALS AND METHODS

Experimental site. The trial was conducted at the experimental station of the Senegalese Institute for Agricultural Research (ISRA), specifically in Nioro du Rip. The station is located at the interface between the Sahelian and Sudanese zones, at latitude 13°45'00'', and longitude 15°48'00''. It benefits from a 4- to 5-month rainy season that is very wet but is always marked by high interannual variability.

The soils are predominantly sandy, but have slightly higher clay and silt content, and higher water-holding capacities than the Centre of the groundnut-growing region. Site soil analytical characteristics are presented in Table 1.

Total annual rainfall was 858.5 mm, but relatively light at the beginning and end of the season. The mean annual temperature ranges from 22.8 to 35.6 °C; while humidity ranges from 20.2 to 93.6%. The highest humidity levels are generally recorded between July and September, a period that coincides with heavy rainfall.

Experimental materials. Maize variety, Kabamanoj, an F1 hybrid hybrid was the experimental crop. Seeds of Kabamanoj were supplied by the Syngenta Foundation. The variety has an average growth cycle of 85-90 days and a yield potential of 10 metric tonnes per hectare. This variety is well-suited to the local agroclimatic conditions, and its yield components, specifically kernel filling and the number of ears per plant, are highly valued by farmers.

The fertilisers used included NPK (15-15-15) and urea (46%N) at the rates of 200 and 400 $kg.ha^{-1}$; and 200 and 350 $kg.ha^{-1}$, respectively.

Experimental design. Treatments were laid out in a split-plot design, with three replicates (blocks) in a factorial arrangement involving two factors: mineral fertilisation and planting

TABLE 1. Baseline soil physico-chemical characteristics and textural classification of the experimental site

Soil depth	USDA textural class	pH (1:2.5)	OM (%)	Total C (%)	C/N ratio
0-20 cm	Sandy	6.10	0.51 ± 0.03	0.297 ± 0.017	11.41 ± 1.92
20-40 cm	Loamy sand	5.33	0.37 ± 0.07	0.216 ± 0.037	10.84 ± 2.91

Values are presented as mean ± standard deviation (SD); OM = Organic matter; Total C = Total carbon

density. The main-plots was mineral fertilisation, whereas the sub-plots were planting density. Main plot size was 21 m by 3 m; while subplot size was 3 m by 3 m. Each main plot was divided into five sub-plots 3 m long, corresponding to the planting densities. The main plots were spaced 2 m apart and the sub-plots 1.5 m apart.

A border of four rows of seedlings was left around the entire trial to limit edge effects. The mineral fertilisation treatments and their nutrient composition are presented in Table 2. The planting density treatments and subplot characteristics are presented in Table 3.

Field management. The field site was bush cleared manually and tractor farrowed into a fine seed bed. Manual flat seeding was carried out in holes at a rate of two seeds per hole, at the spacing of (i) 0.75 m x 0.25 m, (ii) 0.60 m x 0.25 m, (iii) 0.60 m x 0.15 m, (iv) 0.50 m x 0.25 m, and (v) 0.50 m xx 0.15 m; corresponding to the different planting density treatments. Thinning was done to one plant per hole at 10 days after seeding (DAS).

Fertiliers were applied according to the mineral fertilisation rates under study (Table 2). The base fertiliser (NPK 15-15-15) was applied at sowing; while urea was split applied, 50% at 20 DAS) and the rest at the booting-flowering stage (approximately 41 DAS).

Manual weeding and pest control (fall army worm) were done following the routines recommended for the region.

Data collection. The following parameters were measured during the experiment; the days to male flowering (DASF), plant height at 30 (PH30), 45 (PH45), and 75 (PH75) days after sowing, and stem diameter at the collar (DIAM) at physiological maturity. All these parameters were evaluated on ten plants randomly selected from the sampling area.

Other parameters were measured at harvest; including grain weight per ear (GWE), number of grains per ear (NGE), hundred-grain

TABLE 2. Code, fertilisation treatment and nutrient composition

Code	Treatment	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
F0	Absolute control	0	0	0
F1	200 kg ha^{-1} NPK (15-15-15) + 200 kg ha^{-1} urea (46-0-0)	122	30	30
F2	300 kg ha^{-1} NPK (15-15-15) + 250 kg ha^{-1} urea (46-0-0)	160	45	45
F3	350 kg ha^{-1} NPK (15-15-15) + 300 kg ha^{-1} urea (46-0-0)	190.5	52.5	52.5
F4	400 kg ha^{-1} NPK (15-15-15) + 350 kg ha^{-1} urea (46-0-0)	221	60	60

P_2O_5 and K_2O values were calculated based on the nutrient contents of NPK (15-15-15) and urea (46-0-0)

TABLE 3. Planting density treatments and subplot characteristics

Code	Planting density (kg.ha^{-1})	Plant spacing (m)	Number of rows per subplot
D1	53,333	0.75 × 0.25	4
D2	66,667	0.60 × 0.25	5
D3	111,111	0.60 × 0.15	5
D4	80,000	0.50 x 0.25	6
D5	133,333	0.50 × 0.15	6

weight (HGW), grain yield (GYLD), and aboveground dry matter yield (SYLD). Samples were taken in plots excluding the border rows on each side of the plot and one planting hill at each end of the seed row to minimise border effects. Harvesting was done at physiological maturity, detected when a black layer had formed at the base of the grains and the husks had turned brown and dry. Aboveground biomass and ear (with grains) weight; and grains wight after threshing were also determined.

The aboveground biomass materials from the net plot was dried in a screenhouse at ambient temperature for three weeks. Approximately 3 kg subsample was taken and oven dried at 65 °C for 72 hours for dry mass determination. A grain counter was used to determine the hundred-grain weight (HGW). To calculate grain yield per plot, the grain moisture content was adjusted to 14% to allow comparison among treatments.

Data analysis. Data collected were analysed using a two-factor split-plot analysis of variance (ANOVA). Planting density and mineral fertilisation were treated as fixed factors, while blocks/replicates were treated as random factors.

The normality of the data was tested using the Shapiro-Wilk test, and the homogeneity of variances across factor levels was assessed using Bartlett's test. The Least Significant Difference (LSD) test was used to compare means at the 5% significance; wherever significant means were evident.

A principal component analysis (PCA) was performed on the standardised data matrix to better visualise the complex relationships between the measured parameters and the two factors studied. To classify the treatments according to their agronomic characteristics, a hierarchical cluster analysis (HCA) was performed using the first two principal components derived from the previous principal component analysis (PCA). Euclidean distance and Ward's clustering method were used to group the treatments. All statistical analyses were performed using R version 4.4.2 (R Development Core Team, 2024).

RESULTS

Stem diameter. The results of the ANOVA revealed no significant effect ($P>0.05$) of the interaction between mineral fertilisation and planting density, nor of sowing density itself, on stem diameter at male flowering. However, mineral fertilisation had a significant effect ($P < 0.05$) on stem diameter (Table 4). Thus, mineral fertilisation treatments F2, F3 and F4 developed the greatest stem diameter earliest, with a value of 54 DAS; while treatments F0 and F1 were the latest (57 DAS).

Treatments F1, F3 and F4 yielded the largest stem diameter (3.4 cm), contrasting with the absolute control F0, which recorded the lowest value (2.6 cm) (Table 4).

Plant height. The interaction between planting density and mineral fertilisation was not significant ($P>0.05$) for plant height at 30 DAS, 45 DAS and 75 DAS (Table 4). Thus, the single factor effects of planting density and mineral fertilisation were considered separately. Planting density had no significant effect on plant height at 30 DAS, 45 DAS, and 75 DAS. However, mineral fertilisation had a significant effect on plant height at 45 DAS and 75 DAS (Table 4). At 45 DAS, the greatest plant height was observed under treatment F3 (83.8 cm), whereas treatment F4 produced the highest value at 75 DAS (166.4 cm). The lowest plant height was observed in the unfertilised control (F0) (Table 4).

Grain yield. The interaction between planting density and mineral fertilisation did not significantly affect maize grain yield ($P>0.05$). Planting density per se significantly influenced grain yield ($P < 0.05$) (Table 5). Density D3 (0.60 x 0.15 m) was the most productive; whereas density D1 (0.75 m x 0.25 m) was the least productive. For mineral fertilisation,

TABLE 4. Effect of mineral fertilisation and planting density on maize phenology and growth

Source of variation	DASF	PH30	PH45	PH75	DIAM
D1	55±3.3	16.9±4.7	73.8±32.1	151.2±31.7	3.3±0.8
D2	55±4	16.8±4.8	67.3±31.4	151.8±28.6	3.4±0.5
D3	55±2.9	18.5±4.5	73.1±29.3	157±31.4	3.3±0.7
D4	55±3.8	15.9±4.5	68.8±34.0	151.5±33.5	3.4±0.6
D5	56±3.81	15.5±4.4	61.6±29.2	144.1±37.5	3±0.6
F0	57±4.49^{a}	15.9±6.6	48.1±35.8^{b}	116.1±38.8^{c}	2.6±0.9^{b}
F1	57±2.1^{ab}	14.9±3.6	53.5±1 8.7^{b}	143.9±18.4^{b}	3.5±0.4^{a}
F2	54±3.2^{bc}	17.7±4.6	79.5±29.4^{a}	163.5±27.2^{ab}	3.3±0.7^{a}
F3	54±3.1^{c}	17.6±4.4	83.8±27.1^{a}	165.5±24.6^{ab}	3.5±0.5^{a}
F4	54±3.1^{bc}	17.4±3.0	79.5±23.8^{a}	166.4±15.6^{a}	3.5±0.3^{a}
Overall mean	55	16.7	68.9	151.1	3.3
Planting density (D)	0.44257	0.2235	0.24139	0.50049	0.180897
Mineral fertilization (F)	0.02807	0.5081	0.00512	0.0001007	0.001616
Interaction (D* F)	0.84848	0.9718	0.84436	0.963781	0.978766

DASF = days to male flowering; PH30 = plant height at 30 DAS; PH45 = plant height at 45 DAS; PH75 = plant height at 75 DAS; DIAM = stem diameter at the collar. For each column, means not followed by different letters are not significantly different at the 5% level according to the Least Significant Difference (LSD) test

the ANOVA showed highly significant differences ($P<0.009$) in grain yield. Thus, treatment F4 stood out with a yield of 5.6 ± 1.4 t ha^{-1}. The absolute control, F0 was less productive at1.7 ± 1.3 t·ha^{-1}.

Above ground dry matter yield. The interaction between mineral fertilisation option and density had no significant effect on aboveground matter yield ($P>0.05$); nor were the single factor effects of mineral fertilisation. However, sowing density had a significant effect ($P<0.05$) on biomass yield (Table 5). Planting density D1 produced the highest yield; whereas planting density D1 produced the lowest aboveground dry matter yield.

Hundred-grain weight. The mineral fertilisation by planting density treatment interaction had no significant effect on 100-grain weight (Table 5). However, their single factor effects had significant effects ($P < 0.05$). Planting density D3 (0.60 m × 0.15 m) recorded the highest weight (16.1 g); while D5 (0.50 m × 0.15 m) was lighter, with a value of 15 g. On the other hand, 100-grain weight was not statistically ($P>0.05$) affected by the mineral fertilisation options (Table 5).

Grain weight and number per ear. There was no significant effect ($P>0.05$) of the interaction between mineral fertilisation and planting density on either grain weight per ear or number of grains per ear; nor was the single effect factor of planting density. For the mineral fertilisation, however, the ANOVA values revealed highly significant differences ($P<0.001$) of both grain weight and number per ear (Table 5). F3 recorded the highest value of 38.7 g per ear; while the absolute control F0 presented the lowest value overall.

Principal component and hierarchical cluster analysis. Principal component analysis (PCA) was performed on the standardised data matrix comprising all

TABLE 5. Effect of mineral fertiliser treatments and planting density on grain yield and their components

Source of variation	GYLD (t ha^{-1})	SYLD (t ha^{-1})	HGW (g)	GWE (g)	NGE
D1	4.0 ± 1.1^{c}	4.7 ± 1.4^{b}	15.2±3.9^{a}	30.5±20.9^{a}	172±101.5^{a}
D2	4.2 ± 1.1^{bc}	5.0 ± 1.3^{b}	15.9±3.2^{a}	32.9±18.1^{a}	186±76.9^{a}
D3	5.1 ± 1.6^{a}	6.9 ± 3.0^{a}	16.1±3.6^{a}	30.3±16.3^{a}	169±80^{a}
D4	4.6 ± 1.5^{abc}	5.0 ± 1.6^{b}	15.2±4.2^{a}	31.4±19.2^{a}	180±75.4^{a}
D5	4.6 ± 1.7^{ab}	5.9 ± 1.8^{ab}	15±3.7^{a}	22.5±15.2^{a}	148±77.8^{a}
F0	1.7 ± 1.3^{c}	3.1 ± 3.0^{a}	11.7±3.6^{b}	12.5±12.1^{c}	95±60.5^{c}
F1	4.5 ± 1.1^{bc}	5.2 ± 1.6^{a}	16±3.6^{a}	25.1±13.3^{bc}	147±54.1^{bc}
F2	5.3 ± 1.5^{ab}	6.6 ± 2.3^{a}	16.3±4.2^{a}	33.7±21.5^{ab}	181±88^{ab}
F3	5.5 ± 1.3^{a}	6.5 ± 1.3^{a}	16.5±2.5^{a}	38.7±14.6^{a}	219±69.7^{a}
F4	5.6 ± 1.4^{a}	6.1 ± 0.9^{a}	16.4±2.3^{a}	36.1±14.9^{ab}	204±66.4^{a}
Overall mean	4.5	5.5	15.5	29.4	149.3
Planting density (D)	0.049396	0.00607	0.823742	0.252627	0.5128756
Mineral fertilization (F)	0.009136	0.0783	0.005487	0.001442	0.0005382
Interaction (D* F)	0.800437	0.87574	0.751178	0.792106	0.698193

GYLD = grain yield; SYLD = Aboveground dry matter yield; HGW = hundred-grain weight; GWE = grain weight per ear; NGE = number of grains per ear. For each column, means followed by the same letter are not significantly different at the 5% level according to the Least Significant Difference (LSD) test

measured parameters. Examination of the factor loading matrix revealed that the first two components explained 89.3% of the total observed variability (Fig. 1). The first component explained 78.6% of the variability. It is primarily defined by the variables height at 75 days after sowing (PH75), grain weight per ear (GWE), and number of grains per ear (NGE).

The second component explained 10.7% of the variability. The traits that contributed most to defining this axis are height at 30 DAS (PH30), collar diameter (DIAM), and straw yield (SYLD).

Hierarchical ascending classification (HAC) identified three classes of individuals ranked according to their performance levels (Fig. 2). Cluster 1 comprised of a single individual, namely the absolute control (F0), which performed the worst. For this class, grain yield, grains per ear, grain weight per ear, height at 75 DAS, diameter, and hundred-grain weight were low. Cluster 2 consisted of 5 individuals; namely, D1, D2, D4, D5 and F1; which had the lowest heights at 30 DAS. Cluster 3 included mineral fertilisation treatments, F2, F3, F4 and D3. These individuals were earlier maturing and recorded the highest grain and straw yields, as well as the tallest heights (PH30, PH45, and PH75).

DISCUSSION

Plant growth and phenology parameters. The lack of significant effect of planting density on plant height, collar diameter and phenology (Table 4) could be explained by the morphological stability of the Kabamanoj hybrid maize across various stand density conditions (Tollenaar and Lee, 2011). Indeed, modern maize hybrids are generally selected for their ability to maintain growth and development under high densities; due to improved phenotypic plasticity and a more efficient leaf architecture (Duvick, 2005; Tollenaar and Lee, 2011).

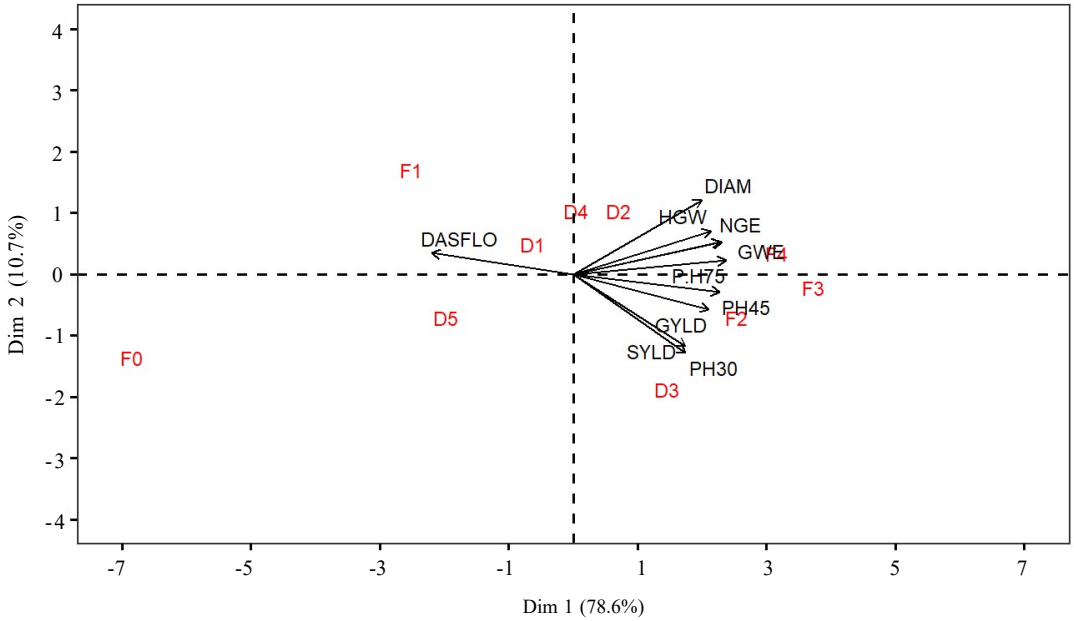

Figure 1. Distribution of mineral fertiliser application rates and seeding density along the main axes defined by the variables under study.

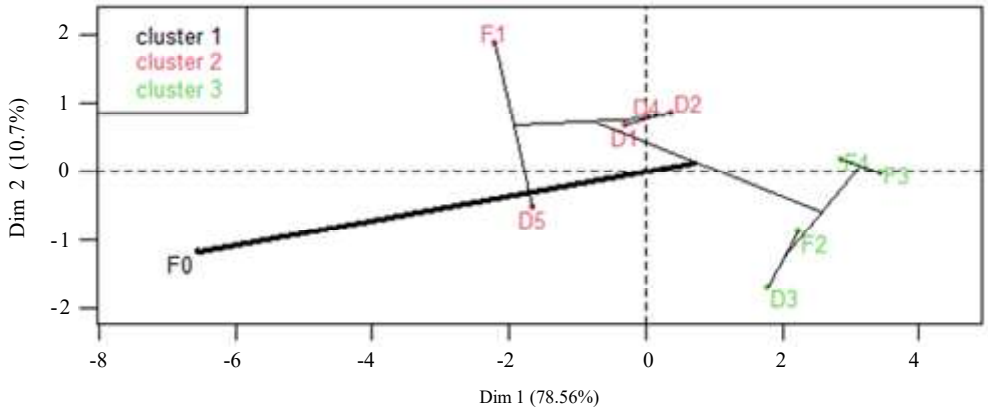

Figure 2. Map showing the representation of individuals according to the hierarchical ascending classification.

The stability could also be an indication of the hybrid's good adaptation to the agroecological characteristics of the Senegalese Groundnut Basin, with sandy soils low in organic matter (Table 1) and high rainfall variability. Similar observations were made in previous studies aimed at evaluating the effects of planting density (Mbuya *et al.,* 2020).

Although the numerical values were lower for some growth parameters (PH45, PH75 and stem diameter) at high densities, the differences were not statistically significant ($P>0.05$). This shows that increasing planting density did not generate a sufficiently high level of competition to affect hybrid's vegetative growth. This stability could be linked to better

architecture of the canopy, favouring more efficient interception of photosynthetically active radiation (PAR); as well as improved radiation use efficiency (RUE). Andrade *et al.* (2002) also demonstrated that reducing row spacing improved light interception and the conversion of radiation into biomass up to a critical density limit. Sher *et al.* (2021) suggested that modern hybrids tolerant to high densities, generally have better leaf architecture and vertical leaf distribution, reducing the adverse effects of shading.

The significant effect of mineral fertilisation on plant height and collar diameter (Table 4); with plants in the fertilised plots being taller and visually more vigorous growth than those grown under the absolute control, could be associated with increased nitrogen and phosphorus availability, nutrients crucial in the biosynthesis of proteins, chlorophyll and in biomass accumulation (Bindraban *et al.,* 2020).

Grain yield and yield components. The absence of significant interaction effect of mineral fertilisation and planting density on grain yield and other yield components (Table 5), could be attributed to the stability of the Kabamanoj hybrid. Indeed, under the environmental conditions of the study, the effects of mineral fertilisation were not influenced by planting density. The significant effect of planting density on grain and other yield components could be due to unlike the competition between plants of the hybrid for environmental resources (water, light, soil nutrients), where the availability of these resources affects canopy development, the distribution of photosynthates and grain formation. Density D3 (111,111 plants ha^{-1}) was more productive in terms of both grain and aboveground dry matter; while D1 (53,333 plants ha^{-1}) recorded the lowest yields. Indeed, yield increased progressively from D1 to D3 before stabilising or decreasing slightly at higher densities.

This response indicates a quadratic relationship between sowing density and yield, with the optimal sowing density being around D3 (111,111 plants ha^{-1}). This could be explained by the fact that at this density, the spatial coverage of the canopy and light interception was likely optimal, facilitating the conversion of light into biomass and grain yield. These results conform to those of Assefa *et al.* (2018), who established that modern maize hybrids achieve their highest yield potential at high densities through radiation interception and optimised resource use. Several other studies have demonstrated that reducing row spacing improves light interception, enhances radiation use efficiency, and promotes greater biomass accumulation and grain yield. The results also showed that beyond D3, and particularly at D5, yields decreased. This may be due to increased intraspecific competition for water, nutrients and light as well as reduced efficiency in radiation use, limiting grain space utilisation and increases the efficiency of photosynthetic radiation use (Andrade *et al.,* 2002; Tollenaar and Lee, 2011). According to Sher *et al.* (2021), when the leaf area index (LAI) exceeds a critical value, shading of the space between plants prevents basal leaves from carrying out photosynthetic activities and thus limits the accumulation of productive biomass.

An interesting finding was the absence of a significant effect of density on yield components, including hundred-grain weight, grains weight per ear and number of grains per ear (Table 5). In general, high plant densities lead to a significant reduction in ear weight and grain number due to greater competition among maize plants for available environmental resources. Nevertheless, the Kabamanoj hybrid in this study maintained relatively stable yield components, despite the increase in planting density. This stability indicates the hybrid's good tolerance to high densities and considerable phenotypic plasticity. According to Duvick (2005) and Tollenaar and Lee (2011), genetic improvements have increased the ability of modern hybrids to withstand high densities without a marked reduction in yield

components. Thus, this hybrid could play a major role in introducing maize hybrids into the maize-groundnut intercropping system of the Groundnut Basin of Senegal, where farmers tend to sow maize rather densely.

The significant effect of mineral fertilisation on grain yield and its components (Table 5), could be attributed to the hybrid's ability to mobilise the mineral nutrients available in the soil, particularly N and P convert them into carbohydrates and transport them to the reproductive organs, thereby increasing yield. Fertilisation options, F4 and F2, were more productive in terms of both grain and stover; unlike the unfertilised plots (F0), which yielded the lowest values (Table 5). The low yields observed in the unfertilised plots demonstrates that mineral fertilisation is essential for improved maize yields in tropical soils, particularly in soils deficient in organic matter in the Senegalese Groundnut Basin (Table 1).

The gradual increase in yield with increasing fertiliser rates may explain an improvement in N use efficiency (NUE); whereby intensive fertilisation probably contributed further to higher photosynthetic activity, as well as better ear nutrition for more active grain filling (Su *et al.*, 2020; Gheith *et al.,* 2022). However, although F4 yielded the highest grain yield, the relatively similar performance of F2 suggested that the latter could be economically sustainable for farmers.

An interesting finding was the absence of a significant interaction between planting density and mineral fertilisation on yield grain and yield components (Table 5). This indicates that the hybrid's response to fertilisation was not influenced by planting density. This result demonstrated the good adaptation of the Kabamanoj hybrid to intensified production systems, as well as stability in the use of available resources (Tollenaar and Lee, 2011). This stability is important for approaches to the sustainable intensification of hybrid maize cultivation under the agroecological conditions of the Groundnut Basin of Senegal.

CONCLUSION

The optimum combination of mineral fertilisation and planting density for hybrid maize grain and above ground yield in the Groundnut growing Basin of Senegal is D3 (111,111 plants ha^{-1}), combined with mineral fertilisation F4 (400 kg ha^{-1} NPK + 350 kg ha^{-1} urea). The grain yield attained at this treatment combination was 5.2±1.6 t ha^{-1}; while above ground dry weight was 6.8±3.0 t ha^{-1}, respectively.

Mineral fertilisation generally promoted earlier physiological maturity and recorded the highest collar diameter. Furthermore, plant height was greater with high fertiliser rates. Overall, the results highlight the importance of integrating maize hybrids tolerant to high planting densities with effective mineral fertiliser management to sustainably improve maize yields in Senegal.

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