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RESEARCH ARTICLE

EFFECTS OF MINERAL FERTILISATION STRATEGIES ON GROWTH, YIELD AND AGRONOMIC EFFICIENCY OF PEARL MILLET (*Pennisetum glaucum* (L.) R. BR.) VARIETIES IN THE SENEGALESE GROUNDNUT BASIN

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Abstract

In Senegal, millet (*Pennisetum glaucum* (L.) R. Br.) is the main cereal crop. However, its production is primarily limited by low soil fertility and mineral fertilisation techniques that are not always suited to the various agro-ecological zones and to all millet varieties. It was against this backdrop that this study was initiated to evaluate the response to different mineral fertilisation options with a view to optimising the production of millet hybrids under the growing conditions of the central groundnut-growing region of Senegal. The trial was set up during the 2023 wet season at the National Centre for Agronomic Research (CNRA) in Bambey. The experimental design was a split-plot design with three replicates and included the variety as the main-plot with five treatments (Taaw, ICMH177111, ICMH147007, Souna du Baol and Thialack 2) and mineral fertilisation as the subplot with four levels (F0: unfertilised control; F1: 75 kg ha⁻¹ of NPK 15-15-15 + 75 kg ha⁻¹ of urea (46% N); F2: 150 kg ha⁻¹ of NPK 15-10-10 + 100 kg ha⁻¹ of urea (46% N); F3: 50 kg ha⁻¹ of DAP 18-46-0 + 25 kg ha⁻¹ of urea (46% N) as a microdose) and variety as a secondary factor with five treatments (Taaw, ICMH177111, ICMH147007, Souna du Baol and Thialack 2). The parameters monitored and calculated related to phenology, growth, yields and their components, and agronomic efficiency. The results showed significant differences for most of the variables measured. For the mineral fertiliser treatments, F2 recorded the greatest plant height (182.8±26.3 cm), whilst F0 had the lowest (157.2±14.6 cm).

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Regarding thousand-grain weight and ear diameter, no differences were observed. Treatments F1 and F2 yielded the highest grain yields, with values of 2216.9±356.7 kg ha⁻¹ and 2273.9±499.5 kg ha⁻¹ respectively. Furthermore, F2 produced the highest biomass yield at 5,207.2 ± 1,364.5 kg ha⁻¹. Regarding the varieties, the duration of the growing

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season was not affected. The Taaw hybrid achieved the highest grain yields as well as dry biomass yields, with respective values of $2,611.6 \pm 355.5 \text{ kg ha}^{-1}$ and $5,638.9 \pm 1,303 \text{ kg ha}^{-1}$. Thus, microdosed mineral fertilisation proved to be much more efficient than the research recommendations

Introduction:-

Millet [*Pennisetum glaucum* (L) R. Br.] is ranked as the 7th most important cereal in the world (FAOSTAT, 2021). It is the quintessential Sahelian crop due to its adaptation to the specific growing conditions in this region (Kadri et al., 2019). According to the FAO, global millet production was estimated at 28.2 million tonnes in 2019, rising to 30.5 million tonnes in 2020. India is the world's largest producer, with a global market share of 33.3 per cent in 2020. In Africa, millet is grown across more than 21 million hectares, and nearly 500 million people depend on it for their survival (Saïdou, 2011). Africa accounts for 46 per cent of global millet production. This production comes mainly from West African countries, led by Nigeria, followed by Niger, Mali, Burkina Faso and Senegal. In Senegal, millet is the cornerstone of food security. It forms the basis of the daily diet of rural populations. It has become the leading crop, ahead of groundnuts in terms of area under cultivation, and the second most important after rice in terms of annual production (FAOSTAT, 2017). A production of 1,097,033 tonnes was recorded in 2023 across an area of 969,693 hectares (DAPSA, 2023). Millet is a cereal grown primarily for human consumption, but also for fodder and livestock feed in many households (Kanfany et al., 2018). It remains the main food crop for the rural population, which accounts for nearly 70 per cent of the national population. However, the growth and productivity of millet are hampered by the impact of pests and diseases (Lakshmana, 2008). Added to this are a water deficit, a gradual decline in soil fertility, the cultivation of marginal land and a lack of fallow periods (Kadri et al., 2019). Furthermore, since 2000, cereal prices have been rising steadily. The food deficit has become chronic, mainly due to the population's consumption patterns and dietary habits (Sy, 2011). Furthermore, declining soil fertility is one of the major constraints limiting millet productivity. For optimal, long-term productivity, appropriate soil management is essential.

Thus, mineral fertilisation is one of the methods for improving soil fertility that has proven its worth over several decades in Senegal by promoting higher yields. Indeed, the high cost of mineral fertiliser necessitates the search for techniques to improve fertiliser efficiency, which depends, amongst other factors, on the method of application. In Senegal, Badiane et al. (2001) emphasized the need for adequate nutrient supply to improve millet yields under semi-arid conditions. Bagayoko et al. (2011) also reported that fertilizer microdosing, through the localized application of nitrogen and phosphorus, can increase grain yield while reducing the amount of fertilizer required. However, the efficiency of mineral fertilizers depends not only on the application rate but also on how nutrients are applied and their availability to crops. According to Fofana et al. (2008), soil fertility and rainfall conditions are among the key factors affecting nutrient use efficiency in millet production. These findings highlight the importance of adapting fertilizer rates and application methods to local growing conditions to improve millet productivity and make better use of available nutrients, especially in areas characterized by poor soils and limited access to mineral fertilizers. Consequently, particular attention must be paid to increasing the agronomic efficiency of mineral fertilisers whilst avoiding high fertiliser doses to preserve soil health. It is against this backdrop that this study has been conducted, with the overall aim of contributing to increased millet yields in Senegal. More specifically, the study aims to evaluate the effect of different mineral fertilization strategies on the growth, grain yield, biomass production and agronomic efficiency of pearl millet varieties in the Senegalese Groundnut Basin.

Material and Methods:-

Study Area:-

The trial was conducted in rainy conditions at the research station of the National Centre for Agronomic Research (CNRA) in Bambey, which is the main station in the northern part of the groundnut-growing region. It is situated in the heart of the groundnut-growing region, in the Diourbel region, Bambey department, specifically in the commune of Ngogom, with the following geographical coordinates: $14^{\circ}42'$ north latitude; $16^{\circ}28'$ west longitude. The Bambey station experiences a typical Sahelian climate characterised by a long dry season lasting 8 to 9 months and a rainy season lasting 3 to 4 months. Rainfall varies significantly from year to year. The predominant soil types are tropical ferruginous soils. The trial was set up near the CNRA weather station in Bambey. Only climatic data recorded during the experimental period (July–October 2023) were collected. Regarding rainfall, the total amount of rain recorded at the experimental site for the 2023 wet season was 633.4 mm, distributed over 37 days. Daily temperature trends during the experiment showed a range of between 22°C and 27.5°C for the minimum temperature and between 27.4°C and 37.5°C for the maximum temperature (DAPSA, 2023). Relative humidity, meanwhile, fluctuated significantly during the trial, ranging from 45 per cent to 78 per cent for the minimum and from 82 per

cent to 100 per cent for the maximum. The soils at the Bambey National Centre for Agricultural Research are lightly leached tropical ferruginous soils with a sandy to sandy-loam texture. Soil samples were taken prior to sowing from the 0–20 cm and 20–40 cm horizons and then analysed at the Soil, Water and Plant Laboratory of the CNRA in Bambey. The results of the pre-sowing soil analysis are shown in Table 1.

Table 1: Physico-chemical characteristics of the soil prior to the experiment

Soil depth (cm)	Clay (%)	Silt (%)	Sand (%)	pH (H ₂ O)	Available P (ppm)	Total N (%)	OM (%)	CEC (méq/100g)	C/N ratio
0-20	4.28	2.2 2	93.3	6.8	10.662	0.024	0.55	4.44	12.78
20-40	8.71	2.3	89	6.63	6.11	0.03	0.41	6.01	12.11

Available P = available phosphorus; Total N = total nitrogen; OM = organic matter; CEC = cation exchange capacity; C/N = carbon-to-nitrogen ratio.

Plant material :-

The plant material consists of five millet varieties, including three hybrids – one of which was developed by ISRA (Taaw) and the other two by ICRISAT in Niger (ICMH177111) and Burkina Faso (ICMH147007) – and two population varieties developed by ISRA in Bambey (Souna du Baol and Thialck 2). The characteristics of the millet varieties under trial are presented in Table 2.

Table 2: Characteristics of the varieties studied

Variety name	Code	Genetic type	Origin	Plant height (cm)	Maturity cycle (days)	Yield (t ha ⁻¹)
Taaw	V1	Hybride topcross	Senegal	220 cm	65-75	4.2
ICMH 177111	V2	Hybride F1	Niger	210 cm	90	2-3,5
ICMH147007	V3	Hybride F1	Burkina Faso	200 cm	80-85	3.0
Souna du Baol	V4	Population	Senegal	275 cm	87	2,5
Thialack 2	V5	Population	Senegal	250 cm	95	3.0

Experimental design:-

The experimental design used was the split-plot design. It consisted of three (3) replicates, each comprising 20 treatments, making a total of 60 treatments. The factors studied were the variety in the main-plot, with five treatments: V1: TAAW, V2: ICMH177111, V3: ICMH147007, V4: Souna du Baol, V5: Thialack 2; and the mineral fertiliser treatments in the subplot, at four levels: F0: Absolute control 0 kg ha⁻¹; F1: 75 kg ha⁻¹ of NPK 15-15-15 + 75 kg ha⁻¹ Urea (46-0-0); F2: 150 kg ha⁻¹ of NPK (15-10-10) + 100 kg ha⁻¹ Urea (46-0-0); F3: 50 kg ha⁻¹ of DAP (18-46-0) + 25 kg ha⁻¹ Urea (46-0-0) applied locally as a microdose. The blocks are separated by 2-metre-wide aisles. Each block consists of five sub-blocks spaced 2 m apart. The small plots were spaced 1.8 m apart. Each sub-block in turn contained four small experimental plots. The experimental plot measures 5.4 m long by 3.6 m wide, giving an area of 19.44 m², corresponding to the mineral fertilisation options. The basic plot consists of four rows sown at a spacing of 0.9 m × 0.9 m, making a total of 24 planting holes. A border of four rows of seedlings was left all around the trial.

Crop management:-

The previous crop on this plot was cowpea. The soil was ploughed to a depth of 20 cm using a tractor, followed by cross-harrowing to break up clods of earth and improve aeration and soil structure. This work was carried out to ensure a good seedbed, thereby creating soil and climatic conditions favourable to successful germination and seedling emergence. The individual plots were marked out using stakes and the sowing rows were marked out using a row marker. Manual flat-sowing into holes was carried out with spacings of 0.9 metres between rows and within rows, at a rate of 5 to 6 seeds per hole. Sowing took place on 24 July 2023 in moist conditions following 37.6 mm of rainfall. Thinning to 3 plants per hill was carried out at 15DAS. During thinning, any missing holes were replanted to increase planting density at emergence. Fertilisers were applied in accordance with the mineral fertiliser rates under investigation. Basal fertiliser was applied at sowing, and urea at thinning (15 DAS) and during the tillering stage (approximately 45 DAS). For treatments F1 and F2, the base fertiliser was broadcast evenly across the entire experimental plot, and the urea was applied locally around the planting hills. This was followed by light raking to work the fertiliser into the soil. Treatment F3 was applied as a micro-dose using templates according to the treatment

rate (4.04 g/hill of DAP and 2.025 g/hill of urea). The technique involved applying the fertiliser dose into hills 5 cm deep at 10 cm from the planting hill. Two weeding and loosening operations were carried out manually to control weeds and loosen the soil. The first weeding and loosening operation took place on 8 August 2023 (15th day after sowing) and was followed by thinning. The second weeding and loosening operation took place on 23 August 2023. A guard service was put in place after sowing until 15 DAS, to prevent birds from digging up the seeds or rodents from damaging the young plants, and to ensure the grains filled out properly until harvest, thereby minimising damage from seed-eating birds. Harvesting took place as soon as the grains were observed to have reached physiological maturity. It was carried out according to the maturity date of each variety on a yield plot comprising 8 test plots per basic plot, followed by the general harvest. The ears were harvested using a harvesting knife and secateurs. All the test plots within the yield square were harvested by separating the above-ground biomass from the ears. The biomass and ears were dried in a greenhouse at room temperature for three weeks after harvesting, followed by drying in an oven at 65°C for 48 hours. Threshing was carried out by women who carefully placed the ears from each treatment into a mortar and then pounded them with a pestle to release the grains from the ears. This was followed by winnowing, which separates the grains from the chaff (glumes, glumelles, etc.).

Data collection:-

Measurements and observations were carried out on four (4) plants from the experimental plot, focusing on the following agro-morphological variables:-

Duration from sowing to flowering (DSF): The date of male flowering was considered to have been reached when at least 50 per cent of the four plants monitored on the experimental plot had reached this stage.

Plant height (PH): This was measured from the ground to the ligule of the last leaf to emerge on the 30th (PH30), 45th (PH45) and 60th (PH60) days after sowing (DAS) on the four (4) observation plants in each experimental plot, using a graduated ruler.

Ear diameter (DIAM): Ear diameter was determined on 10 ears selected at random from each sub-plot using a vernier calliper.

Yields and components: Yield and its components were determined in each sub-plot, namely: grain yield (GYIELD), dry biomass yield (BYIELD) and thousand-grain weight (TGW). The thousand-grain weight for each experimental plot was calculated by averaging the weights of three (3) batches of 1,000 grains.

Agronomic Efficiency: The agronomic efficiency of a fertiliser is defined as the ratio of the surplus yield (the increase in yield resulting from the application of a given quantity of fertiliser) to the quantity of fertiliser applied per hectare (Traore et al., 2018). The agronomic efficiency of fertiliser use was determined for each treatment using the formula:

$$AE = \frac{\text{Yield surplus (kg)}}{\text{Amount of fertiliser applied (kg)}}$$

Data analysis:-

The raw data collected during the field experiment were entered into Microsoft Excel 2016 for data organisation, calculation of yield and its components, and preparation of tables and graphs. All statistical analyses were performed using R software version 4.2.3. Prior to analysis of variance (ANOVA), the normality of residuals was assessed using the Shapiro–Wilk test, while the homogeneity of variances was evaluated using Bartlett's test. Analysis of variance was performed according to a split-plot experimental design, with millet varieties assigned to the main plots and mineral fertilisation treatments to the subplots. The statistical model used for the split-plot experimental design was expressed as follows:

$$Y_{ijk} = \mu + R_i + V_j + (RV)_{ij} + F_k + (VF)_{jk} + \varepsilon_{ijk}$$

where Y_{ijk} represents the observed value of the studied variable; μ is the overall mean; R_i is the effect of the i th replication (block); V_j is the effect of the j th millet variety (V1, V2, etc.) assigned to the main plots; $(RV)_{ij}$ represents the main-plot error term; F_k is the effect of the k th mineral fertilisation treatment (F0, F1, F2 and F3) assigned to the subplots; $(VF)_{jk}$ represents the interaction effect between millet variety and mineral fertilisation; and ε_{ijk} is the subplot residual error. The effects of millet varieties were tested against the main-plot error, whereas fertilisation treatments and their interactions with varieties were tested against the subplot error. When significant differences were detected, treatment means were compared using the least significant difference (LSD) test at the 5% significance level ($p \leq 0.05$). Pearson's correlation analysis was also performed to assess the relationships between grain yield and yield-related parameters.

Results:-

Effect of mineral fertiliser treatments and variety on the duration from sowing to flowering:-

The results of the analysis of variance showed that the duration from sowing to flowering was not significantly influenced by either the mineral fertiliser treatment or the variety, with an overall mean of 54 ± 3.3 DAS (Figure 1). However, in absolute terms, the unfertilised plots (F0) were the latest to flower, with an average of 55 ± 3.6 DAS, whereas the plots fertilised with the F3 treatment (53 ± 3.5 DAS) were the earliest. In terms of variety, the Taaw hybrid was the earliest maturing (52 ± 2.7 DAS) and the control variety, Souna du Baol, was the latest maturing (55 ± 2.2 DAS).

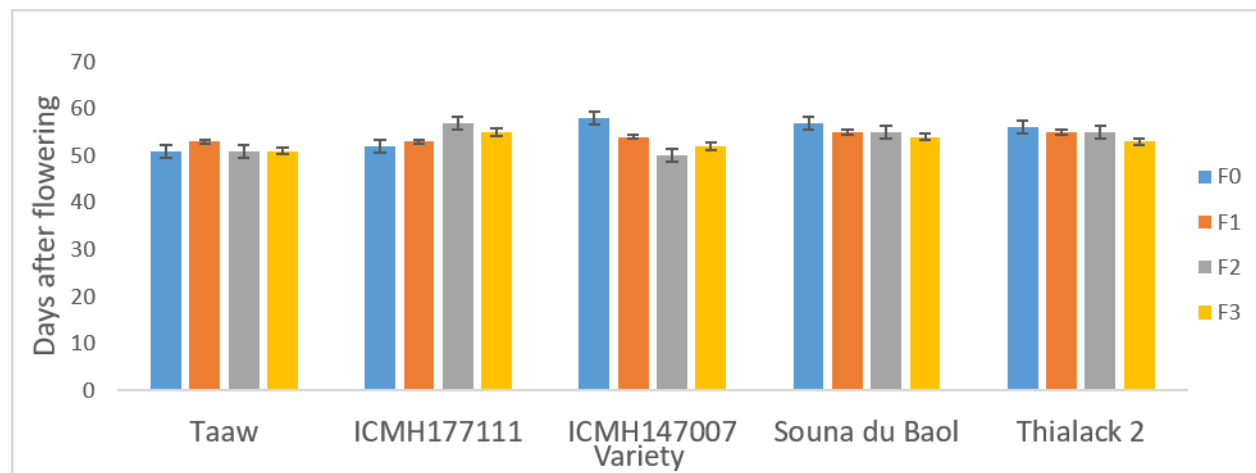


Figure 1: Effect of mineral fertiliser treatments and variety on the time from sowing to flowering. The bars represent the standard deviation.

Effect of mineral fertilisation treatments and variety on growth variables:-

Plant height at 30 DAS: The results of the analysis of variance at the 5 per cent significance level revealed a highly significant effect of mineral fertilisation treatments and variety on plant height at 30 DAS (Table 3). Among the mineral fertiliser treatments, F2 recorded the highest value (21.5 ± 6 cm), whilst F0 recorded the lowest (17.2 ± 4.7 cm). As regards variety, the Taaw hybrid stood out from the rest of the group with a value of 26.1 ± 5.7 cm, whilst the lowest value was obtained with the ICMH147007 hybrid (15.6 ± 2.9 cm). The interaction between mineral fertiliser treatment and variety did not significantly affect height at 30 DAS (Table 3).

Plant height at 45 DAS: Analysis of variance showed that mineral fertiliser treatments and variety had a highly significant impact on plant height at 45 DAS (Table 3). About mineral fertiliser treatments, plants in the plots fertilised with F2 recorded the highest values (125.1 ± 29 cm). However, the lowest value (101 ± 30.7 cm) was observed in the unfertilised plots (F0). As for variety, the highest values were recorded in plots sown with the Taaw hybrid (154.2 ± 18 cm), in contrast to the ICMH177111 and ICMH147007 hybrids, which had the lowest heights, with values of 93.1 ± 21.4 cm and 96.5 ± 29 cm respectively. As for the interaction between the mineral fertiliser treatment and the variety, the analysis of variance showed no significant effect on plant height at 45 DAS (Table 3).

Plant height at 60 DAS: For the mineral fertiliser treatments, an extremely significant effect ($P < 0.001$) was demonstrated by the analysis of variance on plant height at 60 DAS. However, F2 recorded the highest value (182.8 ± 26.3 cm) and F0 the lowest (157.2 ± 14.6 cm). Regarding variety, the analysis of variance revealed that the Taaw hybrid and the two population varieties, Thialack 2 and Souna du Baol, stood out from the rest of the group with values of 187.7 ± 18.2 cm, 188.3 ± 19.5 cm and 192.9 ± 20.4 cm respectively. The lowest values were obtained for the hybrids ICMH177111 and ICMH147007, with respective values of 146.7 ± 23.8 cm and 149.5 ± 10 cm. Analysis of variance for the interaction between the mineral fertiliser treatment and variety showed a significant effect on plant height at 60 DAS ($P = 0.0155 < 0.05$) (Table 3).

Ear diameter (DIAM): The results of the analysis of variance revealed that variety has a highly significant effect on ear diameter (Table 3). Indeed, the hybrid ICMH147007 stood out with the highest value (2.6 ± 0.1 cm), in contrast to the varieties Thialack 2 and Souna du Baol, which had the smallest diameters, both measuring 1.8 ± 0.2 cm. Regarding mineral fertilisation treatments, the analysis of variance shows that there is no significant difference ($P = 0.8552 > 0.05$) in ear diameter. However, arithmetically, F1 (2.1 ± 0.4 cm) and F3 (2.1 ± 0.3 cm) recorded the largest diameters, whereas F2 and F0 had the smallest diameters, both

measuring 2.0 ± 0.3 cm. As for the interaction between the mineral fertilisation treatment and the variety, the analysis of variance showed no significant effect on ear diameter (Table 3).

Table 3: Effect of mineral fertilisation and variety on growth parameters:-

Source of variation		Growth parameters			
Fertilisation (F)		PH30(cm)	PH45(cm)	PH60(cm)	DIAM
F0		17.2 $\pm$ 4.7 ^b	101 $\pm$ 30.7 ^b	157.2 $\pm$ 14.6 ^c	2,0 $\pm$ 0,3
F1		18.2 $\pm$ 4.1 ^b	114.8 $\pm$ 31.4 ^{ab}	180.4 $\pm$ 28.4 ^{ab}	2,1 $\pm$ 0,4
F2		21.5 $\pm$ 6 ^a	125.1 $\pm$ 29 ^a	182.8 $\pm$ 26.3 ^a	2,0 $\pm$ 0,3
F3		19.2 $\pm$ 4.1 ^b	122.4 $\pm$ 31.9 ^a	171.7 $\pm$ 32.4 ^b	2,1 $\pm$ 0,3
Variety (V)					
V1		26.1 $\pm$ 5.7 ^a	154.2 $\pm$ 18 ^a	187.7 $\pm$ 18.2 ^a	2,1 $\pm$ 0,1 ^b
V2		18.5 $\pm$ 2.1 ^b	93.1 $\pm$ 21.4 ^c	146.7 $\pm$ 23.8 ^b	2.0 $\pm$ 0.1 ^b
V3		15.6 $\pm$ 2.9 ^b	96.5 $\pm$ 29 ^b	149.5 $\pm$ 10 ^b	2.6 $\pm$ 0.1 ^a
V4		18.1 $\pm$ 1.9 ^b	121.3 $\pm$ 18.5 ^b	192.9 $\pm$ 20.4 ^a	1.8 $\pm$ 0.2 ^c
V5		16.9 $\pm$ 2.9 ^b	113.7 $\pm$ 27 ^b	188.3 $\pm$ 19.5 ^a	1.8 $\pm$ 0.2 ^c
Mean $\pm$ Ecartype (n=3)		19.1 $\pm$ 3.8	115.8 $\pm$ 31.5	173.1 $\pm$ 27.6	2.1 $\pm$ 0.2
Pr values					
Fertilisation (F)		0.001534 **	0.008343 **	9.292e-06 ***	0.8552ns
Variety (V)		0.004200 **	0.005535 **	0.002394 **	3.68e-05 ***
Interaction (F*V)		0.733505 ^{ns}	0.261516 ^{ns}	0.015568 *	0.06132 ^{ns}

*, **, *** significance level at 5%, 1% and 0.1%; (ns) not significant; n: number of blocks; PH30: height at 30 JAS; **PH45**: height at 45 JAS; PH60: height at 60 JAS. For each column, means not marked with a letter are not statistically different at the 5% significance level according to the least significant difference test. V1: TAAW, V2: ICMH177111, V3: ICMH147007, V4: Souna du Baol, V5: Thialack 2; F0: Absolute control 0 kg ha⁻¹; F1: 75 kg ha⁻¹ of NPK 15-15-15 + 75 kg ha⁻¹ Urea (46-0-0); F2: 150 kg ha⁻¹ of NPK (15-10-10) + 100 kg ha⁻¹ of Urea (46-0-0); F3: kg ha⁻¹ of DAP (18-46-0) + 25 kg ha⁻¹ of Urea (46-0-0).

Effect of mineral fertiliser treatments and variety on yields and their components:-

Thousand-grain weight: Analysis of variance shows that thousand-grain weight was not statistically affected by the mineral fertiliser treatments (Table 4). However, arithmetically, F0 (7.2 $\pm$ 0.9 g) and F1 (7.2 $\pm$ 0.8 g) recorded the highest values, in contrast to F2 and F3, which had a lower weight, both with an identical value of 7.1 $\pm$ 0.7 g. Regarding variety, the analysis of variance revealed a highly significant effect on thousand-grain weight. Thus, the hybrids Taaw, ICMH177111 and ICMH147007 achieved the highest thousand-grain weights with respective values of 7.6 $\pm$ 0.5 g, 7.7 $\pm$ 0.4 g and 7.8 $\pm$ 0.5 g, whilst the varieties Souna du Baol and Thialack 2 had the lowest thousand-grain weights, with values of 6.3 $\pm$ 0.4 g and 6.7 $\pm$ 0.6 g respectively. As for the interaction between the mineral fertiliser treatment and the variety, the analysis of variance showed no significant effect on the thousand-grain weight (Table 4).

Grain yield: The results of the analysis of variance revealed a very highly significant effect of the fertiliser treatments on grain yield. Thus, F1 and F2 yielded the highest grain yields, with values of 2216.9 $\pm$ 356.7 kg ha⁻¹ and 2273.9 $\pm$ 499.5 kg ha⁻¹ respectively, whereas F0 was less productive (1708.7 $\pm$ 520.2 kg ha⁻¹) (Table 4). Regarding variety, the analysis showed a significant effect. The Taaw hybrid was the most productive, with a grain yield of 2,611.6 $\pm$ 355.5 kg ha⁻¹. In contrast, the varieties ICMH147007, Thialack 2 and Souna du Baol were the least productive, with respective values of 1,771.9 $\pm$ 534.3 kg ha⁻¹, 1,879.0 $\pm$ 402.2 kg ha⁻¹ and 1,916.7 $\pm$ 308.5 kg ha⁻¹. The interaction between mineral fertilisation treatments and variety did not significantly affect grain yield (Table 4). **Dry biomass yield:** The results of the analysis of variance showed a highly significant effect of mineral fertilisation options on dry biomass yield (P=0.0052) (Table 4). Indeed, the plots fertilised with F2 recorded the highest values at 5,207.2 $\pm$ 1,364.5 kg ha⁻¹. However, the lowest values were recorded on the unfertilised plots (F0) and the plots fertilised with F3 and F1, which had identical effects on biomass yield, with respective values of 4,226.7 $\pm$ 776.3 kg

ha⁻¹, 4,464.4±871.2 kg ha⁻¹ and 4,620.9±636.2 kg ha⁻¹. Regarding variety, the analysis of variance showed a significant effect on dry biomass yield. The Taaw hybrid was more productive, with a value of 5,638.9 ± 1,303.4 kg ha⁻¹, unlike the other varieties—ICMH147007, Thialack 2 and ICMH177111—whose biomass yields were statistically identical, with respective values of 4,091 ± 769 kg ha⁻¹, 4,316.3 ± 704.8 kg ha⁻¹ and 4,325.9 ± 524.5 kg ha⁻¹. The interaction between mineral fertilisation options and variety did not significantly affect dry biomass yield (Table 4)

Table 4: Effect of mineral fertiliser treatments and variety on yields and their components.

Source of variation			Yields and their components		
			Thousand grain weight (g)	Grain yield (kg ha ⁻¹)	Dry biomass yield (kg ha ⁻¹)
Fertilisation (F)					
F0			7.2±0.9	1708.7±520.2 ^c	4226.7±776.3 ^b
F1			7.2±0.8	2216.9±356.7 ^a	4620.9±636.2 ^b
F2			7.1±0.7	2273.9±499.5 ^a	5207.2±1364.5 ^a
F3			7.1±0.7	2003.4±462.4 ^b	4464.4±871.2 ^b
Variety (V)					
V1			7.6±0.5 ^a	2611.6±355.5 ^a	5638.9±1303.4 ^a
V2			7.7±0.4 ^a	2074.6±463.9 ^{ab}	4325.9±524.5 ^b
V3			7.8±0.5 ^a	1771.9±534.3 ^b	4091±769 ^b
V4			6.3±0.4 ^b	1916.7±308.5 ^b	4776.8±781.2 ^{ab}
V5			6.7±0.6 ^b	1879.0±402.2 ^b	4316.3±704.8 ^b
Mean ± Ecartye (n=3)			7.2±0.7	2050.7±504.3	4629.8±996.7
Pr values					
Fertilisation (F)			0.40145 ^{ns}	2.184e-05 ***	0.005212 **
Variety (V)			6.522e-05 ***	0.04212*	0.049703 *
Interaction (F*V)			0.15603 ^{ns}	0.35977 ^{ns}	0.292369 ^{ns}

*, **, *** significance level at 5%, 1% and 0.1%; (ns) not significant; n: number of blocks. For each column, means not marked with a letter are not statistically different at the 5% significance level according to the least significant difference test. V1: TAAW, V2: ICMH177111, V3: ICMH147007, V4: Souna du Baol, V5: Thialack 2; F0: Absolute control 0 kg ha⁻¹; F1: 75 kg ha⁻¹ of NPK 15-15-15 + 75 kg ha⁻¹ of Urea (46-0-0); F2: 150 kg ha⁻¹ of NPK (15-10-10) + 100 kg ha⁻¹ of Urea (46-0-0); F3: kg ha⁻¹ of DAP (18-46-0) + 25 kg ha⁻¹ of Urea (46-0-0).

Agronomic efficiency of mineral fertiliser options: The agronomic efficiency of the mineral fertiliser rates applied in treatments F1, F2 and F3 (microdose) is shown in Table 5. However, efficiency varied between 2.26 and 3.93 kg kg⁻¹. The microdose mineral fertiliser option (F3) was more efficient (3.93 kg kg⁻¹) compared with treatments F1 and F2 (research recommendation), which were less efficient with values of 3.39 kg kg⁻¹ and 2.26 kg kg⁻¹ respectively.

Table 5: Agronomic efficiency according to mineral fertiliser options.

Mineral fertiliser treatment	Grain yield (kg ha ⁻¹)	Yield increase compared with the control (kg ha ⁻¹)	Amount of fertiliser applied (kg ha ⁻¹)	AE (kg kg ⁻¹)
F1	2216,9	508,2	150	3.39
F2	2273,9	565,2	250	2.26
F3	2003,4	294,7	75	3.93

F1: 75 kg ha⁻¹ of NPK 15-15-15 + 75 kg ha⁻¹ of Urea (46-0-0); F2: 150 kg ha⁻¹ of NPK (15-10-10) + 100 kg ha⁻¹ of Urea (46-0-0); F3: 50 kg ha⁻¹ of DAP (18-46-0) + 25 kg ha⁻¹ of Urea (46-0-0)

Variabilité du rendement et des caractères contributifs:-

Analysis of the correlation results between the various observed variables shows that there are often very strong relationships of dependence between many traits (Table 6). Correlations were assessed between pairs of variables to estimate the relationships and dependencies between them. Grain yield (GYIELD) was negatively correlated with the duration from sowing to flowering (DSF) ($r = -0.4$) and positively correlated with ear diameter ($r = 0.28$) and thousand-grain weight (PMG) ($r = 0.32$). For dry biomass yield (BYIELD), a negative correlation was observed with the duration from sowing to flowering (DSF) ($r = -0.57$), ear diameter (DIAM) ($r = -0.05$) and thousand-grain weight (TGW) ($r = -0.09$). Furthermore, grain yield was strongly and positively correlated with dry biomass yield ($r = 0.85$). The duration from sowing to flowering was negatively correlated with ear diameter ($r = -0.51$) but positively correlated with thousand-grain weight ($r = 0.69$). The sowing-to-flowering duration (DSF) was strongly and positively correlated with the thousand-grain weight (TGW) ($r = 0.69$). Furthermore, it was observed that plant height was positively correlated with yields.

Table 6: Correlation between the agromorphological parameters studied

	PH45	DSF	DIAM	PH30	PH60	TGW	GYIELD	BYIELD
PH45	1	-0.85	0.61	0.87	0.82	-0.21	0.8	0.76
DSF		1	-0.51	-0.82	-0.42	0.69	-0.4	-0.57
DIAM			1	0.15	0.33	-0.04	0.28	-0.05
PH30				1	0.74	-0.39	0.73	0.93
PH60					1	0.31	0.96	0.84
TGW						1	0.32	-0.09
GYIELD							1	0.85
BYIELD								1

Discussion:-

Phenological parameters:-

The results showed no significant differences in the plants' sowing-to-flowering cycle, regardless of the mineral fertiliser treatments applied or the variety. However, on average, the fertilised plots were characterised by a shorter sowing-to-flowering period compared with the control plots. This could be explained by the availability of the mineral nutrients contained in these fertilisers and their efficient uptake by the plants. Indeed, these results are consistent with those of Traoré et al. (2021), who found that the effects of mineral fertilisers on early maturity are linked to the rapid release of nutrients that are available to the plant. Furthermore, these results could be explained more specifically by the effect of phosphorus, which is a factor in early maturity. This phosphorus could account for the shortening of the vegetative phase in the black-grain variety, as it is a factor in early maturity, as reported by Kati (2012). The results also showed that, among the mineral fertiliser treatments tested, F3 (50 kg ha⁻¹ DAP + 25 kg ha⁻¹ urea in microdoses) was the earliest maturing. These results are consistent with those of Tabo et al. (2007), who found that the effectiveness of microdosing is linked to the early development of seedlings, enabling the plants to maintain good vigour from the outset to withstand various stresses.

As regards the varieties, the Taaw hybrid was the earliest maturing, in contrast to the Souna du Baol variety, which had the longest growing season. This finding could be explained by genetic diversity or phenotypic variability within the material tested. These results corroborate those of Sy et al. (2015) and Kanfany et al. (2018) on material from Senegal and pure lines developed from accessions collected in West and Central Africa, as well as on the millet collection from Côte d'Ivoire. This variability could be utilised in the national programme to develop or improve varieties adapted to the growing conditions of the groundnut-growing region and well-received by farmers. Thus, local African varieties exhibit flowering periods ranging from 40 to 160 days, which follow the climatic gradient of their range (Haussmann et al. 2006).

Growth parameters:-

Regarding growth parameters, the results showed that fertilisation has a significant effect on plant height at 30th, 45th and 60th DAS. However, the tallest plants were observed on the plots fertilised with F2 (150 kg ha⁻¹ + 100 kg ha⁻¹ urea) at 30th, 45th and 60th days after sowing. This increase in plant height for F2, which contains more nitrogen compared with the other mineral fertiliser options, could be explained by the effect of nitrogen on the plants. Indeed, nitrogen is the most important element for plant life and determines plant development by stimulating the optimal uptake of other nutrients from the soil. As indicated by Ilunga et al. (2018), the high nutrient content of this mineral fertiliser (NPK), particularly nitrogen—which is an essential element for growth—certainly contributes to good plant growth. According to Kouassi et al. (2019), nitrogen stimulates vegetative growth. It is the driving force and is used to build all the green parts that ensure plant growth and life (FAO, 2005). These findings are also consistent with those of N'Dayegamiye (2007), who found that nitrogen is the most important nutrient for crop growth. At 60 DAS, the results show an interaction between the mineral fertiliser treatments and the variety. These results could be explained by the fact that, at this stage, the plant's nutrient requirements increase to support its growth.

Nevertheless, these results contrast with those obtained by Soma (2010), who noted that from a certain stage of sorghum development (60 DAS), the application of mineral fertiliser has no effect on plant height in short-cycle varieties. Regarding the effect of fertilisers on ear diameter, no statistically significant difference was observed. However, in the ranking of means, the plots fertilised with F1 and F3 achieved the highest mean. Our results are consistent with those of Ndiaye et al (2019), who demonstrated that the various rates of organic matter and mineral fertiliser applied had no significant effect on the diameter of millet ears. Regarding variety, analysis of the results revealed variation across all growth parameters. At 30 DAS and 45 DAS, the Taaw hybrid recorded the greatest plant height compared with the other varieties. This finding could be explained by their genetic diversity. According to Alhassane (2009), the potential values for plant height are genetically determined. At 60 DAS, the results showed that the hybrids tested were shorter (average 161.3±17.3 cm) than the varieties Souna du Baol and Thialack 2 (average 190.6±19.9 cm). Indeed, this shorter stature enables them to withstand strong winds and lodging. Regarding ear diameter, the results showed that the hybrids tested had the largest diameter (2.2 ± 0.1 cm) compared with the population varieties (1.8 ± 0.2 cm). These results corroborate those of Zangréet al. (2009), who had shown that the ear was the most discriminating trait between millet ecotypes in West Africa.

Yields and components:-

Grain yield: The results of the analysis of variance revealed that the mineral fertiliser treatments had highly significant effects on grain yield. However, the fertilised plots recorded the highest yields, whereas the unfertilised plots (F0) recorded the lowest yields. The increase in yield for F1, F2 and F3 compared with F0 was 30.1 per cent, 33.5 per cent and 17.6 per cent respectively. Indeed, these results may be since mineral fertilisers enable plants to meet their requirements for these elements. As for the microdose, its performance is thought to be linked to the concentration of nutrients in the root systems, which improves accessibility and utilisation efficiency whilst reducing losses (Muehlig-Versen et al., 2003). Furthermore, amongst the fertilised plots, the highest yields were obtained with F1 (2216.9±356.7 kg ha⁻¹) and F2 (2273.9±499.5 kg ha⁻¹), which contain more nitrogen than F3 (2003.4±462.4 kg ha⁻¹). A linear increase in yields was observed as the amount of nitrogen supplied via mineral fertilisers increased. According to Samira et al. (1998) and Torbert et al. (2001), the availability of nutrients such as nitrogen in fertiliser helps to increase yield. Similarly, according to Vidal (1963), nitrogen uptake determines millet growth throughout its vegetative cycle and has a positive influence on grain and biomass yields. The analysis also showed that the yields obtained with the research recommendation (F1 and F2) were higher than those with the microdose (F3). These results contradict those obtained in Burkina Faso by Taondaet al. (2008) and Saba (2011). Indeed, these authors concluded that the difference between the microdose and the standard dose was not statistically significant. About variety, the results revealed that the hybrids yielded better than the open-pollinated varieties (Thialack 2 and Souna du Baol). This agronomic superiority of hybrids over open-pollinated varieties could be explained by their high vigour, which promotes high yields. Indeed, hybrids are the result of a cross between two parents selected for their disease resistance, drought tolerance and high yield. In other words, the offspring perform better than either of the two parents involved in the cross (heterosis effect). This contrasts with local landraces, which are well adapted to traditional farming methods but respond only weakly to increased input levels. These results are like those obtained by Deffanet al. (2015) and Moussa et al. (2018) on improved and local maize varieties. Furthermore, the low yield of the local varieties could be explained by bird damage to the mature grains and attacks by downy mildew, which were observed during the trial. These results are consistent with those of Belemviréet al. (2008), who state that several factors interact such that the yields obtained from these varieties are generally lower than those stated in national catalogues.

Dry biomass yield: The results of the analysis showed that mineral fertiliser treatments have a very significant effect on biomass yield. Indeed, the plots fertilised with F2 achieved the highest yields. These results could be explained by the greater plant height achieved with F2, which contains more nitrogen. Furthermore, as with grain yield, the application of mineral fertiliser for biomass production appears to have provided the nutrients necessary for the development of the plant's tillers, resulting in increased straw yield. Similar results were obtained by Gala et al. (2011), who demonstrated that the number of tillers increases with higher fertiliser application rates. Regarding the variety factor, the results revealed that the Taaw hybrid was the most productive, followed by the Souna du Baol variety. These results show that varieties with the greatest plant height achieve the highest dry biomass yields. These results corroborate those of Thiaw (2020), who showed that sorghum genotypes with the greatest durra-type heights have the highest dry biomass yields.

Thousand-grain weight: The analysis indicates that the mineral fertiliser treatments had no significant effect on thousand-grain weight. On average, the thousand-grain weight, at 7.15 ± 0.77 g, is lower than that found by Diouf et al. (2014), which ranged from 10 to 12 g. This result may be due to the fertilisation of the cowpea plants carried over from the previous season. Consequently, the plants may not have felt the need to take up additional mineral fertiliser during the grain-filling stage. This is more likely given that cowpea is a species generally effective at nitrogen fixation thanks to the rhizobia associated with its roots. It can be introduced into millet-based crop rotation systems to improve soil fertility and increase yields (Traoré, 2009). These results confirm the findings of Ndiaye and Diatta (2020), who demonstrated that organo-mineral fertilisation had no effect on the grain size of Sanio millet and plateau rice. Regarding the varieties studied, the highest thousand-grain weights were obtained from the hybrids and the lowest from the population varieties. This may be explained by poor grain filling due to diseases (charcoal, ergot and downy mildew) and genetic factors. According to FAO reports (1993), grain weight depends, amongst other things, on genetic factors (specific to each variety) as well as environmental factors and agronomic practices. The low thousand-grain weight in Bambey could be explained, according to Békoye and Dadié (2015), by weight loss resulting from attacks by piercing-sucking insects which absorb the sap from the grains at the milky stage, thereby reducing their weight.

Agronomic efficiency:-

In this study, micro-dosed mineral fertilisation proved to be much more efficient than the fertilisation practice recommended by research; in other words, the low dose was more efficient than the high doses. This could be explained by the localised application of fertiliser using micro-dosing technology, as well as by the reduction in nitrogen losses through volatilisation. Thus, micro-dosing of fertilisers was attributed to better utilisation of soil nutrients due to the proliferation of lateral roots within the topsoil. Our results are consistent with the FAO report (2012) on this technology, which reduces the risk of nutrient losses, leading to improved fertiliser efficiency and higher yields. It is higher than the national average of 500–800 kg ha⁻¹ for millet over the last twenty (20) years (FAOSTAT, 2021). Microdosing not only allows for a reduction in NPK, and urea compared with the recommendations from millet research but also improves the efficiency of the applied mineral fertiliser. However, its manual application (localised fertiliser application) is labour-intensive and requires significant manpower over large areas, hence the recommendation for mechanisation to reduce the workload and facilitate its scaling up.

Correlation between the observed agro-morphological variables:-

Analysis of the correlation results between the various observed variables shows that there are relationships between the different traits. For grain yield, a negative correlation ($r = -0.4$) was observed with the duration from sowing to flowering. These results show that the longer the growing season, the lower the grain yield. This could be explained by the fact that long-season varieties are unlikely to reach maturity and produce grain due to certain constraints encountered towards the end of the growing season, such as water deficit, the presence of seed-eating birds, etc. Our results are consistent with those of Sy et al. (2015), who showed that the longer the growth cycle, the lower the grain yield, as the variety is unlikely to reach maturity and produce grain. Furthermore, grain yield was positively correlated with ear diameter ($r = 0.28$) and thousand-grain weight ($r = 0.32$). This indicates that, as thousand-grain weight or ear diameter increases, grain yield increases. These results are consistent with those of Fané (2018), who concluded that variety yield is more important than the individual parameters that make it up. For dry biomass yield, a negative correlation was observed with the duration from sowing to flowering ($r = -0.57$). This indicates that long-cycle varieties are less productive in terms of biomass. The same finding was reported by Serba et al. (2020), who argue that long-cycle varieties are not preferred in the selection of dual-purpose millet varieties. The highly significant positive correlation between plant height (PH60) and yield ($r = 0.96$) shows that yield increased when plant height increased. This could be explained by the fact that the Taaw hybrid stands out as having the highest grain yield and is also amongst the tallest varieties. These results are consistent with those obtained by Monneveux

(1989), who states that grain productivity is higher in tall-stemmed varieties compared with short-stemmed ones. Furthermore, a strong positive correlation was observed between grain yield and dry biomass yield ($r = 0.85$); this indicates that as grain yield increases, so does biomass yield. This could be because the Taaw and ICMH177111 hybrids are dual-purpose varieties (grain and fodder). These results corroborate those of Serba et al. (2020), who found a positive correlation between these two traits.

Conclusion:-

The results of the evaluation of millet hybrids under different fertilisation regimes showed significant differences for most of the parameters analysed. The millet plants developed well and produced good yields, as evidenced by the variation in thousand-grain weight, which ranged from 6.3 ± 0.4 g to 7.8 ± 0.5 g. For the mineral fertiliser treatments, the plots fertilised with F1 and F2 yielded the highest grain yields, with values of $2,216.9 \pm 356.7$ kg ha⁻¹ and $2,273.9 \pm 499.5$ kg ha⁻¹ respectively. In addition, the F2 treatment yielded the highest dry biomass yield at $5,207.2 \pm 1,364.5$ kg ha⁻¹. Regarding the varieties, the duration of the growing season was not significantly affected. The Taaw hybrid was more productive in terms of both grain and dry biomass, with respective values of $2,611.6 \pm 355.5$ kg ha⁻¹ and $5,638.9 \pm 1,303$ kg ha⁻¹. Analysis of the correlation coefficients indicates numerous relationships between the measured parameters. In the context of this study, micro-dosing not only enables a 50 per cent reduction in fertiliser rates compared with the recommendations for millet but is also more efficient than the practice promoted by research in Senegal.

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