International Journal of Plant & Soil Science

Volume 38, Issue 10, Page 286-295, 2026; Article no.IJPSS.166373
ISSN: 2320-7035

Effect of Organo-mineral Fertilization on Phenological Development, Growth, and Yield of Maize under Experimental Station Conditions

Bacar Ainta Seck Ndiaye [a,b], Adama Diouf [a*], El Hadji Malick Lèye [c], Ndiogou Gueye [a], Malick Ndiaye [a] and Mame Arama Fall-Ndiaye [a]

[a] *Department of Plant Biology, Faculty of Sciences and Techniques, Cheikh Anta Diop University of Dakar, P.O. Box 5005, Dakar, Senegal.*
[b] *Department of Plant Protection, Km 15, Rufisque Road, Dakar, Senegal.*
[c] *Senegalese Institute for Agricultural Research (ISRA), Bel Air Research Center, Dakar, Senegal.*

Authors' contributions

This work was carried out in collaboration among all authors. Authors BASN and AD conceptualized the study, wrote the protocol, performed the statistical analysis, and wrote the first draft of the manuscript. Author EHML provided resources. All authors managed the literature searches and read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i106348

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/166373

Original Research Article

Received: 28/06/2026
Accepted: 21/09/2026
Published: 25/09/2026

Abstract

Maize (*Zea mays* L.) is one of the major cereal crops grown in Senegal. However, maize yields remain low due to poor soil fertility and inadequate nutrient management. This study aimed to evaluate the effect of combined organic and mineral fertilisation on maize (*Zea mays* L.) growth and yield. The study was conducted during the rainy season at the experimental station of the Department of Plant Protection in Tambacounda. A randomised complete block design was used, comprising eight treatments replicated three

**Corresponding author: E-mail: adama1.diouf@ucad.edu.sn;*

Cite as: *Ndiaye, B. A. S., Diouf, A., Lèye, E. H. M., Gueye, N., Ndiaye, M., & Fall-Ndiaye, M. A. (2026). Effect of Organo-mineral Fertilization on Phenological Development, Growth, and Yield of Maize under Experimental Station Conditions. International Journal of Plant & Soil Science, 38(10), 286–295. https://doi.org/10.9734/ijpss/2026/v38i106348*

times. The treatments included an absolute control, NPK fertiliser alone, cattle manure, sheep manure, poultry manure, and combinations of NPK with cattle manure, sheep manure, and poultry manure in equal proportions (50/50). The results showed that poultry manure-based treatments significantly improved plant height, whereas mineral NPK fertiliser resulted in the highest number of leaves (12.44). The combination of poultry manure and NPK resulted in earlier female flowering at 49 days after sowing (DAS). This treatment also produced superior ear and grain weights compared with sheep and cattle manure. The 1,000-grain weight and maize biomass improved significantly, by 47% and 98%, respectively, compared with the absolute control. These results indicate that combining poultry manure with mineral NPK fertiliser can enhance maize growth, phenological development, and productivity under rainfed conditions in the Tambacounda region.

Keywords: *Maize; organo-mineral fertilisation; poultry manure; NPK fertiliser; phenology; plant growth; grain yield; biomass; integrated nutrient management; Tambacounda.*

1. Introduction

Maize (*Zea mays* L.) plays a central role in sub-Saharan African agricultural systems for both human consumption and livestock feed (Badiane, 2020). In Senegal, it is the third most widely produced cereal after pearl millet and rice and is cultivated mainly in the central, southern, and eastern regions. This cereal is also grown in the Senegal River Valley, primarily during recession farming periods (ISRA, 2008). As a key food crop, maize occupied 27,668 hectares, with an estimated production of 787,750 metric tons during the 2022-2023 growing season (DAPSA, 2023; Ndiaye *et al*., 2025). A staple food for many households, maize contributes to farmers' incomes, particularly in rural areas, while serving as a crucial raw material for animal feed manufacturing (Ndiaye *et al*., 2025). In Senegal, yield gaps between average recorded yields and the potential yields of improved maize varieties stem partly from declining soil fertility caused by erosion, accelerated organic matter mineralisation, and often insufficient or unbalanced mineral fertilisation (Akanza *et al*., 2016). Recent field evidence from maize systems in other low-fertility settings also shows that crop growth and yield respond to fertiliser rate, application method, and the combined use of organic and inorganic nutrient sources (Ahirwar *et al*., 2025; Mohammed & Abera, 2025).

Modern agriculture relies heavily on mineral inputs to sustain intensive production and meet the growing demand for agricultural products (FAO, 2000). However, the excessive or inappropriate application of these fertilisers can lead to environmental degradation, including soil, water, and air pollution. Phosphate-based fertilisers affect soil and water quality, whereas potash fertilisers exhibit no short-term causal environmental impact (Alom *et al*., 2025). Furthermore, the high cost of chemical fertilisers severely restricts their accessibility for smallholder farmers. Consequently, recent research has focused on agroecological approaches to address these physical, chemical, and biological soil challenges. Agroecology relies on various techniques, notably organic fertilisation and composting. These amendments supply essential nutrients to crops while improving long-term soil properties. Organic fertilisers and composts increase organic carbon content, stimulate biological activity, enhance soil water retention, and improve the availability of diverse nutrients such as nitrogen, phosphorus, potassium, magnesium, and calcium (Venkateswarlu *et al*., 2008). Recent long-term evidence indicates that integrating manure with mineral fertiliser can support sustained maize productivity and improve soil nutrient status under contrasting rainfed and sub-Saharan conditions (Abrol *et al*., 2024; Laub *et al*., 2023). Poultry-manure-based organo-mineral fertiliser has also been associated with improved nitrogen uptake, nutrient-use efficiency, and yield-related responses in maize (Yeasmin *et al*., 2024).

Despite the growing global interest in organic fertilisers, their use remains sparsely documented in the Tambacounda region. Nevertheless, the local availability of organic resources such as poultry manure and cattle or sheep dung presents valuable opportunities to reduce dependence on mineral fertilisers and sustainably boost agricultural productivity.

Therefore, this study was conducted to evaluate the effects of different organic, mineral, and organo-mineral fertilisation practices on the growth, phenological development, and yield of maize under rainfed conditions in the Tambacounda region.

2. Materials and Methods

2.1 Study Area

The experiment was conducted at the Department of Plant Protection station in Tambacounda (13°31’50.13670’’ W, 13°31’5.03870’’ N, 45 m altitude) during the rainy season (Fig. 1). The climate in this area is tropical, with a rainy season from June to October and a dry season from November to May. The average temperature in the region is 29°C. The soil is classified as deep leached tropical ferruginous soil. Rainfall recorded from crop establishment (July) to harvest is presented in Table 1.

Monthly rainfall totals showed peak precipitation in September (259.5 mm), whereas July (140.5 mm) and October (39 mm) recorded the lowest rainfall.

Table 1. Monthly rainfall record (ANCAR rainfall station, Missirah)

Days/Month	May	June	July	August	September	October	November
Monthly Total (mm)	0	171	140.5	149.6	259.5	39	0
Cumulative Total (mm)	0	171	311.5	461.1	720.6	759.6	759.6

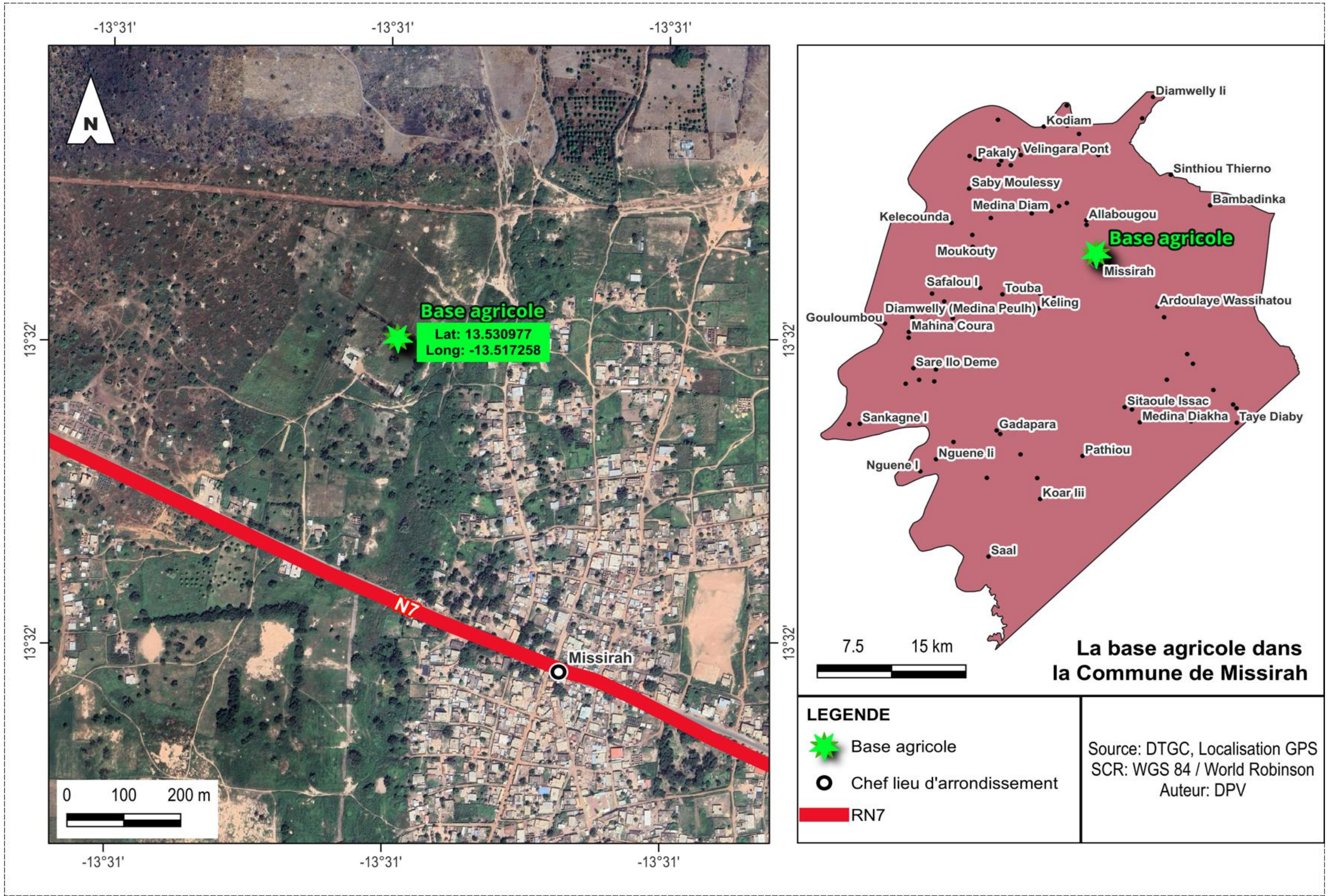

Fig. 1. Location of the experimental site in the Missirah area (Tambacounda)

2.2 Plant Material

The variety used was the Kabamanodj F1 hybrid maize, which is widely adopted by farmers in the area. It has a maturity cycle ranging between 95 and 105 days. This variety, promoted by the *Société de Produits Industriels et Agricoles* (SPIA) Senegal alongside rural development services, is well adapted to tropical conditions.

2.3 Applied Fertilisers

Different fertiliser sources were evaluated, including three types of organic manure: cattle manure from kraaled cattle, sheep manure from enclosed pens, and poultry manure from poultry houses. Two mineral fertilisers were also used: NPK (15-15-15) and urea (46% N).

2.4 Experimental Design

The trial was laid out in a randomised complete block design with three replications under station conditions. Blocks were separated by 1 m, and individual plots were spaced 0.5 m apart. Plot dimensions were 4 m × 3 m, corresponding to an elementary plot area of 12 m².

Eight treatments consisting of various combinations and doses of organic and mineral fertilisers were evaluated. Recommended mineral fertiliser rates were set at 200 kg/ha NPK as basal dressing and 150 kg/ha urea applied in two split applications: 100 kg/ha at 30 days after sowing (DAS) and 50 kg/ha at 45 DAS. Organic manures were applied at a standard rate of 5 t/ha.

The treatment combinations were as follows:

- F0: Absolute control (no organic or mineral fertilisation);
- F1: 100% Recommended Mineral Fertilisation (NPK + urea alone);
- F2: 100% Sheep manure;
- F3: 100% Cattle manure;
- F4: 100% Poultry manure;
- F5: Organo-mineral fertilisation (50% Cattle manure + 50% Mineral fertiliser);
- F6: Organo-mineral fertilisation (50% Sheep manure + 50% Mineral fertiliser);
- F7: Organo-mineral fertilisation (50% Poultry manure + 50% Mineral fertiliser).

2.5 Crop Management

2.5.1 Sowing and Field Preparation

The experimental area was cleared of plant debris and deep-ploughed (20–30 cm). Sowing was carried out after the second effective rainfall event, with three seeds planted per hill at a depth of 5 cm and at a spacing of 80 cm between rows and 30 cm between hills. Thinning was carried out at the 4- to 5-leaf stage to maintain two plants per hill.

2.5.2 Fertiliser Application and Maintenance

Cattle manure, sheep manure, and poultry manure were applied at 5 t/ha (120 g/hill for full rates; 60 g/hill for half rates) and incorporated into the soil one week before sowing to facilitate organic matter decomposition and minimise volatilisation losses.

NPK (15-15-15) was localised at planting at 200 kg/ha (5 g/hill for full rates; 2.5 g/hill for half rates). Urea was top-dressed as a side application at 100 kg/ha at 30 DAS and 50 kg/ha at 45 DAS (2.5 g/hill for full rates; half the dose for reduced rates). Manual weeding was conducted twice, at 15 and 30 DAS.

2.6 Evaluated Parameters

2.6.1 Growth Parameters

Growth observations were recorded every 15 days on 16 central hills selected from the four middle rows of each plot, avoiding border rows. Measured parameters included plant height (H, measured in cm from soil level to the base of the tassel) and leaf number per plant (LN).

2.6.2 Yield and Phenological Parameters

Female flowering (silking) was recorded as the number of days from sowing to the date when 50% of the plants in the net plot displayed visible silks.

Harvesting was restricted to the net plot area (the four central rows, excluding border plants). Evaluated yield components included grain yield, fresh aboveground biomass (stems and leaves), and 1,000-grain weight. Ears were harvested and shelled manually; grains were subsequently dried and weighed. For aboveground biomass, stems were cut at ground level across the entire net plot area, placed in labelled bags, and weighed using an electronic scale.

2.6.3 Statistical Analysis

Data were subjected to analysis of variance (ANOVA) at a significance threshold of 0.05 using XLSTAT software (Addinsoft, version 2016). Mean comparisons were performed to evaluate differences among treatment means.

3. Results

3.1 Effect of Different Treatments on Maize Growth Parameters

3.1.1 Plant Height

The evolution of maize plant height according to the treatments is presented in Table 2. Analysis of variance (ANOVA) revealed significant differences among treatments at all observation dates ($p < 0.0001$). The Newman-Keuls test (at the 5% threshold) highlighted a clear hierarchy in crop response to the different fertilisers.

Maize plant height increased significantly with fertiliser application. Treatment F7 (50/50: poultry manure combined with mineral fertiliser) produced the greatest plant heights at all observation dates between 15 and 60 days after sowing (DAS). This treatment induced the most substantial growth, with heights ranging from 60.4 cm to 180 cm. Although treatments with poultry manure alone (F4) and mineral fertiliser alone (F1) showed notable growth performance, they remained statistically lower than treatment F7. In contrast, treatments based on cattle manure (F3), sheep manure (F2), and the control (F0) showed lower growth. At 60 DAS, analysis of variance revealed a highly significant difference ($p < 0.0001$) between F7 (180 cm) and F0 (123 cm), indicating growth limitation associated with low nutrient availability in unamended soils.

Table 2. Effect of fertilizers on maize plant height after two months of cultivation

Treatments	H15	H30	H45	H60
F0	34,083 a	51,250 a	88,771 a	123,833 a
F1	50,417 b	71,083 b	125,771 d	169,063 d
F2	37,958 a	56,375 a	99,625 b	139,521 b
F3	36,000 a	54,333 a	97,958 b	136,375 b
F4	55,271 c	85,375 c	148,875 e	177,625 e
F5	61,104 d	73,563 b	112,354 c	152,104 c
F6	62,229 d	72,438 b	125,854 d	165,229 d
F7	60,417 d	87,750 c	153,813 e	180,813 e
p-value	$2,3842^{e-69}$	$2,636^{e-54}$	$2,289e^{e-52}$	$1,6149^{e-51}$

F0: unamended control; F1: mineral fertilization; F2: sheep manure; F3: cattle manure; F4: poultry manure; F5: 50% (cattle manure + mineral fertilization); F6: 50% (sheep manure + mineral fertilization); F7: 50% (poultry manure + mineral fertilization); H15: height at 15 days; H30: height at 30 days; H45: height at 45 days; H60: height at 60 days. Values with the same letters are not significantly different at the 5% threshold, Newman-Keuls test

3.1.2 Number of Leaves

The evolution of the average number of leaves (LN) per plant is presented in Table 3. Data analysis revealed a highly significant influence of fertilisation treatments on leaf number from the beginning of the cycle. At 15 DAS, treatment F7 was significantly higher than all other treatments ($p < 0.0001$). This trend continued until 45 DAS ($p < 0.0001$) compared with the control (F0). Treatment F1 produced the highest leaf number at 60 DAS (12.44) and showed a highly significant effect compared with the organic treatments alone (F2: 10.71; F3: 10.65) and the control (F0: 10.65).

Table 3. Evolution of the number of leaves on maize plants for each fertilizer after two months of cultivation

Treatments	LN15	LN30	LN45	LN60
F0	5.146 a	6.188 a	8.646 a	10.646 a
F1	6.271 d	7.188 b	10.958 d	12.438 d
F2	5.771 bc	6.625 a	8.979 a	10.708 a
F3	5.521 b	6.438 a	8.896 a	10.646 a
F4	6.271 d	8.750 c	10.271 bc	11.979 c
F5	5.896 bcd	7.104 b	10.000 b	11.500 b
F6	6.146 cd	7.396 b	10.542 c	11.854 c
F7	6.875 e	8.625 c	11.146 d	12.063 c
p-value	$1,416^{e-23}$	$5,678^{e-40}$	$2,548^{e-9}$	$4,729^{e-40}$

F0: unamended control; F1: mineral fertilization; F2: sheep manure; F3: cattle manure; F4: poultry manure; F5: 50% (cattle manure + mineral fertilization); F6: 50% (sheep manure + mineral fertilization); F7: 50% (poultry manure + mineral fertilization); LN15: leaf number at 15 days; LN30: leaf number at 30 days; LN45: leaf number at 45 days; LN60: leaf number at 60 days. Values with the same letters are not significantly different at the 5% threshold, Newman-Keuls test

3.2 Effects of Treatments on Agronomic Parameters

Analysis of variance revealed a significant effect of treatments across all studied parameters (Table 4). Treatments significantly influenced ear weight ($p = 0.006$), biomass ($p = 0.018$), grain weight ($p = 0.005$), 1,000-grain weight ($p = 0.004$), and the number of days to flowering ($p = 0.019$). Coefficients of determination (R^2 ranging from 0.603 to 0.685) indicated that more than 60% of the observed variability was explained by the treatments.

Table 4. Effects of different treatments on agronomic parameters

Treatments	Ear weight (kg)	Biomass (kg)	Grain weight (kg)	1000-Grain weight (kg)	FFD
F0	0.990 b	1.518 a	0.775 b	0.165 c	59.667 a
F1	2.553 ab	2.415 a	2.073 ab	0.197 bc	51.333 ab
F2	1.062 b	1.525 a	0.845 b	0.190 bc	57.667 ab
F3	1.227 b	1.505 a	0.983 b	0.175 bc	55.667 ab
F4	2.813 ab	2.950 a	2.337 ab	0.223 ab	51.333 ab
F5	2.300 ab	2.093 a	1.900 ab	0.193 bc	52.667 ab
F6	2.507 ab	2.287 a	2.078 ab	0.195 bc	54.333 ab
F7	3.702 a	3.012 a	3.110 a	0.242 a	49.000 b
p-value	0.006	0.018	0.005	0.004	0.019

F0: unamended control; F1: mineral fertilization; F2: sheep manure; F3: cattle manure; F4: poultry manure; F5: 50% (cattle manure + mineral fertilization); F6: 50% (sheep manure + mineral fertilization); F7: 50% (poultry manure + mineral fertilization); FFD: female flowering days. Values with the same letters are not significantly different at the 5% threshold, Newman-Keuls test

The analysis of variance allowed comparisons among treatments and identification of significant differences. Table 4 shows that the treatment combining 50% poultry manure and 50% mineral fertiliser (F7) produced a significant increase in ear weight compared with the control. Other treatments, particularly manures combined with mineral fertiliser (F5 and F6), mineral fertiliser alone (F1), and poultry manure alone (F4), showed intermediate weights, whereas the other organic manures alone (F2 and F3) and the control (F0) had considerably lower weights. Treatment F7 differed significantly from treatments F3 ($p = 0.014$) and F2 ($p = 0.011$), as well as from the control, F0 ($p = 0.011$).

For grain weight, treatment F7 differed significantly from the control, F0 ($p = 0.009$), and from the organic fertilisers alone, F3 and F2 ($p = 0.012$ and $p = 0.010$, respectively). The highest grain weight (3.11 kg) was obtained with poultry-based organo-mineral fertilisation (F7), whereas the lowest grain weight (0.775 kg) was observed in the control (F0), with a significant difference ($p < 0.05$).

For 1,000-grain weight, analysis of variance and the Newman-Keuls test showed that treatment F7 differed significantly from the control (F0). The highest 1,000-grain weight (0.242 kg) was obtained with treatment F7, whereas the lowest weight (0.165 kg) was observed in F0, with a significant difference ($p < 0.05$).

Regarding flowering time, the combination of poultry manure and mineral fertiliser (F7) significantly reduced the number of days to female flowering (49 DAS), indicating accelerated development. The results showed a significant difference between treatment F7, which reached female flowering at 49 DAS, and the control, for which flowering occurred at 59 DAS ($p = 0.020$).

In terms of biomass, the highest biomass was obtained with the treatment combining mineral fertiliser and poultry manure (F7), at 3.012 kg, whereas the control (F0) showed the lowest biomass (1.518 kg). Although analysis of variance revealed a significant treatment effect on biomass ($p = 0.018$), mean separation testing did not distinguish statistically different groups at the 5% threshold. This indicates a trend towards increased biomass, particularly for F7, but with substantial inter-treatment variability. Similarly, application of the Newman-Keuls test at the 5% threshold did not separate distinct groups.

3.3 Relationship between Studied Parameters and Applied Treatments

Pearson's correlation matrix (Table 5) revealed significant correlations ($p < 0.05$) between growth parameters and yield components. Yield variables such as ear weight, biomass, grain weight, and 1,000-grain weight were all positively and significantly correlated with one another at $p < 0.05$. The strong positive correlation between ear weight and grain weight ($r = 0.99$) indicates that these two variables increased together. The positive correlation between biomass and grain weight ($r = 0.89$) suggests that vegetative development was associated with yield build-up. The 1,000-grain weight was positively correlated with grain weight ($r = 0.81$).

Table 5. Pearson correlation matrix between parameters

Variables	Ear weight (kg)	Biomass (kg)	Grain weight (kg)	1000-Grain weight (kg)	FFD
Ear weight (kg)	1	0.89	0.99	0.81	-0.61
Biomass (kg)	0.89	1	0.89	0.77	-0.57
Grain weight (kg)	0.99	0.89	1	0.81	-0.61
1000-Grain weight (kg)	0.81	0.77	0.81	1	-0.69
FFD	-0.61	-0.57	-0.61	-0.69	1

Values in bold are different from 0 at a significance level alpha = 0.05; FFD: female flowering days

Days to female flowering were negatively and significantly correlated with all yield variables. The strongest negative correlation was with 1,000-grain weight, suggesting that earlier flowering was associated with higher yield-related values under the conditions of the experiment.

Similarly, the number of days to flowering was negatively and significantly correlated with all yield variables, particularly 1,000-grain weight (r = -0.69) and grain weight (r = -0.61).

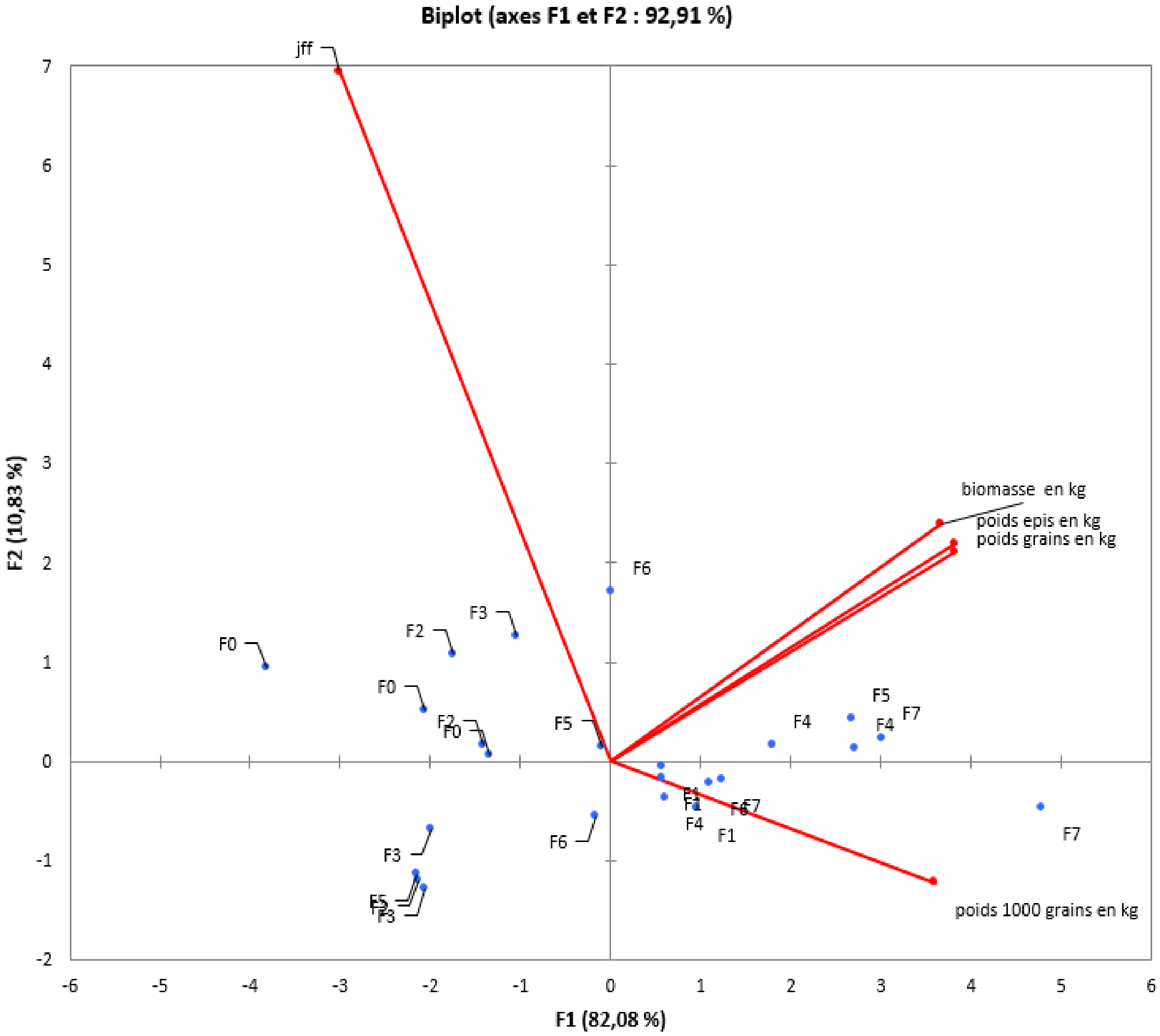

Fig. 2. Relationship between tested treatments and studied parameters

Fig. 2 presents the principal component analysis (PCA) based on the agro-morphological parameters of maize and the tested treatments. Axis F1 explains 82.08% of the variance, and axis F2 explains 10.83%. Together, the two axes account for 92.91% of the studied variability. Group 1 (F7, F4, F5, F6, and F1), located on the positive x-axis, was associated with higher values for the yield parameters. These treatments were also associated with earlier flowering than the Group 2 treatments.

Group 2 (F0, F2, and F3), located on the negative x-axis, was associated with lower values for the yield parameters and later flowering than Group 1.

4. Discussion

The results of this study revealed a significant effect of fertilisation treatments on growth parameters, phenological development, and yield components of maize. The evaluated vegetative parameters highlighted the superior performance of the combined poultry manure and mineral fertiliser treatment (F7). This enhanced performance may be attributed to the spatiotemporal complementarity between the two input sources: immediate nutrient release from mineral fertiliser is complemented by the gradual mineralisation of organic matter, providing crop nutrition throughout the growing cycle. Inorganic fertilisers provide nutrients in readily available forms that can be rapidly absorbed by plants during the early stages of growth. The immediate availability of nitrogen stimulates vegetative development, while phosphorus promotes root growth and potassium improves physiological processes associated with grain formation and stress tolerance. Similar observations have been reported in recent studies, where the sole application of mineral fertiliser increased vegetative growth and yield of maize under tropical conditions (Pandey *et al*., 2025; Yusuf, 2026).

As Sanginga and Woomer (2009) observed, combining organic and mineral inputs optimises production conditions, as organic matter improves soil physical, chemical, and biological properties (soil structure, water retention, and microbial activity), while mineral fertilisers supply readily available nutrients to improve agronomic efficiency. The prompt response to mineral fertilisers stems from rapid NPK availability, whereas poultry manure offers a dual benefit by improving soil structure alongside the relatively rapid, progressive mineralisation of its nutrient content (Kimuni *et al*., 2014). This combination may optimise plant nutrition, limit leaching losses, and promote medium- to long-term soil fertility.

Specifically, the distinct advantages of poultry manure over other organic sources relate to rapid nutrient availability. Ouedraogo *et al*. (2014) highlighted the pivotal role of available phosphorus released into the soil by poultry manure for plant growth, metabolic processes, and energy transfer. These results corroborate those of Siene *et al*. (2020), who reported several distinct patterns associated with the faster mineralisation phase of organic nitrogen. In line with this, Siene *et al*. (2020) confirmed that organic nitrogen in organic fertilisers such as poultry manure or droppings mineralises more rapidly than that in other organic fertilisers. Mineral fertilisation alone (F1: NPK + urea) exerted strong effects on leaf production. These results could be explained by the fact that mineral fertiliser provides mineral elements that are directly assimilable by plants, which promotes rapid growth. This reflects the nutrient richness of mineral inputs, particularly nitrogen, an essential driver of vegetative canopy expansion (Ilunga Tabu *et al*., 2018; Traoré *et al*., 2021). According to Kouassi *et al*. (2019), mineral fertiliser promotes tillering and reduces the senescence of green leaves during the reproductive phase. This finding corroborates that of Mauricette (2022), who demonstrated that nitrogen is a key growth factor for the vegetative development of all above-ground parts of the plant. Furthermore, a recent field study in Ghana showed that mineral fertiliser alone produced vegetative growth comparable to integrated nutrient management (Essilfie *et al*., 2024; Yusuf, 2026).

Plants receiving organo-mineral fertilisation with poultry manure (F7) flowered earlier and completed their cycle in a shorter period than the control, indicating improved nutritional status from the early developmental stages. Rapid mineral uptake enables plants to reach physiological flowering thresholds earlier (Kimuni *et al*., 2014), accelerating phenological transitions and reducing overall crop duration.

Significant improvements in ear weight, grain weight, 1,000-grain weight, and total biomass under organo-mineral fertilisation underscore the role of improved root-zone dynamics. Organic amendments increase water retention and create favorable rhizosphere conditions that maximise nutrient uptake efficiency (Nyembo Kimuni *et al*., 2014; Maftoun *et al*., 2004). Yield gains following organic application are thus attributable to soil structural enhancements that promote root growth and nutrient assimilation, either directly from organic matter decomposition or through the retention of applied mineral nutrients (Maftoun *et al*., 2004).

The high 1,000-grain weight achieved with combined poultry manure and mineral fertiliser aligns with findings by Farhad *et al*. (2009), who reported maximum 1,000-grain weight at higher poultry manure rates. This effect is driven by adequate nutrient supply, enabling greater photoassimilate accumulation during grain filling (Gomgnimbou *et al*., 2019). Combined organic-mineral applications foster root development, enhancing nutrient uptake and biological activity in sub-Saharan agricultural systems (Kaho *et al*., 2011; Kouassi *et al*., 2019). The results obtained from this study corroborate those of Omololu *et al*. (2024), who reported that organic manure application improved maize growth and yield. Applying organic manure also increased maize plant height, leaf development, and crop yield at harvest.

5. Conclusion

Under the experimental conditions in Tambacounda, fertilisation treatments significantly influenced maize growth, phenology, and yield components. Among the tested treatments, the combination of 50% poultry manure and 50% mineral fertiliser (F7) produced the greatest plant height, the earliest female flowering, and the highest ear weight, grain weight, 1,000-grain weight, and aboveground biomass. Mineral fertiliser alone produced the highest leaf number at 60 days after sowing, indicating that treatment responses varied among measured traits. Compared with the unfertilised control, F7 increased 1,000-grain weight and biomass by approximately 47% and 98%, respectively. These findings indicate that combining poultry manure with mineral fertiliser can improve nutrient supply and crop performance under the rainfed conditions of the study area. The results support the use of integrated organic and mineral nutrient sources as a practical fertilisation approach for maize production in Tambacounda. Further validation across seasons and locations would be needed before extending the findings beyond the experimental station conditions.

6. Limitation

This study was conducted during a single rainy season at one experimental station; therefore, the findings represent the specific environmental and management conditions of the trial. Treatment responses may reflect the rainfall pattern, soil conditions, maize hybrid, fertiliser rates, and crop management used during the experiment. The three-replication randomised complete block design supports comparisons among treatments within the study, but the findings should be interpreted primarily for conditions similar to those at the Tambacounda station. Multi-season and multi-location evaluation would be needed to assess the consistency of the observed responses.

Acknowledgements

We would like to thank especially Malang SANE, Sirifo CAMARA, Babading DANFAKHA, and Demba DIAKHOUMPA for assistance during the experiment. We are grateful to Missirah Agricultural Monitoring and Alert Base for technical assistance.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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Peer-review history:
The peer review history for this paper can be accessed here: https://pr.sdiarticle5.com/review-history/166373