Afropolitan Journals

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ISSN: 3027-2637 www.afropolitanjournals.com

Productivity of Maize (*Zea mays* L.) Varieties in Response to Integrated Coal and Inorganic Fertilizer Applications in Nigeria's Sudan Savanna

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***DOI**: https://doi.org/10.62154/ajasfr.2025.020.01024*

Abstract

This study investigated the effects of varying combinations of coal fertilizer (CF), NPK, and cow dung on the productivity of two maize varieties (SAMMAZ 27 and 29) across two Sudan Savanna locations in Nigeria; BUK and Dambatta, during the 2024 dry season. The experiment employed a split-plot design with variety occupying the main plot, and varied fertilizer combinations as subplots and replicated three times. Data were collected on vegetative growth, chlorophyll content, NDVI, reproductive development, and yield parameters. Significant ($P < 0.001$) differences were observed in the number of leaves per plant at 6 WAS, with 25% CF + 75% NPK, 50% CF + 50% NPK, and 100% NPK producing the highest values. Plant height and chlorophyll content were significantly greater in Dambatta at 8 WAS, while BUK supported superior early growth (stem girth and leaf number). Fertilizer effects were most pronounced at 6 and 8 WAS, with integrated treatments (25-50% CF + 50-75% NPK) consistently outperforming sole organic inputs. At 8 WAS, 50% CF + 50% NPK recorded the highest chlorophyll content (56.9 SPAD units). Stover yield was significantly ($P < 0.001$) influenced by fertilizer and location, with 100% NPK yielding the highest biomass at BUK (14,995.2 kg ha^{-1}). Grain yield showed no significant variation across treatments, although BUK recorded higher overall yield (2,106.8 kg ha^{-1}). SAMMAZ 29 produced significantly more stover than SAMMAZ 27, while NDVI and stem girth responses varied by location and treatment. These findings show that combining CF with NPK enhances biomass production while maintaining grain yield. Integrated nutrient management should be promoted as a cost-effective, sustainable alternative to sole fertilizer use, offering farmers higher productivity and supporting soil fertility restoration in the Sudan Savanna.

Keywords: Maize, Coal Fertilizer, NPK, Integrated Nutrient Management, Sudan Savanna, Yield Performance.

Introduction

Maize (*Zea mays* L.) is a major cereal crop globally and particularly in Nigeria, where it serves as both a staple food and a key raw material for agro-industrial processes. It contributes significantly to food security, rural livelihoods, and income generation. Beyond household consumption as pap, *tuwo*, and grits, maize is used extensively in animal feed, brewing, starch production, pharmaceuticals, and biofuels (Onumah et al., 2022). Its versatility has led to sustained demand across subsistence and commercial sectors.

Despite its importance, maize productivity in Nigeria's Sudan Savanna is constrained by nutrient-poor soils (Kamara et al., 2019). Maize is a heavy feeder, requiring substantial amounts of nitrogen (N), phosphorus (P), and potassium (K) for optimal growth and yield (Adhikary et al., 2020). However, the region's soils are chronically low in N and P (Tofa et al., 2022), and the high cost and long-term negative impacts of synthetic fertilizers such as soil degradation and reduced biodiversity further threaten sustainability (Kamara et al., 2020).

Continued reliance on conventional NPK fertilizers has yielded diminishing returns. While region-specific recommendations exist, they often ignore other essential macro- and micronutrients. Overuse of NPK causes nutrient imbalances, depletes soil micronutrients, increases greenhouse gas emissions, and accelerates soil acidification (Das et al., 2023; Wang et al., 2023). Additionally, resource-poor farmers face limited access to these inputs due to high costs and dependence on non-renewable resources (Tyagi et al., 2022; Jote, 2023). Excess nitrogen application, in particular, results in nutrient losses through volatilization, leaching, and denitrification, contributing to environmental pollution and economic inefficiency (Ransom et al., 2020).

These limitations highlight a critical challenge: how to sustain maize productivity in the Sudan Savanna under nutrient-deficient soils and high input costs, while reducing the ecological risks of chemical fertilizer dependence.

Given these constraints, there is a growing need for sustainable, climate-smart alternatives. Coal-based fertilizers represent a promising solution. Produced from low-rank coal and enriched with humic substances, they supply organic carbon and essential plant nutrients (Akimbekov et al., 2021; Luo et al., 2025). Their porosity and cation exchange capacity enhance soil structure, microbial activity, and nutrient retention (Symanowicz & Toczko, 2023). Coal-based amendments also act as slow-release fertilizers and contribute to carbon sequestration by reducing CH_4 and CO_2 emissions (Chen et al., 2022).

Futura coal fertilizer, a locally available carbon-based formulation, has potential to replenish degraded soils, lower reliance on costly synthetic fertilizers, and improve soil resilience. Although coal-based fertilizers have shown promise in other regions, their agronomic performance under tropical agro-ecological conditions, particularly in Nigeria's Sudan Savanna, remains underexplored (Luo et al., 2025). With rising population and food demand, identifying region-specific, cost-effective fertilization strategies is urgently needed (Beah et al., 2021).

This study therefore investigates the potential of Futura coal fertilizer, alone and in combination with NPK and cow dung, to improve maize productivity in the Sudan Savanna. Specifically, the study aimed to:

i. assess the growth and yield performance of two maize varieties under varying CF application rates;
ii. determine the optimal CF rate for maximizing yield; and
iii. compare the agronomic performance of CF with conventional fertilizers.

We hypothesize that integrated CF and NPK will improve vegetative growth and stover yield compared to sole fertilizer inputs, that CF application will enhance chlorophyll content and NDVI, and that balanced CF-NPK combinations will sustain grain yield while reducing reliance on costly synthetic fertilizers.

Materials and Methods

Experimental Sites

The field trials were conducted during the 2024 dry season (March-June) at two locations within the Sudan Savanna agro-ecological zone of Nigeria: Center for Dryland Agriculture (CDA), Training and Research Farm, Bayero University, Kano (Latitude 11.981893° N; Longitude 8.416033° E), and a Farmer's field in Dambatta Local Government Area, Kano State (Latitude 12.369255° N; Longitude 8.568760° E). Both sites are characterized by a semi-arid climate with low organic matter and nutrient-depleted soils, typical of the Sudan Savanna zone.

Treatments and Experimental Design

The experiment was laid out in a split-plot design with three replications. The main plots comprised seven fertilizer treatments, while the sub-plots consisted of two maize varieties (SAMMAZ 27 and SAMMAZ 29). The sub-plots measured 3 m × 3 m with a 0.5 m buffer between plots and 1.0 m between replications. Fertilizer sources used included: Urea (nitrogen), Single Super Phosphate (phosphorus), and Muriate of Potash (potassium).
The coal fertilizer combination levels were as follows:

F1 Control (no fertilizer)

F2 100% coal fertilizer 120 kg ha^{-1}

F3 50% coal + 50% NPK 60 kg coal + 60:30:15 kg ha^{-1} N:P: K

F4 75% coal + 25% NPK 90 kg coal + 30:15:7.5 kg ha^{-1} N:P: K

F5 25% coal + 75% NPK 30 kg coal + 90:45:22.5 kg ha^{-1} N:P: K

F6 100% NPK (conventional) 120:60:30 kg ha^{-1} N:P: K

F7 Cow dung (organic benchmark) 10,000 kg ha^{-1}

Varietal Characteristics

The two early-maturing maize varieties evaluated were:

- SAMMAZ 27 (EV99DT-W-STR1): White-grained, 90-95 days maturity, drought and *Striga* resistant, with streak virus resistance and a yield potential of 5.5 t ha^{-1}.
- SAMMAZ 29 (2000SynEE-W-STR): White-grained, 80-85 days maturity, drought and *Striga* tolerant, streak virus tolerant, with a yield potential of 4.0 t ha^{-1}.

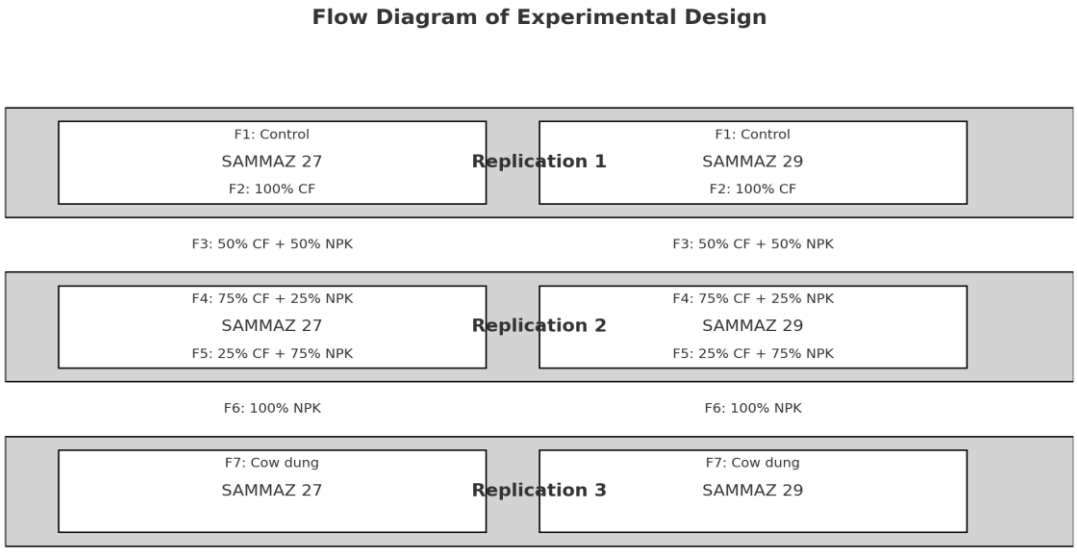


Figure 1: Flow Diagram of Experimental Design

- Replication: 3 replications of the split-plot design.
- Two maize varieties (SAMMAZ 27 and SAMMAZ 29) as Main plot factors
- Seven fertilizer treatments (F1-F7) under each variety as Sub-plot factor

Coal Fertilizer Analysis

Coal fertilizer samples were analyzed in triplicate for their physical and chemical characteristics using standard laboratory procedures. Parameters assessed included: pH, electrical conductivity (EC), Organic carbon, total nitrogen (N), total phosphorus (P), and total sulfur (S), Exchangeable macro- and micronutrients: calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu)

Soil Sampling and Laboratory Analysis

Baseline Soil Sampling

Before land preparation, composite soil samples were collected from a 0–30 cm depth using an auger at four random points per site. Samples were air-dried, sieved (2 mm), and analyzed for baseline physical and chemical properties.

Endline Soil Sampling

At the conclusion of the experiment, post-harvest soil samples were collected from each plot using the same sampling protocol to assess treatment effects on soil fertility.

Soil Parameters Analyzed

- Particle size distribution (texture)
- Soil pH (1:2.5 soil-water suspension)
- Organic carbon (Walkley-Black method)

- Total nitrogen (Kjeldahl method)
- Available phosphorus (Bray-1 method)
- Electrical conductivity (1:2 soil-water extract)
- Cation exchange capacity (CEC)
- Exchangeable acidity

All analyses followed standard soil laboratory procedures (AOAC, 2005).

Cultural Practices

Land Preparation and plot description

The land was prepared and 42 plots were marked out as 9 m^2 raised basins. The main plot size was 3.0 m × 3.0 m (9 m^2), while the net plot was 3.0 m × 1.5 m (4.5 m^2) which was made up of the two inner rows. There were discards of 0.5, 0.5 and 1.0 m between plots, blocks and replications, respectively. The total area used for the experiment was approximately 516 m^2.

Sowing

Two seeds per hole were sown at a spacing of 75 cm × 25 cm inter-row and intra-row based on treatment combination, and later thinned to one plant per stand.

Weed Control

All plots were kept weed free by manual hoe weeding at 3 and 6 WAS.

Fertilizer Application

Fertilizer application to each plot was according to treatment combination. Urea was applied in two split doses, the first half at time of sowing and the second half at six weeks after sowing. SSP, MoP, cow dung and the coal fertilizer were applied in full doses at time of sowing.

Data Collection

Assessment of Growth and Growth-Related Characters

Three randomly tagged plants from each net plot were selected for data collection, the following parameters were measured on bi-weekly basis:

Normalized difference vegetation index (NDVI) using Green Seeker, chlorophyll content with SPAD meter, plant height using meter rule, was measured from the base of the plant to the tip of the flag leaf; Stem girth using Vernier caliper, and Number of leaves per plant.

Assessment of Yield and Yield Related Characters

This was computed per net plot for the following parameters:

Number of plant stands was recorded. At harvest, the total number of plants within each net plot was counted to assess stand density and plant survival rate.

Number of cobs. Each plant was inspected, and the number of cobs per plant recorded. Only cobs meeting a predefined size or maturity criteria were included in the count.

Weight (Kg) of the total maize stalks without cobs was taken. The maize stalks were cut at ground level, and the total weight of the stalks from each plot (excluding cobs) was measured using a suitable scale. This measurement was taken to provide data on the biomass produced.

Weight (Kg) of the cobs was taken. The total weight of all cobs harvested from each net plot was recorded separately from the stalk weight to evaluate the cob yield.

Five cobs were taken at random from each net plot, bulked and their weight immediately taken

The five cobs were shelled, then the grains were weighed.

Days to 50% Tasseling. This is the number of days from sowing to when 50% of plants tasseled per plot.

Days to 50% silking. This was the number of days from sowing to when 50% of plants silked per plot.

Anthesis-silking interval (ASI). This was calculated as using the below formular,

$$ASI = Number\ of\ days\ to\ 50\%\ silking\ - Number\ of\ days\ to\ 50\%\ tasseling$$

Stalk to cob ratio per net plot. Calculated as

$$Stalk\ to\ cob\ ratio\ per\ net\ plot = \frac{Number\ of\ cobs\ per\ net\ plot}{Number\ of\ stands\ per\ net\ plot} \quad \text{.....Equa. 1}$$

Stover yield in Kg per hectare. Calculated as

$$Stover\ yield\ kgha^{-1} = \frac{Weight\ of\ stalk\ per\ net\ plot \times 10{,}000\ m^2\ (1\ ha)}{Net\ plot\ size} \quad \text{.....Equa. 2}$$

Cob yield in Kg per hectare. Calculated as

$$Cob\ yield\ kgha^{-1} = \frac{Weight\ of\ cobs\ per\ net\ plot \times 10{,}000\ m^2\ (1\ ha)}{Net\ plot\ size} \quad \text{.....Equa 3}$$

Grain yield per hectare. Calculated as

$$Grain\ yield\ kgha^{-1} = \frac{Grain\ yield\ per\ net\ plot \times 10{,}000\ m^2\ (1\ ha)}{Net\ plot\ size}, \quad \text{.....Equa 4}$$

Data Analysis

The data collected were subjected to analysis of variance (ANOVA) using GENSTAT (17th Edition). Significant means were separated using Student Neuman Keul's Test at 5% level of probability.

Results

Chemical properties of futura coal fertilizer (carbontilizer)

Table 1 presented the results obtained from laboratory analysis of Futura coal fertilizer. The coal fertilizer was found to contain, 29.13% organic carbon, 2.38% total nitrogen, and 0.51 mg/kg of available phosphorous. Exchangeable potassium was 0.22 cmol/kg. Additionally,

the concentrations of calcium and magnesium were 72.70 mg/kg and 150.25 mg/kg, respectively. Micronutrient analysis showed zinc at 10.85 mg/kg, iron at 110.20 mg/kg, and copper at 37.40 mg/kg. Manganese and molybdenum were also present, with values of 106.60 mg/kg and 6.40 mg/kg, respectively.

Chemical properties of cow dung

The chemical properties of the cow dung used in the experiment, as shown in Table 2, reveal that it contained 52.86 g/kg of organic carbon and 3.33% total nitrogen. The total sulfur content was 0.17 g/kg, while total phosphorous was measured at 21.86 g/kg. The pH value of the cow dung was 7.40, and the electrical conductivity (EC) was 1.59 µs/cm. Sodium and potassium concentrations were 0.33 g/kg and 0.08 g/kg, respectively. Calcium and magnesium contents were recorded at 5.55 g/kg and 2.17 g/kg. The micronutrients manganese, zinc, iron, and copper were present at concentrations of 0.01 mg/kg, 0.04 mg/kg, 0.84 mg/kg, and 0.04 mg/kg, respectively.

Baseline soil properties of the experimental sites

Table 3 highlights the baseline soil properties of the experimental sites, BUK and Dambatta The soil pH was recorded as 6.09 at BUK and 6.32 at Dambatta, with Dambatta showing a 3.78% higher pH than BUK. Electrical conductivity (EC) was 109.43 µs/cm at BUK and 106.23 µs/cm at Dambatta, indicating that BUK had an EC value 3.01% higher than Dambatta. Organic carbon (O.C.) was 0.45% at BUK and 0.42% at Dambatta, with BUK showing a 7.14% higher O.C. content. Total nitrogen (N) was 0.05% at BUK and 0.04% at Dambatta, making nitrogen 25.0% higher at BUK. Available phosphorous (P) concentrations were slightly lower at BUK (5.58 mg/kg) compared to Dambatta (5.62 mg/kg), with Dambatta having a 0.72% higher value. Calcium (Ca) content was 2.68 cmol(+)/kg at BUK and 3.01 cmol(+)/kg at Dambatta, with Dambatta showing a 12.31% higher concentration. Magnesium (Mg) was recorded at 0.87 cmol(+)/kg at BUK and 0.92 cmol(+)/kg at Dambatta, with Dambatta having a 5.75% higher value. Potassium (K) was slightly higher at Dambatta (0.17 cmol(+)/kg) compared to BUK (0.16 cmol(+)/kg), with a 6.25% increase. Sodium (Na) concentrations were 0.10 cmol(+)/kg at BUK and 0.09 cmol(+)/kg at Dambatta, making Na 11.11% higher at BUK. Exchangeable acidity (EA) was 0.00 cmol(+)/kg at both locations.

The effective cation exchange capacity (ECEC) was 3.81 cmol(+)/kg at BUK and 3.62 cmol(+)/kg at Dambatta, with BUK showing a 5.25% higher value. Zinc (Zn) concentrations were 0.38 mg/kg at BUK and 0.41 mg/kg at Dambatta, with Dambatta having a 7.89% higher value. Copper (Cu) content was recorded at 2.79 mg/kg at BUK and 2.82 mg/kg at Dambatta, with Dambatta showing a 1.08% higher concentration. Manganese (Mn) content was significantly higher at BUK (26.38 mg/kg) compared to Dambatta (23.21 mg/kg), with a 13.66% higher concentration at BUK. Iron (Fe) was also higher at BUK (166.81 mg/kg) by 9.81% compared to Dambatta (151.89 mg/kg).

Table 1: Baseline Soil Properties of the Experimental Sites (BUK and Dambatta)

Soil Properties	Location	
	BUK	Dambatta
pH (1:1)	6.09	6.32
EC (µs/cm)	109.43	106.23
O.C (%)	0.45	0.42
N (%)	0.05	0.04
P (mg/kg)	5.58	5.62
Ca (cmol(+)/kg)	2.68	3.01
Mg (cmol(+)/kg)	0.87	0.92
K (cmol(+)/kg)	0.16	0.17
Na (cmol(+)/kg)	0.10	0.09
EA (cmol(+)/kg)	0.00	0.00
ECEC (cmol(+)/kg)	3.81	3.62
Zn (mg/kg)	0.38	0.41
Cu(mg/kg)	2.79	2.82
Mn (mg/kg)	26.38	23.21
Fe (mg/kg)	166.81	151.89

Agronomic Variables

Number of leaves per plant

Location significantly ($P < 0.001$) affected leaf production at all growth stages (Table 4). BUK plants produced more leaves at early stages (2-6 WAS; 4.7-11.2 leaves) compared to Dambatta (4.1-10.4 leaves), but at 8 WAS the trend reversed, with Dambatta recording a higher leaf count (12.3 vs. 11.5). This suggests a late-stage growth advantage at Dambatta. Fertilizer effects were most pronounced ($P < 0.001$) at 6 WAS, where the integrated treatments of 50% CF + 50% NPK and 25% CF + 75% NPK produced the highest leaf counts (11.4-11.5), comparable to 100% NPK (11.5), and all significantly greater than the control, cow dung, and 100% CF (10.0-10.3). No fertilizer effects were observed at 2, 4, or 8 WAS. Variety alone did not influence ($P > 0.05$) leaf number.

Significant interaction effects were observed between L × V at 2, 4, 6, and 8 WAS (Fig, 2), and between L × F at 4 and 6 WAS (Fig. 3). The variety × location effect on the number of leaves at 2 WAS showed that SAMMAZ 27 and SAMMAZ 29 grown at BUK produced significantly more leaves than both varieties grown in Danbatta (Fig 2). At 4 and 6 WAS, SAMMAZ 29 at BUK consistently produced the highest number of leaves compared to all other variety-location combinations. However, at 8 WAS, SAMMAZ 27 at BUK recorded a significantly lower leaf count than SAMMAZ 29 at BUK and SAMMAZ 27 in both BUK and Danbatta, which all had higher leaf numbers.

Fig. 3 presents the fertilizer × location effects on the number of leaves per plant at 4 and 6 WAS. At 4 WAS, the highest leaf count was observed with 25% CF + 75% NPK in BUK (9.3), comparable to 50% CF + 50% NPK and 100% NPK (9.0 each). At 6 WAS, the same integrated

treatments at BUK again outperformed others (12.1-13.1 leaves), while treatments at Dambatta produced fewer leaves (9.7-10.9).

Table 4: Effect of Location, Fertilizer and Variety on Number of leaves per plant of Maize at 2, 4, 6 and 8 WAS

Treatment	Weeks after sowing (WAS)			
	2	4	6	8
Location (L)				
BUK	4.7a	8.4a	11.2a	11.5b
Dambatta	4.1b	7.8b	10.4b	12.3a
P-Value	<0.0001	0.010	0.005	0.003
SE±	0.07	0.16	0.22	0.19
Fertilizer (F)				
Control	4.1	7.6	10.0b	11.9
100% CF	4.2	7.6	10.3b	11.5
50% CF + 50% NPK	4.5	8.4	11.5a	12.4
75% CF + 25% NPK	4.4	8.1	10.6ab	11.6
25% CF + 75% NPK	4.3	8.5	11.4a	12.3
100% NPK	4.5	8.4	11.5a	12.5
Cow dung	4.6	8.3	10.3b	11.2
P-Value	0.1547	0.1680	0.0189	0.0833
SE±	0.13	0.29	0.37	0.36
Variety (V)				
SAMMAZ 27	4.3	8.0	10.7	11.8
SAMMAZ 29	4.4	8.3	11.0	12.0
P-Value	0.7521	0.1424	0.3478	0.4513
SE±	0.07	0.16	0.21	0.19
Interactions				
L x F	0.4222	0.0180	0.0008	0.2333
L x V	0.0305	0.0261	0.0049	0.0054
F x V	0.2578	0.8927	0.5986	0.1209
L x F x V	0.9735	0.1669	0.7381	0.8655

Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK

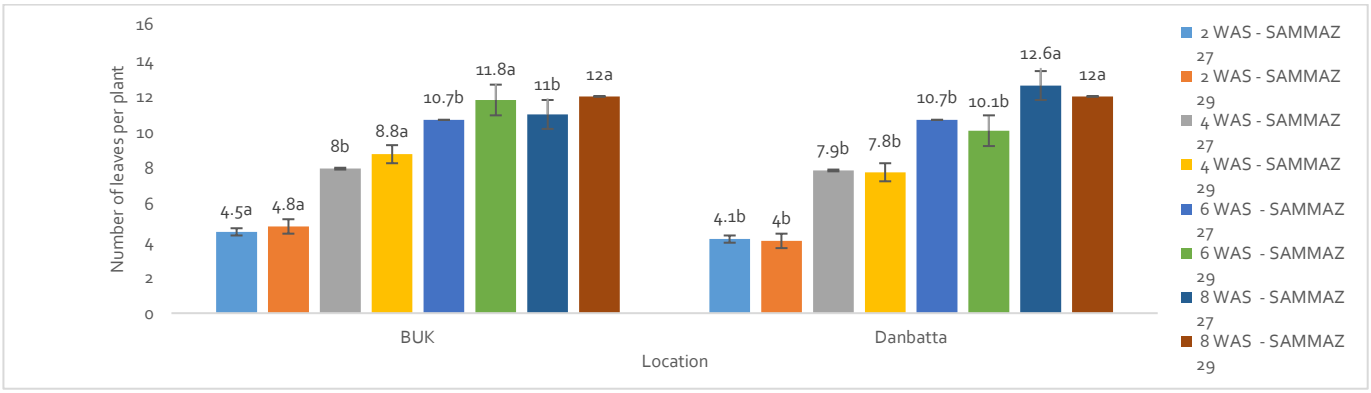


Figure 2: Location x Variety interaction on number of leaves per plant of maize at 2,4 6 and 8 WAS

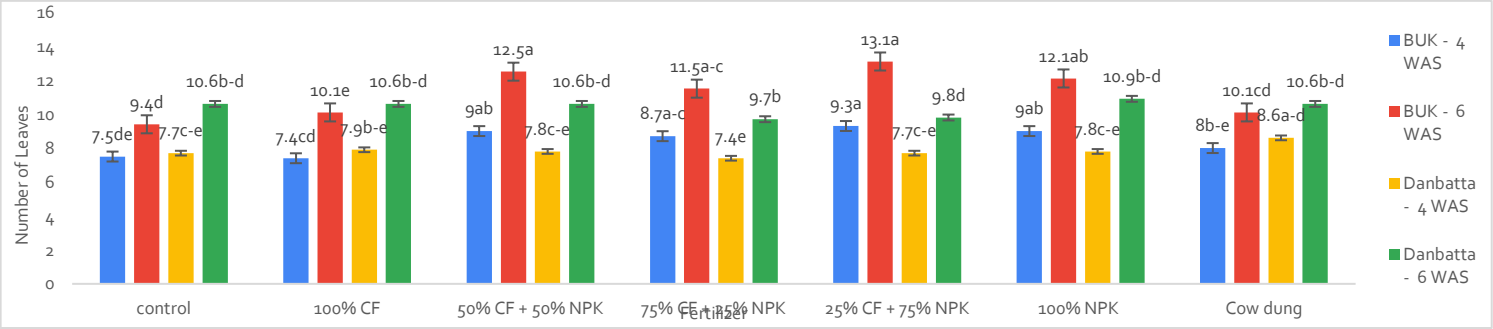


Figure 3: Fertilizer x Location on Number of leaves per plant of Maize at 4 and 6 WAS.

Plant height (cm)

The effects of location, fertilizer, and variety on plant height of maize at 2, 4, 6, and 8 WAS are presented in Table 5. Location significantly ($P < 0.001$) influenced plant height across all stages. Dambatta consistently produced taller plants (14.2-156.0 cm) compared to BUK (12.4-119.8 cm), indicating a strong growth advantage at this site.

Fertilizer effects were significant only at 8 WAS. Integrated treatments (25% CF + 75% NPK, 50% CF + 50% NPK) and 100% NPK produced the tallest plants (144.5-150.1 cm), significantly exceeding the control, cow dung, and 100% CF (127.2-130.5 cm).

Variety effects emerged at later stages: at 6 and 8 WAS, SAMMAZ 29 grew significantly taller (102.8 cm and 142.4 cm) than SAMMAZ 27 (87.8 cm and 133.4 cm), suggesting a varietal advantage under favorable conditions.

Significant location × fertilizer (L × F) interactions occurred at 4 and 8 WAS (Fig. 4). At 4 WAS, cow dung in Dambatta produced the tallest plants (51.0 cm), whereas the control at BUK resulted in the shortest (31.5 cm). By 8 WAS, integrated and NPK treatments at Dambatta consistently supported superior height, confirming site-specific fertilizer responsiveness.

Table 5: Effect of location, fertilizer and variety on plant height of Maize at 2, 4, 6 and 8 WAS

Treatment	Weeks after sowing (WAS)			
	2	4	6	8
Location (L)				
BUK	12.4b	38.2b	84.4b	119.8b
Dambatta	14.2a	42.6a	106.2a	156.0a
P-Value	0.0040	0.0199	0.0002	<0.0001
SE±	0.42	1.28	4.01	2.86
Fertilizer (F)				
Control	12.9	36.1	88.8	129.1c
100% CF	12.8	37.2	91.4	130.5bc
50% CF + 50% NPK	12.9	42.4	99.8	148.8a
75% CF + 25% NPK	14.0	40.7	86.7	135.2a-c
25% CF + 75% NPK	12.9	42.2	110.3	150.1a
100% NPK	13.5	41.8	98.2	144.5ab
Cow dung	14.1	42.4	91.7	127.2c
P-Value	0.8083	0.3213	0.2359	0.0067
SE±	0.78	2.40	6.65	5.39
Variety (V)				
SAMMAZ 27	13.2	38.7	87.8b	133.4b
SAMMAZ 29	13.5	42.1	102.8a	142.4a
P-Value	0.6079	0.0700	0.0066	0.0303
SE±	0.42	1.28	3.77	2.86
Interaction				
L x F	0.6923	0.0207	0.0727	0.0090
L x V	0.3091	0.5022	0.9672	0.4061
F x V	0.4152	0.5572	0.6136	0.7396
L x F x V	0.3737	0.7641	0.6497	0.3667

Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK

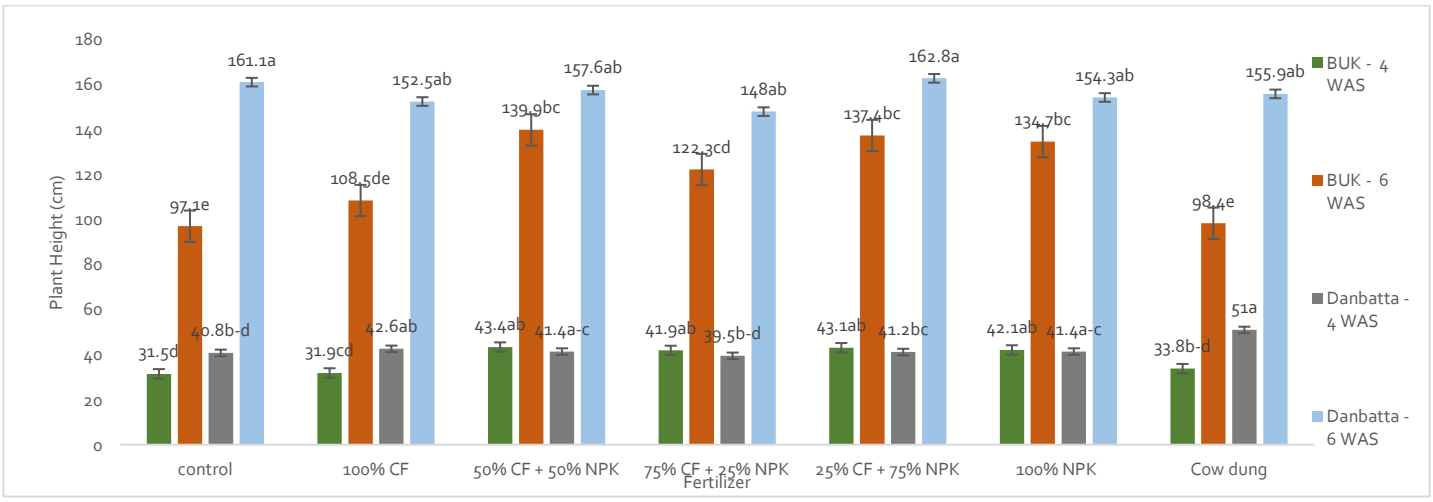


Figure 4: Fertilizer x Location on plant height of Maize at 4 and 8 WAS

Leaf chlorophyll content (SPAD)

Table 6 presents the effects of location, fertilizer, and variety on leaf chlorophyll content of maize at 2, 4, 6, and 8 WAS. Location significantly ($P < 0.05$) influenced chlorophyll content at 4, 6, and 8 WAS. Dambatta consistently recorded higher SPAD values (48.3-56.4) than BUK (35.1-42.4), indicating more favorable photosynthetic conditions at this site during mid to late vegetative stages.

Fertilizer effects were evident ($P < 0.001$) at 6 and 8 WAS. At 6 WAS, 25% CF + 75% NPK (52.4 SPAD) achieved the highest chlorophyll levels, followed by 100% NPK (50.0) and 50% CF + 50% NPK (48.6). The lowest values occurred with 100% CF (38.7) and cow dung (38.8). At 8 WAS, 50% CF + 50% NPK maintained the highest chlorophyll content (56.9), with 25% CF + 75% NPK (52.7) and 100% NPK (51.5) also performing well. Organic-only inputs (100% CF, cow dung) consistently produced lower chlorophyll content (41.5-46.1).

Variety had no significant ($P > 0.05$) effect at any stage. A significant location × fertilizer interaction was observed at 6 WAS at BUK, (Fig. 5), where the 25% CF + 75% NPK treatment at BUK recorded the highest chlorophyll content (56.2 SPAD), while the and cow dung and control treatment at BUK had the lowest (31.7 & 30.9 SPAD) compared with remaining interaction combinations that are at par.

Table 6: Effect of location, fertilizer and variety on Leaf chlorophyll content of Maize at 2, 4, 6 and 8 WAS

Treatment	Weeks after sowing (WAS)			
	2	4	6	8
Location (L)				
BUK	33.2	35.1b	42.4b	38.9b
Dambatta	35.2	56.4a	48.3a	56.4a
P-Value	0.2566	<0.0001	0.0140	<0.0001
SE±	1.23	1.43	1.75	1.98
Fertilizer (F)				
Control	29.4	40.8	40.8bc	43.1bc
100% CF	35.3	40.4	38.7c	41.5c
50% CF + 50% NPK	34.5	49.8	48.6ab	56.9a
75% CF + 25% NPK	36.9	48.5	48.1ab	41.7c
25% CF + 75% NPK	35.4	48.1	52.4a	52.7ab
100% NPK	35.0	48.3	50.0ab	51.5a-c
Cow dung	32.7	44.0	38.8c	46.1bc
P-Value	0.3611	0.0606	0.0042	0.0237
SE±	2.30	2.67	2.91	3.73
Variety (V)				
SAMMAZ 27	34.3	45.2	44.3	47.2
SAMMAZ 29	34.1	46.2	46.4	48.0
P-Value	0.8861	0.6165	0.3723	0.7619
SE±	1.23	1.43	1.65	1.98

Interaction				
L x F	0.9186	0.9168	0.0276	0.0556
L x V	0.1536	0.4876	0.9880	0.9848
F x V	0.1414	0.1994	0.8441	0.6792
L x F x V	0.7767	0.8198	0.6220	0.6268

Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK

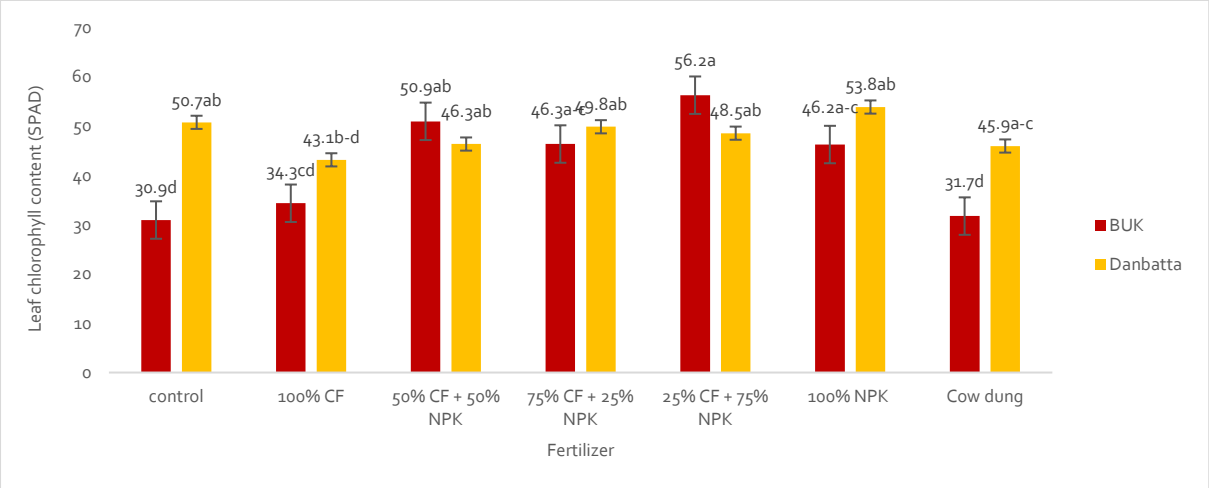


Figure 5: Fertilizer x Location on Leaf chlorophyll content of Maize at 6 WAS
Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK

Normalized difference vegetation index (NDVI)

The effects of location, fertilizer, and variety on the Normalized Difference Vegetation Index (NDVI) of maize at 2, 4, 6, and 8 WAS is shown in Table 7. Location significantly ($P < 0.05$) influenced NDVI at 2, 4, and 8 WAS. Dambatta supported greater early vigor (0.38 vs. 0.28 at 2 WAS) and sustained vegetative activity later (0.56 vs. 0.52 at 8 WAS), while BUK recorded higher NDVI at 4 WAS (0.44 vs. 0.39), suggesting site-specific shifts in canopy development. Fertilizer had no significant ($P > 0.05$) effect on NDVI at any stage. Variety differences emerged only at 8 WAS, where SAMMAZ 29 exhibited a higher NDVI (0.57) than SAMMAZ 27 (0.52), indicating better canopy greenness during the late vegetative phase. Significant ($P < 0.05$) location × fertilizer (L × F) interactions occurred at 4 and 6 WAS(Fig.6). At 4 WAS, 25% CF + 75% NPK in BUK produced the highest NDVI (0.49), while 75% CF + 25% NPK in Dambatta recorded the lowest. At 6 WAS, most fertilizer treatments in BUK showed higher NDVI values than those in Dambatta, although the control in BUK remained among the lowest. These results suggest a location-dependent fertilizer response, with BUK showing greater sensitivity to treatment variation in early vegetative growth.

Table 7: Effect of location, fertilizer and variety on Normalized Difference Vegetation Index (NDVI) at 2, 4, 6 and 8 WAS

Treatment	Weeks after sowing (WAS)			
	2	4	6	8
Location (L)				
BUK	0.28b	0.44a	0.65	0.52b
Dambatta	0.38a	0.39b	0.63	0.56a
P-Value	<0.0001	0.0062	0.5501	0.0500
SE±	0.01	0.01	0.02	0.01
Fertilizer (F)				
Control	0.32	0.39	0.60	0.61
100% CF	0.32	0.40	0.62	0.56
50% CF + 50% NPK	0.33	0.42	0.64	0.53
75% CF + 25% NPK	0.34	0.40	0.66	0.52
25% CF + 75% NPK	0.31	0.46	0.67	0.55
100% NPK	0.33	0.42	0.66	0.50
Cow dung	0.35	0.43	0.63	0.53
P-Value	0.9240	0.3764	0.6268	0.0603
SE±	0.02	0.02	0.03	0.02
Variety (V)				
SAMMAZ 27	0.33	0.40	0.63	0.52b
SAMMAZ 29	0.33	0.43	0.65	0.57a
P-Value	0.9063	0.1101	0.3379	0.0057
SE±	0.01	0.01	0.02	0.01
Interaction				
L x F	0.9677	0.0458	0.0143	0.6239
L x V	0.3706	0.1585	0.3379	0.8746
F x V	0.2145	0.1562	0.8856	0.6222
L x F x V	0.6773	0.5235	0.7403	0.5020

Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK.

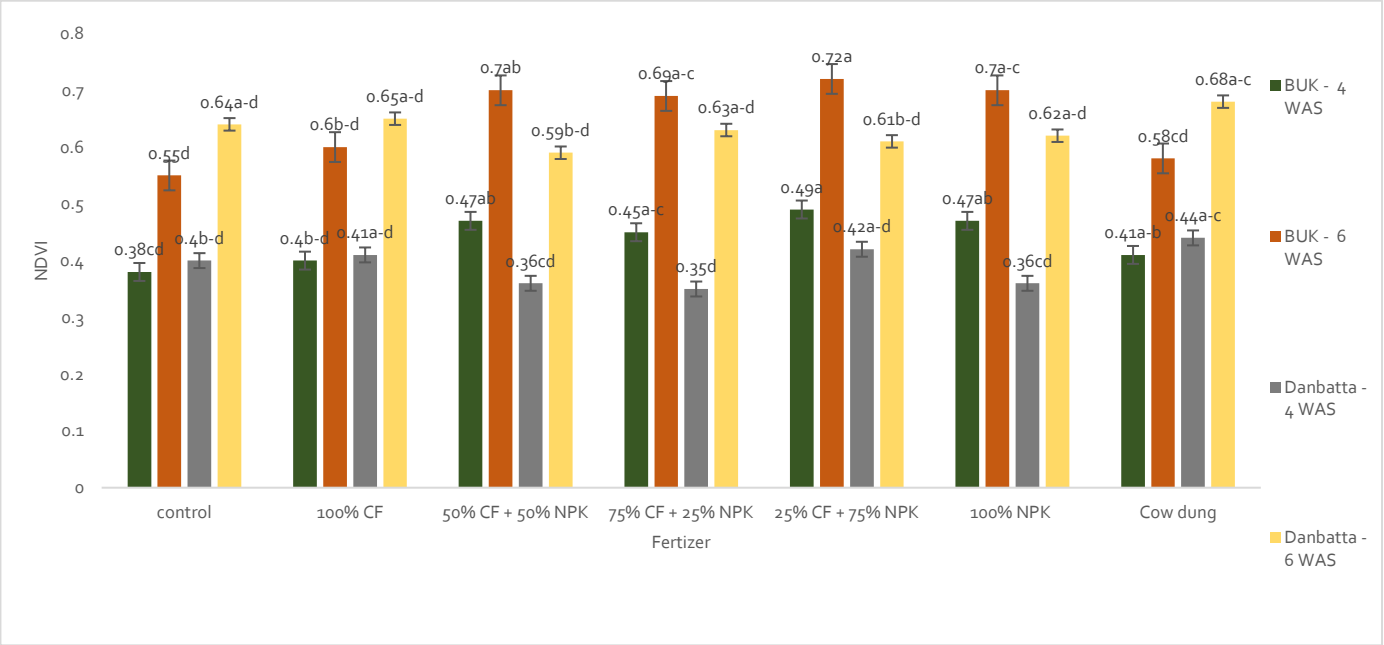


Figure 6: Fertilizer x Location on NDVI of Maize at 4 and 6 WAS

Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK

Stem girth (mm)

The effects of location, fertilizer, and variety on the stem girth of maize at 2, 4, 6, and 8 WAS are shown in Table 8. Location significantly ($P < 0.05$) affected stem girth at 2, 6, and 8 WAS ($P < 0.05$). BUK consistently produced thicker stems (3.4 cm, 19.3 cm, and 19.0 cm, respectively) compared to Dambatta (3.1 cm, 17.0 cm, and 17.8 cm), indicating stronger stem development at BUK.

Fertilizer effects were significant at 6 and 8 WAS. At 6 WAS, 75% CF + 25% NPK (20.2 cm) and 25% CF + 75% NPK (20.1 cm) yielded the largest girths, while at 8 WAS, 75% CF + 25% NPK (20.2 cm) again outperformed other treatments, followed closely by 25% CF + 75% NPK (19.2 cm) and 100% CF (19.4 cm). Varietal effects were not significant ($P > 0.05$) across growth stages.

Tables 8: Effect of location, fertilizer and variety on stem girth of Maize at 2, 4, 6 and 8 WAS

Treatment	Weeks after sowing (WAS)			
	2	4	6	8
Location (L)	3.1b	9.9	17.0b	17.8b
BUK	3.4a	10.7	19.3a	19.0a
Dambatta	0.0045	0.1752	0.0016	0.0303
P-Value	0.07	0.43	0.50	0.40
SE±				
Fertilizer (F)	3.1	9.1	15.0c	16.4c
Control	3.2	9.7	16.2bc	17.4bc
100% CF	3.2	10.7	18.9a	19.4ab

Treatment	Weeks after sowing (WAS)			
	2	4	6	8
50% CF + 50% NPK	3.3	11.0	18.1ab	18.5a-c
75% CF + 25% NPK	3.4	10.7	20.2a	20.2a
25% CF + 75% NPK	3.3	10.1	20.1a	19.2ab
100% NPK	3.3	10.8	18.5ab	17.6bc
Cow dung	0.8165	0.6154	0.0009	0.0064
P-Value	0.13	0.81	0.84	0.71
SE±				
Variety (V)	3.2	10.1	18.0	18.6
SAMMAZ 27	3.3	10.5	18.3	18.2
SAMMAZ 29	0.0603	0.5002	0.6154	0.3998
P-Value	0.07	0.43	0.48	0.39
SE±				
Interaction				
L x F	0.0585	0.0003	0.0041	0.3180
L x V	0.5058	0.2781	0.1865	0.3938
F x V	0.5492	0.4970	0.6971	0.7552
L x F x V	0.9461	0.6762	0.0657	0.2216

Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK

Significant location × fertilizer interactions were observed at 4 and 6 WAS (Fig. 7). At 4 WAS, 25% CF + 75% NPK in BUK produced relatively high stem girth (12.2 mm), comparable to other integrated treatments, but greater than sole 100% CF (7.6 mm) and cow dung (7.4 mm) at the same site. In contrast, cow dung in Dambatta resulted in the widest stems (14.3 mm), significantly exceeding most treatments.

At 6 WAS, BUK favored integrated and inorganic treatments, with 50% CF + 50% NPK (20.1 mm), 25% CF + 75% NPK (19.4 mm), and 100% NPK (20.5 mm) achieving the largest stems, while the control (12.7 mm) remained lowest. Meanwhile, in Dambatta, cow dung again produced the highest girth (22.3 mm), outperforming all other treatments. Overall, the results highlight location-specific responses: BUK favored integrated CF + NPK or inorganic fertilizers, while Dambatta responded more strongly to organic amendments such as cow dung.

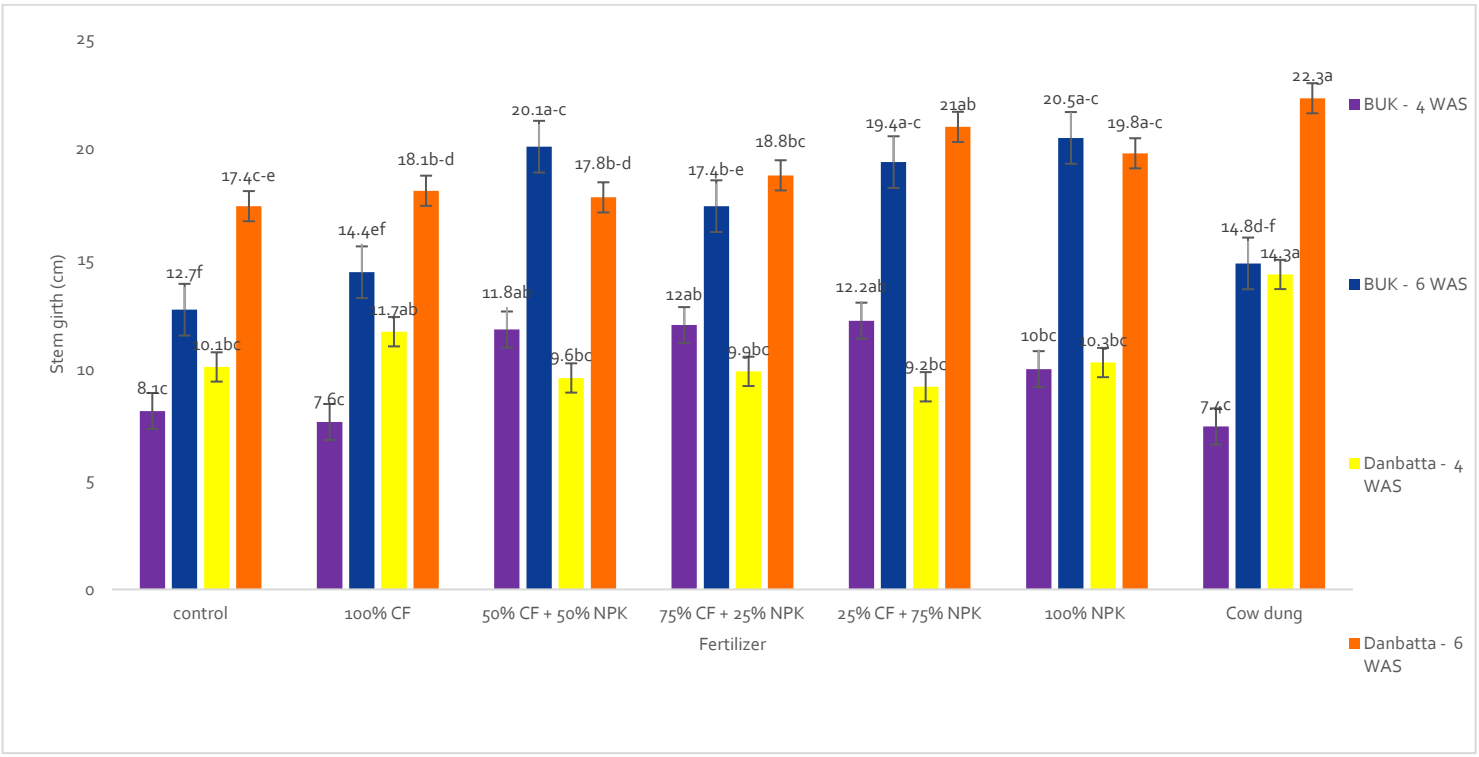


Figure 7: Fertilizer x Location on Stem girth of Maize at 4 and 6 WAS
Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK

Yield and Yield-related Parameters

Days to 50% tasseling, Days to 50% silking, and Anthesis-silking interval (ASI)

Table 9 shows the effects of location, fertilizer, and variety on days to 50% tasseling, days to 50% silking, and anthesis-silking interval (ASI) of maize. Significant ($P < 0.05$) effects of location were observed for silking and ASI, but not tasseling. Maize in BUK silked later (60.8 days) and had a wider ASI (7.0 days) than in Dambatta (57.9 days, ASI = 4.8 days), suggesting greater reproductive stress under BUK conditions.

Fertilizer regimes significantly ($P < 0.05$) influenced tasseling and silking. The control delayed tasseling (56.1 days) and silking (60.8 days), while 25% CF + 75% NPK and 100% NPK accelerated development, reducing tasseling and silking to 52 days and 57 days, respectively. ASI, however, was unaffected by fertilizer.

Varietal effects were significant for silking and ASI. SAMMAZ 29 silked later (60.4 days) and had a wider ASI (6.5 days) compared with SAMMAZ 27 (58.4 days; ASI = 5.3 days), indicating slower and potentially more stress-sensitive reproductive progression in SAMMAZ 29.

A significant location × fertilizer interaction was detected for tasseling and silking (Fig. 8). In BUK, the control (58.8 days), 100% CF, and cow dung (57.0 days) caused increase in days to 50% tasseling, whereas integrated and inorganic fertilizers consistently shortened time to reproductive stages. By implication, Dambatta and high-NPK regimes supported faster and less stress-prone tasseling, while BUK conditions and organic-dominant treatments delayed reproductive development and widened ASI, signaling potential yield penalties under stress.

Table 9: Effect of location, fertilizer and variety on Days to 50% tasseling, Days to 50% silking and Anthesis-silking interval (ASI) of Maize.

Treatment	Days to 50% Tasseling	Days to 50% Silking	Anthesis-Silking Interval (ASI)
Location (L)			
BUK	54.3	60.8a	7.0a
Dambatta	53.2	57.9b	4.8b
P-Value	0.0805	<0.0001	0.0004
SE±	0.45	0.45	0.43
Fertilizer (F)			
Control	56.1a	60.8a	5.3
100% CF	55.1ab	60.8a	6.5
50% CF + 50% NPK	53.0bc	58.0b	5.0
75% CF + 25% NPK	52.8bc	60.6a	7.8
25% CF + 75% NPK	52.0c	57.5b	5.6
100% NPK	52.1c	57.0b	5.3
Cow dung	55.0ab	60.8a	5.8
P-Value	0.0028	0.0010	0.1711
SE±	0.86	0.87	0.75
Variety (V)			
SAMMAZ 27	53.4	58.4b	5.3b
SAMMAZ 29	54.0	60.4a	6.5a
P-Value	0.3268	0.0024	0.0401
SE±	0.45	0.45	0.42
Interaction			
L x F	0.0049	0.0004	0.7462
L x V	0.8384	0.7592	0.7698
F x V	0.7203	0.2152	0.3807
L x F x V	0.8157	0.8624	0.4329

Means followed by the same letter(s) in a column are not significantly different at P ≤ 0.05 using SNK

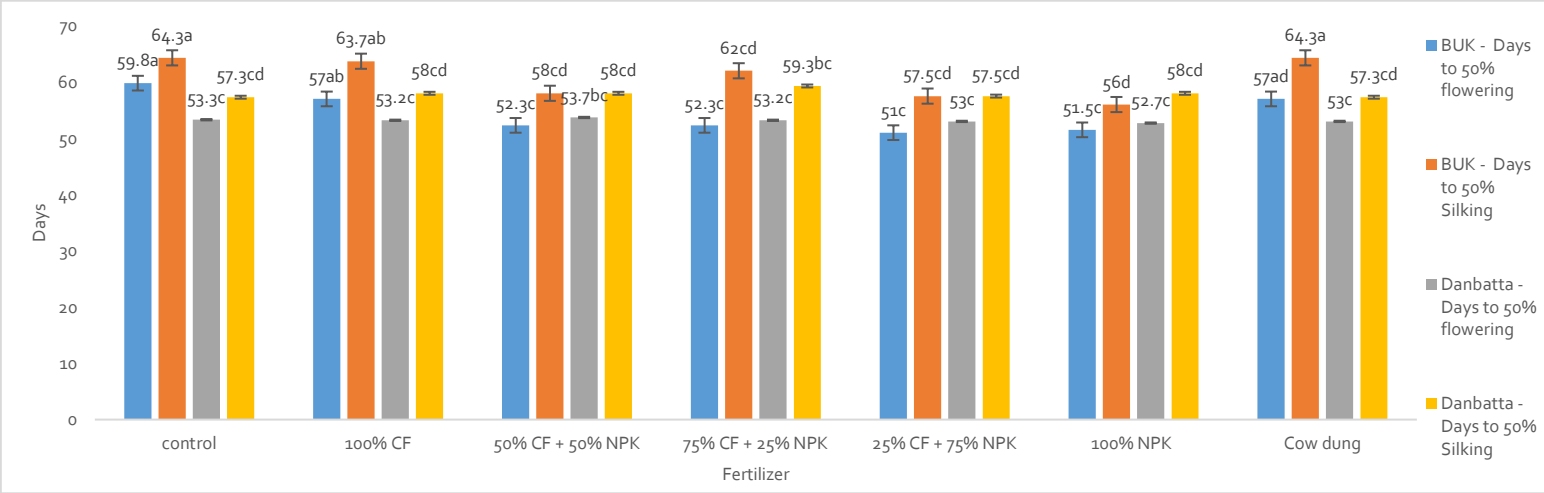


Figure 8: Effect of fertilizer and location on Days to 50% tasseling and Days to 50% silking of Maize.

Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK

Stand-to-cob (S:C) ratio, Cob yield, Stover yield, and Grain yield per hectare

The effects of location, fertilizer, and variety on stand-to-cob (S:C) ratio, cob yield, stover yield, and grain yield per hectare in maize are presented in Table 10. Grain yield was significantly higher ($P < 0.05$) in BUK (2106.8 kg ha^{-1}) compared to Dambatta (1324.5 kg ha^{-1}), confirming BUK's advantage for grain production. Cob and stover yields were slightly higher in BUK, though not statistically different.

Fertilizer significantly ($P < 0.001$) influenced the stand-to-cob (S:C) ratio but not cob, stover, or grain yield. The highest S:C ratio occurred with 25% CF + 75% NPK (1.1), outperforming the control (0.7), 100% CF (0.8), and cow dung (0.8), suggesting more efficient cob formation with integrated fertilizer use. While cob and grain yields were numerically highest with integrated and NPK treatments, differences were not statistically significant, indicating similar yield potential across fertilized plots.

SAMMAZ 29 produced significantly ($P < 0.001$) greater stover yield (11,805.1 kg ha^{-1}) than SAMMAZ 27 (9898.4 kg ha^{-1}). Varieties did not differ in S:C ratio, cob yield, or grain yield.

Interaction effects:

Location × Fertilizer is shown in Figure 9, where 25% CF + 75% NPK in BUK recorded the highest cob yield (4357.4 kg ha^{-1}), similar to 50% CF + 50% NPK, 75% CF + 25% NPK, and 100% NPK, but all substantially exceeded the control (1687.0 kg ha^{-1}). For stover, BUK again favored fertilizer-intensive regimes, with 50% CF + 50% NPK yielding 14,995.2 kg ha^{-1}, far above the control (7629.6 kg ha^{-1}). In Dambatta, cob yields under cow dung (3177.8 kg ha^{-1}) and the control (3142.6 kg ha^{-1}) were relatively better than in BUK, showing site-specific differences.

A significant L × V interaction was obtained and is presented in Figure 10. SAMMAZ 29 produced the highest stover yield in BUK (3383.6 kg ha^{-1}), significantly greater than the same variety in Dambatta (2412.0 kg ha^{-1}).

By implication, Integrated CF + NPK treatments consistently enhanced cob and stover production, particularly at BUK, while SAMMAZ 29 demonstrated superior biomass potential. However, grain yield remained statistically similar across fertilizer treatments, suggesting that integrated fertilization mainly boosts vegetative biomass rather than grain output under Sudan Savanna conditions.

Table 10: Effect of location, fertilizer and variety on Stand-to-cob (S:C) ratio, Cob yield, Stover yield, and Grain yield per hectare

Treatment	Stand-Cob (S:C) Ratio/Net Plot	Cob yield (Kg ha^{-1})	Stover yield (Kg ha^{-1})	Grain yield (Kg ha^{-1})
Location (L)				
BUK	1.0	3091.5	11295.2	2106.8a
Dambatta	1.0	2685.9	10408.4	1324.5b
P-Value	0.0501	0.1219	0.2341	<0.0001
SE±	0.04	182.23	520.52	94.29
Fertilizer (F)				
Control	0.7c	2414.8	8819.6	1408.5
100% CF	0.8c	2566.5	9109.3	1662.8
50% CF + 50% NPK	1.0ab	2996.1	11830.3	1879.0
75% CF + 25% NPK	0.9bc	2926.8	11593.2	1805.6
25% CF + 75% NPK	1.1a	3633.5	11834.8	1835.1
100% NPK	1.0a-c	3030.6	12139.6	1762.4
Cow dung	0.8c	2652.8	10635.4	1656.3
P-Value	0.0054	0.2338	0.0719	0.5463
SE±	0.08	349.16	997.4	180.67
Variety (V)				
SAMMAZ 27	0.9	2879.7	9898.4b	1704.6
SAMMAZ 29	0.9	2897.8	11805.1a	1726.7
P-Value	0.3066	0.9442	0.0124	0.8690
SE±	0.04	181.9	519.49	94.10
Interaction				
L x F	0.3353	0.0012	0.0003	0.0662
L x V	0.2529	0.0325	0.5541	0.6094
F x V	0.7528	0.7221	0.8268	0.6822
L x F x V	0.9923	0.3970	0.3365	0.0724

Means followed by the same letter(s) in a column are not significantly different at P ≤ 0.05 using SNK

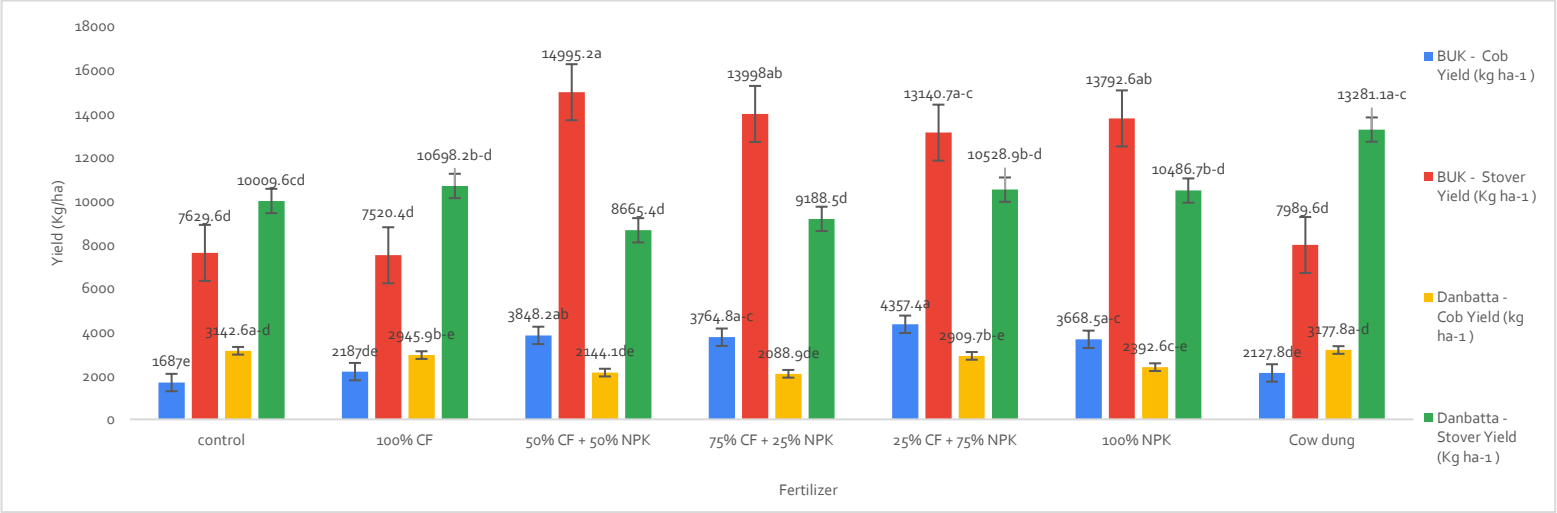


Figure 9: Fertilizer x Location interaction on cob yield and stover yield of Maize.
Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK

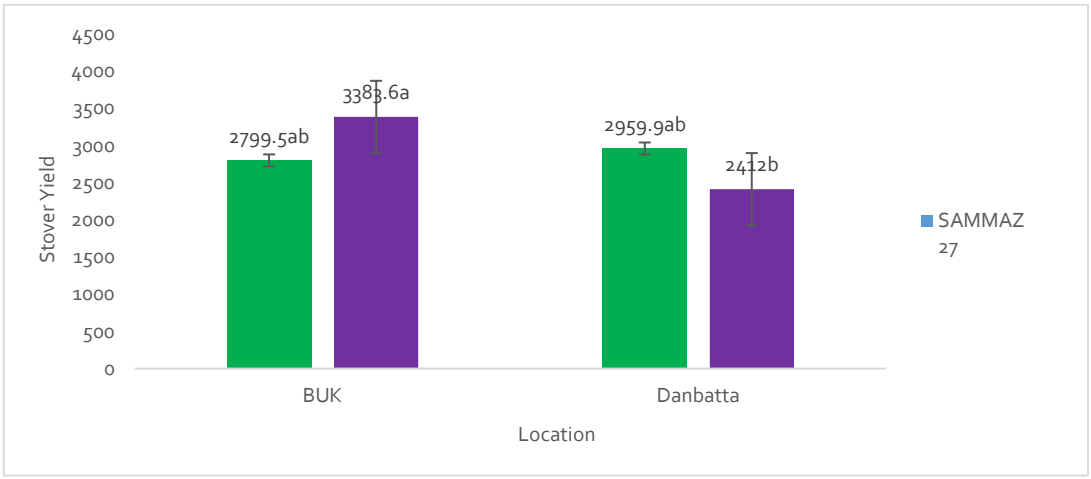


Figure 10: Effect of location and variety interaction on stover yield of maize
Means followed by the same letter(s) are not significantly different at P ≤ 0.05 using SNK

Contrast analysis of stover and grain yield under different fertilizer treatments at BUK and Dambatta

Table 11 presents the contrast analysis results for stover yield and grain yield under different fertilizer treatments at BUK and Dambatta. At BUK, stover yield showed highly significant differences in multiple contrasts. The stover yield from 100% NPK was significantly higher than that from 100% CF (6272**) and cow dung (5803**). Similarly, Low CF had a significantly lower stover yield than cow dung (-5151.1**), while Medium CF and High CF also produced significantly lower stover yields than cow dung (-7005.6** and -6209.7**, respectively). In contrast, comparisons between different CF levels did not show significant differences in stover yield. Grain yield, however, showed no significant differences in any of the contrasts. At Dambatta, stover yield was significantly lower in Medium CF and High CF compared to cow dung (-4091* and -4093*, respectively). However, all other contrasts for

stover and grain yield were not significant, indicating no major differences in grain yield across the fertilizer treatments. The ability of 100% NPK to significantly increase stover yield compared to 100% CF and cow dung at BUK can be attributed to the greater efficiency of inorganic fertilizers (NPK) in promoting vegetative biomass production. Inorganic fertilizers provide readily available nutrients, which accelerate plant growth and stover accumulation more effectively than organic sources like cow dung or composted fertilizer. This makes NPK especially suitable for fodder-focused production systems or scenarios where maximizing biomass is a priority.

Table 11: Contrast Analysis of Fertilizer Effects on Stover Yield and Grain Yield at BUK and Dambatta

Contrast Analysis	BUK			Dambatta	
	Stover yield	Grain yield		Stover yield	Grain yield
100% NPK vs 100% CF	6272**	480.37ns		-211.5ns	-281.1ns
100% NPK vs Cow Dung	5803**	495.56ns		-2794ns	-283.3ns
100% CF vs Cow Dung	-469.3ns	15.185ns		-2583ns	-2.222ns
High CF vs Low CF	1055.6ns	47.5ns		-991.7ns	-102.9ns
High CF vs Medium CF	-795.9ns	-29.54ns		-1.248ns	-170ns
Medium CF vs Low CF	1854.4ns	77.037ns		-990.5ns	67.099ns
Low CF vs Cow Dung	5151.1**	517.78ns		-3101ns	-257.9ns
Medium CF vs Cow Dung	7005.6**	594.81ns		-4091*	-190.8ns
High CF vs Cow Dung	6209.7**	565.28ns		-4093*	-360.7ns
100% NPK vs High CF	-406.7ns	-69.72ns		1298.1ns	77.407ns
100% NPK vs Medium CF	-1203ns	-99.26ns		1296.9ns	-92.57ns
100% NPK vs Low CF	651.85ns	-22.22ns		306.44ns	-25.48ns
100% CF vs High NPK	-5620**	-502.6ns		517.93ns	255.64ns
100% CF vs Medium NPK	-7475**	-579.6ns		1508.43ns	188.54ns
100% CF vs Low NPK	-6679**	-550.1ns		1509.6ns	358.52ns

Discussion

Growth and Growth-related Parameters as Affected by Location

Leaf development, chlorophyll content, and plant height varied significantly by location due to baseline soil fertility differences. At early stages (2-6 WAS), BUK produced more leaves, likely supported by higher organic C, N, Mn, and Fe, which enhance microbial activity, chlorophyll synthesis, and photosynthesis (Liu et al., 2021; Wang et al., 2022; Tao et al., 2023; Nik-Khah et al., 2024). By 8 WAS, Dambatta surpassed BUK in leaf number and chlorophyll, reflecting its higher Ca and Mg levels and favorable pH that improve nutrient availability (He et al., 2024; Hartemink & Barrow, 2023). Plant height was consistently greater in Dambatta, highlighting the importance of Ca and Mg in hormonal regulation and cell elongation (He et al., 2024). NDVI differences across stages reflected canopy expansion

and chlorophyll dynamics, with location-driven effects aligning with earlier findings on NDVI responsiveness and nitrogen sensitivity (Farias et al., 2023; Mohammad et al., 2022; Burns et al., 2022).

Growth and Growth-related Parameters as Affected by Fertilizer

Fertilizer effects were strongest at 6-8 WAS, coinciding with peak nitrogen demand during rapid vegetative growth. Integrated CF + NPK treatments (25-75% combinations) consistently matched or outperformed sole NPK in leaf number, chlorophyll content, and stem girth, demonstrating synergistic nutrient availability (Gudabe et al., 2022; Meena et al., 2024; Susilowati et al., 2024). In contrast, sole CF and cow dung lagged behind, likely due to slower mineralization rates (Afrida & Tampubolon, 2022; Fatihi, 2022). These results support integrated nutrient management as a means of enhancing crop growth while reducing reliance on inorganic fertilizers.

Yield and Yield-related Parameters as Affected by Location

Location significantly influenced reproductive development. Maize in BUK showed delayed silking and a wider ASI (7.0 vs. 4.8 days), likely due to lower soil N and Zn, which are critical for silk elongation and pollen viability (Rajesh et al., 2021; Yu et al., 2023). Despite reproductive delays, BUK achieved higher grain yield (2106.8 vs. 1324.5 kg ha^{-1}), possibly due to more efficient source-sink partitioning (Li et al., 2022). Cob and stover yields did not differ significantly, suggesting biomass accumulation was largely stable across sites (Ertiro et al., 2020).

Yield and Yield-related Parameters as Affected by Fertilizer levels

Fertilizer significantly accelerated tasseling and silking, with 25% CF + 75% NPK and 100% NPK promoting the earliest tasseling (52-57 days), while the control delayed reproductive stages (56-61 days). This confirms nitrogen's role in hastening flowering and improving reproductive efficiency (Yadete et al., 2024; Okab & Abed, 2022). The highest S:C ratio (1.1) was achieved under 25% CF + 75% NPK, indicating superior cob formation compared with the control (0.7). Though grain yield differences were not statistically significant, integrated CF + NPK treatments consistently produced numerically higher yields than sole inputs. This trend supports the findings of Bhatt & Ghimire (2024); Yadav et al. (2024) and Kumar et al. (2024), who demonstrated that integrated nutrient management improves yield stability and nutrient use efficiency in maize.

Contrast Analysis

Stover yield responded strongly to fertilizer contrasts, particularly at BUK, where 100% NPK significantly outperformed 100% CF and cow dung, consistent with findings on the superiority of integrated inorganic-organic regimes (Ahirwar et al., 2025). Cow dung performed better than CF across sites, reflecting faster nutrient release, as noted by Rewe et al. (2021). This has practical implications for mixed crop-livestock systems, where higher stover biomass can support feed and fuel availability (Padwar et al., 2023). In contrast, grain

yield showed limited responsiveness to fertilizer contrasts, aligning with Medina-Cuéllar et al. (2021), who reported plateau effects of nitrogen beyond certain thresholds.

Novelty, Limitations, and Future Directions

This study is the first to evaluate coal fertilizer (CF) integration with inorganic NPK in maize production. Findings reveal that partial substitution of NPK with CF (25-75% blends) sustains or improves vegetative growth and stover production, with potential to reduce dependence on inorganic fertilizers. This supports sustainable nutrient management and introduces CF as a novel organic amendment for sub-Saharan maize systems.

However, limitations include the single-season scope and two-site evaluation, which may not capture inter-annual variability or broader environmental interactions. Multi-season and multi-location trials are necessary to validate these findings, assess long-term soil health impacts, and optimize CF-NPK ratios for different agroecological zones. Future studies should also investigate CF's decomposition dynamics, nutrient release patterns, and potential contributions to soil organic matter stabilization.

Conclusion

This study evaluated the effects of coal fertilizer (CF), NPK, and cow dung, alone and in combination, on the growth and productivity of two maize varieties under Sudan Savanna conditions. The objectives were to assess varietal performance, determine the optimal coal fertilizer-NPK combination, and compare these inputs with conventional fertilizer sources. The results confirmed our hypothesis that integrated CF and NPK applications enhance vegetative growth and stover yield compared to sole fertilizer inputs. Treatments with 25-50% CF combined with 50-75% NPK consistently improved plant height, chlorophyll content, and stem girth, often matching or surpassing 100% NPK. Grain yield showed limited responsiveness to fertilizer combinations, but biomass accumulation was significantly higher under integrated treatments, particularly in BUK.

The key research contribution of this study lies in demonstrating the agronomic value of coal-based fertilizer as a complementary input to inorganic NPK in the Sudan Savanna. This contributes to nutrient management theory by showing that integrating carbon-rich fertilizers with mineral inputs can sustain vegetative growth without relying exclusively on costly synthetic fertilizers. At the policy level, our findings highlight coal fertilizer as a potential indigenous resource to reduce fertilizer import dependency and improve soil resilience.

For farmers, the practical recommendation is to apply coal fertilizer in combination with NPK at ratios of 25-50% CF with 50-75% NPK to maximize stover yield, which is particularly valuable in mixed crop-livestock systems. While grain yield was not significantly increased, the enhanced biomass can provide fodder, fuel, and soil organic matter benefits, improving overall farm productivity.

Future research should validate these findings across multiple seasons and soil types, and assess long-term impacts on soil fertility, nutrient cycling, and climate-smart agriculture outcomes.

References

Aboderin, O. S., Bankole, F., Oyekunle, M., & Olaoye, G. (2023). Yield stability and inter-trait relationships of maize hybrids under low- and optimum-nitrogen conditions. *Agriculture (Pol'nohospodárstvo), 69*(4), 171-186. https://doi.org/10.2478/agri-2023-0015

Adhikari, K., Bhandari, S., Aryal, K., Mahato, M., & Shrestha, J. (2021). Effect of different levels of nitrogen on growth and yield of hybrid maize (*Zea mays* L.) varieties. *Journal of Agriculture and Natural Resources, 4*(2), 48-62. https://doi.org/10.3126/janr.v4i2.33656

Afrida, E., & Tampubolon, K. (2022). Limiting factors of agronomic characteristics for maize through nutrient omission techniques. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 7*(2), 109-118. https://doi.org/10.11118/actaun.2022.010

Ahirwar, H., Kulhare, P. S., Tagore, G. S., Prajapati, S. S., & Singh, V. (2025). Effects of organic and inorganic fertilizers on soil properties, nutrient dynamics, and maize yield (*Zea mays* L.). *International Journal of Plant & Soil Science, 37*(1), 384-392. https://doi.org/10.9734/ijpss/2025/v37i15280

Akimbekov, N. S., Digel, I., Tastambek, K. T., Sherelkhan, D. K., Jussupova, D. B., & Altynbay, N. P. (2021). Low-rank coal as a source of humic substances for soil amendment and fertility management. *Agriculture, 11*(12), 1261. https://doi.org/10.3390/agriculture11121261

Beah, A., Kamara, A., Jibrin, J. M., Akinseye, F. M., Tofa, A., & Ademulegun, T. (2021). Simulation of the optimum planting windows for early and intermediate-maturing maize varieties in the Nigerian Savannas using the APSIM model. *Frontiers in Sustainable Food Systems, 5,* 624886. https://doi.org/10.3389/fsufs.2021.624886

Behera, H. S., & Kumar, R. (2025). Timing of nitrogen treatment in maize (*Zea mays* L.) produced in Punjab's coarse loamy Typic Haplustept soil. *Asian Journal of Soil Science and Plant Nutrition, 11*(1), 314-322. https://doi.org/10.9734/ajsspn/2025/v11i1483

Bhatt, S., & Ghimire, S. (2024). Quantifying the impact of nitrogen levels on spring maize varieties (*Zea mays* L.) in Kanchanpur, Nepal. *Innovations in Agriculture, 7,* 1-7. https://doi.org/10.3897/ia.2024.124217

Burns, B. W., Green, V., Hashem, A., Massey, J., Shew, A. M., Adviento-Borbe, M. A., & Milad, M. (2022). Determining nitrogen deficiencies for maize using various remote sensing indices. *Precision Agriculture, 23,* 791–811. https://doi.org/10.1007/s11119-021-09861-4

Chen, Z., Huang, G., Li, Y., Zhang, X., Xiong, Y., Huang, Q., & Jin, S. (2022). Effects of lignite bioorganic fertilizer on greenhouse gas emissions and pathways of nitrogen and carbon cycling in saline-sodic farmlands of Northwest China. *Agricultural Water Management, 271,* 107806. https://doi.org/10.1016/j.agwat.2022.107806

Ertiro, B. T., Olsen, M., Das, B., Gowda, M., & Labuschagne, M. (2020). Genetic dissection of grain yield and agronomic traits in maize under optimum and low-nitrogen stressed environments. *International Journal of Molecular Sciences, 21*(2), 543. https://doi.org/10.3390/ijms21020543

Fatihi, M. (2022). Role of nitrogen (N) in plant growth, photosynthesis pigments, and N use efficiency: A review. *Agrisost, 28,* 1–8. https://doi.org/10.5281/zenodo.7143588

Farias, G. D., Bremm, C., Bredemeier, C., de Lima Menezes, J., Alves, L. A., Tiecher, T., & de Faccio Carvalho, P. C. (2023). Normalized difference vegetation index (NDVI) for soybean biomass and nutrient uptake estimation in response to production systems and fertilization strategies. *Frontiers in Sustainable Food Systems, 6,* 959681. https://doi.org/10.3389/fsufs.2022.959681

Gitelson, A., Viña, A., Inoue, Y., Arkebauer, T., Schlemmer, M., & Schepers, J. (2022). Uncertainty in the evaluation of photosynthetic canopy traits using the green leaf area index. *Agricultural and Forest Meteorology, 320,* 108955. https://doi.org/10.1016/j.agrformet.2022.108955

Gudabe, A. B., Raji, M. A., & Musa, M. (2022). Enhancing maize productivity through integrated nutrient management in the Sudan Savanna of Nigeria. *Journal of Agricultural Science and Practice, 9*(1), 1-10.

Hartemink, A. E., & Barrow, N. J. (2023). Soil pH–nutrient relationships: The diagram. *Plant and Soil, 486*(1), 209-215. https://doi.org/10.1007/s11104-022-05861-z

He, Z., Shang, X., Jin, X., Wang, X., & Xing, Y. (2025). Calcium and magnesium regulation of kernel sugar content in maize: Role of endogenous hormones and antioxidant enzymes. *International Journal of Molecular Sciences, 26*(1), 200. https://doi.org/10.3390/ijms26010200

Jote, C. A. (2023). The impacts of using inorganic chemical fertilizers on the environment and human health. *Organic and Medicinal Chemistry International Journal, 13*(3), 555864. https://doi.org/10.19080/OMCIJ.2023.13.555864

Kamara, A., Ajeigbe, H., Ndaghu, N., Kamsang, L., Ademulegun, T., & Solomon, R. (2019). Using a participatory approach and legume integration to increase the productivity of early maturing maize in the Nigerian Sudan Savannas. *International Journal of Agronomy,* 5154943. https://doi.org/10.1155/2019/5154943

Kamara, A., Menkir, A., Chikoye, D., Tofa, A., Fagge, A. A., Dahiru, R., Solomon, R., Ademulegun, T., Omoigui, L., Aliyu, K., & Kamai, N. (2020). Mitigating *Striga hermonthica* parasitism and damage in maize using soybean rotation, nitrogen application, and Striga-resistant varieties in the Nigerian savannas. *Experimental Agriculture, 56*(4), 620-632. https://doi.org/10.1017/S0014479720000198

Kumar, E. A., Reddy, R. U., Chaitanya, K., Reddy, M. M., & Triveni, S. (2024). Yield attributes and yield of maize as influenced by different paddy straw management options and nitrogen levels in rice–maize cropping systems. *Asian Journal of Soil Science and Plant Nutrition, 10*(2), 575–581. https://doi.org/10.9734/ajsspn/2024/v10i2314

Li, Q., Ren, Y., Fu, H., Li, Z., Kong, F., & Yuan, J. (2022). Cultivar differences in carbon and nitrogen accumulation, balance, and grain yield in maize. *Frontiers in Plant Science, 13,* 992041. https://doi.org/10.3389/fpls.2022.992041

Liu, Y., Pan, Y., Yang, L., Ahmad, S., & Zhou, X. B. (2021). Stover return and nitrogen application affect soil organic carbon and nitrogen in a double-season maize field. *Plant Biology, 24*(2), 387-395. https://doi.org/10.1111/plb.13370

Luo, P., Zhang, W., Xiao, D., Hu, J., Li, N., & Yang, J. (2025). Biochar-based fertilizers: Advancements, applications, and future directions in sustainable agriculture: A review. *Agronomy, 15*(5), 1104. https://doi.org/10.3390/agronomy15051104

Medina-Cuéllar, S. E., Tirado-González, D. N., Portillo-Vázquez, M., Orozco-Cirilo, S., López-Santiago, M. A., Vargas-Canales, J. M., Medina-Flores, C. A., & Salem, A. Z. M. (2021). Optimal nitrogen fertilization to reach the maximum grain and stover yields of maize (*Zea mays* L.): Tendency modeling. *Agronomy, 11*(7), 1354. https://doi.org/10.3390/agronomy11071354

Meena, R. S., Yadav, G. S., & Mitran, T. (2024). Integrated nutrient management: A sustainable approach for improving crop yield and soil health. *Agronomy Today, 6*(2), 45-52.

Muhammad, I., Yang, L., Ahmad, S., Farooq, S., Al-Ghamdi, A. A., Khan, A., Zeeshan, M., Elshikh, M. S., Abbasi, A. M., & Zhou, X. B. (2022). Nitrogen fertilizer modulates plant growth, chlorophyll pigments and enzymatic activities under different irrigation regimes. *Agronomy, 12*(4), 845. https://doi.org/10.3390/agronomy12040845

Nik-Khah, N., Mirkalaei, A. A. M., & Deliri, M. S. (2024). Maize growth and yield production affected by the single and interactive effects of iron, zinc, and manganese in arid and semi-arid areas. *Journal of Crop Science and Biotechnology, 27,* 429-438. https://doi.org/10.1007/s12892-024-00240-9

Padwar, G., Padwar, G. K., & Dubey, S. (2023). Studies on stover yield of maize with basal application of fertilizer and foliar spraying of *Gluconacetobacter diazotropicus* on available nutrients in soil.

International Journal of Plant & Soil Science, 35(21), 232-238. https://doi.org/10.9734/ijpss/2023/v35i213969

Okab, S. I., & Abed, Z. A. (2022). Effect of nitrogen fertilizers on growth and yield traits of maize. *Iraq Journal of Market Research and Consumer Protection, 14*(2), 40-49. https://jmracpc.uobaghdad.edu.iq/index.php/IJMRCP/article/view/301

Onumah, G., Ponsioen, T., Dhamankar, M., & Bello, M. (2022). *Maize value chain analysis in Nigeria*. Value Chain Analysis for Development (VCA4D). European Commission / INTPA & Agrinatura.

Rajesh, S., Singh, V., Tiwari, D., Pratap, P., & Reddy, V. D. (2021). Influence of zinc and spacing on growth and yield of baby corn (*Zea mays* L.). *International Journal of Current Microbiology and Applied Sciences, 10*(1), 434-438. https://doi.org/10.20546/ijcmas.2021.1001.053

Ransom, C. J., Jolley, V. D., Blair, T. A., Sutton, L. E., & Hopkins, B. G. (2020). Nitrogen release rates from slow- and controlled-release fertilizers influenced by placement and temperature. *PLoS One, 15*(6), e0234544. https://doi.org/10.1371/journal.pone.0234544

Rawal, N., Vista, S., Khadka, D., & Paneru, P. (2024). Grain yield, nitrogen accumulation, and its use efficiency of maize (*Zea mays* L.) as influenced by varying nitrogen rates. *International Journal of Agronomy, 2024,* 4104123. https://doi.org/10.1155/2024/4104123

Rewe, M. K., Muindi, E., Ndiso, J., Kinusu, K., Mailu, S., Njeru, P., & Thomas, R. (2021). Effect of bioslurry from fixed dome and tubular (flexi) biodigesters on selected soil chemical properties, maize (*Zea mays* L.) growth, yield and quality. *International Journal of Plant & Soil Science, 33*(20), 158-171. https://doi.org/10.9734/ijpss/2021/v33i2030642

Susilowati, T., Herlina, L., & Widodo, T. (2024). Effect of integrated use of organic and inorganic fertilizers on maize yield and nutrient uptake. *Journal of Soil and Crop Improvement, 14*(1), 58–66.

Symanowicz, B., & Toczko, R. (2023). Brown coal waste in agriculture and environmental protection: A review. *Sustainability, 15*(18), 13371. https://doi.org/10.3390/su151813371

Tao, Y., Liu, C., Piao, L., Yang, F., Liu, J., Jan, M. F., & Li, M. (2023). Effect of Mn deficiency on carbon and nitrogen metabolism of different genotype seedlings in maize (*Zea mays* L.). *Plants, 12*(6), 1407. https://doi.org/10.3390/plants12061407

Tofa, A. I., Babaji, B. A., Aliyu, K. T., Ademulegun, T. D., & Bebeley, J. F. (2022). Maize yield as affected by the interaction of fertilizer nitrogen and phosphorus in the Guinea Savanna of Nigeria. *Heliyon, 8*(11), e11587. https://doi.org/10.1016/j.heliyon.2022.e11587

Tyagi, J., Ahmad, S., & Malik, M. (2022). Nitrogenous fertilizers: Impact on environmental sustainability, mitigation strategies, and challenges. *International Journal of Environmental Science and Technology, 19*(11), 11649-11672. https://doi.org/10.1007/s13762-022-04027-9

Wang, L., Liu, S., Ma, G., Wang, C., & Sun, J. (2022). Soil organic carbon and nitrogen storage under a wheat–maize cropping system in northern China modified by nitrogen application rates. *PeerJ, 10,* e13568. https://doi.org/10.7717/peerj.13568

Wang, Z., Xing, A., & Shen, H. (2023). Effects of nitrogen addition on the combined global warming potential of three major soil greenhouse gases: A global meta-analysis. *Environmental Pollution, 334,* 121848. https://doi.org/10.1016/j.envpol.2023.121848

Yadav, A., Panchal, V., & Kawade, A. (2024). Assessment of growth and yield of maize through integrated nutrient management practices. *Archives of Current Research International, 24*(12), 225-230. https://doi.org/10.9734/acri/2024/v24i121013

Yadete, E., Gurmu, S., & Biya, M. (2024). Effects of time and rate of nitrogen fertilizer application on phenology, growth, and yield of maize at Jimma, Southwestern Ethiopia. *World Journal of Agricultural Science and Technology, 2*(4), 185-197. https://doi.org/10.11648/j.wjast.20240204.19

Yu, N., Ren, B., Zhao, B., Liu, P., & Zhang, J. (2023). Nitrogen rate affects reproductive development and grain set of summer maize by influencing fatty acid metabolism. *Plant and Soil, 487,* 341-354. https://doi.org/10.1007/s11104-023-05930-x