Australian Journal of Crop Science AJCS

Aust J Crop Sci. 19(03):225-235 (2025) | https://doi.org/10.21475/ajcs.25.19.03.p202

ISSN:1835-2707

Evaluating fertilizer effects on growth, yield, and nutritional value of Tiger Nut (*Cyperus esculentus* L.) in Ghana

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***Received:* 15/11/2024**

***Revised:* 15/01/2025**

***Accepted:* 17/01/2025**

Abstract: This study assessed the effects of organic and inorganic fertilizers, both individually and in combination, on the mineral composition, yield, and soil chemical properties of Cyperus esculentus (tiger nut) tubers. The experiment was carried out over three growing seasons in the forest-savanna transition zone, where the soil is classified as Acrisol. A 2 x 4 factorial arrangement within a Randomized Complete Block Design (RCBD) was employed, comparing two varieties of tiger nut (brown and black) under four fertilization treatments: no fertilizer (control), 2,000 kg ha^{-1} poultry manure, 300 kg ha^{-1} NPK 15:15:15, and a combination of 1,000 kg ha^{-1} poultry manure + 150 kg ha^{-1} NPK 15:15:15. The findings indicated that the two tiger nut varieties responded similarly across all measured parameters. The application of poultry manure, both alone and in combination with NPK 15:15:15, significantly improved soil properties, particularly calcium, sodium, hydrogen, and aluminum levels, across all seasons. Additionally, the combined treatment of poultry manure and NPK 15:15:15 consistently enriched the tubers with essential nutrients such as phosphorus, potassium, iron, manganese, copper, and zinc throughout the study period. The sole use of poultry manure enhanced the levels of phosphorus and potassium in the nuts across all seasons. In conclusion, the combined application of poultry manure and NPK 15:15:15 significantly increased tiger nut yield, improved soil nutrient content, and enhanced the nutritional quality of the nuts compared to the control and other treatments. Therefore, this combined fertilization approach is recommended for farmers as it effectively boosts both the yield and quality of tiger nuts, providing a sustainable option for soil fertility management.

Keywords: *Cyperus esculentus*, mineral composition, NPK 15:15:15, poultry manure, yield properties, soil chemical properties.

Introduction

Tiger nut (*Cyperus esculentus* L.) is a crucial root tuber crop widely cultivated for its versatility as a cash crop, its use in cereals, and its value as an oilseed, as well as for direct consumption across temperate and tropical regions, including Ghana, Nigeria, Sierra Leone, and Cameroon (Maduka & Ire, 2018). Belonging to the Cyperaceae family, this perennial, grass-like plant produces edible tubers that are highly prized for their rich nutritional content and adaptability to various culinary and industrial purposes (Sánchez-Zapata et al., 2012). Historically, tiger nuts have been cultivated for centuries, serving not only as a staple food but also as a medicinal ingredient in diverse cultures (Tadayyon, 2013).

Tiger nuts are nutritionally significant, containing high levels of dietary fiber, carbohydrates, protein, iron, calcium, oil, and other essential minerals (Adejunitan, 2011). However, concerns about global mineral malnutrition remain prevalent (Stein, 2010), especially since essential minerals largely come from plant-based sources (Gupta et al., 2014). In sub-Saharan Africa, including Ghana, soil infertility presents a significant challenge to agricultural productivity and crop nutrition (Chianu et al., 2012). To address this issue, farmers often resort to using expensive soil amendments such as organic and inorganic fertilizers to boost soil fertility and crop yields (Hammad et al., 2022).

Balancing the benefits of fertilization with cost-effectiveness and minimizing environmental impacts poses a significant challenge. Over-fertilization can diminish nutritional content, alter root development (Oliveira et al., 2005; Jennings, 2009), and cause environmental problems (Wu & Ge, 2019). Soil amendments, particularly organic options like poultry manure, are vital for improving plant health, growth, yield, and nutrient content (Antonangelo et al., 2021).

While inorganic fertilizers provide immediate nutrient availability (Iqbal et al., 2019), organic fertilizers like poultry manure release nutrients gradually through microbial decomposition (Geng et al., 2019). A combined approach, utilizing both organic and inorganic fertilizers, is essential for sustaining soil and crop productivity (Makinde et al., 2010), which in turn impacts the nutritional quality of the crops (Funda et al., 2011).

This study examines the effects of organic (poultry manure) and inorganic (NPK 15:15:15) fertilizers, both individually and in combination, on the growth, yield, soil properties, and nutritional content of Cyperus esculentus tubers. The insights gained from this research will contribute to food security, promote healthier diets, and enhance the nutritional value of tiger nuts, benefiting both human and animal health (Roy et al., 2006). These findings support ongoing efforts to optimize fertilizer practices for improved crop composition and quality (Souri & Hatamian, 2019). Understanding these interactions is vital for maintaining the nutritional and economic value of tiger nuts, which are crucial to the communities that depend on this important crop.

Results

Treatments' effect on yield and yield components

Table 1 and Supplementary Table 1 demonstrate that during the major season of 2019, the black variety produced larger nuts compared to the brown variety. However, no significant differences were observed between the varieties during the minor season of 2019 and the major season of 2020. Fertilizer application significantly ($p \leq 0.05$) influenced nut girth across all seasons. The combined treatment of poultry manure and NPK 15:15:15 produced the largest nut girth, while the control consistently resulted in the smallest nuts. The interaction between variety and fertilizer application was significant ($p \leq 0.05$), with different effects on nut girth across the seasons.

Fresh nut weight was also significantly affected ($p \leq 0.05$) by fertilizer application in all seasons. The combined application of poultry manure and NPK 15:15:15 consistently yielded the heaviest nuts, which were comparable to those produced by NPK 15:15:15 alone in the 2019 major season. The interaction between variety and fertilizer was significant, with the combined treatment leading to the best performance in both varieties, while the control consistently resulted in the lowest nut weight.

The application of both poultry manure and NPK 15:15:15 significantly improved the harvest index across all seasons, while the control treatment consistently had the lowest harvest index. Significant ($p \leq 0.05$) interactions were noted between variety and fertilizer application, with the combined treatment generally resulting in a higher harvest index for both the black and brown varieties.

The number of nuts per plant did not differ significantly ($p > 0.05$) between the varieties during the 2019 seasons. However, in the major season of 2020, the black variety produced significantly ($p \leq 0.05$) more nuts than the brown variety. Fertilizer application significantly impacted the number of nuts across all three seasons, with the combined treatment resulting in the highest nut yield and the control treatment the lowest. Neither poultry manure nor NPK 15:15:15 applied individually showed a significant difference ($p > 0.05$) compared to the control. The combined application was particularly effective for the black variety, consistently leading to the highest nut production across all seasons.

Total nut yield (tonnes per hectare) did not significantly differ between the varieties ($p > 0.05$). However, fertilizer application had a significant impact ($p \leq 0.05$) on total nut yield across all seasons, with the combined treatment consistently producing the highest yields. Significant interactions ($p \leq 0.05$) were observed between variety and fertilizer application, with the brown variety responding better to the combined mineral and organic fertilizers during both 2019 seasons, while the black variety performed best with the combined treatment in the 2020 major season. The control treatment consistently resulted in the lowest total nut yield for both varieties.

Soil chemical properties

The findings presented in Table 2 and Supplementary Table 2 indicate that there was no significant difference ($p > 0.05$) in soil exchangeable potassium levels between the two tiger nut varieties across all seasons. However, fertilizer application significantly affected ($p \leq 0.05$) exchangeable potassium levels in each of the three seasons. In the 2019 major season, all treatments with nutrient applications showed similar exchangeable potassium levels. However, during the 2019 minor and 2020 major seasons, the combined fertilizer treatment led to the highest exchangeable potassium levels, except when poultry manure was applied alone. Notably, the black variety under the control treatment exhibited the lowest exchangeable potassium levels in the 2019 minor and 2020 major seasons. The interaction between variety and fertilizer application significantly influenced exchangeable potassium levels in the 2019 minor and 2020 major seasons but had no significant effect in the 2019 major season.

Similarly, the results showed that soil exchangeable calcium levels did not significantly differ ($p > 0.05$) between the two tiger nut varieties throughout the study. However, fertilizer application had a significant impact ($p \leq 0.05$) on exchangeable calcium in all seasons. The combined treatment consistently resulted in the highest exchangeable calcium levels, while the control treatment had the lowest. Both poultry manure alone and NPK 15:15:15 alone resulted in higher mean exchangeable calcium levels than the control. Additionally, significant interactions ($p \leq 0.05$) between variety and fertilizer application were observed, suggesting that the effectiveness of the combined treatment varied depending on the tiger nut variety and the season.

The exchangeable magnesium content did not significantly differ ($p > 0.05$) between the tiger nut varieties across all seasons. However, fertilizer application significantly influenced ($p \leq 0.05$)

Table 1. Effect of fertilizers and tiger nut varieties on nut girth, fresh nut weight, harvest index, number of nuts per plant, and total nut yield.

	Nut girth (mm)			Fresh nut weight (g)			Harvest index		
Treatments	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS
Varieties									
Black	1.68±0.16[a]	1.50±0.11[a]	1.35±0.25[a]	46.91±10.40[a]	30.18±4.98[a]	28.16±4.32[a]	0.88±0.07[a]	0.47±0.06[a]	0.55±0.16[a]
Brown	1.55±0.16[b]	1.52±0.21[a]	1.45±0.20[a]	46.17±8.62[a]	31.71±7.15[a]	27.99±5.73[a]	0.84±0.10[a]	0.49±0.11[a]	0.50±0.15[a]
Fertilizers									
Control	1.43±0.14[b]	1.37±0.15[b]	1.18±0.12[c]	37.25±6.21[c]	24.60±3.22[c]	23.30±4.25[c]	0.80±0.12[b]	0.39±0.05[c]	0.41±0.18[b]
PM	1.55±0.10[b]	1.48±0.13[b]	1.48±0.10[b]	48.65±1.49[b]	32.52±2.23[b]	29.90±2.99[ab]	0.88±0.05[ab]	0.50±0.03[b]	0.58±0.11[ab]
NPK	1.68±0.08[a]	1.52±0.10[ab]	1.25±0.10[c]	41.90±6.62[bc]	28.15±2.25[c]	26.32±2.79[bc]	0.85±0.07[ab]	0.46±0.05[b]	0.50±0.13[ab]
PM+NPK	1.78±0.12[a]	1.67±0.14[a]	1.68±0.12[a]	58.35±7.23[a]	38.50±4.49[a]	32.78±4.11[a]	0.91±0.44[a]	0.60±0.06[a]	0.63±0.11[a]

	No. of nuts per plant			Total nut yield (ton ha^{-1})		
Treatments	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS
Varieties						
Black	71.95±30.33[a]	24.82±13.21[a]	44.45±21.14[a]	4.20±2.27[a]	1.38±0.90[a]	2.58±1.18[a]
Brown	68.25±30.97[a]	23.57±12.16[a]	39.63±19.46[a]	4.60±2.55[a]	1.46±1.04[a]	2.49±1.19[a]
Fertilizers						
Control	39.50±12.91[c]	11.37±1.33[c]	23.37±2.03[c]	2.17±0.92[c]	0.53±0.10[c]	0.77±0.08[c]
PM	69.37±23.19[b]	20.47±1.70[b]	35.10±6.62[b]	4.25±1.61[b]	1.25±0.08[b]	1.53±0.34[b]
NPK	65.63±26.59[b]	21.00±1.95[b]	35.63±4.29[b]	3.63±1.64[bc]	1.07±0.21[bc]	1.28±0.15[b]
PM+NPK	105.90±27.40[a]	43.93±3.01[a]	74.07±4.55[a]	7.55±1.02[a]	2.82±0.80[a]	3.65±0.48[a]

Averages with the same alphabet within a column are not significantly distinct at a 5% probability measure as determined by Tukey's test. 2019 MAS = 2019 Major Season, 2019 MIS = 2019 Minor Season and 2020 MAS = 2020 Major Season, PM = poultry manure, NPK = NPK 15:15:15, PM+NPK = combination of poultry manure and NPK 15:15:15.

exchangeable magnesium levels during the major seasons of 2019 and 2020.

The combined application of organic and inorganic fertilizers led to significantly higher ($p \leq 0.05$) exchangeable magnesium levels compared to other treatments during these seasons. Furthermore, significant interactions ($p \leq 0.05$) between variety and fertilizer application were noted, with the combined treatment applied to the black variety resulting in the highest exchangeable magnesium levels. Conversely, the control treatment for the brown variety exhibited the lowest exchangeable magnesium content during the major seasons of 2019 and 2020.

Regarding soil exchangeable sodium, the results showed no significant differences ($p > 0.05$) between the two tiger nut varieties. However, fertilizer application significantly affected ($p \leq 0.05$) soil exchangeable sodium throughout the study. The combined treatment of poultry manure and NPK 15:15:15 produced the highest soil exchangeable sodium values, while the control treatment had the lowest. Significant interactions ($p \leq 0.05$) were also observed between variety and fertilizer application, with the combined treatment showing varying effects on exchangeable sodium across different seasons for each variety.

For soil exchangeable hydrogen, the variety of tiger nuts did not have a significant effect ($p > 0.05$), but fertilizer treatments significantly impacted ($p \leq 0.05$) exchangeable hydrogen levels in all three seasons. The highest levels of soil exchangeable hydrogen were observed with the combined fertilizer application, while the control treatment had the lowest. Significant interactions ($p \leq 0.05$) between variety and fertilizer treatments were noted for exchangeable hydrogen in all seasons.

Soil exchangeable aluminum levels were not significantly influenced ($p > 0.05$) by the variety of tiger nuts, but fertilizer application had a significant impact ($p \leq 0.05$). The combined treatment consistently led to the highest soil exchangeable aluminum levels, while the control treatment showed the lowest values. In specific seasons, significant differences ($p \leq 0.05$) were found among the fertilizer treatments, with the combined treatment generally outperforming others. Additionally, significant interactions ($p \leq 0.05$) between variety and fertilizer application were observed, with the combined treatment producing the highest exchangeable aluminum levels across all varieties and seasons.

Tiger nut mineral content

In Table 3 and Supplementary Table 3, the analysis revealed no significant variation ($p > 0.05$) in phosphorus content between the two tiger nut varieties. However, phosphorus content varied significantly ($p \leq 0.05$) across all fertilizer treatments in all seasons. The highest phosphorus levels were consistently observed with the combined application of fertilizers, except when poultry manure was used alone. Throughout the study, the black variety consistently exhibited higher phosphorus content, while the control groups of both varieties and certain fertilizer treatments had the lowest phosphorus levels in specific seasons. During the major season of 2019, the black variety demonstrated higher potassium content than the brown variety. Fertilizer application significantly influenced ($p \leq 0.05$) potassium content across all seasons. The combined treatment consistently resulted in the highest potassium content in all three seasons for the black variety, whereas the control group of the brown variety recorded the lowest potassium levels.

Table 2. Effect of fertilizers and tiger nut varieties on soil exchangeable potassium, exchangeable calcium, exchangeable magnesium, exchangeable sodium, exchangeable hydrogen, and exchangeable aluminum.

		Potassium (cmol kg^{-1})			Calcium (cmol kg^{-1})			Magnesium (cmol kg^{-1})	
Treatments	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS
Varieties									
Black	0.82±0.18^{a}	0.58±0.13^{a}	0.50±0.11^{a}	14.54±4.19^{a}	9.27±2.86^{a}	10.30±1.57^{a}	5.40±2.16^{a}	3.12±1.71^{a}	4.91±1.83^{a}
Brown	0.82±0.16^{a}	0.64±0.08^{a}	0.55±0.11^{a}	13.14±3.03^{a}	8.82±2.01^{a}	10.09±2.05^{a}	4.38±2.47^{a}	4.26±2.02^{a}	4.17±2.29^{a}
Fertilizers									
Control	0.67±0.10^{b}	0.52±0.10^{c}	0.43±0.09^{c}	9.47±1.28^{c}	6.27±0.90^{c}	8.21±0.09^{c}	3.00±1.51^{b}	3.14±1.58^{a}	2.72±1.39^{b}
PM	0.82±0.12^{ab}	0.65±0.08^{ab}	0.56±0.09^{ab}	15.04±2.59^{b}	9.49±1.44^{b}	10.46±0.09^{b}	4.72±2.03^{b}	3.66±2.04^{a}	4.48±1.77^{b}
NPK	0.81±0.16^{ab}	0.56±0.11^{bc}	0.49±0.09^{bc}	12.96±1.93^{b}	8.58±1.61^{b}	9.69±0.09^{b}	4.30±2.04^{b}	3.47±1.84^{a}	4.07±1.83^{b}
PM+NPK	0.97±0.13^{a}	0.71±0.07^{a}	0.63±0.08^{a}	17.86±2.05^{a}	11.83±1.63^{a}	12.42±0.08^{a}	7.56±1.05^{a}	4.50±2.39^{a}	6.88±0.55^{a}
		Sodium (cmol kg^{-1})			Hydrogen (cmol kg^{-1})			Aluminum (cmol kg^{-1})	
Treatments	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS
Varieties									
Black	0.29±0.07^{a}	0.22±0.05^{a}	0.19±0.04^{a}	0.40±0.06^{a}	0.50±0.07^{a}	0.30±0.08^{a}	0.27±0.06^{a}	0.34±0.06^{a}	0.24±0.04^{a}
Brown	0.30±0.08^{a}	0.21±0.04^{a}	0.19±0.04^{a}	0.41±0.07^{a}	0.49±0.07^{a}	0.30±0.08^{a}	0.28±0.06^{a}	0.31±0.05^{a}	0.25±0.04^{a}
Fertilizers									
Control	0.21±0.01^{d}	0.17±1.58^{c}	0.14±0.01^{d}	0.34±0.03^{c}	0.42±0.02^{c}	0.22±0.03^{c}	0.21±0.02^{d}	0.27±0.02^{c}	0.20±0.01^{d}
PM	0.26±0.04^{b}	0.23±2.04^{b}	0.21±0.01^{b}	0.42±0.04^{b}	0.52±0.03^{b}	0.33±0.04^{b}	0.29±0.01^{b}	0.35±0.04^{ab}	0.26±0.02^{b}
NPK	0.33±0.01^{c}	0.20±1.84^{bc}	0.17±0.01^{b}	0.38±0.04^{bc}	0.46±0.03^{c}	0.25±0.03^{c}	0.25±0.03^{c}	0.31±0.03^{bc}	0.22±0.02^{b}
PM+NPK	0.40±0.01^{a}	0.27±2.39^{a}	0.24±0.01^{a}	0.49±0.03^{a}	0.58±0.06^{a}	0.40±0.03^{a}	0.34±0.03^{a}	0.39±0.04^{a}	0.30±0.01^{a}

Averages with the same alphabet within a column are not significantly distinct at a 5% probability measure as determined by Tukey's test. 2019 MAS = 2019 Major Season, 2019 MIS = 2019 Minor Season and 2020 MAS = 2020 Major Season, PM = poultry manure, NPK = NPK 15:15:15, PM+NPK = combination of poultry manure and NPK 15:15:15.

Notably, there were significant interactions ($p \leq 0.05$) between variety and fertilizer application concerning potassium content.

No significant differences ($p > 0.05$) were observed in calcium content between the two varieties across the three seasons. However, in the minor season of 2019, the combined treatment of poultry manure and NPK 15:15:15 significantly increased calcium content ($p \leq 0.05$) compared to other treatments, except for poultry manure alone. In the 2019 and 2020 major seasons, NPK 15:15:15 alone exhibited calcium content comparable to that of poultry manure and the control. The control treatment consistently resulted in the lowest calcium content across all treatments. Additionally, significant interactions ($p \leq 0.05$) were noted between variety and fertilizer application during the 2019 minor season. The combined treatment on the black variety yielded the highest calcium content, while the control treatment on the brown variety produced the lowest. These findings underscore the impact of fertilizer combinations and variety on calcium content in tiger nuts.

Magnesium content was similar between the two varieties across all three seasons. In the major seasons of 2019 and 2020, magnesium content in tiger nuts did not significantly vary among different fertilizer treatments. However, during the 2019 minor season, significant differences ($p \leq 0.05$) in magnesium content were observed among fertilizer treatments. The combined application of poultry manure and NPK 15:15:15 resulted in similar magnesium content to other treatments, excluding the control. Notably, NPK 15:15:15 alone led to the highest magnesium content, while the control treatment had the lowest. There were no significant interactions ($p > 0.05$) between variety and fertilizer application concerning magnesium content throughout the study.

Sodium content remained similar between the two varieties across all seasons. Fertilizer treatments had a significant impact ($p \leq 0.05$) on sodium content during the 2019 major season, with the control group showing a marked difference ($p \leq 0.05$) from the nutrient-applied treatments. Overall, nutrient-applied treatments improved the sodium content of tiger nuts compared to the control. Significant interactions ($p \leq 0.05$) between variety and fertilizer application were observed in the major seasons of 2019 and 2020. The highest sodium content was recorded with the combined application of poultry manure for the brown variety and NPK 15:15:15 for the black variety. The control group produced the lowest sodium content in the 2019 major season, while the control of both varieties recorded the lowest sodium levels in the 2020 major season.

No significant differences ($p > 0.05$) in iron content were found between the two varieties. However, fertilizer application significantly affected iron content ($p \leq 0.05$) across all seasons. The highest iron content was consistently observed in tiger nuts treated with the combined fertilizer application, while the control group had the lowest. Significant interactions were noted between variety and fertilizer application, with the brown variety showing the highest iron content in the 2019 major and minor seasons, and the black variety having the highest iron content in the 2020 major season.

In Table 4 and Supplementary Table 4, the analysis showed no significant differences ($p > 0.05$) in manganese content between the varieties. However, fertilizer treatments significantly affected ($p \leq 0.05$) manganese content throughout the study. The highest manganese content was observed with the combined application of poultry manure and NPK 15:15:15, while the control group recorded the lowest. Significant

Table 3. Effect of fertilizers and tiger nut varieties on phosphorus, potassium, calcium, magnesium, sodium, and iron contents of tiger nuts.

		Phosphorus content (%)			Potassium content (%)			Calcium content (%)	
Treatments	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS
Varieties									
Black	0.16±0.03^{a}	0.21±0.06^{a}	0.16±0.04^{a}	1.10±0.18^{a}	1.42±0.24^{a}	1.06±0.19^{a}	0.33±0.13^{a}	0.30±0.12^{a}	0.31±0.13^{a}
Brown	0.17±0.03^{a}	0.17±0.03^{b}	0.15±0.03^{a}	0.94±0.11^{a}	1.23±0.23^{a}	0.96±0.23^{a}	0.31±0.09^{a}	0.25±0.08^{a}	0.27±0.06^{a}
Fertilizers									
Control	0.13±0.02^{b}	0.15±0.03^{b}	0.12±0.02^{b}	0.96±0.10^{b}	1.10±0.10^{b}	0.78±0.07^{b}	0.25±0.08^{a}	0.19±0.07^{c}	0.27±0.08^{a}
PM	0.20±0.02^{a}	0.22±0.03^{a}	0.19±0.01^{a}	1.17±0.13^{a}	1.47±0.30^{a}	1.20±0.15^{a}	0.38±0.09^{a}	0.32±0.11^{ab}	0.24±0.10^{b}
NPK	0.15±0.02^{b}	0.16±0.03^{b}	0.13±0.02^{b}	0.95±0.09^{b}	1.24±0.13^{ab}	0.94±0.09^{b}	0.29±0.10^{a}	0.24±0.08^{bc}	0.26±0.10^{a}
PM+NPK	0.19±0.02^{a}	0.22±0.05^{a}	0.18±0.02^{a}	1.09±0.16^{a}	1.48±0.21^{a}	1.14±0.19^{a}	0.37±0.12^{a}	0.36±0.08^{a}	0.33±0.10^{a}
		Magnesium content (%)			Sodium content (%)			Iron content (mg kg^{-1})	
Treatments	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS
Varieties									
Black	0.13±0.10^{a}	0.13±0.03^{a}	0.12±0.07^{a}	0.03±0.01^{a}	0.03±0.01^{a}	0.03±0.01^{a}	230.38±85.34^{a}	117.60±40.77^{b}	176.04±61.85^{a}
Brown	0.12±0.05^{a}	0.12±0.03^{a}	0.12±0.04^{a}	0.03±0.01^{a}	0.03±0.01^{a}	0.03±0.01^{a}	231.97±110.82^{a}	146.14±21.6^{a}	158.53±62.26^{a}
Fertilizers									
Control	0.09±0.04^{a}	0.10±0.22^{b}	0.08±0.03^{a}	0.02±0.00^{b}	0.03±0.01^{a}	0.02±0.00^{a}	167.02±28.65^{b}	100.03±25.27^{c}	116.33±19.44^{c}
PM	0.14±0.07^{a}	0.13±0.03^{ab}	0.13±0.05^{a}	0.04±0.01^{a}	0.03±0.01^{a}	0.04±0.01^{a}	226.03±46.48^{b}	136.12±30.40^{b}	176.10±46.61^{b}
NPK	0.15±0.11^{a}	0.14±0.03^{a}	0.14±0.08^{a}	0.04±0.01^{a}	0.03±0.01^{a}	0.04±0.01^{a}	176.90±38.12^{b}	123.40±23.75^{bc}	135.20±27.28^{bc}
PM+NPK	0.14±0.06^{a}	0.14±0.02^{a}	0.13±0.05^{a}	0.04±0.01^{a}	0.03±0.01^{a}	0.04±0.01^{a}	354.73±108.54^{a}	167.93±25.60^{a}	241.50±54.44^{a}

Averages with the same alphabet within a column are not significantly distinct at a 5% probability measure as determined by Tukey's test. 2019 MAS = 2019 Major Season, 2019 MIS = 2019 Minor Season and 2020 MAS = 2020 Major Season, PM = poultry manure, NPK = NPK 15:15:15, PM+NPK = combination of poultry manure and NPK 15:15:15.

Table 4. Effect of fertilizers and tiger nut varieties on manganese, copper, and zinc contents of tiger nut.

		Manganese content (mg kg^{-1})			Copper content (mg kg^{-1})			Zinc content (mg kg^{-1})	
Treatments	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS	2019 MAS	2019 MIS	2020 MAS
Varieties									
Black	23.70±6.54^{a}	21.62±6.91^{a}	19.53±2.83^{a}	34.71±11.55^{a}	34.44±6.49^{a}	25.03±5.57^{a}	28.85±5.52a	32.98±3.46a	24.35±3.66a
Brown	22.10±3.98^{a}	29.95±3.80^{b}	19.33±3.40^{a}	34.39±12.96^{a}	32.80±9.78^{a}	22.31±5.99^{a}	30.59±6.28a	33.10±7.51a	24.94±4.02a
Fertilizers									
Control	17.48±2.51^{c}	17.08±4.02^{b}	15.64±1.41^{b}	26.33±4.48^{b}	22.88±2.61^{c}	18.68±2.83^{b}	23.02±4.85b	29.80±3.22b	20.11±2.84c
PM	24.37±4.67^{ab}	24.91±5.98^{ab}	19.84±2.61^{a}	35.34±9.87^{ab}	34.41±4.24^{b}	23.88±5.38^{ab}	29.84±3.41a	33.28±1.51ab	24.32±2.39b
NPK	21.11±2.77^{bc}	20.44±3.98^{b}	20.19±2.40^{a}	29.22±7.90^{b}	33.61±2.86^{b}	24.61±6.10^{ab}	31.56±3.84a	31.69±4.85ab	25.54±1.94ab
PM+NPK	28.64±3.86^{a}	40.71±6.06^{a}	22.05±1.49^{a}	47.31±13.11^{a}	43.58±3.92^{a}	27.51±5.78^{a}	34.47±4.75a	37.40±8.76a	28.61±1.83a

Averages with the same alphabet within a column are not significantly distinct at a 5% probability measure as determined by Tukey's test. 2019 MAS = 2019 Major Season, 2019 MIS = 2019 Minor Season and 2020 MAS = 2020 Major Season, PM = poultry manure, NPK = NPK 15:15:15, PM+NPK = combination of poultry manure and NPK 15:15:15.

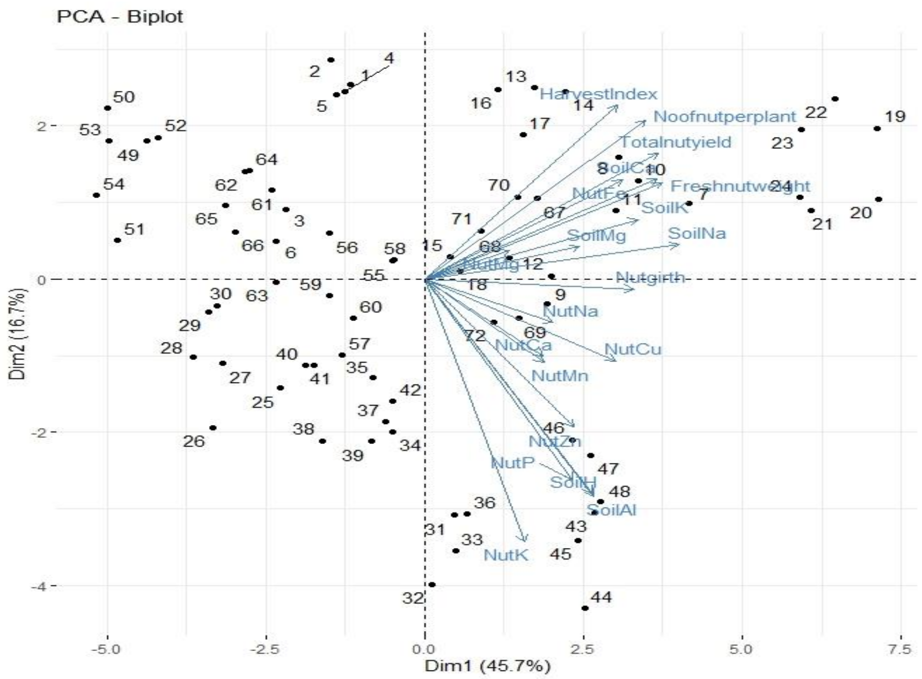

Figure 1. Principal component analysis (PCA) biplot distribution of the 20 variables in the season.

interaction effects were noted, with the combined treatment yielding the highest manganese content in both the 2019 and 2020 major seasons for the black variety.

Copper content did not significantly vary (p > 0.05) between the two varieties across all seasons. However, fertilizer application had a significant influence (p ≤ 0.05) on copper content throughout the study. The highest copper content was observed with the combined treatment of poultry manure and NPK 15:15:15, while the control group consistently showed the lowest levels. In the major season of 2019, the combined treatment was significantly different from most other treatments. During the minor season of 2019, the combined treatment differed significantly from other fertilizer treatments, with poultry manure alone and NPK 15:15:15 alone showing similar copper content, which was not significantly different from the control (p > 0.05). In the major season of 2020, the combined treatment had similar copper content to other treatments, except the control. Significant interactions (p ≤ 0.05) were also observed between variety and fertilizer application for copper content during the minor season of 2019, where the combined application to the brown variety resulted in the highest copper content.

Zinc content did not show significant variation (p > 0.05) between the two tiger nut varieties. However, it differed significantly with fertilizer treatments across all seasons. The combined application of poultry manure and NPK 15:15:15 resulted in the highest zinc content, while the control group had the lowest. In the 2019 major season, the control group showed significantly lower zinc content (p ≤ 0.05) compared to other treatments. During the 2019 minor season, the control was similar to fertilizer-applied treatments, except for the combined treatment. In the 2020 major season, the combined treatment had significantly higher zinc content (p ≤ 0.05) compared to other treatments, except for NPK 15:15:15 alone. Significant interactions (p ≤ 0.05) between variety and fertilizer application were observed in the 2020 major season, with the combined treatment on the brown variety showing the highest zinc content, while the control group of the black variety had the lowest levels.

Principal component analysis

The PCA analysis was performed to explore the relationships among 20 parameters, including soil nutrients, nut nutrient composition, and yield parameters. The results revealed that the first principal component (PC1) accounted for 45.72% of the total variance, indicating that it captured the largest amount of variation in the dataset. PC2 explained an additional 16.67% of the variance, followed by PC3 (7.52%) and PC4 (6.90%). Together, these four components accounted for 76.81% of the total variance. The variable loadings on each principal component provided insights into the relationships between the variables and the components. In PC1, several variables related to soil nutrients (K, Ca, Mg, Na, Al, and H), nut nutrient composition (P, K, Ca, Fe, Mn, Cu, and Zn), and agronomic parameters (Fresh nut weight, Nut girth, Harvest Index, Number of nuts per plant, Total nut yield) showed positive loadings, indicating their positive contribution to PC1. PC2 was positively associated with soil nutrients (Al, and H), nut nutrient composition (P, K, Ca, Na, Mn, Cu, and Zn), and nut girth. PC3 exhibited positive associations with soil nutrients (Al, and H), nut nutrient composition (K, Mg, Mn, Cu, and Zn), and agronomic parameters (Nut girth, Harvest Index, Number of nuts per plant). Similarly, PC4 showed positive associations with soil nutrients (Ca, and Mg), nut nutrient composition (P, K, Mg, Na, Fe, and Zn), and the number of nuts per plant (Table 5).

The PCA biplot visually represented the ordination of the 20 parameters in a Cartesian coordinate system. It provided a clear visualization of the contribution of each

Table 5. Eigenvalues and variance percentages of the principal component analysis (PCA) of twenty (20) parameters.

Principal components	PC 1	PC 2	PC 3	PC 4
Eigenvalue	9.143	3.334	1.504	1.381
Percentage variance	45.72	16.67	7.25	6.90
Cumulative percentages	45.72	62.39	69.91	76.81
Eigenvectors/loadings				
Soil K	0.79056	-0.18370	-0.02519	-0.29170
Soil Ca	0.86059	-0.30698	-0.02273	0.03573
Soil Mg	0.57357	-0.09901	-0.04418	0.50443
Soil Na	0.94125	-0.10580	-0.04730	-0.05295
Soil Al	0.62625	0.66796	0.10479	-0.06648
Soil H	0.61900	0.65869	0.15840	-0.10360
Nut P	0.54814	0.61658	-0.22758	0.22542
Nut K	0.36837	0.80703	0.03962	0.16366
Nut Ca	0.43904	0.23767	-0.74789	-0.10487
Nut Mg	0.31525	-0.08818	0.78682	0.37998
Nut Na	0.47473	0.13290	-0.09219	0.63436
Nut Fe	0.73251	-0.30463	-0.31298	0.16273
Nut Mn	0.44101	0.25472	0.23520	-0.45209
Nut Cu	0.70843	0.25095	0.22239	-0.28965
Nut Zn	0.55045	0.45561	0.01873	0.01506
Fresh nut weight	0.87867	-0.29678	-0.00282	-0.19268
Nut girth	0.77390	0.03088	0.09847	-0.09558
HarvestIndex	0.71410	-0.53453	0.09469	-0.09943
Noofnutperplant	0.81700	-0.48862	0.01734	0.12358
Totalnutyield	0.86569	-0.38711	-0.02072	-0.00256

Eigenvalues greater than 1 were selected to represent the PCA analysis.

variable to the total variation. The biplot indicated that the first axis (Dim1) accounted for 45.7% of the total variation, while the second axis (Dim2) explained an additional 16.7% of the variation. Figure 1 shows the PCA biplot, displaying the relationships and contributions of the variables to the total variations observed in the dataset.

Discussion

The application of treatments significantly enhanced nut yield (tonnes per hectare) compared to the control across all three trial seasons. The improved fertility likely increased leaf area and chlorophyll content, thereby boosting photosynthesis and carbohydrate production in seeds (Bukhari et al., 2020). Fertilizer treatments also enhanced plant metabolism and auxin activity, leading to higher yields. Additionally, poultry manure improved the soil's physical, chemical, and biological properties, enhancing growth metrics and yield characteristics (Agbade et al., 2017). The effectiveness of manure in boosting yields may stem from its ability to enhance respiration, increase cell permeability through hormone synthesis, or integrate these mechanisms.

These findings are consistent with Singh et al. (2012), who observed higher garlic yields with organic manure and mineral fertilizer. Similarly, Timon et al. (2019) reported improved yields with poultry manure, NPK 15:15:15, and cattle dung. Thalooth et al. (2015) also found that combining organic and synthetic fertilizers significantly boosted onion yields.

The combination of poultry manure and NPK 15:15:15 fertilizer notably altered the soil's mineral content, yielding the highest magnesium levels in 2019 and 2020. Sodium content peaked in the 2019 minor season with either poultry manure alone or combined with NPK and in the 2020 major season with the combined treatment. Calcium levels influenced by all treatments consistently exceeded the control. Naramabuye et al. (2008) similarly reported increases in sodium, calcium, and magnesium concentrations with the combined application of poultry manure and NPK fertilizer. The rise in exchangeable cations (Ca and Na) can be attributed to the nutrient-rich organic matter's negative charge released into the soil (Soremi et al., 2017). This aligns with Chukwu et al. (2012), who found that both organic and chemical fertilizers increased exchangeable calcium and magnesium in the soil. Olatunji et al. (2012) also observed higher calcium content in plots treated with poultry manure and NPK across two crop cycles.

The highest exchangeable potassium values were recorded in plots treated with the combined poultry manure and NPK 15:15:15. The decomposition of manure adds exchangeable cations to the soil, enhancing its properties and increasing nitrogen, phosphorus, and potassium availability. This increase in exchangeable potassium aligns with findings by Islam et al. (2013) and Verma et al. (2005). Adeniyan et al. (2011) also noted an increase in soil potassium with the combined application of poultry manure and NPK fertilizer. Other studies (Olatunji et al., 2012; Islam et al., 2013) also emphasize the significant impact of poultry manure and NPK 15:15:15 on soil mineral composition, ultimately improving agricultural productivity.

Phosphorus (P) and potassium (K) levels in tiger nut tubers increased significantly with the combination of poultry manure and NPK 15:15:15. This can be attributed to optimal nutrient uptake and the absence of competitive interactions, leading to a balanced soil nutrient profile (Das and Teng, 2000). The increased mineral availability was further enhanced by chelate formation with micronutrients present in poultry manure (Ayeni & Adetunji, 2010). These findings align with Yaduvanshi (2003), who reported higher P and K concentrations in peanut kernels after applying poultry manure and NPK 15:15:15.

All fertilizer treatments significantly increased sodium (Na) content in the 2019 major season, consistent with Sultana et al. (2014) in onion bulbs. Manihot esculenta also showed significantly higher Na content after poultry manure fertilization (Odedina et al., 2011). However, unlike Yaduvanshi (2003), who observed increased magnesium levels in peanuts, the magnesium content in tiger nuts did not show significant changes in response to treatments. Contrary to other studies that reported higher calcium levels with combined organic and chemical fertilizers (Ncayiyana et al., 2018; Yoldas et al., 2011), calcium concentration in tiger nuts was not significantly affected by fertilizer treatments. Soil acidity in the 2019 minor season may have hindered calcium absorption (Camberato and Mitchell, 2011).

Iron (Fe), manganese (Mn), and copper (Cu) content in tiger nuts increased with the combined application of poultry manure and NPK 15:15:15, facilitating optimal nutrient uptake (Das, 2000). Ayeni and Adetunji (2010) noted that poultry manure's organic matter enhanced micronutrient availability, corroborating Coolong et al.'s (2005) findings in onions. Ayeni et al. (2008) similarly reported increased Fe, Mn, and Cu content in maize with poultry manure application. Zinc (Zn) content in tiger nuts increased in response to fertilizer treatments during both the 2019 and 2020 seasons, particularly under the combined poultry manure and NPK 15:15:15 treatment, consistent with Ayeni et al.'s (2008) findings in maize.

Materials and methods

Location of research

Field trials were conducted during the 2019 major and minor seasons, as well as the 2020 major season, at the Centre for Agricultural Technology, Research and Production (CATReP), University of Energy and Natural Resources (UENR), Ghana. This campus is located between latitudes 7° and 7° 30' North and longitudes 3° and 3° 30' West, within the forest-savanna transition zone. The soil in this area is classified as Acrisol, which is characterized by acidity, low nutrient content, high clay composition, and susceptibility to erosion and leaching (Manu et al., 2022; Nketia et al., 2018). The soil type, identified as sandy loam (Table 1), corresponds to Ghana's major (April-July) and minor (August-November) farming seasons. Rainfall and temperature patterns are shown in Supplementary Figure 1 (Koffi et al., 2020). The major farming season, from April to July, features heavy and consistent rainfall, which is ideal for cultivating water-intensive crops such as maize and yams—key crops for food security (Asamoah and Ansah-Mensah, 2020). The minor season, from August to November, is marked by less frequent and unpredictable rainfall, making it suitable for shorter-cycle crops like vegetables, which remain important for agriculture despite the reduced precipitation (Cudjoe et al., 2021).

Preliminary soil and poultry manure analysis

Before the first planting season, an initial soil sampling was conducted to assess the chemical properties of the field. Soil samples were collected randomly from a 0-15 cm depth using a nested plot method, then air-dried, crushed, and sieved through a 2-mm mesh for laboratory analysis. Poultry manure sourced from university farms was also subjected to nutritive analysis (Table 6). The results indicated that the soil was a slightly alkaline sandy loam (pH 7.46) with low levels of organic carbon (2.50%), organic matter (4.31%), and total nitrogen (0.38%), which are considered poor by Landon's standards (2014).

Experimental design and treatments

The experiment was laid out in a randomized complete block design with a 2x4 factorial arrangement, replicated three times. The treatments consisted of two tiger nut varieties (black and brown) and four fertilizer levels: 2,000 kg ha^{-1} poultry manure, 300 kg ha^{-1} NPK 15:15:15, 1,000 kg ha^{-1} poultry manure combined with 150 kg ha^{-1} NPK 15:15:15, and a control. The trials, conducted in 2019 and 2020 on land that had been fallow for four years, involved planting tiger nut seeds provided by Kofi Vanyo Company. The seeds were soaked for 72 hours before being planted in 3m x 3m plots with a spacing of 0.6m x 0.3m. Fertilizers were applied two weeks after planting, with manual weeding carried out as needed, and harvesting took place three months post-planting. The fertilizers used were NPK 15:15:15 at 300 kg ha^{-1} and poultry manure at 2,000 kg ha^{-1}.

Data collection

Yield and yield components

Harvest index (HI) = $\frac{Economic\ yield}{Biological\ yield}$, (Equ. 1)

where the economic index = weight of seeds and biological yield = total dry weight

(ii) Yield in tonnes per hectare: The oven-dried tiger nut tubers were converted into tons/ha.

Thus, Nut yield in tons ha^{-1} = $\frac{Yield/plot}{Plot\ size} \times 0.001$ (Equ. 2)

(iii) Number of nuts: Number of nuts = $\frac{\text{Total number of nuts from 5 plants}}{5}$ (Equ. 3)

(iv) Nut Fresh weight: Twenty nuts, randomly selected from five tagged plants after harvest, were weighed individually using a top-scale balance. Their total weight was averaged per treatment.

Nut Fresh Weight = $\frac{\text{(Sum of Fresh Weights of 20 Nuts)}}{20}$ (Equ. 4)

(v) Nut size: Twenty nuts from each of the five tagged plants were randomly chosen post-harvest. Nut size was measured along the vertical axis using a caliper. Sizes were summed and then averaged per experimental unit.

Average Nut Size = $\frac{\text{(Sum of 20 nut sizes)}}{20}$ (Equ. 5)

Soil chemical properties

To determine the concentrations of exchangeable bases (Mg^{2+}, Ca^{2+}, Na^{+}, K^{+}) and exchangeable acidity, a 1.0M Ammonium Acetate solution at pH 7.0 was used for the extraction process. The concentrations of calcium and magnesium ions were quantified using complexometric

Table 6. Initial soil and poultry manure analysis.

Soil Properties	Values
Chemical properties	
pH (1:2.5, H_2O)	7.46
Organic carbon (%)	2.50
Organic matter (%)	4.31
Total nitrogen (%)	0.38
Phosphorus (%)	0.12
Exchangeable cations (Cmol/kg)	
Potassium	0.88
Calcium	11.93
Magnesium	4.26
Sodium	0.18
Effective cation exchange capacity (Cmol/kg/Me/100g)	17.35
Poultry Manure	
Nitrogen (%)	2.16
Phosphorus (%)	0.32
Potassium (%)	0.98

titration with EDTA, employing a cal red indicator specifically for calcium and an erichrome black T indicator for the combined calcium and magnesium ions. The magnesium concentration was then calculated by subtracting the calcium concentration from the combined total. Flame photometry was utilized to measure the concentrations of potassium and sodium ions in the extract (Motsara and Roy, 2006).

For the extraction of exchangeable acidity, a 1N KCl solution was used, while the determination of hydrogen and aluminum ions involved titration with 0.025M NaOH, with phenolphthalein as the indicator. Sodium fluoride was added during the process, and the concentration of H^+ ions was subsequently determined (McLean, 1965).

Total potassium content was determined through HF-H_2SO_4 digestion (Jackson, 1964). Water-soluble potassium was extracted by shaking 2 g of soil with 20 mL of distilled water, while exchangeable potassium was obtained using 20 mL of 1.0 M NH_4OAc at pH 7.0. The non-exchangeable potassium fraction was extracted with 1N boiling HNO_3, using a 1:10 soil-to-solution ratio (Haylock, 1956). All forms of potassium were quantified using flame photometry (Motsara and Roy, 2006).

Mineral composition of tiger nut

Sample processing: Tiger nut samples were harvested 90 days after sowing, thoroughly washed with distilled water, and oven-dried at 105°C. The dried samples were then milled using a Fritsch pulverisette 141 Rotor-Speed mill and stored in labeled air-tight zip bags for subsequent mineral composition analysis.

Laboratory analysis

The samples were digested using a mixture of salicylic acid, concentrated sulphuric acid, hydrogen peroxide, and a selenium catalyst. The digestion solution was prepared by mixing 3.5 g of selenium acid with 1000 mL of sulphuric acid, which was then heated to 300°C until it turned light yellow. A total of 7.2 g of salicylic acid was added to 100 mL of the selenium-sulphuric acid mixture. A 0.3 g sample was combined with 2.5 mL of the digestion solution and heated at 110°C for 1 hour. Hydrogen peroxide was then added, and the mixture was reheated at 330°C until it became pale yellow or colorless. After cooling, 50 mL of distilled water was added to the solution. The levels of P, Ca, Mg, Na, K, Zn, Cu, Fe, and Mn were measured using a Unicam Solaar Atomic Absorption Spectrophotometer (AAS) at specific wavelengths: 766.5 nm, 589.0 nm, 285.2 nm, 422.7 nm, 324.8 nm, 279.5 nm, 213.9 nm, and 248.3 nm. Total phosphorus was assessed using the ascorbic acid blue color method, with measurements taken at 880 nm using a Helios Gamma spectrophotometer (Thermo Spectronic; Helios Gamma, UK) (Okalebo et al., 2002).

Data analysis

The R software package (2010) was used to analyze the variance of the parameters. Using the Least Significant Difference with a 5 % probability, the means were differentiated.

Conclusion

The study revealed that applying both organic (poultry manure) and inorganic (NPK 15:15:15) fertilizers had a significant impact on the growth, yield, soil properties, and nutritional quality of Cyperus esculentus tubers. When used alone, poultry manure enhanced soil fertility by increasing organic matter, improving soil structure, and boosting microbial activity, which supported steady plant growth and development. On the other hand, NPK fertilizer, being rich in readily available nutrients, accelerated plant growth and significantly increased tuber yield. Interestingly, the combined use of poultry manure and NPK fertilizer produced the most notable results, surpassing the effects of either treatment used independently. This integrated approach not only optimized plant growth and tuber yield but also enriched soil health and improved the tubers' nutritional content by elevating essential nutrient levels. Consequently, the combined application of organic and inorganic fertilizers is recommended for achieving the best outcomes in Cyperus esculentus cultivation, ensuring high yield and sustainable soil management.

Acknowledgment

The authors extend their sincere appreciation to the technicians at the Centre for Agricultural Technology, Research, and Production, University of Energy and Natural Resources, Dormaa Ahenkro Campus, for their invaluable expertise and support in setting up the experiment and collecting data.

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