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Poultry manure improves soil properties and grain mineral composition, maize productivity and economic profitability

Taiwo Michael Agbede

Research information on poultry manure's impact on soil characteristics, mineral composition and maize performance is scarce, despite the vital role nutrient levels play in supporting human health. The objective of this study was to examine the effects of poultry manure on soil properties, grain mineral content, growth, grain yield and economic benefit of maize. A two-year field experiment (2022–2023) was conducted at the Teaching and Research Farm of Adekunle Ajasin University, Akungba-Akoko, Ondo State using five poultry manure levels (0, 5, 10, 15, and 20 t ha^{-1}) in a randomized complete block design with three replications. Poultry manure significantly reduced soil bulk density and improved porosity, moisture content, chemical properties, and grain mineral composition. Maize growth and yield increased with higher manure levels, but the 10 t ha^{-1} treatment produced the best outcomes, offering comparable nutritional quality and yield to the 15 and 20 t ha^{-1} treatments. Relative to the control, grain yield increased by 54.6%, 94.6%, 93.5%, and 91.4% for 5, 10, 15, and 20 t ha^{-1} treatments, respectively. The 10 t ha^{-1} application rate was the most cost-effective and beneficial for improving soil properties and maize productivity, as indicated by the benefit-to-cost ratio. This study recommended the use of 10 t ha^{-1} poultry manure for soil fertility management, sustainable nutrition, and enhanced maize performance in the study area. The findings highlight poultry manure's potential to improve soil properties, maize yield, and nutrient content, contributing to better human nutrition in areas with depleted soils.

Soil degradation and poor soil fertility management practices are the major factors underlying poor agricultural productivity and its attendant low nutritional qualities of most crops in sub-Saharan Africa[1]. Severely degraded land is a major challenge that threatens the productivity and sustainability of crops worldwide, as a result of repeated use of the same land for cultivation[2]. It has been reported that excessive use of synthetic fertilizers may lead to degradation of soil organic matter, nutrient imbalance, soil acidification and environmental pollution[3,4]. Prolonged and exclusive use of chemical fertilizers can harm soil health by depleting organic matter, causing soil compaction, reducing water infiltration and retention, and contaminating natural resources[5–7]. Chen[8] also observed that excessive use of chemical fertilizer without the addition of manure can result in nutrient depletion, extreme pH levels, and contamination of soil and groundwater. Moreover, the continuous and excessive application of chemical fertilizers has been shown to diminish the growth, yield, and nutritional quality of many crops[9].

Maize is a major staple food crop grown in diverse agro-ecological zones and farming systems, and consumed by people with varying food preferences and socio-economic backgrounds in sub-Saharan Africa (SSA)[10]. It is a healthy carbohydrate source, and the cereal crop is acknowledged with "antioxidants" activity[10]. Maize contains essential minerals such as phosphorus, magnesium, and zinc. These minerals are vital for bone health, enzyme function, and immune system support. Maize is generally used for animal feed. It is widely processed into various types of products such as cornmeal, grits, starch, flour, tortillas, snacks, and breakfast cereals[10]. Maize flour is used to make chapatis or flat breads. The leaves are commonly utilized as livestock fodder[10]. Maize accounts for almost half of the calories and protein consumed in Eastern and Southern Africa (ESA), and one-fifth of the calories and protein consumed in West Africa[11]. More than 300 million people in SSA depend on maize as a source of food security and economic wellbeing[11].

The soils in Akungba-Akoko, located in southern Nigeria, have drawn the attention of researchers and agricultural experts due to their low fertility status, unique characteristics, and increased soil acidity caused

Department of Agronomy, Faculty of Agriculture, Adekunle Ajasin University, Akungba-Akoko P.M.B. 001, Ondo State, Nigeria. email: taiwo.agbede@aaua.edu.ng

by continuous crop cultivation and the use of mineral fertilizers[3]. While chemical fertilizers can enhance crop productivity in these soils and play a crucial role in sustaining short-term productivity in agro-ecosystems, studies reveal that their excessive and indiscriminate application can lead to adverse effects. These include a decline in soil quality and fertility, soil organic matter (SOM), soil acidification, nutrient imbalances, and negative impacts on enzymatic activity. Such effects can post risks to the copiotroph community[12], and present challenges to long-term sustainability[13,14]. Most crops experience yield reduction and a loss of nutritional value due to the adverse effects of excessive use of chemical fertilizers. Consequently, there is an urgent need to explore alternative approaches emphasizing sustainability in crop yield, resource utilization, soil health, soil quality, and practicality for local farmers[13].

Poultry manure, a valuable organic fertilizer rich in essential nutrients, has gained increasing attention for its potential impact on crop growth and yields. Poultry manure is rich in organic matter and supplies nutrients necessary for crop productivity. It has been observed that applying poultry manure to the soil, increases soil organic matter and other plant nutrients, improves soil physical and chemical qualities, and increases crop yields[15,16]. Studies have shown varying responses of maize to poultry manure application across different countries. For instance, the study by Boateng et al.[17] showed a significant increase in maize yields in Ghana with the application of poultry manure, which they attributed to improved soil fertility and greater nutrient availability. In Asian countries like China and India, rice cultivation is vital. Amanullah et al.[18] observed that poultry manure application positively influenced rice grain yield and growth parameters, including days to panicle initiation, plant height, number of tillers, leaf area and panicle development.

Although poultry manure is known to contribute essential nutrients to the soil, there is a lack of detailed information on how these nutrients interact with the specific nutrient deficiencies commonly found in Southwest Nigeria's soils. Understanding the dynamics of nutrient uptake by maize and its impact on nutritional quality is crucial, as soil characteristics can vary significantly even within a relatively small geographic area. There are gaps in the understanding of how poultry manure affects maize nutritional quality across different regions within Southwest Nigeria. Additionally, there is limited research on the impact of poultry manure application on soil properties, growth, yield, and maize nutritional quality grown in severely degraded tropical Alfisols of Southwest Nigeria. Addressing these gaps would enable more informed and sustainable agricultural practices in Southwest Nigeria, leading to improved soil fertility, higher crop yields, and better maize nutritional quality in the region. The working hypothesis in this study was that amending soils with poultry manure would significantly improve the soil properties, agronomic characteristics of maize and concentrations of key inorganic minerals for human nutrition in the edible portions of the maize crop when compared to the untreated control. Hence, the objective of this study was to assess how application of poultry manure, affected the soil properties, mineral composition, growth, yield, and economic productivity of maize grown on severely degraded tropical agricultural soils in southwest Nigeria.

Results

Initial soil analysis

The physical and chemical properties of the soil before sowing in 2022 are presented in Table 1. The soil was sandy loam in texture, acidic, and had high bulk density and low total porosity. Soil organic matter (OM), total N, available P and exchangeable K, exchangeable Ca and exchangeable Mg were very low, according to the recommended critical levels of 3.0% OM, 0.20% N, 10.0 mg kg^{-1} available P, 0.16–0.20 cmol kg^{-1} exchangeable K, 2.0 cmol kg^{-1} exchangeable Ca, and 0.40 cmol kg^{-1} exchangeable Mg[19], indicating poor soil fertility. It will, therefore, be unable to sustain crop yield without the addition of external inputs.

Property	Value	Class
Sand (%)	75.0	
Silt (%)	20.0	
Clay (%)	5.0	
Textural class	Sandy loam	
Bulk density (Mg m^{-3})	1.51	
Total porosity (%)	43.0	
Moisture content (%)	13.8	
pH (water)	4.35	Acidic
Organic matter (%)	1.25	Low
Total N (%)	0.12	Low
Available P (mg kg^{-1})	9.1	Low
Exchangeable K (cmol kg^{-1})	0.11	Low
Exchangeable Ca (cmol kg^{-1})	1.85	Low
Exchangeable Mg (cmol kg^{-1})	0.36	Low

Table 1. Physical and chemical properties of soil (0–15 cm depth) before the experiment.

Poultry manure property	Value
pH (water)	6.8
Organic carbon (%)	29.5
Nitrogen (%)	3.03
C:N	9.7
Phosphorus (%)	1.38
Potassium (%)	2.35
Calcium (%)	1.20
Magnesium (%)	0.58
Sulphur (%)	0.32
Manganese (%)	0.36
Iron (%)	0.14
Copper (%)	0.38
Zinc (%)	0.23
Sodium (%)	0.27

Table 2. Chemical composition of poultry manure used for the experiment.

Year	Bulk density (Mg m^{-3})	Total porosity (%)	Moisture content (%)
2022	1.27a	25.63b	7.96a
2023	1.19b	27.27a	7.32b
Poultry manure treatment			
Control (no poultry manure)	1.51a	43.0e	10.7e
5 t ha^{-1} poultry manure	1.39b	47.5d	12.9d
10 t ha^{-1} poultry manure	1.22c	54.0c	14.5c
15 t ha^{-1} poultry manure	1.12d	57.7b	17.8b
20 t ha^{-1} poultry manure	1.00e	62.3a	20.5a
Year (Y)	0.000	0.000	0.000
Poultry manure (PM)	0.000	0.000	0.000
Y × PM	0.000	0.000	0.000

Table 3. Effect of year and poultry manure on soil physical properties (0–10 cm depth). The means in columns followed by similar letters are not significantly different at $P < 0.05$ according to Duncan's multiple range test (DMRT); $P < 0.0001$, ANOVA.

Chemical composition of poultry manure used for the experiment

The chemical composition of poultry manure used for the experiment are presented in Table 2. The chemical composition of poultry manure was relatively high in N, P, K, Ca, Mg, and organic carbon at the level required for the growth of maize[3,20]. Application of poultry manure in the short term is expected to benefit the crop and soil.

Effects of poultry manure on soil physical properties

Application of poultry manure influenced soil physical properties (Table 3). Year 1 (2022) had higher bulk density and moisture content and lower total porosity compared with year 2 (2023). The application of poultry manure at rates of 5, 10, 15, and 20 t ha^{-1} resulted in lower soil bulk density and increased total porosity and moisture content relative to the control. As the amount of poultry manure increased, there was a corresponding increase in soil moisture and total porosity, while soil bulk density decreased. Particularly, applying poultry manure at rates of 15 or 20 t ha^{-1} led to the lowest soil bulk density and the highest total porosity and moisture content. When averaged across cropping seasons, the application of 20 t ha^{-1} poultry manure decreased soil bulk density by 34% and increased total porosity and moisture content by 45% and 92%, respectively, compared to the control. Similarly, the application of 15 t ha^{-1} poultry manure reduced soil bulk density by 26% and enhanced total porosity and moisture content by 34% and 66%, respectively, compared to the control. Application of 10 t ha^{-1} poultry manure resulted in a reduction in soil bulk density by 19% and an increase in total porosity and moisture content by 26% and 36%, respectively, relative to the control.

When studied as individual factors, both year (Y) and poultry manure (PM) had significant effects on bulk density, total porosity, and moisture content (Table 3). The interaction between year and poultry manure (Y × PM) also showed a significant impact on bulk density, total porosity, and moisture content.

Year	pH (water)	OC (%)	Total N (%)	Avail. P (mg kg^{-1})	Exch. K (cmol kg^{-1})	Exch. Ca (cmol kg^{-1})	Exch. Mg (cmol kg^{-1})
2022	5.71a	1.89a	0.19a	13.1a	0.09a	2.19a	0.68a
2023	5.79a	1.97a	0.19a	13.5a	0.09a	2.27a	0.70a
Poultry manure treatment							
Control (no poultry manure)	5.35b	1.25e	0.13e	8.8e	0.12e	1.76e	0.35e
5 t ha^{-1} poultry manure	5.86a	1.58d	0.17d	10.5d	0.15d	1.98d	0.52d
10 t ha^{-1} poultry manure	5.93a	1.95c	0.19c	13.4c	0.18c	2.24c	0.74c
15 t ha^{-1} poultry manure	5.86a	2.29b	0.21b	15.9b	0.20b	2.45b	0.86b
20 t ha^{-1} poultry manure	5.75a	2.56a	0.24a	17.8a	0.23a	2.71a	0.97a
Year (Y)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Poultry manure (PM)	0.000	0.000	0.000	0.000	0.000	0.000	0.031
Y × PM	0.024	0.000	0.002	0.000	0.000	0.016	0.000

Table 4. Effects of year and poultry manure on soil chemical properties (0–15 cm depth). The means in columns followed by similar letters are not significantly different at $P < 0.05$ according to Duncan's multiple range test (DMRT); $P < 0.0001$, ANOVA.

Year	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})
2022	1.88a	0.31a	1.80a	0.036a	0.31a	25.73a	8.06a	20.29a
2023	1.89a	0.31a	1.82a	0.036a	0.31a	27.01a	8.12a	20.57a
Poultry manure treatment								
Control (no poultry manure)	1.24d	0.24d	1.42c	0.019e	0.09e	18.36c	4.55c	12.92c
5 t ha^{-1} poultry manure	1.59c	0.28c	1.75b	0.029d	0.15d	23.54b	6.32b	17.86b
10 t ha^{-1} poultry manure	2.26a	0.35a	1.98a	0.045a	0.19a	30.02a	9.89a	23.81a
15 t ha^{-1} poultry manure	2.18a	0.34a	1.96a	0.044ab	0.18ab	29.98a	9.86a	23.79a
20 t ha^{-1} poultry manure	2.16ab	0.33ab	1.93a	0.043bc	0.17bc	29.96a	9.84a	23.75a
Year (Y)	0.000	0.023	0.000	0.000	0.001	0.003	0.014	0.000
Poultry manure (PM)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Y × PM	0.000	0.008	0.001	0.000	0.000	0.000	0.003	0.000

Table 5. Effects of year and poultry manure on mineral composition of maize grains. The means in columns followed by similar letters are not significantly different at $P < 0.05$ according to Duncan's multiple range test (DMRT); $P < 0.0001$, ANOVA.

Effects of poultry manure on soil chemical properties

Application of poultry manure influenced soil chemical properties (Table 4). Year 1 (2022) had soil pH, organic carbon (OC), total nitrogen (TN), available phosphorus (P), exchangeable potassium (K), exchangeable calcium (Ca), and exchangeable magnesium (Mg) similar to second year (2023). The application of poultry manure at rates of 5, 10, 15, and 20 t ha^{-1} resulted in increased soil pH, OC, TN, P, K, Ca, and Mg. As the amount of poultry manure increased, there was a corresponding increase in soil pH, OC, TN, P, K, Ca, and Mg. Particularly, applying poultry manure at rates of 15 or 20 t ha^{-1} led to the highest soil OC, TN, P, K, Ca, and Mg, but soil pH tended to decrease above the use of 10 t ha^{-1} poultry manure.

When studied as individual factors, both year (Y) and poultry manure (PM) had significant effects on soil pH, OC, TN, P, K, Ca, and Mg (Table 4). The interaction between year and poultry manure (Y × PM) also had a significant influence on soil pH, OC, TN, P, K, Ca, and Mg.

Effects of poultry manure on the mineral composition of maize grains

The effects of poultry manure application on mineral composition of maize grains are shown in Table 5. The concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), copper (Cu), and zinc (Zn) were similar in both years. The application of poultry manure had a significant influence on the concentrations of mineral nutrients in the maize grains. In general, different levels of poultry manure application led to increased concentrations of N, P, K, Ca, Mg, Fe, Cu, and Zn compared to those in the control, where no poultry manure was applied. The application of poultry manure resulted in a significant ($P < 0.05$) increase in the mineral concentrations of N, P, K, Ca, Mg, Fe, Cu, and Zn across the various application rates ranging from 0 to 20.0 t ha^{-1}. In both years, the use of 10 t ha^{-1} poultry manure produced the highest mineral concentrations compared to other treatments. However, the mineral concentrations observed in this treatment were not significantly different from those in the 15 and 20 t ha^{-1} poultry manure treatments. The control had the lowest values of mineral nutrition in the maize grains. Pooled over the two years, 10 t ha^{-1} poultry manure treatment increased concentrations of N, P, K, Ca, Mg, Fe, Cu, and Zn by 82, 46%, 39%, 137%, 156%, 64%, 117%, and 84%, respectively, compared to those in the control.

Year	Plant height (cm)	Number of leaves per plant	Leaf area (m^2)	Stem girth (cm)
2022	270.7a	16.1a	893.2b	1.62b
2023	271.7a	16.2a	953.8a	1.74a
Poultry manure treatment				
Control (no poultry manure)	236.2c	14.3c	762.6c	1.36c
5 t ha^{-1} poultry manure	259.6b	15.5b	876.1b	1.57b
10 t ha^{-1} poultry manure	288.1a	17.1a	994.2a	1.85a
15 t ha^{-1} poultry manure	287.0a	17.0a	993.8a	1.83a
20 t ha^{-1} poultry manure	285.1a	16.9a	990.7a	1.81a
Year (Y)	0.084	0.000	0.000	0.003
Poultry manure (PM)	0.000	0.000	0.000	0.000
Y × PM	0.023	0.015	0.002	0.000

Table 6. Effect of year and poultry manure on growth parameters of maize at 9 weeks after sowing. The means in columns followed by similar letters are not significantly different at $P < 0.05$ according to Duncan's multiple range test (DMRT); $P < 0.0001$, ANOVA.

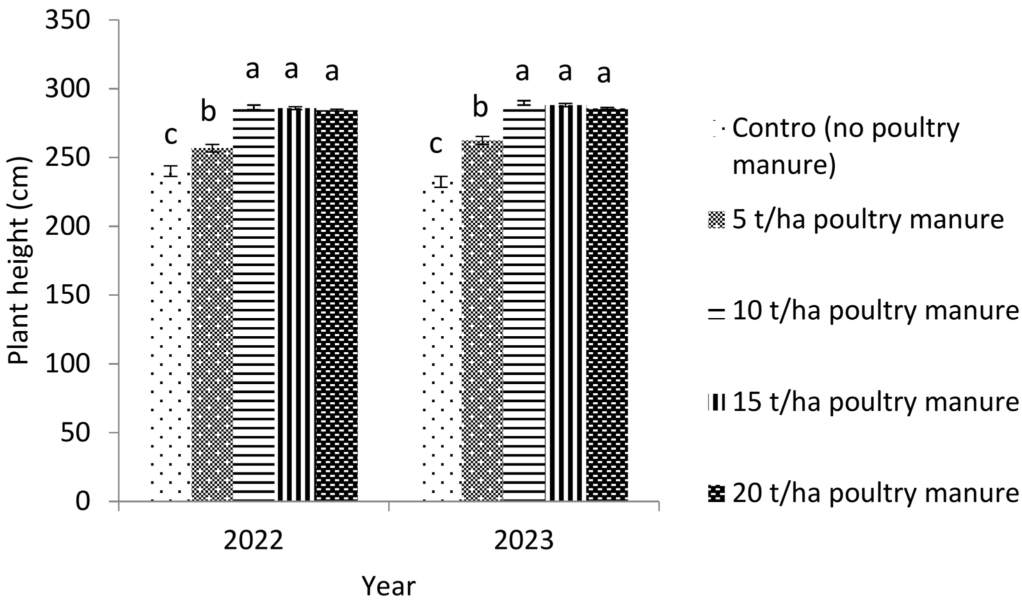

Fig. 1. Effect of poultry manure on maize plant height in 2022 and 2023.

When considered as individual factors, year (Y) influenced the concentrations of N, P, K, Ca, Mg, Fe, Cu, and Zn. Poultry manure (PM) affected the concentrations of N, P, K, Ca, Mg, Fe, Cu, and Zn (Table 5). The interaction of Y × PM influenced the concentrations of N, P, K, Ca, Mg, Fe, Cu, and Zn.

Effects of poultry manure on growth parameters of maize

The effects of poultry manure on various growth parameters of maize are presented in Table 6. Plants in both years were similar in height (Fig. 1, Table 6) and with similar number of leaves but had higher leaf area, and stem girth in the second year (Table 6). The application of poultry manure significantly increased plant height (Fig. 1, Table 6), number of leaves per plant, leaf area, and stem girth (Table 6) compared with the control. A general trend of increase in all growth parameters with increasing level of poultry was observed during the 2 years. In both the years, use of 10 t ha^{-1} poultry manure produced the tallest plants, most leaves, largest leaf areas and widest stems, although these values were not significantly different from those in the 15 t ha^{-1} and 20 t ha^{-1} poultry manure treatments. Intriguingly, the 10 t ha^{-1} application rate emerged as a favorable choice over 15 and 20 t ha^{-1}, suggesting a potential phenomenon of diminishing returns. When averaged across cropping seasons, the application of 10 t ha^{-1} poultry manure increased plant height, number of leaves per plant, leaf area and stem girth by 22%, 20%, 30%, and 36%, respectively, compared to the control.

When considered as individual factors, year (Y) affected number of leaves, leaf area, and stem girth but not plant height. Poultry manure (PM) affected plant height, number of leaves, leaf area, and stem girth (Table 6). The interaction of Y × PM affected plant height, number of leaves, leaf area, and stem girth.

Year	Biomass yield (t ha^{-1})	Number of grains per cob	Weight of cob (g)	Weight of 1000 grains (g)	Grain yield (t ha^{-1})
2022	6.79b	483.17b	176.85a	358.35b	3.00b
2023	7.13a	513.99a	177.83a	386.01a	3.17a
Poultry manure treatment					
Control (no poultry manure)	2.35c	432.5c	153.4c	324.2c	1.85c
5 t ha^{-1} poultry manure	5.24b	478.3b	168.2b	355.4b	2.86b
10 t ha^{-1} poultry manure	9.10a	529.4a	189.9a	398.5a	3.60a
15 t ha^{-1} poultry manure	9.08a	527.6a	188.5a	393.2a	3.58a
20 t ha^{-1} poultry manure	9.02a	525.1a	186.7a	389.6a	3.54a
Year (Y)	0.000	0.023	0.740	0.000	0.000
Poultry manure (PM)	0.000	0.000	0.000	0.004	0.000
Y × PM	0.016	0.000	1.000	0.000	0.000

Table 7. Effect of year and poultry manure on grain yield and yield components of maize. The means in columns followed by similar letters are not significantly different at $P < 0.05$ according to Duncan's multiple range test (DMRT); $P < 0.0001$, ANOVA.

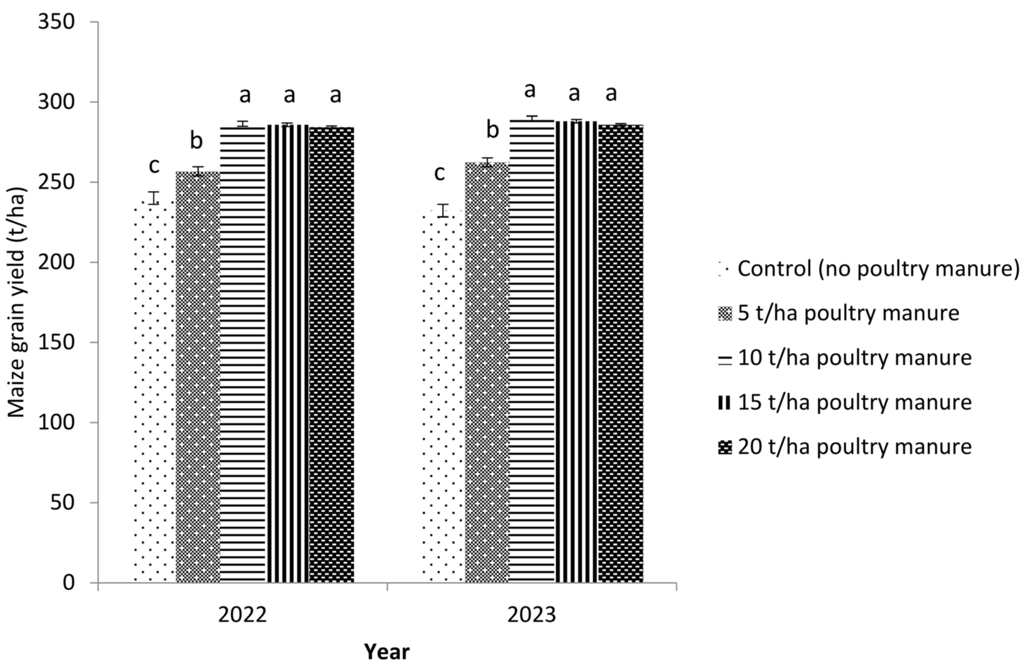

Fig. 2. Effect of poultry manure on the maize grain yield in 2022 and 2023.

Effect of year and poultry manure on grain yield and yield components of maize

The effects of poultry manure on various parameters, including dry biomass yield, number of grains per cob, weight of cob, weight of 1000 grains, and maize grain yield, are shown in Table 7. Plants in both years were similar in weight of cob but had higher dry biomass yield, number of grains per cob, weight of 1000 grains, and maize grain yield (Fig. 2, Table 7) in the second year. The application of poultry manure led to a significant ($p = 0.05$) increase in these parameters across application rates ranging from 0–20 t ha^{-1}. Notably, the application rate of 10 t ha^{-1} resulted in the highest dry biomass yield, number of grains per cob, weight of cob, weight of 1000 grains, and maize grain yield. However, these values did not significantly differ from those in the 15 t ha^{-1} and 20 t ha^{-1} poultry manure treatments. Compared with the control treatment, the application of poultry manure at rates of 5, 10, 15 and 20 t ha^{-1} increased the maize grain yield by 54.6%, 94.6%, 93.5%, and 91.4%, respectively. Interestingly, the 10 t ha^{-1} application rate emerged as a preferred choice over the 15 and 20 t ha^{-1} poultry manure treatments, suggesting a potential phenomenon of diminishing returns.

When examined as individual factors, year (Y) influenced dry biomass yield, number of grains per cob, weight of 1000 grains, and maize grain yield but did not influence weight of cob. Poultry manure (PM) influenced dry biomass yield, number of grains per cob, weight of cob, weight of 1000 grains, and maize grain yield (Fig. 2, Table 7). The interaction of Y × PM influenced dry biomass yield, number of grains per cob, weight of 1000 grains, and maize grain yield but did not influence weight of cob.

Treatment	Gross return gain (US$ ha^{-1})	Production increase value (US$ ha^{-1})	Production increase (%)	Cost of transportation of poultry manure (US$ ha^{-1})	Net return over each fertilization (US$ ha^{-1})	Return rate or value/ cost ratio of each fertilization
Control (no poultry manure)	1126	–	–	–	–	–
5 t ha^{-1} poultry manure	1740	614	55	55	559	11
10 t ha^{-1} poultry manure	2191	1065	95	65	970	16
15 t ha^{-1} poultry manure	2178	1052	93	75	959	14
20 t ha^{-1} poultry manure	2154	1028	91	85	937	12

Table 8. Economics of producing maize under each level of poultry manure tested in 2022 and 2023. In the year of 2022, the price of grain yield of maize was US$ 430 t ha^{-1}. In the year of 2023, the price of grain yield of maize was US$ 787 ha^{-1}. US$1 = N430 in 2022. US$1 = N750 in 2023.

Optimizing profitability

Effect of poultry manure treatments on maize production

The cost of transportation for each level of poultry manure treatment (Table 8) increased with the rate of amendment. The application of poultry manure at 10 t ha^{-1} yielded the highest gross return of US$2,191 ha^{-1} and a net return of US$970 ha^{-1}. This was followed by the 15 t ha^{-1} and 20 t ha^{-1} treatments, which had gross returns of US$2,178 ha^{-1} and US$2,154 ha^{-1}, respectively, and net returns of US$959 ha^{-1} and US$937 ha^{-1}, respectively. The lowest gross return, US$1,126 ha^{-1}, was observed in the control. Regardless of the rate, all levels of poultry manure treatment resulted in greater net profits compared to the control. Among all treatments, poultry manure at 10 t ha^{-1} proved to be the most cost-effective and profitable for maize production, as demonstrated by its high return rate or value-to-cost ratio of 16.

Discussion

The findings from the initial soil analysis revealed that the soil's physical and chemical properties were suboptimal for supporting crop yield without external inputs. The soil was classified as sandy loam, acidic, and characterized by high bulk density and low total porosity, indicating poor soil structure and aeration. Furthermore, organic matter (OM) and key soil nutrients, including total nitrogen (N), available phosphorus (P), exchangeable potassium (K), calcium (Ca), and magnesium (Mg), were significantly below critical levels, underscoring the necessity for soil amendments[19]. The chemical composition of the poultry manure used for the experiment was rich in essential nutrients, suggesting its potential to improve soil fertility and crop growth in the short term. The reduced bulk density and increased porosity and moisture observed in poultry manure treated plots compared with the control could be attributed to the increased soil organic matter from the poultry manure. Organic matter improves soil structure and aeration, reduces soil bulk density, and enhances water infiltration and retention[3]. Bulk density is a critical factor for water infiltration, root distribution, and root function, all of which influence water uptake and plant growth. A reduction in soil bulk density can significantly impact maize root growth. The increase in soil total porosity due to manure application is likely attributed to improved soil particle aggregation resulting from enhanced soil organic matter. Over a period of two years, the use of poultry manure led to significant improvements in soil physical properties. Notably, in the second year, the soil exhibited lower bulk density, higher total porosity, and increased moisture content compared to the first year. This was due to the residual effect of the poultry manure, which continued to decompose and add organic matter to the soil, thereby reducing soil compaction and lowering bulk density. This is because organic matter helps create larger and more stable soil aggregates, which improves soil structure and water holding capacity. The gradual breakdown of organic matter also contributed to increased pore space, promoting better aeration and water infiltration. The application rates of 10, 15 and 20 ha^{-1} of the poultry manure influenced physical parameters, with the highest application rate producing the lowest bulk density and the highest soil moisture content and total porosity. These findings are consistent with previous studies that highlight the beneficial effects of organic amendments on soil physical properties[3,20].

The application of poultry manure also positively influenced soil chemical properties. Both years showed similar soil pH, organic carbon (OC), total nitrogen (TN), available P, exchangeable K, Ca, and Mg. The similarity in these soil chemical properties in both years can be attributed to the residual effects of poultry manure applied in the first year, which continued to enhance soil fertility in the second year. Increasing the poultry manure application rates led to significant improvements in these soils chemical properties. The soil nutrient concentrations increased with poultry manure application, which was due to the release of nutrients from the poultry manure after decomposition. The application rates of 10, 15 or 20 t ha^{-1} were particularly effective in enhancing soil OC, TN, P, K, Ca, and Mg, aligning with the results from similar studies where poultry manure has been used to improve soil fertility[20,21]. As the organic matter components of the poultry manure decomposed, nutrients were released to the soil. The increase in soil OC and nutrients with rates of application in plots amended with poultry manure compared with those in the control, could be attributed to various mechanisms and processes; the addition/release of nutrients contained in poultry manure, reduced nutrient leaching, improved nutrient retention, modified soil microbial dynamics and increased decomposition of organic materials/nutrient transformation in the soil[22–25]. Soil pH tended to decrease slightly above the 10 t ha^{-1} application rate, indicating a potential threshold for optimal manure application. A reduction in soil pH with poultry manure addition beyond 10 t ha^{-1} compared to the 15 and 20 t ha^{-1} treatments might be associated with the release of organic acids during the decomposition of poultry manure[26].

The mineral composition of maize grains improved significantly with the application of poultry manure. The concentrations of essential minerals such as N, P, K, Ca, Mg, Fe, Cu, and Zn were notably higher in treatments with poultry manure compared to the control. The 10 t ha^{-1} application rate produced the highest mineral composition of maize grains, which did not differ significantly from the 15 and 20 t ha^{-1} treatments. These findings are in agreement with studies that demonstrate the role of organic amendments in enhancing the nutritional quality of crops[22].

The increased concentrations of N, P, K, Ca, Mg, Fe, Zn, and Cu in maize grains, as well as improvements in growth, dry biomass yield, number of grains per cob, weight of cob, weight of 1000 grains, and overall maize grain yield in the poultry manure treatment group, can be attributed to increased macronutrient availability, which is an important factor in soil fertility[27]. The application of poultry manure led to increased nutrient availability in the soil, resulting in higher nutrient uptake by maize plants. These improvements can be linked to enhanced soil quality, nutrient release into the soil solution, improved chemical properties, beneficial microorganisms, and balanced plant nutrition. These results are consistent with findings by Gunes et al.[28], who reported increased mineral composition and growth of lettuce plants following poultry manure application. The positive effects on maize grain N, P, K, Ca, Mg, Fe, Zn, and Cu concentrations, growth, and grain yield can also be attributed to improved soil friability and water-holding capacity[21], as well as reduced nutrient losses and leaching[16]. Additionally, the application of poultry manure in a subtropical environment has been shown to enhance growth, yield, and leaf N, P, K, Ca, and Mg uptake by sweet potato plants[29]. Processed poultry manure has also been found to increase the growth and N, P, K, Zn, Cu, and Mn concentrations in both bean and maize plants[30].

The significant influence of poultry manure application on the mineral composition of maize grains, as well as growth and yield, indicated that poultry manure contains some macronutrients and micronutrients that are released into the soil during mineralization. The values of the minerals N, P, K, Ca, Mg, Fe, Cu, and Zn increased at different poultry manure application levels. The findings that maize growth, yield, and mineral composition in maize grains increase with poultry manure application rate might be attributable to improved soil fertility due to the favourable impacts of organic matter after poultry manure incorporation. This is consistent with the soil chemical properties of the poultry manure (Table 2). These findings revealed that poultry manure promotes nutrient cycling by improving the physical, chemical, and biological properties of the soil, allowing for better utilization of the applied poultry manure: resulting in greater nutrient uptake and allocation to the maize grains. According to Cockell[31], minerals are the inorganic substances that must be ingested and absorbed in adequate amounts to satisfy a wide variety of essential metabolic and/or structural functions in the body. The consumption of an optimum concentration of minerals is essential for growth and good health[31]. The application of poultry manure as a source of macronutrients had a positive influence on the growth, yield and N, P, K, Ca, Mg, Fe, Cu, and Zn concentrations of maize grains. Poultry manure is known for its ability to improve soil fertility, crop yield and nutrient uptake by plants[28,29].

The growth parameters of maize, including plant height, number of leaves per plant, leaf area, and stem girth, showed significant improvement with the application of poultry manure. The 10 t ha^{-1} application rate consistently produced the tallest plants, most leaves, largest leaf areas, and widest stems, although the differences were not statistically significant compared to the 15 and 20 t ha^{-1} treatments. These results suggest that 10 t ha^{-1} is an optimal rate for maximizing maize growth parameters. The grain yield and yield components, including dry biomass yield, number of grains per cob, weight of cob, weight of 1000 grains, and overall maize grain yield, were significantly enhanced by the application of poultry manure. The application rate of 10 t ha^{-1} proved to be the most effective, increasing maize grain yield by 94.6% compared to the control. These results are consistent with the observed benefits of poultry manure in other studies, which report substantial yield improvements with organic amendments[15–17,21].

Applying poultry manure above 10 t ha^{-1} did not further improve maize grain minerals, growth, and yield because the soil might have reached its nutrient saturation point, limiting the plants' ability to uptake additional nutrients, and excessive manure could lead to nutrient imbalances or toxicity, which can inhibit plant growth. Additionally, over-application of poultry manure at 15 and 20 t ha^{-1} can cause environmental issues such as nutrient runoff, further impacting plant health negatively.

The results of this study highlight the significant impact of poultry manure treatments on the profitability of maize production. As presented in Table 8, the cost of transportation for each level of poultry manure treatment increased with the rate of amendment. This indicates that higher application rates require more resources for transportation, which is a crucial factor to consider when planning manure treatments. The data clearly show that the application of poultry manure at 10 t ha^{-1} yields the highest gross and net returns. With a gross return of US\$2,191 ha^{-1} and a net return of US\$970 ha^{-1}, the 10 t ha^{-1} treatment stands out as the most profitable among the tested levels. This is followed by the 15 t ha^{-1} and 20 t ha^{-1} treatments, which also produce substantial gross and net returns, although slightly lower than the 10 t ha^{-1} treatment. The gross returns for the 15 t ha^{-1} and 20 t ha^{-1} treatments are US\$2,178 ha^{-1} and US\$2,154 ha^{-1}, respectively, with net returns of US\$959 ha^{-1} and US\$937 ha^{-1}, respectively. These results indicate a diminishing return on investment with higher rates of poultry manure application beyond 10 t ha^{-1}. The marginal increase in gross returns does not proportionately offset the additional costs, making the higher treatments less cost-effective. In contrast, the control, which did not receive any poultry manure treatment, yielded the lowest gross return of US\$1,126 ha^{-1}. This stark difference underscores the importance of organic amendments in enhancing maize productivity and profitability. The control's performance also emphasizes that any level of poultry manure treatment is more beneficial than none. Among all treatments, the 10 t ha^{-1} application rate proved to be the most cost-effective and profitable for maize production. This is evidenced by its high return rate or value-to-cost ratio of 16, which means that for every dollar spent, there is a return of \$16. This impressive ratio highlights the effectiveness of the 10 t ha^{-1} treatment in maximizing profits relative to its costs. For maize producers, especially in regions with similar agro-ecological conditions, these findings provide clear guidance on making the best use of poultry manure application for maximum economic benefit. While higher rates of manure application do result in higher gross returns, the additional costs associated with these rates reduce their net profitability. Therefore, applying poultry manure at 10 t ha^{-1} is recommended for achieving the best balance between cost and return. The study confirms that poultry manure is a valuable organic amendment for enhancing maize production profitability. Among the different application rates tested, 10 t ha^{-1} emerges as the most advantageous, offering the highest net returns and an excellent value-to-cost ratio. This rate optimizes both productivity and profitability, making it the preferred choice for farmers seeking to improve their economic outcomes in maize farming.

Conclusion
The application of poultry manure significantly improved both the physical and chemical properties of the soil, enhanced the mineral composition of maize grains, and increased the growth parameters and yield components of maize. The 10 t ha^{-1} application rate consistently emerged as optimal, indicating a balance between soil properties, input costs and crop performance. These findings underscore the potential of poultry manure as a sustainable soil amendment for improving crop productivity in sandy loam soils with poor fertility.

Materials and methods
Site description
The experiment was carried out at the Teaching and Research Farm, Adekunle Ajasin University, Akungba-Akoko, Ondo State, Nigeria. The site is located at latitudes 7° 28″ 9.15′ to 7° 29″ 15.18′ North of the equator and longitudes 5° 44″ 15.96′ to 5° 46″ 14.78′ East of the Greenwich Meridian[32], with altitudes ranging from 317 to 352 m above sea level. Soils of the area were formed predominantly from Precambrian basement complex rocks such as gray gneiss, quartzo-feldspathic gneiss, charnockite; granite gneiss; and porphyritic gneiss[33], which form parts of the African crystalline shield[34]. Rainfall is bimodal, with mean annual rainfall ranging between 1200 and 1400 mm, with most occurring from March to July and from mid-August to November. The mean annual air temperature is between 21 and 32 °C. The natural rainforest vegetation that previously characterized the study area gradually receded to derived savannah due to human activities.

Preparation of poultry manure
Poultry manure (PM) was obtained from the poultry unit of the Teaching and Research Farm of the University. The poultry manure was collected from egg-laying chickens of the Leghorn breed, which were reared in battery cages. The chickens were fed with Top Feeds Layer Mash and maintained for a period of 12 months from the onset of their laying cycle. The PM was composted for 3 weeks to facilitate mineralization.

Land preparation, incorporation of poultry manure and treatments
The site was manually cleared, and weeds were removed. Thereafter, the soil was then disked to a 15 cm depth using a traditional hoe. The experimental site was laid out to the required plot size of 4 m × 2 m. The PM was weighed and uniformly spread over the soil on the plots according to the required rates (0, 5, 10, 15 and 20 t ha^{-1}). The PM was manually incorporated into the soil to a depth of approximately 10 cm with a hoe. The blocks were spaced 1 m apart, and the plots were separated by 0.5 m. The experiment was laid out in a randomized complete block design (RCBD) with three replications. The treatments consisted of five levels of poultry manure (0, 5, 10, 15 and 20 t ha^{-1}).

Sowing of maize/crop establishment
Maize (*Zea mays*) hybrid seeds, Oba super 6 (pro-vitamin A maize) obtained from Premier Seed Nigeria Limited, Akure was used as a text crop, and seeds were sown on 25th May, 2022 and 15th July, 2023, respectively, at a spacing of 50 cm × 50 cm. Two maize seeds were sown per hole at a depth of 5 cm. After emergence, the seedlings were thinned to one per hole, resulting in a population of 32 plants per plot. Weeding was performed manually at 21 and 70 days after sowing.

Soil analysis
Before the commencement of the experiment in 2022, soil samples were taken from 0–15 cm depth at 10 different points selected randomly from the experimental site. The soil samples collected were bulked, air-dried and sieved using a 2-mm sieve for routine chemical analysis, as described by Carter and Gregorich (2007)[35]. Particle size analysis was performed using the hydrometer method. The textural class was determined using a textural triangle. The soil pH was determined in a soil/water (1:2) suspension using a digital electronic pH meter. Soil organic carbon was determined by the Walkley and Black procedure by wet oxidation using chromic acid digestion. Total N was determined using micro-Kjeldahl digestion and distillation techniques, and available P was determined by Bray-1 extraction followed by molybdenum blue colorimetry. Exchangeable K, Ca and Mg were extracted with a 1 N ammonium acetate (NH_4OA_C) solution (pH 7). Thereafter, exchangeable K was analyzed with a flame photometer, and exchangeable Ca and Mg were determined with an atomic absorption spectrophotometer.

Chemical analysis of poultry manure used for the experiment
Small quantities of approximately 5 g subsamples of the poultry manure used in the experiments were analyzed to determine its nutrient composition. The samples were air-dried and crushed to pass through a 2-mm sieve

before analysis. The samples were analyzed for organic C, total N, P, K, Ca, Mg, and S, as well as the concentrations of trace elements such as manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), and sodium (Na) as described by Tel and Hagarty[36]. The percentage of organic carbon was determined by the Walkley and Black procedure using the dichromate wet oxidation method, and total N was determined by micro-Kjeldahl digestion, followed by distillation and titration. The determination of P, K, Ca and Mg was performed using the wet digestion method based on 25–5-5 mL of HNO_3-H_2SO_4-$HClO_4$ acids. Phosphorus was measured colorimetrically by the molybdate blue method in an autoanalyzer. Potassium was measured by flame photometry, while Ca and Mg were analyzed using an atomic absorption spectrophotometer. Sulphur content in the poultry manure sample was quantified with the use of a vario MACRO cube elemental analyzer. To determine the concentrations of trace elements, such as manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), and sodium (Na), sample of poultry manure with known quantity was incinerated at 760 °C in a muffle furnace. The resulting ash was treated with HCl, diluted with deionized water, and then analyzed for trace element concentrations. Mn, Fe, Cu, and Zn levels were determined in poultry manure sample through the use of an atomic absorption spectrophotometer, while the concentration of Na was measured using a flame photometer.

Determination of growth and maize yield

Ten maize plants were randomly selected per plot for the determination of growth parameters (plant height, number of leaves per plant and leaf area) at the mid-flowering stage of maize plants. Plant height was measured manually using a meter rule, from the base of the plant at the soil surface to the tip of the highest leaf in the foliage. The number of leaves was determined by manual counting, and the leaf area was calculated using the model ($A = KL \times B$) developed by Musa and Usman[37], where L = length, B = breath and K = coefficient value for maize, which is 0.75, and A = leaf area. The stem girth was measured using a Vernier caliper. At crop maturity (105 days after sowing), the plants were finally harvested. The final biomass (i.e., stover) and grain yield, number of grains per cob, cob weight, and thousand grain weight were determined as yield characteristics. The grains were air-dried to a moisture content of 12%.

Analysis of the mineral composition of maize grains

Mineral composition analysis of maize grains was conducted at 120 days after sowing, focusing on the 10 central plants from each plot at the experimental site. Five randomly selected maize plants of uniform size were harvested from each plot; threshed and washed with clean water. Samples from each plot were combined and ground into a paste. The resulting paste was thoroughly mixed to create a uniform seed tissue sample from the five selected maize plants. A 100 g sample of the combined maize paste was then subjected to oven drying at 60 °C for 24 h. After drying, the samples were ground in a mill using a stainless steel grinding tool and stored in airtight containers for subsequent chemical analysis. The mineral elements in the maize grains were determined following the methods recommended by the Association of Official Analytical Chemists[38]. To determine level of mineral nitrogen (N) in the maize grains, micro-Kjeldahl digestion was used. For the digestion process, the samples were treated with a mixture of 12 cm^{-3} HNO_3, H_2SO_4 and $HClO_4$ at a ratio of 7:2:1 (v/v/v). The phosphorus content was determined using the molybdenum blue colorimetric technique, while an atomic absorption spectrophotometer was used to analyze the potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), copper (Cu), and zinc (Zn) contents in the maize grains.

Statistical analysis

The collected data were subjected to analysis of variance (ANOVA). The treatment means were separated using the Duncan's multiple range test (DMRT) at $P < 0.05$ probability level.

Cost-to-benefit analysis

A cost-to-benefit analysis was conducted to evaluate the relative economic returns of the treatments using annual market prices of 2022 and 2023. The total yield and cost–benefit analyses were calculated in US dollars (with an exchange rate of 1 USD = 430.00 NGN in 2022 and 1 USD = 750.00 NGN in 2023) based on the harvest from the central bed (1 m^2) of each plot. Costs of farm services were sourced from Okusa market in Akoko South West Local Government Area of Ondo State, Nigeria. The economics of maize production under different levels of poultry manure application was evaluated during the 2022 and 2023 growing seasons. The treatments consisted of varying rates of poultry manure (0, 5, 10, 15, and 20 t ha^{-1}). The economic analysis was conducted by estimating the following parameters: Gross return (US\$ ha^{-1}), production increase value (US\$ ha^{-1}), production increase (%), cost of transportation of poultry manure (US\$ ha^{-1}), net return over each fertilization (US\$ ha^{-1}) and return rate/value cost ratio of each fertilization. Gross return was calculated based on the total maize grain yield obtained per hectare, multiplied by the prevailing market price of maize (US\$ t ha^{-1}) during the harvest period. Gross return values were expressed in US\$ ha^{-1}. The production increase value was determined as the difference in gross return between the control (0 t ha^{-1} poultry manure) and each manure treatment (5, 10, 15 and 20 t ha^{-1}). This value was also presented in US\$ ha^{-1}. The percentage increase in production was calculated by comparing the yield obtained under each poultry manure treatment to the control, using the formula:

$$\text{Production Increase}\,(\%) = \frac{\text{Yield under treatment} - \text{Yield under control}}{\text{Yield under control}} \times 100 \tag{1}$$

The cost of transportation of poultry manure to the experimental site was estimated based on the distance from the manure source to the field, the quantity of manure applied per hectare, and the cost per kilometer of transportation. The total cost of transportation was calculated in US\$ ha^{-1}. Net return over each fertilization was determined as the difference between the gross return and the total cost associated with each poultry manure treatment, using cost of transportation of poultry manure. The result was expressed in US$ ha^{-1}. The return rate/value cost ratio (VCR) for each fertilization treatment was calculated as the ratio of the net return over each fertilization to the total cost incurred per hectare under each treatment. The return rate/VCR was expressed as a unitless ratio, indicating the economic efficiency of each fertilization level.

Data availability
All datasets generated and/or analysed during the current study are included in this article.

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Author contributions

T.M.A: Conceptualization, Data curation, Formal analysis, Fund acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing—original draft, Writing—review & editing.

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Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

I confirm that all the research meets ethical guidelines and adheres to the legal requirements of the study country.

Compliance with international, national and/or institutional guidelines

Experimental research (either cultivated or wild), comply with relevant institutional, national, and international guidelines and legislation. Experimental studies were carried out in accordance with relevant institutional, national or international guidelines or regulation.

Additional information

Correspondence and requests for materials should be addressed to T.M.A.