Nitrogen

Article

Poultry Manure Induced Garden Eggs Yield and Soil Fertility in Tropical and Semi-Arid Sandy-Loam Soils

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Abstract: Synthetic nitrogen fertilizer use comes with unsustainable financial and environmental costs, making it not attractive to small-scale and organic farmers. Poultry manure (PM) when available is a primary fertilizer source for small-scale and organic farmers but there is still limited research on its effects of specific crops and soil fertility under specific practices. The study investigated PM effects on garden egg in three seasons in Ghana and PM effects soil fertility in sandy-loam soils of Arizona after three years under flood irrigation and no-till. The PM application improved garden egg growth (dry matter by 73%) and increased yield by 66% in slightly acidic sandy-loam tropical soils, which could be related to soil mineral improvement. In the semi-arid soil, three years PM application increased cation exchange capacity (41%), P (471%), K (18%), S (244%), Ca (45%), Mg (31%), Zn (5%) and Mn (19%) with reduction in nitrate (−26%), Fe (−38%) and Cu (−11%). The reduction in the nitrate and Fe in the semi-arid Arizona cropland could be associated to flood irrigation and high soil pH, respectively. To gain the full potential from PM applications, best management practice is recommended to reduce nitrate leaching.

Keywords: garden eggs yield; flood irrigation; poultry manure; small-scale farmers; organic farmers; and soil minerals

Citation: Mpanga, I.K.; Adjei, E.; Dapaah, H.K.; Santo, K.G. Poultry Manure Induced Garden Eggs Yield and Soil Fertility in Tropical and Semi-Arid Sandy-Loam Soils. *Nitrogen* **2021**, *2*, 321–331. https://doi.org/10.3390/nitrogen2030022

Academic Editor: Wim De Vries

Received: 14 February 2021
Accepted: 8 July 2021
Published: 13 July 2021

1. Introduction

Nitrogen (N) is a major plant nutrient for most plants and can be applied in the form of urea, ammonium, nitrate and ammonium nitrate. These synthetic N forms, obtained through the Haber-Bosch process, are estimated in 2017 to produce about 120 Tg year^{-1} and is expected to reach 165 Tg year^{-1} by 2050, which comes with detrimental effects to the environment [1]. The synthetic N forms produced through the Haber-Bosch process are expensive, limiting the use among small-scale and resource-limited farmers in developing countries. Organic farmers, small-scale and resource-constrained farmers, therefore, depend on alternatives such as N-fixing plants, compost and manure (including poultry manure-PM), green manure, guano and bone meal as the primary N source for their crops. These organic N sources are primarily made available to plants through mineralization by soil microbes that convert the organic N to ammonium ions and nitrate for plant utilization [2,3].

The use of manure in crop production and pastureland is on the rise as a sustainable option due to many benefits, such as reducing nutrient management costs, improving soil health and crop yield [4,5]. For example, in Arizona, manure applications increased by 30% from 2012 to 2017, based on the United States Department of Agriculture census of agriculture data [6]. Even though manure (including PM) is bulky, making handling a bit challenging, it remains the most valuable resource for small-scale farms [7] due to the high cost of synthetic fertilizers [8]. Poultry manure is a primary fertilizer among small-scale farmers and farmers in developing countries such as Ghana and other African countries with low income due to its low cost. Other benefits include making heavy clay soils light to prevent the clay particles from binding together and increasing the cation exchange capacity. PM nutrients are also slowly released to plants, making them durable and less leached in the soil [9]. However, the nitrate-N form could still be leached easily by practices such as flood irrigation, especially on sandy soil, which needs more investigations in specific conditions. It is an essential organic soil amendment resource, a complete fertilizer due to the composition of both major nutrients NPK (nitrogen, phosphorus and potassium) and minor elements for most commercial crop productions such as garden eggs in Ghana.

Garden egg (*Solanum Melongena*) is one of the three most consumed commercial vegetables in Ghana after tomato and pepper. The total production of garden eggs in Ghana was estimated at over 66 million lbs in 2007 [10]. Garden eggs grow well on well-drained soils with high organic matter, making PM application in garden eggs interesting. Combining PM with synthetic NKP fertilizers was reported to increased garden egg yield compared to the sole application of NPK in acidic soil in Ghana [11] without comparing sole PM to no fertilization and the linkage to soil mineral improvement, which is very important to organic and small-scale producers not using synthetic fertilizers in their operations. Therefore, this study investigated PM effects on garden egg growth and yield in Ghana's tropical climate (West Africa) and soil minerals in Arizona (USA). The study hypothesized that PM application would improve:

(1) growth and yield of garden eggs in Ghanaian tropical sandy-loam soils.
(2) soil fertility in a semi-arid fine sandy-loam pastureland under no-till and flood irrigation.

2. Materials and Methods

2.1. Effect of PM on Growth and Yield of Garden Eggs in Ghana

2.1.1. Study Area

Three different field experiments were conducted in two locations in Ghana. The first experiment was established in March 2011 at the University of Education's Teaching and Research Farm, Ashanti Mampong. The second and third experiments were undertaken in Fiapre, Sunyani West municipality, near the Catholic University College of Ghana in 2020 major growing season (March–June) and minor growing season (August–November). Ashanti Mampong lies in the moist semi-deciduous forest zone [12], with a monthly rainfall of 70 mm in March 2011 and 203 mm in October 2011. The area had an average monthly temperature of 28 °C in March 2011 and 24 °C in October 2011. Sunyani falls within the dry semi-deciduous forest zone and semi-equatorial climate zone with an average monthly rainfall of 453 mm in October 2020 with average temperature of 24 °C [12]. Both study locations have Chromic Luvisol (forest Ochrosol) soils [13,14] according to the FAO-UNESCO classification system [14] and are ideal for the cultivation of cocoyam, maize, cassava, cocoa, plantain, yam and vegetables. The Physico-chemical soil properties of the study locations are presented in Table 1.

Table 1. Soil and poultry manure physico-chemical properties of experimental locations in Ghana.

	Soil Texture	Soil pH (water)	Organic Carbon (%)	Organic Matter (%)	Total N (g/kg)	Available P (mg/kg)	Available K (mg/kg)
2011-Ashanti Mampong	Sandy loam	5.5	0.37	0.64	4.0	15.85	70.30
2020 (major season)-Sunyani	Sandy loam	5.5	1.08	1.85	1.2	5.32	65.30
2020 (minor season)-Sunyani	Sandy loam	5.7	1.09	1.78	1.5	5.21	70.37

2.1.2. Experimental Design and Treatments

Treatment (no fertilization (NF) and PM application) were evaluated in a Randomized Complete Block Design with three replicates.

2.1.3. Land Preparation and PM Composition and Application Rates

The field was prepared by slashing the vegetation with a cutlass followed by hoeing to loosen the soil. The area was then laid into dimensions of 4 m × 3 m (12 m^2) per plot, 1 m between plots and 2 m between blocks. The PM was obtained locally from poultry farm in both locations and had a total N of 23 g/kg, 33 g/kg and 30 g/kg for 2011 at Ashanti-Mampong, 2020 (major and minor season) at Sunyani, respectively, which was used to determine the PM application rates with soil N status and plant requirement. The N rates of 147 kg·N per ha in 2011, 201 kg·N per ha in 2020 major season and 191 kg·N per ha in 2020 minor season was applied from the fresh PM by hand and incorporated immediately using a hand-held rake.

2.1.4. Nursery Establishment and Transplanting

Nursery practices (seeding, plant variety and planting density) was the same for all the trial locations and years as below. A nursery bed of 2 m by 1.2 m was used to raise the garden egg seedlings using a local variety called "Ntrowa Pa," locally obtained from a certified agriculture inputs dealer (Farmers Link Agrochemicals, Sunyani, Ghana). The seeds were sown thinly in rows of 15 cm apart, covered with mulch and watered until germination. The mulches were removed after germination and replaced with a shade of palm fronds over the nursery beds to protect the young seedlings against sunshine. The seedlings were thinned two weeks after germination to avoid overcrowding and to have healthy seedlings. The seedlings were watered when needed to supplement the rain until they reached the desired transplantable stage of four weeks. At four weeks old, the seedlings were hardened-off for two days by reducing the amount and watering interval, while the shade was also entirely removed at week three to prepare them for the harsh field conditions. The seedlings were watered to full capacity before transplanting to soften the soil for easy lifting of seedlings with a ball of earth around their roots. The seedlings were transplanted at a spacing of 75 cm × 50 cm with a total of forty (40) plants per plot size of 12 m^2 (24 plants in harvest area) and watered copiously afterward.

2.1.5. Cultural Practices

The plots were weeded (hand hoeing) three times to prevent weeds from competing with the crops for nutrients, sunlight and water. The plants were also watered as and when necessary, mostly when there was a short dry period. The plants were also sprayed with an insecticide (Lambda—2.5% Cyhalothrin, 20% Alkyl Benzene sulphonate, 57% Alkyl Benzene ethoxylate and 23% solvents (Methanol Isobutanol and Aromex 23%)) at the rate of 100 mL per 15 L of water from day 21 after planting (DAP) at two weeks interval to prevent and control insect-pest attack. The same cultural practices were carried out for all the experimental locations and years. No significant disease was observed in the field throughout the study.

2.1.6. Data Collection

The data were collected for the same parameters using the same procedures, methods and instrumentation for all fieldwork and years. Plant establishment for each plot was obtained by counting the number of plants on each plot at 21 DAP and expressed as a percentage. Four plants from the three central rows of each plot were randomly selected and tagged for height measurements using a meter rule. Plant height was taken from the ground level to the tip of the tallest leaf, and then the average for each plot was calculated. The number of leaves per plant for the four selected plants was obtained by counting the leaves and determining the average. The number of branches per plant for the four selected plants was obtained by counting, after which the average was determined. The stem diameter of four plants selected at random from each plot was measured using a vernier caliper. The average of the four plants on each plot was then determined. The canopy width of the four selected plants was measured with a meter rule, and the average per plot was determined. Four fresh plants were sampled from the two middle rows, enveloped, oven-dried for 48 h at a temperature of 75 °C and the dry weight was measured using an electronic scale. Fruits harvested from each plot were counted separately to obtain the number of fruits harvested for that plot. The Fruits harvested from plants in each plot were weighed, recorded and converted into kilograms per hectare. The length and width of five fruit samples, randomly selected from each plot, were measured using vernier calipers. Averages were then determined and recorded.

2.2. PM Effects on Soil Fertility in an Arizonan Semi-Arid Sandy-Loam Soil

2.2.1. Study Areas and the Soil Properties

The study was conducted from 2017 to 2020 at the University of Arizona Cracchiolo DK Ranch Experiment Station at Cornville in the Verde Valley, pastureland (Figure S1c) in Yavapai County, Arizona, USA. Based on the Natural Resources Conservation Service (NRSC) soil map, the area is under the soil survey name Black Hills-Sedona Area (Coconino and Yavapai Counties Soil Survey-AZ639). Area elevation is about 3000 to 5000 feet with a slope range of 0 to 3 percent and annual precipitation of 12 to 16 inches. Yearly air temperature is about 15–19 °C with 180 to 220 frost-free days. The soil taxonomic classification is fine sandy loam, well-drained with slow run-off and moderate permeability, $pH_{\text{(water)}}$ range of 7.9–8.4.

2.2.2. PM Source, Mineral Composition and Application Rates

The PM was sourced locally within Arizona (Hickman's Family Farms, Buckeye, Arizona) with an estimated mineral composition as in Table 2. The application rate was 2239.5 kg ha^{-1} $year^{-1}$(split applied in March and September every year), which gave 68 kg N ha^{-1}, 59 kg P ha^{-1} and 50 kg K ha^{-1}.

Table 2. Estimated mineral composition of the poultry manure used in the study.

Total N (g/kg)	Total P (g/kg)	Total K (g/kg)	Total Ca (g/kg)	Total Mg (g/kg)	Total Na (g/kg)	Total Zn (g/kg)	Total Fe (g/kg)	Total Cu (g/kg)	Total Mn (g/kg)	Total S (g/kg)	Dry Matter (%)
38.4	26.3	22.1	119.3	7.6	7.0	6540.8	1320.4	637.7	5577.9	69,062.0	30.2

Source of poultry manure: Hickman's Family Farms, Buckeye, Arizona.

2.2.3. Irrigation Method and Rate

The irrigation method used was flooding only in the late spring to late fall without winter irrigation. Water was let out from the open ditches through valves (Figure S1a) and allowed to gently flood fields completely (Figure S1b), which took about 3 h per acre each week at summer peak (June–August) and bi-weekly in spring and fall.

2.2.4. Soil Sampling and Mineral Analysis

The soils were sampled at 15 cm depth using hand-held core sampler and oven-dried at 65 °C (plus or minus 2 °C) in a forced-air oven for 16 h or until dry. After oven-drying, samples were gently pulverized using an open mesh bottom hammer style soil pulverizer (Humboldt, Raleigh, NC, USA) to remove particles greater than 2 mm. This was based on Texas A&M AgriLife Extension Service soil fertility recommendations. Soil pH was determined in a 1:2 (soil:water) extract using deionized water. Samples were stirred after adding the deionized water and allowed to equilibrate for 30 min. Soil pH measurement measured using a hydrogen-selective electrode [15] and reported on a dry soil basis. Nitrate-nitrogen (NO_3-N) was extracted with a 1 N·KCl solution. Soil nitrate-N was determined using a 10:1 ratio (1 M·KCl: <2 mm pulverized soil). A two-gram soil sample was volumetrically placed in an extraction flask and orbital in a 1-inch orbital throw to agitate at 200 rpm for 5 min before filtration through a Whatman #2 filter. The analysis was then performed via cadmium (Cd) reduction by reducing NO_3-N to NO_2-N using a Cd column followed by spectrophotometric measurement [16,17].

Plant available P, K, Ca, Mg, Na and S were extracted with Mehlich-3 extractant composed of a dilute acid-fluoride-EDTA solution of pH 2.5 that consisted of 0.2 N CH_3-COOH, 0.25 N NH_4NO_3, 0.015 N NH_4F, 0.013 N HNO_3 and 0.001 M EDTA [18,19]. The elements were then determined by Inductively Coupled Plasma (ICP) at Texas A&M AgriLife Extension Service. Orthophosphate (PO_4-P) was determined by the colorimetric method using the ascorbic acid/molybdate reagent after extraction in the Mehlich-3 solution [20]. Plant available micronutrients (Cu, Fe, Mn and Zn) were extracted using a 0.005 M diethylenetriaminepentaacetic acid (DTPA), 0.01 M $CaCl_2$ and 0.10 M triethanolamine solution. A 20 g soil was volumetrically placed in an extraction flask with 40 mL of DTPA extraction solution and orbital in a 1-inch orbital throw to agitated at 180 rpm for 120 min prior to filtration through a Whatman #2 filter [21]. This was then followed by analysis using ICP. Detailed salinity analysis was in the saturated paste of the soil sample with deionized water. The pH and conductivity are measured directly in the paste using a hydrogen ion-selective electrode and conductivity probe. Water was then extracted from the saturated paste using a vacuum extractor followed by determination of Ca, K, Mg and Na in the water by ICP [22].

2.2.5. Experimental Design and Data Analysis

The field was divided into four sections as the replicates with two treatments (data before and after three years of PM application). Pairwise comparison between the two years, assuming equal variance for the samples for all measured soil parameters with four replicates using *t*-test at $p = 0.05$.

3. Results

3.1. Poultry Manure Effects Garden Eggs Phynology

Results showed that establishment of garden eggs at 21 days after planting (DAP) in 2011 was significantly ($p < 0.05$) higher in plants treated with no PM than those treated with PM, while in 2020, plants treated with PM were significantly ($p < 0.05$) higher in plant establishment (Table 3). At the first sampling period (21 DAP), significant differences ($p < 0.05$) were observed between PM and NF in the number of leaves per plant only in 2011. However, at the second sampling period (51 DAP), PM differed significantly ($p < 0.05$) from NF in all three seasons with similar results in the number of branches (Table 3). In addition, at 51 DAP, PM application significantly ($p < 0.05$) affected stem diameter, except in 2011 (Table 3). In terms, of the location, Ashanti-Mampong had better plant heights while higher number leaves and plant diameter were observed in Sunyani with no in plant establishment and canopy (Table 3).

3.2. Poultry Manure (PM) on Garden Eggs Biomass and Yield

The PM treatment was significantly ($p < 0.05$) higher than the NF treatment in dry matter production at both sampling periods for all years, except at 21 DAP in 2020. At harvest, fruit length was significantly affected by PM application, except in 2020. Fruit diameter and fruit yield were also significant ($p < 0.05$) in the PM treatment than the control treatment in all the years (Table 4). Sunyani had a significant effect on dry matter at 21 DAP and fruit length, which may be related to the differences in soil and climate conditions (Table 1) with no differences in fruit diameter and yield. The differences in the locations in terms of fruits and plants traits could also relate to varietal contamination from other varieties since the planting materials are from local farmers.

Table 3. Growth performance of garden eggs in a tropical sandy loam soil in Ghana under poultry manure application.

	%Establishment at 21DAP	Plant Height (cm) 21DAP	Plant Height (cm) 51DAP	No. of Leaves per Plant 21DAP	No. of Leaves per Plant 51DAP	No. of Branches per Plant 21DAP	No. of Branches per Plant 51DAP	Stem Diameter (cm) 21DAP	Stem Diameter (cm) 51DAP	Canopy Width (cm) 21DAP	Canopy Width (cm) 51DAP
2011 (Major Season) Ashanti-Mampong											
NF	85.0(7.5) a	9.7(1.5) b	32.9(3.6) b	5.9(0.2) b	53.1(4.2) b	1.4(0.3) b	10.8(0.6) a	0.4(0.3) a	0.8(0.1) a	28.7(4.9) a	54.7(5.1) b
PM	77.1(9.1) b	11.5(0.5) b	39.4(2.5) a	6.8(0.2) a	63.4(6.9) a	2.3(0.2) a	11.3(0.5) a	0.5(0.4) a	1.1(0.1) a	29.7(3.9) a	63.8(2.5) a
2020 (Major Season) Sunyani											
NF	87.7(6.2) a	17.1(0.6) b	36.8(1.9) b	5.7(0.3) a	27.9(0.5) b	2.1(0.1) a	10.9(0.2) b	0.6(0.0) a	1.5(0.0) b	20.9(0.4) b	39.9(3.1) b
PM	88.7(4.3) a	22.0(0.4) a	58.0(1.5) a	7.8(0.7) a	50.2(1.2) a	2.3(0.1) a	18.4(0.2) a	1.0(0.0) a	2.4(0.1) a	26.8(1.9) a	59.3(0.8) a
2020 (Minor Season) Sunyani											
NF	80.0(2.5) b	11.6(0.3) b	28.4(0.2) b	6.6(0.3) a	28.6(1.3) b	2.1(0.4) a	10.7(0.5) b	0.4(0.1) a	0.9(0.0) b	21.9(1.0) b	38.9(1.9) b
PM	86.7(3.0) a	13.1(0.3) a	46.9(1.2) a	7.0(0.7) a	53.2(3.6) a	2.1(0.3) a	16.8(0.3) a	0.5(0.0) a	1.6(0.0) a	30.5(0.4) a	61.8(1.7) a
Location											
Ashanti-Mampong	81.3(13.7) a	10.6(2) b	36.2(6) a	6.4(0.8) a	58.3(10.5) a	1.9(0.7) a	11.1(0.9) a	0.4(0.1) b	1.0(0.2) b	29.2(6.8) a	59.3(8) a
Sunyani	85.8(5.9) a	15.9(1.8) a	42.5(10.9) a	6.8(0.8) a	40.0(13) b	2.1(0.3) a	14.2(3.8) a	0.6(0.1) a	1.6(0.4) a	25.0(4.1) a	50.0(11.7) a

Poultry manure (PM), No fertilization (NF), Days after planting (DAP). (The same letter (a) means no significant difference while different letter (a, b) means significant differences at $p = 0.05$, the numbers in brackets represent standard deviations). Averages of the two seasons in Sunyani were used for the location analyses.

Table 4. Biomass and yield performance of garden eggs in a tropical sandy loam soil in Ghana under poultry manure application.

	Dry Matter (kg/ha) 21 DAP 51 DAP		Fruit Length (cm)	Fruit DIAMETER (cm)	Fruit Yield (kg/ha)
2011 (Major Season) Ashanti-Mampong					
NF	1(0.4) ^{b}	14(4.3) ^{b}	3.3(0.1) ^{b}	4.4(0.1) ^{b}	454(52.0) ^{b}
PM	2.5(0.5) ^{a}	35.9(1.3) ^{a}	3.7(0.1) ^{a}	5.2(0.1) ^{a}	676(128.3) ^{a}
2020 (Major Season) Sunyani					
NF	3.7(0.4) ^{b}	18(1.5) ^{b}	6.9(0.4) ^{b}	3.3(0.1) ^{b}	400(55.3) ^{b}
PM	7.8(0.5) ^{a}	31.8(0.5) ^{a}	9.6(0.2) ^{a}	5.7(0.1) ^{a}	740(22.2) ^{a}
2020 (Minor Season) Sunyani					
NF	3.8(0.5) ^{a}	19.8(0.9) ^{b}	4.4(0.1) ^{b}	3.3(0.0) ^{b}	299(4.5) ^{b}
PM	4.5(1.2) ^{a}	35.5(1.0) ^{a}	7.2(0.0) ^{a}	4.9(0.0) ^{a}	539(10.8) ^{a}
Location					
Ashanti-Mampong	2.1(1.2) ^{b}	30(15.2) ^{a}	3.5(0.3) ^{b}	4.8(0.4) ^{a}	565.1(194.0) ^{a}
Sunyani	5.9(1.9) ^{a}	31.5(9.7) ^{a}	7.3(1.4) ^{a}	4.5(1.0) ^{a}	512.4(158.3) ^{a}

Poultry manure (PM), No fertilization (NF), Days after planting (DAP), (The same letter (a) means no significant difference while different letter (a, b) means significant differences at $p = 0.05$, the numbers in brackets represent standard deviations). Averages of the two seasons in Sunyani were used for the location analyses.

3.3. *Manure Effect on Soil Minerals and Salt in Arizona Semi-Arid Pasture Soil under Flood Irrigation*

3.3.1. Manure Application and Soil pH

The PM application did not significantly impact the soil pH; only a 2% reduction in soil pH was recorded (Figure 1a).

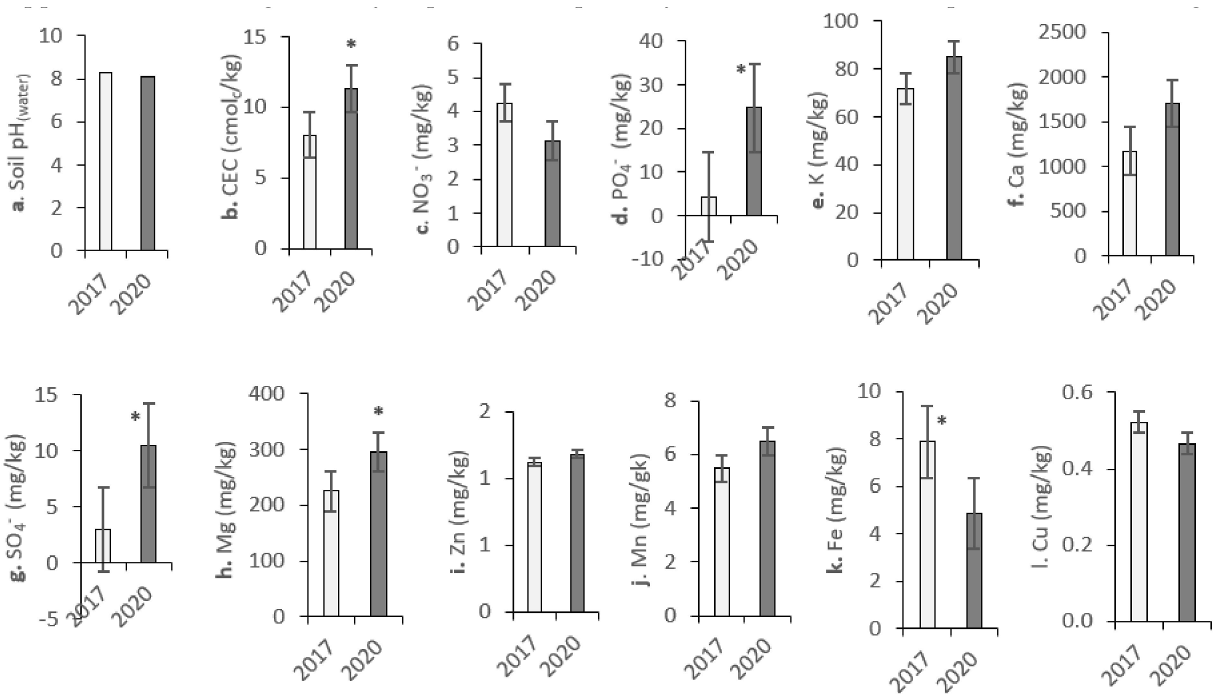

Figure 1. Soil chemical properties of organic transitioning fine sandy loam pastureland after three years of poultry. manure application under flood irrigation with no-till (* = significant in *t*-test at $p = 0.05$).

3.3.2. Manure Application and Soil Cation Exchange Capacity (CEC)

The cation exchange capacity (CEC) was significantly ($p < 0.05$) affected by PM applications with up to 41% increase after three years of annual application (Figure 1b).

3.3.3. Manure Application and Soil Mineral Nutrients

The application of PM to the fine sandy loam pastureland under flood irrigation with no-till affected soil minerals in the soil differently. Nitrate, Fe and Cu levels reduced by 26, 38 and 11% without significant differences (Figure 1c,k,l), while K and PO_4-P levels increased by 18 and 471%, respectively, with a substantial increase in P (Figure 1d,e). Other nutrients such as Ca, S and Mg, also increased by 45, 244 and 31%, respectively, with a significant difference in S and Mg, compared to the control (Figure 1f–h). For the micronutrients, Zn and Mn increased by 5 and 19%, respectively (Figure 1i,j).

3.3.4. Manure Application and Soil Salinity

The base saturation of salts in the study area, Ca represents more than 70% of salt in the area, followed by Mg with about 20%, with K and Na representing the least salt in the area. While Ca recorded just a 2% increase, Mg, K and Na recorded a decline over the study period by 5, 15 and 11%, respectively (Figure 2).

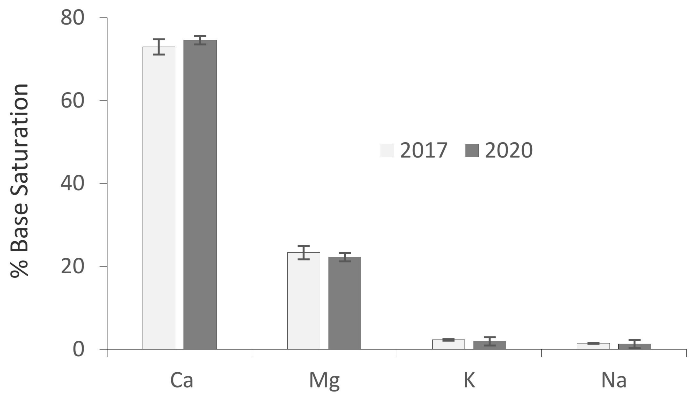

Figure 2. Base saturation in fine sandy loam pastureland after three years of poultry manure application. under flood irrigation with no-till.

4. Discussion

Manure application in the fields has many benefits ranging from improving soil physical, chemical and biological properties to promote plant growth and yield. This study demonstrated that the sole PM application increased garden egg performance and soil minerals on tropical Ghanaian and semi-arid Arizona-United States sandy-loam soils, respectively. The finding in this study, in contrast with previous studies, is essential to organic producers and small producers who cannot use synthetic fertilizers due to regulations or cost.

4.1. PM Effects on Growth and Yield of Garden Eggs

In soils with limited fertility, especially total N (Table 1) in tropical soils, PM application increased growth and yield of garden eggplants (Tables 3 and 4) on a slightly acidic sandy-loam soil. In most cases, on day 21 and 51 after transplanting, plant height, the number of leaves per plant and the canopy width of the garden eggs were over 25% more under PM fertilization when compared to no fertilization (Table 3). The growth performance enhanced by the PM enables better health and photosynthetic assimilation (increased dry matter), which is reflected in the yield performance (Table 4). While the combination of PM with synthetic NKP fertilizers is reported to perform better than sole application of NPK or PM [11,23] it is important to note that not all systems can use synthetic NPK either because of cost or regulations, making the finding in this study that compares PM to no fertilization crucial to the category of producers who are only interested in sole PM applications. Location of the studies had no significant influence on the yield though some slight differences were observed in plant heights and fruits length, which may be due to the difference in varietal traits (Tables 3 and 4). Furthermore, in the long-term, the use of PM could be more beneficial on soil health, carbon sequestration, soil fertility (Figure 1b,d–j) and economical to small-scale and organic producers.

4.2. PM Effects on Soil Dynamics (Physical, Chemical and Biological Properties)

The positive results of PM reported in many studies on increased crop yield [4,24,25] could be associated with the mineral nutrient supply from the PM (Table 2) [9]. In a similar study with tomatoes, compost with PM significantly increased both biomass and shoot N content over the control with no fertilization [26]. Adekiyaa and Agbede also reported an increase in tomato shoots' nutrient content due to PM's application [27]. Associated mechanisms for the crop improvements and yield as observed in the garden eggs (Tables 3 and 4) and other crops after PM applications are related to improving soil health, soil water relations [4,24], soil CEC and both macro and micronutrients (Figure 1b,d–j) [9,27]. These benefits are influenced by many factors such as in creasing soil pH due to the high cations such as Calcium in the PM, increasing in organic matter content and induced microbial activities which slowly release sparingly soluble minerals in PM (Table 2) for plant uptake [9]. This slow release of nutrients from PM permits nutrients availability to the plant throughout the life cycle than the readily available synthetic fertilizers, which can easily be leached away by heavy rains. In addition, application methods and timing, temperatures and farm management practices and systems could influence PM effectiveness in the field [22]. For example, the reduction in nitrate content in the soil of Arizona after three years of PM application (Figure 1c) could relate to the management practices such as no-till and flood irrigation methods used (Figure S1) [28]. Surface manure application without tillage and incorporation can lead to N and P losses through run-off [28–30], which could lead to environmental pollution [25]. Nitrate form of N is very mobile in the soil, especially in sandy soils, hence using flood irrigation could leach it out as observed in Figure 1c.

The continual application of PM could lead to salt build up in the soils, but in this study, the salt contents were relatively low (Figure 2) after three years, which could be due to the flood irrigation (Figure S1). The use of PM is a sustainable practice with both economic and environmental benefits. However, best management practices such as using the right irrigation methods, application rates and timing and tillage practices must be considered critically to minimize possible environmental issues [31–33].

5. Conclusions

Poultry manure (PM) applications improved growth parameters and yield of garden eggs in tropical sandy-loam soils of Ghana and soil fertility response in semi-arid cropland in Arizona. However, best management practices are required to reduce the risk of nitrate leaching.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/nitrogen2030022/s1, Figure S1: A ditch flow (a), flooded pasture field (b), and grazing cattle at the University of Arizona Cracchiolo DK Ranch experiment station (c).

Author Contributions: Conceptualization, I.K.M., E.A., H.K.D. and K.G.S.; methodology, I.K.M., E.A. and K.G.S.; formal analysis, I.K.M. and E.A.; resources, I.K.M. and E.A.; data curation, I.K.M. and E.A.; writing—original draft preparation, I.K.M.; writing—review and editing, I.K.M., K.G.S., E.A. and H.K.D.; visualization, I.K.M. and E.A.; supervision, I.K.M., K.G.S. and H.K.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data for the study is not publish anywhere but stored locally and could be made available by a formal written request.

Acknowledgments: Thanks to Charlee Boroski for coordinating the 2017 soil sampling and analysis at the University of Arizona Cracchiolo DK Ranch in Arizona, USA.

Conflicts of Interest: The authors declare no conflict of interest.

Sample Availability: Not available.

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