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Research article

Influence of organic fertilization on growth and yield of strawberry *(Fragaria × ananassa)* in Kabete and Mbooni areas, Kenya

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ABSTRACT

Strawberries are a valuable crop in Kenya with the potential for significant economic contributions. However, strawberry production in the country has been facing considerable challenges, impacting its economic potential. This study examined the influence of organic manure on strawberry growth and characteristics in Kabete and Mbooni areas in Kenya. The study used a randomized complete block design (RCBD) with three replications. Treatments included livestock manure (well composted mixture of chicken, goat, and cow manure), bokashi manure, and a control, coded as LivManure, BokManure and Control, respectively. Growth parameters including leaf area, number of white flowers and number of runners, as well as yield parameters such as the number and weight of strawberries were assessed from the 3rd to 10th week after transplanting, during the short rain season of 2021. Using R statistical software, linear models were fitted to datasets from both study sites and analyzed using one-way ANOVA, followed by post-hoc tests for multiple comparisons. The rigorous analysis of the Kabete and Mbooni datasets provided insightful revelations about the influence of different treatments on strawberry characteristics, and geographical disparities between the two regions. The analysis of variance (ANOVA) outcomes unveiled significant treatment effects in both sites, with $F(2,69) = 62.57$, $p < 0.001$ for Kabete and $F(2,69) = 49.02$, $p < 0.001$ for Mbooni, highlighting distinct influences of treatments on log values within each group. Post hoc analyses, including Tukey tests and bootstrap comparisons robustly validated the significant differences among the three treatments in each site, supported by p-values <0.001. Effect sizes were also employed to reinforce the findings, and planned contrasts were set to gain more power in the analysis of variance. Comparison between Kabete and Mbooni indicated a significant difference of 9.78 units, with Mbooni area exhibiting significantly higher strawberry characteristics compared to Kabete. The results showed that LivManure treatment had the highest mean in both sites, followed by BokManure and Control treatments, respectively. These findings have important implications for agriculture, and highlight the potential benefits of using LivManure treatment to improve strawberry characteristics in similar agroclimatic settings. These observations can be attributed to the beneficial effects of livestock manure on soil health, which include buffering of the soil reaction, provision of essential plant nutrients and enhancement of soil faunal activities. Balanced use of livestock manure is recommended to enhance soil macro and micronutrients, and soil reaction for improved growth and yield of strawberry.

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1. Introduction

Strawberries, recognized for their unique health benefits [1,2] and global demand (FAO, 2019), are increasingly sought after in modern markets, emphasizing the need for aesthetically pleasing, highly nutritious, and high-quality berries. These fruits are not only rich in minerals, vitamins, organic acids, and anti-carcinogens, but also offer cardiovascular benefits [3]. Nevertheless, strawberry cultivation in Kenya faces multifaceted challenges, including soil degradation, pest and diseases pressures, and high cost of chemical fertilizers [4]. To bolster strawberry growth, quality and productivity, organic fertilizers have gained prominence for their capacity to supply essential nutrients, and promote faunal activities in the rhizosphere [5–7] Strawberry cultivation is a global practice, adapting to various climatic conditions and farming systems [8]. The yield of strawberry hinges upon the cultivation system, and the choice of cultivar [9]. Breeding efforts have also yielded agronomically and climatically resilient strawberry cultivars [10].

For enhanced production and quality, combining inorganic and organic fertilizers, particularly under organic farming systems, has shown promise [7,11,12]. Organic fertilizers have shown to produce more healthier fruits compared to chemical fertilizer treatments [11,12]. The reliance on pesticides and chemical fertilizers in agriculture since the agrarian revolution has had detrimental effects on environmental health, including impacts on flora, fauna, and soil and water pollution [13,14]. Agronomic practices and landscape changes have resulted in adverse nutrient leaching, soil and water pollution, pesticide resistance, and species extinction [15–18], leading to a decline in strawberry yields.

Organic agriculture, leveraging organic sources such as animal manure, compost, and nitrogen-fixing leguminous crops [19], offers a more sustainable approach to supply plant nutrients. Chicken manure, owing to its high nitrogen content, is highly desirable [20]. Besides nutrient supply, organic matter from manure enhances soil health [21], improves moisture retention, nutrient availability, and soil physical properties [22,23], and contributes to crop productivity and soil health [24–27].

Notably, soil macronutrients (nitrogen, phosphorus and potassium), are often limiting in Kenyan soils due to factors like soil pH, continuous cropping, and high leaching rates associated with chemical fertilization [28,29]. Balancing nutrient replenishment through organic and inorganic means is crucial for soil sustainability [30]. Continuous use of chemical fertilizers can lead to soil degradation and declining crop yields [31]. Therefore, there is growing interest in adopting organic soil inputs [32] to maintain soil physico-chemical and biological qualities.

The use of organic soil inputs has become an essential component of sustainable agricultural production systems [33,34], enhancing soil chemical, physical, and biological health [35]. Combining organic materials with chemical formulations fosters soil microbial diversity, nutrient use efficiency, and consequently, plant nutrition and yield [36]. Excessive use of chemical fertilizers has been linked to soil deterioration and yield decline [37].

Studies on horticultural crops reveal that organic production methods yield fruits and vegetables with elevated levels of beneficial compounds, such as flavonoids, phenols, anthocyanins, organic acids, ascorbic acid, and sugars, when compared to conventional systems [38–40]. Growing concerns about the health implications of synthetic chemicals have driven the upward trend in organic agriculture [41]. The simultaneous use of organic and mineral fertilizers in agriculture has shown promise for soil fertility management and increased crop production [42]. Previous research indicates increased strawberry production under organic farming systems [5].

Amidst the rapid population growth in Sub-Saharan Africa, the need for strategies that boost crop production while preserving environmental integrity is pressing. Achieving the United Nations' Sustainable Development Goal Number 2, aiming for zero hunger, faces a significant challenge in the form of soil degradation [43]. Inefficiencies in nutrient use, declining crop yields, and issues like low organic matter, micronutrient deficiency, and soil acidification threaten agricultural systems relying solely on chemical fertilizers [44,45]. Soil acidity, especially in humid areas, results in phosphate fixation, necessitating liming to address the acidity. Despite the need for micronutrients being influenced by macronutrient deficiency, many farmers in Kenya neglect to apply organic inputs to their soils [46,47]. Prior studies in Kenya have documented the benefits of combining organic and inorganic fertilization in crop production, resulting in improved yields, enhanced nutrient use efficiency, soil fertility and increased faunal activities [48–51].

One major challenge impeding the adoption of organic farming is the limited availability of organic inputs.as many serve multiple purposes, including use as animal feeds [52]. Bokashi, as an organic amendment, offers a sustainable solution for soil management. Comprising dried manure, forest soil, rice bran, rice husk charcoal and beneficial micro-organisms, bokashi provides a reliable source of soil nitrogen and enhances soil faunal activities. The primary focus of this study is the declining strawberry production in Kenya, with an evaluation of whether organic amendments can boost strawberry performance and yields. This research investigates the influence of livestock manure and bokashi on strawberry production in Kabete and Mbooni areas in Kenya. Bokashi manure has a nutrient-rich composition [53–55], which includes a diverse array of beneficial microorganisms, making it an exceptional organic fertilizer. Strawberry plants treated with bokashi manure exhibit increased fruit yields, larger and juicier berries, and improved resistance to common pests and diseases [56]. Moreover, bokashi manure's positive impact extends beyond strawberries, benefiting a wide range of garden and agricultural plants. Its ability to enrich soil quality, enhance nutrient availability, and promote microbial activity contributes to healthier and more productive vegetation [57] in a sustainable and environmentally friendly manner.

The significance of this research extends beyond strawberry cultivation and organic soil inputs; it underscores the critical importance of agroecosystem sustainability. In an era marked by growing global population and increased demands for agricultural produce, the imperative for sustainable practices cannot be overstated. Agroecosystem sustainability represents the linchpin upon which food security, environmental health, and economic viability hinge [58,59]. By focusing on the application of organic amendments and their influence on strawberry production, this study not only addresses the pressing issue of declining yields, but also contributes to the broader conversation on how sustainable agricultural practices can mitigate the adverse effects of soil degradation, chemical inputs, and environmental impacts. The benefits of sustainable agricultural practices have also been documented in previous studies [60,61].

2. Materials and methods

2.1. Study area

This study was carried out for one season, from January to March of 2021, in two sites including Kabete and Mbooni areas in Kenya. Kabete site is situated within the University of Nairobi, College of Agriculture and Veterinary Sciences, and lies on latitude 1° 15′ S and longitude 36° 44′ E, having an average altitude of 1940 m above mean sea level. The area falls under agroclimatic zone III (sub-humid), featuring two distinct rainy seasons averaging 1006mm/annum [62], and an average annual temperature of 18 °C [63]. The geology comprises of predominantly trachytes of tertiary age [64], and the soils have been classified as Mollic Nitisols [65]. Mbooni site, on the other hand, is situated in Mbooni Hills (latitude: 1° 42′ S, longitude: 37° 27′ E), and is characterized partly under agroclimatic zone II and partly under agroclimatic zone III, having an altitude of over 1800 m above mean sea level. The prevailing temperatures in Mbooni exhibit variations throughout the year, ranging from 18 °C to 28 °C. The rainfall pattern is bimodal, ranging from 1200 to 1600 mm/annum [32], but is less consistent compared to Kabete's. The soils of Mbooni developed from predominantly granitoid and quartzofeldspathic gneisses, and are classified as Humic Cambisols [32].

2.2. Study design and agronomic practices

This study was deliberately conducted in open fields, to reflect the real-world agricultural conditions commonly practiced by local strawberry growers in the regions. The approach allowed for close emulation of the conditions under which farmers typically cultivate strawberries, ensuring that the findings directly apply to their agricultural practices. The study areas were selected based on diverse geographical and agroecological factors, whereby Kabete in Nairobi County, is characterized by sub-humid climate and well-drained soils, offers an ideal environment for strawberry cultivation. In contrast, the site in Mbooni, located in a sub-humid region bordering a semi-arid region (large part of Makueni County), has relatively warner climate and younger soils, suitable for fruit production compared to Kabete. Conducting research in these distinct areas allowed for exploration of the influence of geographic factors on strawberry characteristics, and assessment of the adaptability of organic amendments under varying environmental conditions, which is crucial for enhancing crop production sustainability. Inherent fertility status of the soil was inferred from previous studies in the same sites [32,66].

The experiment was laid out in a randomized complete block design with three replicates, each consisting of three treatments: livestock manure, bokashi, and a control group. This design resulted in a total of nine plots. Each experimental plot measured four square meters and contained25 strawberry plants. Data collection focused on the nine central plants in each plot. The livestock manure, which was a blend of poultry, goat and cow manure, was first well decomposed separately in heaps, then mixed in a 2:1:1 ratio, respectively. was This ratio was selected based on theoretical principles and a comprehensive review of literature [27,67–71], that suggest the superiority of poultry manure compared to other animal manures. The livestock manure was then mixed thoroughly with the soil using a fork jembe. The bokashi used in this study was sourced from the Kenya Institute of Organic Farming (KIOF). These treatments were applied to the soil a week before planting. Livestock mixture manure was applied at the rate of 5 t/ha (equivalent to 80 kg per plot), while bokashi was applied at the rate of 2 t/ha (equivalent to 40 kg per plot). The application rates were guided by secondary data from previous studies [66] in the study areas, that involved soil analysis. The application rate for bokashi is the blanket recommendation by the manufacturer (KIOF), applicable for most Kenyan soils. The strawberry plants were transplanted from nursery to a well-prepared, fine-tilth seedbed, with a spacing of 30 cm by 30 cm. Standard agronomic practices, including watering, weeding, and pruning, were implemented. Notably, no inorganic inputs were considered due to the agroecological nature of the study.

2.3. Data collection

Data collection rigorously followed established Standard Operating Protocols (SOPs) to guarantee both consistency and accuracy. These SOPs encompassed statistical and experimental aspects, aimed at minimizing the likelihood of outliers and ensuring that plot characteristics accurately represented their respective treatments without interference or interactions. Similar experimental protocols have been employed in other studies [37]. Data for each parameter was collected thrice between the 3rd to 10th week of transplanting. The data collected included leaf area, number of white flowers, number of runners, number of fruits, weight of strawberry fruits, number of leaves, plant coverage and crop appearance. Leaf Area Index (LAI) was calculated using the lengths and the widest section width of the first, middle, and last leaf. The formula for LAI is as follows:

LAI = ((Area of first leaf + Area of middle leaf + Area of last leaf)/3)/Area of the ground.

This calculation considers the average leaf area of the first, middle, and last leaves, and it is divided by the ground area to obtain the LAI. The approach provides a more representative estimate of LAI by averaging the leaf areas of the three leaves. The number of fully developed runners were counted thrice, after every two weeks, from the 6th week after transplanting. The number of strawberry and weight were determined by counting and weighing on a weighing balance, respectively. The total number (count) of fresh leaves was recorded thrice from the 4th week to the 8th week. General appearance of the crops was scored thrice, biweekly, from the 3rd week of transplanting.

2.4. Data analysis

The data was analyzed using R Core Team software [72] version 4.3.1 of 2023, whereby various statistical tests were employed to gain insights into the effects of different treatments on strawberry characteristics in Kabete and Mbooni sites. Descriptive statistics from the pastecs package [73] was used to summarize the central tendencies and distributions of the data. Levene's test from the car package [74] was used to assess the homogeneity of variance among the groups, while Shapiro-Wilk test from the stats package was used to assess the normality of the data distribution. Log transformation of the data was done where either of the assumptions of ANOVA was violated (p-value <0.05). ANOVA models from the car package [74] were fitted to examine the influence of treatments on log values, with planned contrasts enhancing the understanding of treatment effects. The planned contrasts from the emmeans package [75] were defined as [-2,1,1] [0,-1,1] for the first and second contrasts, respectively. Effect size analysis was done using mean difference effect size (mes) and Tukey post hoc tests using the glht function from the multcomp package, version 1.4–17 [76] were applied to discern specific differences among treatment groups. Robustness to the analyses was introduced through the use of trimmed means and bootstrapping techniques from the boot package [77] to provide robustness to the analyses. All analyses aimed to elucidate the significant influence of treatments, offering nuanced insights into the relationships within the datasets, and understanding of agricultural practices' effects on the studied variables. Plotting utilized the ggplot2 function [78].

3. Results

3.1. *Effect of different treatments: descriptive statistics*

In the Kabete site, Control treatment had a mean log value of 0.368, with a median of 0.301, reflecting the distribution's central tendency. The bokashi manure (BokManure group) had a mean log value of 0.929 and median of 0.903. Comparatively, the livestock manure (LivManure group) showcased a mean log value of 1.233, with a median of 1.204. In Mbooni site, Control group exhibited a mean log value of 0.549 with a median of 0.477. BokManure had a mean log value of 0.965 and a median of 0.903, while the LivManure had a mean log value of 1.269 and a median of 1.23. These findings intricately captured the distributional profiles, central tendencies and variabilities of log values across treatment groups, enriching our understanding of the underlying dynamics. Line graphs for both sites are presented in Fig. 1.

For each variable assessed across the three distinct treatments, variations in both the mean and median values were observed. In Kabete, in terms of leaf area, the LivManure treatment exhibited the highest mean and median values (Mean: 1.687159, Median: 1.681250), indicating its potency in promoting leaf growth. Conversely, the Control treatment yielded lower mean and median values (Mean: 1.101531, Median: 1.079217). Notably, the number of runners displayed substantial differences, with the LivManure treatment leading (Mean: 1.143175, Median: 1.146159) and the Control treatment trailing behind (Mean: 0.200976, Median: 0.301247). A similar pattern was observed in the number of white flowers and number of fruits. Additionally, the LivManure treatment consistently excelled in parameters like average weight of fruits (Mean: 1.221197, Median: 1.204147) and number of leaves (Mean: 1.361473, Median: 1.361473). Conversely, the Control treatment often recorded the lowest values. Plant coverage and crop appearance mirrored these trends. These findings underscore the significant impact of treatment type on the tested horticultural variables.

Across the three distinct treatments in Mbooni, significant variations were observed in both the mean and median values of various horticultural variables. In terms of leaf area, the LivManure treatment displayed the highest mean and median values (Mean: 1.710, Median: 1.698), while the Control treatment had the lowest (Mean: 1.253, Median: 1.255). Similar patterns emerged in the number of runners, white flowers, and number of fruits, with the LivManure treatment consistently outperforming the Control treatment.

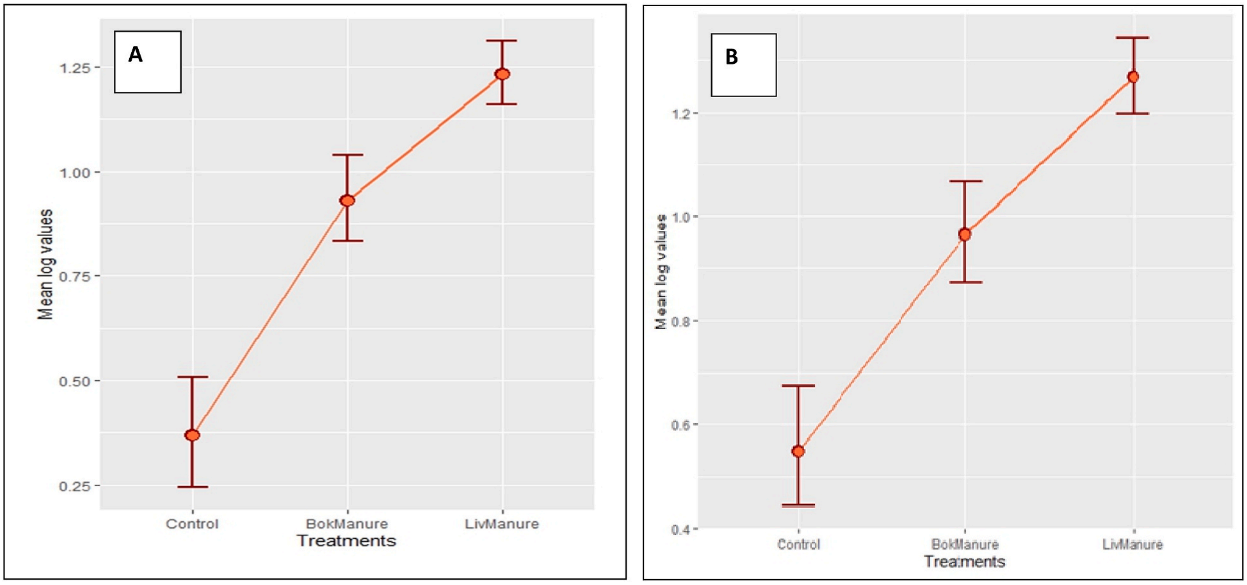

Fig. 1. Distributional presentation of the log mean values across the treatments in Kabete (A) and Mbooni (B).

Moreover, the average weight of fruits and the number of leaves exhibited the same trend, where LivManure excelled. Plant coverage and crop appearance followed a similar pattern as well, further emphasizing the substantial influence of treatment type on these horticultural variables in Mbooni.

3.2. The influence of manure treatments on strawberry characteristics: ANOVA

In Kabete, the extended linear model explored the influence of both treatments and blocks on log values. The results indicated a significant treatment effect ($F(2,68) = 61.773$, $P < 0.001$), indicating varying influence among treatment groups. In Mbooni site, ANOVA, underscores significant variations across the treatments ($F(2,68) = 48.511$, $P < 0.001$), also signifying distinct influence of different treatments on log values. The residuals exhibited a mean square of 0.075 and 0.0646 in Kabete and Mbooni, respectively, representing variability within treatment groups after accounting for treatments and block effects. Blocks in both study sites did not contribute significantly to the variance, suggesting lack of a discernible pattern across blocks.

ANOVA tests were also conducted to examine the impact of different treatments on the various strawberry variables. In Kabete, the results revealed significant treatment effects across the variables. Specifically, a highly significant effect was observed in leaf area ($F(2, 5) = 550.764$, $p < 0.001$), as well as in the number of runners ($F(2, 5) = 112.069$, $p < 0.001$), number of white flowers ($F(2, 5) = 39.168$, $p = 0.001$), number of fruits ($F(2, 5) = 82.18$, $p < 0.001$), average weight of fruits ($F(2, 5) = 141.327$, $p < 0.001$), number of leaves ($F(2, 5) = 1342.394$, $p < 0.001$), and crop appearance ($F(2, 5) = 99.39$, $p < 0.001$). These results highlight the statistically significant impact of the treatments on the measured variables, underscoring the importance of treatment choices in influencing plant growth and characteristics.

In Mbooni, for leaf area, a significant difference was found ($F(2, 5) = 204.579$, $p < 0.0001$). Similarly, for the number of runners, the treatments had a significant impact ($F(2, 5) = 161.36$, $p < 0.0001$). The number of white flowers showed significant differences ($F(2, 5) = 64.441$, $p = 0.00027$). For the number of fruits, the treatments had a significant effect ($F(2, 5) = 113.948$, $p < 0.0001$). The average fruit weight demonstrated significant differences as well ($F(2, 5) = 47.109$, $p = 0.00057$). The number of leaves displayed highly significant variation ($F(2, 5) = 331.403$, $p < 0.0001$), along with plant coverage ($F(2, 5) = 62.778$, $p = 0.000287$) and crop appearance ($F(2, 5) = 170.991$, $p < 0.0001$).

3.3. Increasing the power of ANOVA by setting contrasts

Contrasts were set for both Kabete and Mbooni datasets to enhance the understanding of treatment effects, through assigning specific values to the contrast matrix. In Kabete, subsequent ANOVA had the intercept standing at 0.871, and coefficients for individual contrasts reflecting treatment specific effects (0.238 and 0.152 for bokashi and livestock manure, respectively). The model's adjusted R-squared of 0.6296, F-statistic: 41.22, p-value < 0.001 underscore the statistical significance and explanatory power of the model, accounting for the variance. Mbooni site revealed stronger significant differences after the contrasts (adjusted R-squared = 0.5749, F-

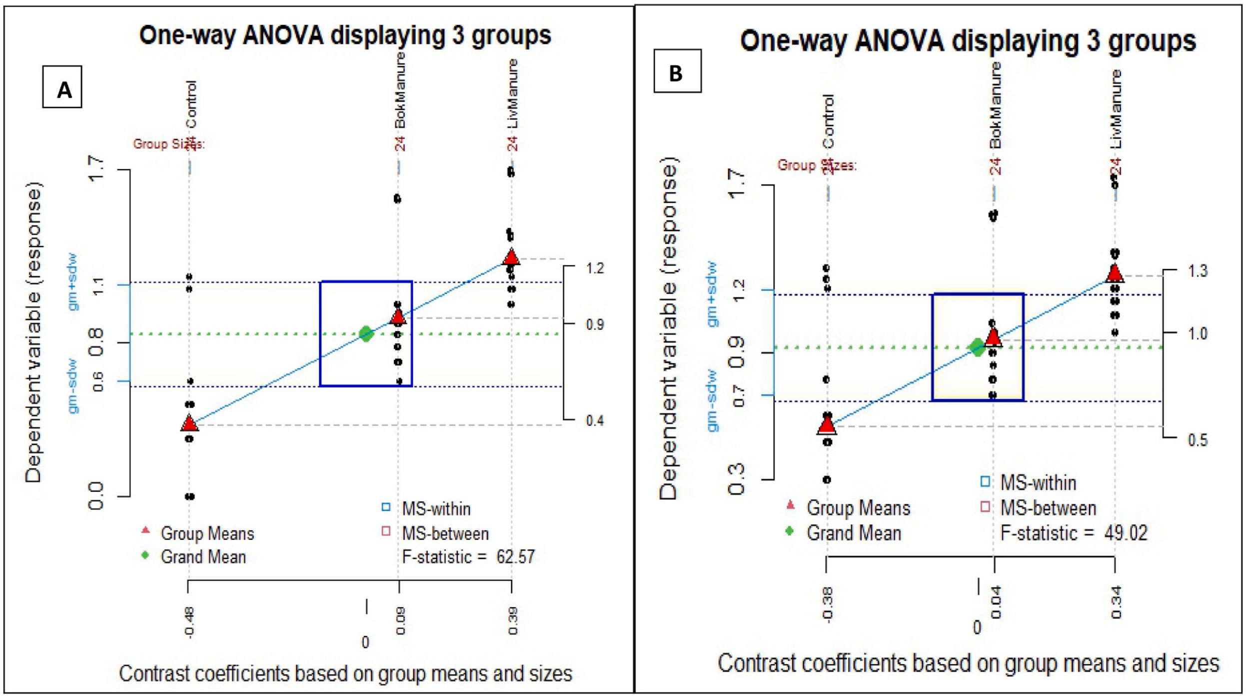

Fig. 2. Graphical ANOVA for Kabete (A) and Mbooni (B).

statistic = 49.02, p-value <0.001). The intercept stood at 0.93, while bokashi and livestock manure had coefficients of 0.19 and 0.15, respectively. The coefficient for blocks was non-significant in both areas. The levels of variation were significantly higher after setting contrasts compared to analysis of variance without contrasts.

3.4. *Graphical analysis of variance (Granova) among the treatments*

In Kabete, the overall grand mean of 0.84 signifies the central tendency across treatments. The ANOVA breakdown showcases a substantial effect of treatments ($F = 62.57$, $p < 0.001$) on log values, with a significant SS.bet/SS.tot ratio of 0.64. Among individual treatment contrasts, control exhibited a weighted mean of 0.37, while bokashi and livestock manure displayed a weighted means of 0.93 and 1.23, respectively. In Mbooni, the grand mean was 0.93 ($F = 49.02$, $p < 0.001$), with a significant SS.bet/SS.tot ratio of 0.59, underscoring the robustness of the observed differences. The ensuing pairwise comparisons revealed intriguing contrasts, with control having a mean log value of 0.55, BokManure with 0.97, and LivManure with 1.27. These findings shed light on the nuanced relationships among treatment groups, thereby enhancing our understanding of the datasets' dynamics. The graphics are presented in Fig. 2.

3.5. *Robust methods: trimmed means and bootstrapping*

Since homoscedasticity assumption is not required for trimmed means, their use in this analysis was aimed to be a robust technique to reduce the influence of any outliers and heavy tailed distributions. Using a generalization of Welch's method, the trimming proportion was set to 0.2, such that the top and bottom 20 % of the data were removed before calculating the means. The results provided a strong evidence for significant differences in log values among the three groups. In Kabete, the calculated F-statistic of 89.8385 with p-value <0.001 indicates significant differences among treatment groups in terms of log values. The effect size measure (explanatory measure of effect size) of 0.83 suggests a substantial effect of the treatments. The bootstrap confidence interval (CI) for the effect size falls between 0.76 and 0.98, which indicates a high degree of confidence in the estimate, reinforcing the robustness of the observed treatment effects and underscoring the substantial and meaningful differentiation in log values across the treatment groups. Mbooni site demonstrated a similar trend with F-statistic of 106.8333 with p-value <0.001, having an effect size of 0.82 and bootstrap CI of 0.7 and 0.94.

Bootstrap resampling was used in this analysis as a robust method to account for variability in the data, and to provide more accurate estimates of the p-value and effect size. The results provided strong evidence for significant differences among the three groups. The mcppb20 analysis was used to discern corresponding post hoc tests, yielding significant contrasts among the three treatment groups across the two study sites.

3.6. *Post-hoc tukey test: between-treatment variations*

This was done after ANOVA to determine treatments' pairwise comparisons. In Kabete, the difference between: BokManure and Control (Estimate = 0.56115, $t = 7.108$, $p < 0.001$), LivManure and Control (Estimate = 0.86486, $t = 10.955$, $p < 0.001$), and LivManure and BokManure (Estimate = 0.30371, $t = 3.847$, $p = 0.000831$) all exhibit significant differences. A plot of the test is presented in Fig. 3. The Tukey method was aimed to control the family-wise error rate when making pairwise comparisons among multiple groups.

In Mbooni site, the difference between: BokManure and Control (estimate = 0.41630, $t = 5.704$, $p < 0.001$), LivManure and Control (estimate = 0.71968, $t = 9.861$, $p < 0.001$), and LivManure and BokManure (estimate = 0.30338, $t = 4.157$, $p = 0.00028$), similarly showing significant differences. A plot of the test is presented in Fig. 4. In Figs. 3 and 4, the confidence interval for the difference between any two group means did not cross zero, signifying that the observed variation was not random.

3.7. *Treatment effects on log values*

Compact letter display was used the present the influence of each independent treatment on the log values (Table 1). Violins from

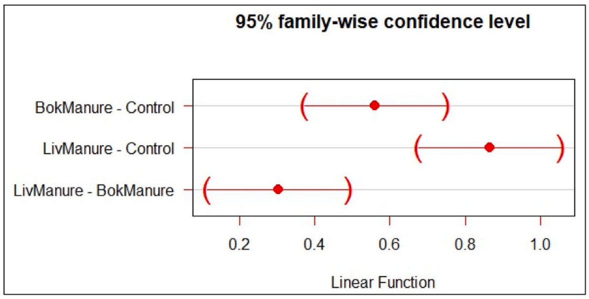

Fig. 3. Graphical presentation of Tukey post hoc test in Kabete site.

both sites (Fig. 5) showed data having some degree of skewness in the higher values direction. The violins were relatively wide in spread, indicating higher variability in the data. Based on the density within the violin, it was evident that there were differences in treatment means across the treatments. The box plots within the violins provided information about the quartiles, median, and potential outliers, therefore complementing the visual cues from the violin plot.

3.8. *Effect sizes: the magnitude of treatment variations*

The effect size analysis offered a revealing lens to examine treatment effects. All comparisons from either group in both sites yielded a large effect size (Cohen's d of 0.8 or larger), having substantial Percentage of Overlapping Area (U3), Common Language Effect Size (CLES) and Cliff's Delta. These results indicate the robust and statistically significant impact captured by the effect size analysis.

3.9. *Trend analysis among the treatments*

In both sites, the treatments factor was explored in terms of its linear and quadratic trends. In Kabete, the intercept stood at 0.84329 with a highly significant t-value of 26.332, indicating a substantial difference from the reference category. The linear coefficient of 0.61155 ($p < 0.001$) signifies a strong linear effect, while the quadratic coefficient of −0.10510 suggests a marginal quadratic effect that is approaching significance ($p = 0.0623$). In Mbooni site, the intercept stood at 0.92764, with a highly significant t-value of 31.134, also indicating a substantial difference from the control. The coefficients of the linear and quadratic terms were estimated to be 0.509 and −0.046, respectively. The linear term was highly significant ($p < 0.001$), whereas the quadratic term was not significant ($p < 0.375$). These observations suggest that the relationship between the treatments and log values is predominantly linear, with effect increasing from Control, to BokManure, to LivManure in that order.

3.9.1. *Comparing Kabete and Mbooni sites*

A Welch Two Sample *t*-test was conducted, and yielded a t-statistic of −0.26981, p-value = 0.7913. The 95 % confidence interval for the difference in means ranges from −10.943 to 8.499. The sample mean for Kabete was 11.125, while that for Mbooni was 12.347. Given the high p value and the confidence interval that includes zero, there is insufficient evidence to reject the null hypothesis that the means of the two datasets are equal.

The *t*-test was followed up by a post-hoc test, whereby Mbooni site exhibited significantly higher plant characteristics than Kabete, with a difference of 9.78 units ($p = 0.0002$). These findings underscore the substantial influence of both treatments and geographical regions on strawberry characteristics, guiding on potential for tailored, region-specific agronomic interventions to enhance productivity. The significant influence of treatments can be attributed to differences in soil conditions and agroclimatic regime, with Mbooni conditions favoring better strawberry production.

4. Discussions

Livestock manure being superior to bokashi and control treatments can be associated to its beneficial implications on soil health which include buffering of the soil reaction, provision of essential plant nutrients and enhancement soil faunal activities. This observation is consistent with the review of [79], who concluded that organic agricultural waste enhances soil health. It is also consistent with the findings of [80], who found that organic manure was important in plant nutrition in a study in North Western Himalayas, and is also supported by the review of [81], who observed agronomically beneficial biochar-soil-plant interactions. The manure may also have enhanced soil faunal activities, such as earthworms, improving the structure of soil and cycling of nutrients. The large leaf area could indicate the potential of livestock manure if applied on crops whose leaves are the products. The observation can also be attributed to the nature of livestock manure as a rich source of organic matter, nutrients and soil fauna which can improve soil health and increase the availability of nutrients for plant growth. This observation is consistent with research findings of [82], who reported that organic fertilizers could shape soil microbial interactions, thereby enhancing the soil health in a blueberry orchard in China. Yadav and Sarkar [83] also found that soil microbes produce growth regulators and facilitate photosynthetic activity.

The high levels of NPK in livestock manure, which are essential nutrients for plant growth, could have resulted in the

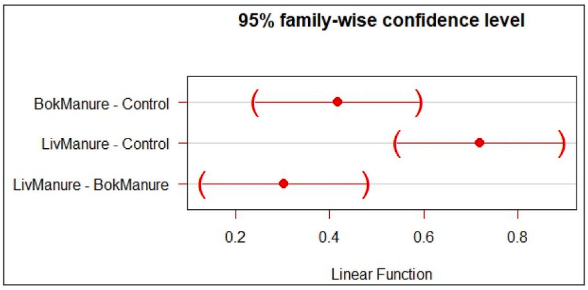

Fig. 4. Graphical presentation of Tukey post hoc test in Mbooni site.

Table 1
Means of log values and compact letter display across the treatments.

	Kabete	Mbooni
Treatments	Mean ± SD	Mean ± SD
LivManure	1.23 ± 0.2^{a}	1.27 ± 0.2^{a}
BokManure	0.93 ± 0.26^{b}	0.97 ± 0.25^{b}
Control	0.37 ± 0.33^{c}	0.55 ± 0.3^{c}

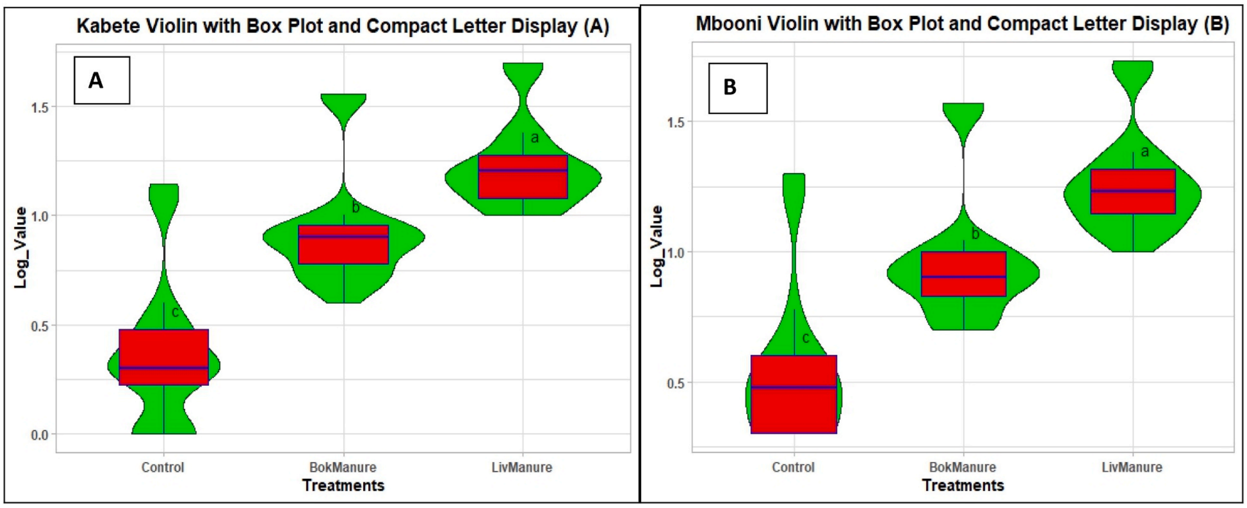

Fig. 5. Violin plots with a box plots and compact letter display for Kabete (A) and Mbooni (B).

predominantly better growth and yield observations in livestock treatments. These nutrients are released slowly over time as the organic matter in the manure breaks down, providing a continuous source of nutrients for the plant. Additionally, the microorganisms in livestock manure could have helped to suppress plant diseases and pests [84], break down organic matter and release nutrients into the soil, improving soil aggregation, water retention, and nutrient supply. This observation is in tandem with the findings of [85], who found that carbon-rich organic amendments helps to retain nutrients in agricultural soils. Livestock manure was predominantly superior compared to the other treatments due to its ability to improve soil structure hence promoting better root growth and soil pH buffering against variation in alkalinity or acidity. This is important because soil reaction affects soil nutrient availability and uptake by plants, especially micronutrients as most soil micronutrients are in toxic levels in low soil pH and deficient when the pH is alkaline. Similar finding has been reported by Ref. [86], who reported that massive soil degradation has taken place over the last four decades.

Previous studies have reported the importance and strategies of maximizing strawberry yields to increase returns on farming investments [87,88]. The yields can be achieved through envisaging organic farming systems in the study area and other parts of the world. Other studies that have observed the beneficial influence of organic inputs on strawberry growth, metabolism and production include [89], who investigated the performance of organic wastes in strawberry cultivation and [90], who examined the response of selected cultivars to foliar application of organic inputs. In both cases, organic soil inputs were recommended due to its impact on soil health, crop performance and environmental management. The applied organic inputs in this study may have enabled the soil to maintain its moisture, further favoring plant growth and production, an effect also reported by Ref. [91].

Strawberry growth in this study was evaluated by determining the number of white flowers, number of runners, and leaf area according [92]. The white flowers were used as precursor for yield, and runners as indicative of strawberry propagation and renewal. Livestock manure had predominantly better effects on strawberry production, which can be attributed to enhanced nutrition from the manure, resulting to more desirable characteristics and physiological processes by the strawberry plant. This finding agrees with observations of [92], who documented the influence of vermicompost on strawberry production. The authors reported that vermicompost improves photosynthesis, enhances ecosystem resilience, and increases soil enzymatic activity and microbial biomass. The leaf area which determines the capacity of a crop to yield dry matter can be influenced by variation in leaf number or size. The rule of the thumb is that, as leaf area index increases, the resultant shading increases loss on lower leaves. The large leaf area index observed in this study may be due to constant slow-releasing nature of the livestock manure that ensured constant, healthy leaf after establishment. A study by Ref. [93] also attributed similar finding to increasing light absorption, and dry matter production as a function of increasing leaf area index.

The superiority of bokashi manure over the control treatment can be attributed to several scientific factors. First, bokashi's anaerobic fermentation process breaks down organic matter into simpler, plant-accessible nutrients, ensuring an ample supply of nitrogen, phosphorus, and potassium. This finding is consistent to observations of previous studies [94,95], increased soil health status and subsequent plant yields from bokashi application. Second, it fosters beneficial microbial communities, such as lactic acid bacteria and yeasts, which bolster soil health, suppress pathogens, and enhance nutrient uptake. This observation has been documented in other studies [57,96,97]. Third, bokashi enhances soil structure and aeration [94], promoting efficient water and nutrient absorption by plant roots. Additionally, its slight acidity contributes to an optimal pH for certain plants, like strawberries. Finally, bokashi's weed suppression abilities reduce competition, fostering a healthier plant population [57,98]. Collectively, these advantages create an environment that propels plant growth and explains its superior performance compared to the control treatment.

Specifically, the trend analysis revealed a strong linear effect increasing from Control, to BokManure to LivManure in that order. This finding is significant, as it suggests that LivManure has the most significant influence on the log values of the tested variables. This information can be useful for researchers and practitioners, who are interested in optimizing treatment strategies to achieve the desired outcome. The trend analysis also provides a quantitative measure of the relationship between treatments and log values, which can be used to predict the influence of different treatments on the outcome variable. This information is valuable for making informed decisions about treatment strategies, and for designing future studies to investigate the underlying mechanisms for the observed effects. The analysis is an informative and valuable approach for analyzing data, and provides a deeper understanding of the influence of different treatments on growth and yield of any subject crops. The use of organic inputs to enhance strawberry production has been reported by Ref. [7].

The observation of Mbooni outperforming Kabete in terms of strawberry production can be attributed to agroclimatic zonation, whereby the relatively warmer climate compared to Kabete may have enhanced strawberry production. The influence of climate between the two areas has been observed in other tropical fruits including mangoes (*Mangifera indica*) and citrus. This finding has also been observed by Ref. [99] in a study on the impact of climate change on tropical fruit production systems and its mitigation strategies, and [100], while working on the influence of climate change on metabolism and biological characteristics in perennial woody fruit crops in the Mediterranean environment.

5. Conclusions and recommendation

The findings of this study highlight the substantial positive influence of livestock manure on strawberry performance and yield. Livestock manure outperformed both the control group and bokashi treatments, indicating its effectiveness in enhancing strawberry growth parameters. These results hold significant implications for organic farmers seeking sustainable approaches to boost crop yields, while also promoting environmental conservation. The superior performance of livestock manure can be attributed to the beneficial organic matter, nutrients, and microorganisms it contributes to the soil.

In light of these findings, strategic use of livestock manure in strawberry cultivation is recommended, for both its productivity benefits, and potential to support environmental protection. Specifically, in terms of future prospects, the combination of bokashi with organic manure presents an intriguing avenue for enhancing strawberry cultivation. This synergistic approach has the potential to harness the benefits of both organic amendments, offering a balanced and sustainable solution for improving crop performance and soil health. Exploring this innovative strategy could yield valuable insights into optimizing organic inputs, and further contribute to the success of organic farming practices.

Furthermore, recognizing the notable variations in strawberry characteristics between the two soil types, this study emphasizes the importance of considering soil characterization in any agricultural setting. The observed differences underscore the significance of tailoring farming practices to soil conditions to achieve optimal crop performance. This research opens the door for further exploration and confirmation of the current findings, including the mechanisms underlying these effects. Future studies can extend the scope by investigating the influence of various types of manure in diverse environmental conditions, and with different crops, offering valuable research opportunities to enhance the understanding of sustainable farming strategies.

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Data availability statement

All data has been availed as supplementary material.

Code availability

The R Studio code used for data analysis and plotting has been submitted as supplementary material.

CRediT authorship contribution statement

S.N. Ombita: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **S.M. Mwendwa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **S.M. Mureithi:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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