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Optimizing Maize Productivity as a Strategic Crop under Alkaline Soil Conditions through Organic Fertilization and Nanoparticle-Based Potassium Sources

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ALKALINE soils often present challenges, including nutrient availability and reduced microbial activity, which can adversely affect plant growth and yield. This study aimed to investigate the effects of different compost types and foliar applications of nanoparticle potassium on maize growth, quality and stress resistance under alkaline soil conditions. Conducted over two seasons (2023 and 2024), the research involved treatments of compost from banana trees and faba beans, along with foliar applications of nanoparticle potassium sources: silicate, citrate, and sulphate. Key parameters measured included growth metrics, chemical constituents, photosynthetic pigments, oxidative stress markers (proline and MDA), enzymatic antioxidants (CAT and POX), yield components, and quality traits. Maize treated with banana tree compost exhibited the highest growth metrics, including plant height, fresh weight, and dry weight. Nano potassium silicate led to superior growth compared to other potassium treatments. Significant increases in nitrogen (N), phosphorus (P), potassium (K), chlorophyll a, chlorophyll b and carotene levels were observed in plants treated with banana tree compost. Nano potassium silicate consistently recorded the highest leaf nutrients and photosynthetic pigment levels. Compost application reduced malondialdehyde (MDA) levels, indicating lower oxidative stress. The combination of banana tree compost and nano potassium silicate minimized stress markers while enhancing enzymatic antioxidant activity. The integration of banana tree compost with nanoparticle potassium significantly improved yield parameters, such as cob weight, grain yield, and quality traits, including protein and carbohydrate content. Finally, the findings demonstrate that combining banana tree compost with nanoparticle potassium can significantly improve maize growth, quality, and stress tolerance in alkaline soils. Future research should explore various compost types and their interactions with nanoparticle fertilizers, focusing on long-term impacts. Such studies will be vital for enhancing food security and promoting sustainable agricultural practices.

Keywords: Maize, Compost, Nanoparticle potassium, Oxidative stress.

Introduction

Enhancing agricultural productivity and optimizing the use of natural resources are critical challenges in modern agriculture, especially with increasing pressure on soil and water (**Sahakyan *et al*. 2022)**. Alkaline soils often present specific problems, such as reduced nutrient availability and impaired microbial activity, which can adversely affect crop growth and yield (**Elsonbaty and El-Sherpiny 2024)**. In this context, compost is considered one of the sustainable solutions that contribute to improving soil fertility and crop quality (**Soliman *et al.* 2024)**. Made from organic plant residues that undergo biological decomposition, compost results in a material rich in essential nutrients beneficial for the soil (**Rashwan 2024)**. The quality of compost varies depending on the type of plant residue used, as each type has a unique composition of nutrients that supports plant growth. For instance, residues from faba beans and banana trees are rich sources of nutrients that enhance the physical and chemical properties of the soil, making them particularly effective in ameliorating the challenges posed by alkaline conditions **(Soliman, 2023).**

On the other hand, potassium fertilizers play a crucial role in supporting essential plant processes, such as regulating water uptake and activating enzymes responsible for protein and starch formation. Recently, the development of nano-potassium fertilizers has emerged as a promising technology. These nano-fertilizers, characterized by their small particle size and increased surface area, offer improved penetration into plant cells, enhancing nutrient uptake efficiency. This shift toward nano-fertilizers is seen as one of the most promising approaches to increase fertilizer efficiency and reduce environmental losses (**Mahil and Kumar 2019; Farrag *et al.* 2024**).

Maize (*Zea mays*) is a strategic crop of great importance for global food security, serving as both a staple food for humans and a primary feed source for livestock, as well as being used in various industries (**Farid *et al.* 2024)**.

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Improving maize quality and productivity through innovative agricultural practices such as the use of compost and nano-fertilizers is a key focus for researchers and farmers worldwide.
The aim of this study is to evaluate the impact of different types of compost derived from specific plant residues, in combination with the application of nano-potassium fertilizers from various sources, on the quality of maize. The study seeks to understand the interactions between these agricultural inputs and their effect on improving the growth performance and productivity of maize, ultimately contributing to sustainable strategies for increasing crop yields.

2. Material and Methods

A field experiment was conducted in the El-Serw region, Damietta, Egypt (coordinates: 31°14′19″N 31°39′14″E) during the 2023 and 2024 growing seasons, utilizing a split-plot design with three replications. The objective of the experiment was to assess the effects of organic fertilization (compost from different plant sources) and nanoparticle potassium sources on the growth performance and productivity of maize.
The main plot factor was organic fertilization, with three treatments: a control (without compost), compost sourced from banana tree residues applied at 7.5 ton fed^{-1} and compost derived from faba bean foliage residues, also applied at 7.5 ton fed^{-1}. The sub-main plot factor consisted of foliar application of different potassium sources, including a control (without application), nano potassium sulphate at 50 mg L^{-1}, nano potassium citrate at 50 mg L^{-1} and nano potassium silicate at 50 mg L^{-1}. This experimental approach aimed to explore the potential benefits of combining organic fertilization (compost from different plant sources) with nanoparticle potassium sources on maize productivity under field conditions (experimental flowchart shown in Fig1).

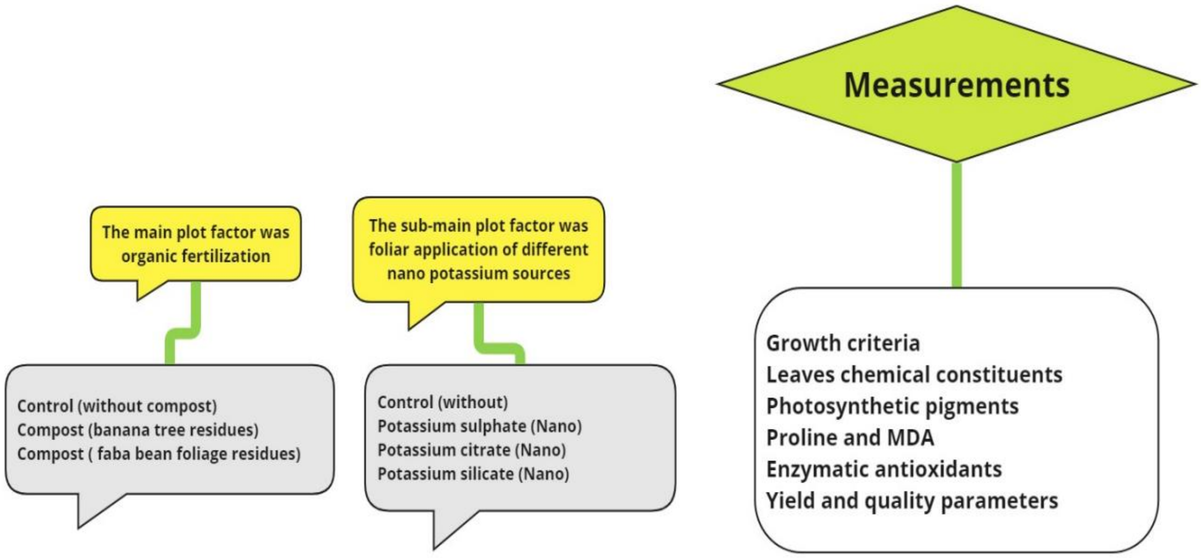

Fig. 1. Experimental flowchart.

Soil Properties and plant residue-composting process

The properties of the initial soil and the organic fertilizers studied were analyzed following the methodology of **Tandon (2005).** The soil exhibited a high pH of 8.50 (in a 1:2.5 suspension) and an electrical conductivity (EC) of 3.78 dSm^{-1}. The ESP value was 16.32%. Nutrient analysis showed low levels of available-N at 30.02 mg kg^{-1} and available-P at 5.05 mg kg^{-1}, while available -K at 190.2 mg kg^{-1}. The organic matter content was 1.00%, and the soil texture was clay, consisting of 33% sand, 48% clay, and 19% silt.

Two types of compost were prepared using different organic materials. The first compost was made from banana tree residues, while the second was produced from faba bean residues. Both organic materials were chopped into small pieces (5–10 cm) to enhance the decomposition process. The composting method followed was adapted from **El-Hammady *et al.* (2003),** where various combinations of organic waste were used. In this study, the compost piles were approximately 1.5 meters in height and 2 meters in width, and the total mass of each pile was around 500 kg. For each compost type, the following additions were made: Chicken manure: added at a rate of 30% of the total weight (150 kg), to accelerate microbial activity and increase nitrogen content. Rock phosphate: added at a rate of 2% (10 kg) to enhance phosphorus availability. Effective microorganisms (EM): applied at a rate of 0.5 L per ton to enhance microbial diversity and speed up the decomposition process. The materials were arranged in piles and regularly turned once every 10 days to ensure adequate aeration and moisture content. Water was added periodically to maintain a moisture level of 50-60%, which is crucial for microbial activity and the breakdown of organic matter into nutrient-rich compost. By following this method, the composting process lasted around 90 days, after which the compost was screened to remove large, undecomposed materials, leaving behind the final product. The chemical analysis of both compost types revealed significant differences in their nutrient composition. The potassium (K) content was notably higher in the banana tree residues compost (15.05 g kg^{-1}) compared to the faba bean residues compost (5.6 g kg^{-1}). This suggests that the banana compost could be more beneficial for potassium-demanding crops. The C/N ratio was slightly lower in the banana compost (11.8) than in the faba bean compost (12.85), indicating a faster decomposition rate for the banana compost due to a more balanced nutrient profile. Both composts showed similar electrical conductivity (EC), with values of 4.00 dSm^{-1} and 4.35 dSm^{-1} for the banana and faba bean composts, respectively, reflecting moderate salinity levels. The pH values for both composts were quite close, with the banana compost at 6.25 and the faba bean compost at 6.30, indicating slightly acidic to neutral conditions favorable for most plants. Organic matter (O.M.) content was higher in the banana compost (34.5%) than in the faba bean compost (30.9%), which could provide better soil structure and water retention benefits when applied to soils. In terms of total carbon (C) and nitrogen (N), the banana compost had slightly higher values (20% C and 1.70% N) compared to the faba bean compost (18% C and 1.4% N). This shows that the banana compost may provide a more consistent supply of carbon and nitrogen over time. Phosphorus (P) content was relatively low in both composts, with 0.82 mg kg^{-1} in the banana compost and 0.70 mg kg^{-1} in the faba bean compost. Lastly, micronutrient analysis showed similar zinc (Zn) and manganese (Mn) levels in both composts. The banana compost contained 20.0 mg kg^{-1} of Zn and 22.0 mg kg^{-1} of Mn, while the faba bean compost had 19.6 mg $kg^{-1}$of Zn and 18.9 mg kg^{-1} of Mn, indicating that both composts could contribute to improving the micronutrient status of the soil.

Synthesis of potassium nanoparticles

The potassium fertilization sources used in this study included potassium sulphate (K_2SO_4, 40% K), potassium citrate ($K_3C_6H_5O_7$, 45.0% K_2O) and potassium silicate (K_2SiO_3, 60.0% K), all sourced from Sigma Chemical Co. (St. Louis, MO, USA). These materials were converted into nanoparticle forms at the Nanotechnology and Advanced Materials Central Lab, Agricultural Research Center, Egypt, using chitosan as a stabilizing agent. Chitosan was chosen specifically because it is a natural, safe, and non-reactive material, serving solely as a carrier for the nanoparticles. Chitosan has a porous structure that allows for the entrapment of nanometer-sized particles within its matrix, enhancing their stability and bioavailability. The conversion of these potassium fertilizers into nanoparticle forms, despite their water solubility, was intended to increase their efficiency. Nanoparticles exhibit enhanced surface area, which can improve the uptake and utilization of potassium by plants, potentially reducing the amount of fertilizer required and minimizing environmental impact. The nanoparticle form also allows for more controlled and sustained release of the nutrients, improving the overall efficiency of the fertilization process (**Kubavat *et al*. 2020**). The process of creating nanoparticle forms did not alter the chemical nature of the potassium compounds but rather modified their physical form for improved performance. Referring to the resulting product as "nano-potassium" in this context reflects the nanometer-scale size of the particles carried by the chitosan matrix, not a chemical transformation of the potassium itself. The correct terminology would be "potassium nanoparticles stabilized by chitosan" or "chitosan-based potassium nanoparticles," as the chitosan serves as the carrier, but does not chemically modify the potassium compounds. The synthesis of nanoparticle fertilizers was accomplished using chitosan as a stabilizing agent through a two-step process. Initially, chitosan (CS), characterized by a molecular weight of 71.3 kDa and a degree of deacetylation of 94%, was dissolved in a 0.5% (v/v) aqueous solution of methacrylic acid. This mixture was stirred magnetically for 12 hours to ensure complete dissolution, with the concentration of chitosan utilized in the synthesis being 0.2% (w/v). In the subsequent step, 0.2 mmol of each potassium source was incorporated into the chitosan solution while maintaining continuous stirring until a clear solution was obtained. The polymerization reaction was conducted at 70°C under magnetic stirring for one hour, leading to the formation of CS-PMAA nanoparticles, which were then cooled in an ice bath. All reagents used in this synthesis were of analytical grade, ensuring high purity and quality **(Corradini *et al.* 2010).** Subsequently, the nanoparticle-rich solution underwent high-speed centrifugation at 15,000 revolutions per minute (rpm) to facilitate the separation of nanoparticles from larger particles. The resulting supernatant, enriched with nanoparticles, was freeze-dried to yield a stable powder form (**Corradini *et al.* 2010; Elshamy *et al.* 2019; Yaseen *et al.* 2020).** Particle size analysis and transmission electron microscopy (TEM) confirmed that the resulting nanoparticles were within the desired size range (Figs 2, 3, and 4).

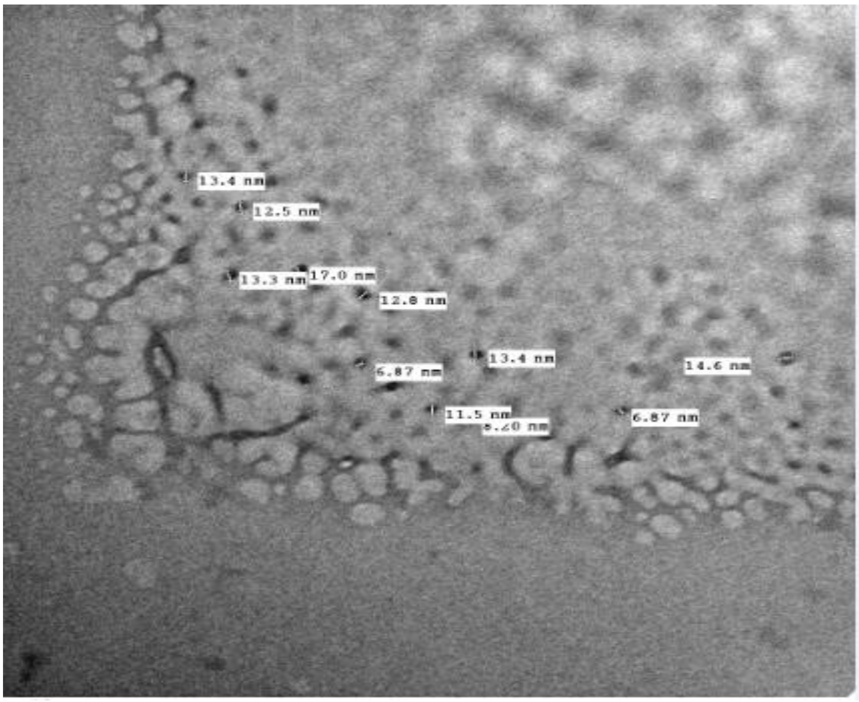

Fig. 2. TEM for potassium sulphate.

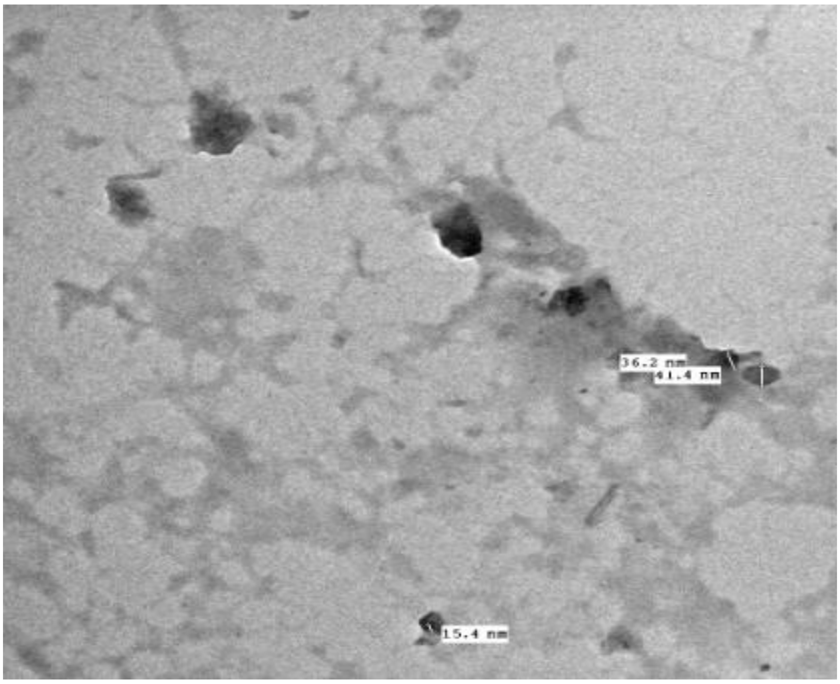

Fig. 3. TEM for potassium citrate.

Cultivation and harvest time

Maize seeds (single cross 10) were planted on May 19th in both growing seasons, adhering to the standard agronomic practices recommended by the Ministry of Agriculture and Soil Reclamation (MASR). Mineral N, P and K fertilization was carried out according to the recommendations of the MASR. Nitrogen was supplied using urea (46% N), phosphorus was provided in the form of calcium superphosphate (15% P_2O_5), and potassium was applied using potassium sulphate (48% K_2O). These fertilizers were used to ensure baseline nutrient availability for the maize plants, allowing for a comparison between the effects of standard mineral fertilization and the added benefits of organic compost and nanoparticle potassium sources. This balanced fertilization was implemented in all experimental plots to maintain uniformity in basic nutrient supply, ensuring that any observed differences in plant growth and productivity could be attributed to the treatments of organic compost and nanoparticle potassium applications rather than deficiencies in essential nutrients. Compost sources were incorporated into the soil one month prior to sowing. Foliar applications of nanoparticle potassium sources were carried out three times during the growing season, specifically at 30, 45 and 60 days after sowing. Harvesting occurred 110 days after sowing.

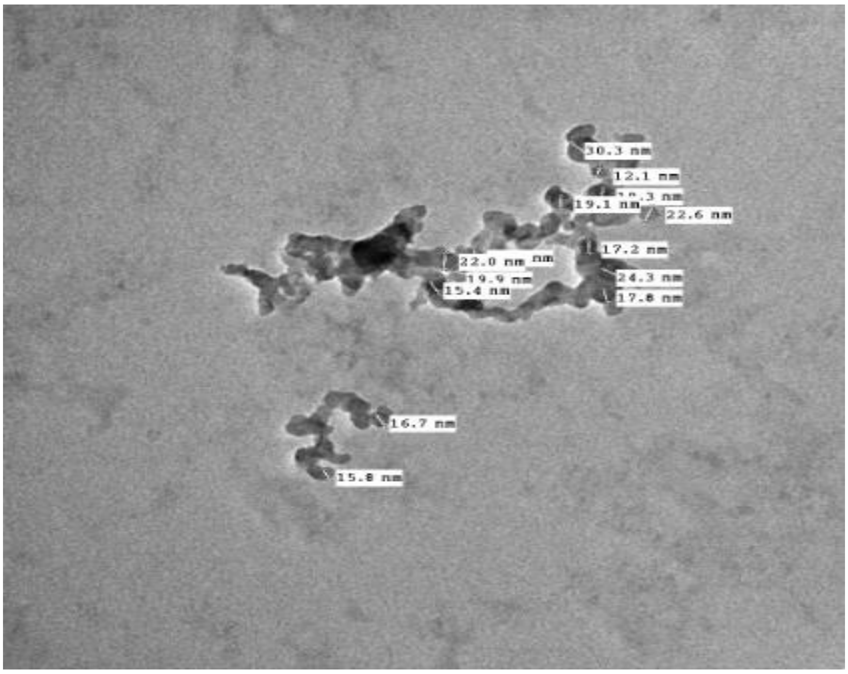

Fig. 4. TEM for potassium silicate.

Data collection

Data collection was conducted at two key stages during the experiment. The first stage occurred 65 days after sowing, where initial growth measurements, chemical composition of the leaves, and antioxidant indicators were recorded. Growth parameters such as plant height, fresh and dry weights and leaf area were measured manually using direct methods. Chlorophyll content (a, b) and carotenoids were assessed spectrophotometrically following the method described by **Rai (1973).** Leaf samples were digested using a mixture of $HClO_4$ and H_2SO_4, following the procedures outlined by **Peterburgski (1968),** to determine nitrogen (N), phosphorus (P) and potassium (K) content in the dry weight of the leaves. Nitrogen was determined using the Micro-Kjeldahl method, phosphorus was measured spectrophotometrically and potassium was analyzed using a flame photometer, as per **Walinga *et al.* (2013).** Additionally, antioxidant indicators such as malondialdehyde (MDA, according to **Valenzuela 1991),** enzymatic antioxidants (catalase [CAT] and peroxidase [POX], according to **Elavarthi and Martin, 2010),** and non-enzymatic antioxidants like proline (according to **Ábrahám *et al.* 2010**) were measured to evaluate the plant's oxidative stress response.

The second stage of data collection took place at harvest, 110 days after sowing, focusing on yield components and seed quality. Yield parameters, including cob weight, cob length, cob diameter, number of seeds per cob, weight of 100 grains, grain yield, biological yield and harvest index, were measured manually. Seed quality was assessed through carbohydrate content using the Anthrone method described by **AOAC (2000),** and protein content was calculated as nitrogen content (determined *via* the Kjeldahl method) multiplied by a factor of 5.75. Seeds were also digested using $HClO_4$ and H_2SO_4, following **Peterburgski (1968),** and nutrient content (N, P, K) in the seeds was analyzed using the same methods as for the leaves.

Statistical analysis

All the collected data were statistically analyzed using analysis of variance (ANOVA) at a 5% significance level. Duncan's multiple range test was applied to differentiate between the treatments means and assess their significance, following standard procedures **(Gomez and Gomez, 1984).**

3. Results

Growth criteria, leaves chemical constituents and photosynthetic pigments

Table 1 illustrates the effects of various compost types and foliar applications of nanoparticle potassium on maize growth performance during the 2023 and 2024 seasons. The data indicate significant differences among treatments, particularly in plant height, fresh weight, dry weight and leaf area. Regarding the main factor involving compost, plants treated with banana tree compost consistently exhibited the highest growth metrics across both seasons, followed closely by faba bean compost. In contrast, the control group (without compost) recorded the lowest values for all parameters, underscoring the positive impact of organic amendments on maize growth. Concerning the sub-main factor of nanoparticle potassium sources, the application of nano potassium silicate led to superior results compared to other potassium treatments, with the highest values observed in most growth measurements. nano potassium citrate came in the second order followed by nano potassium sulphate and lately the control group (without K). The combination of Banana tree residues compost with Nano potassium silicate showed particularly effective outcomes, highlighting the synergistic effects of these treatments. Overall, these results suggest that integrating organic fertilization with advanced potassium sources can significantly improve maize growth performance.

Table 1. Effects of various compost types and foliar application of nanoparticle potassium from different sources on maize growth performance in the 2023 and 2024 seasons.

Treatments		Plant height, cm		Fresh weight, g plant^{-1}		Dry weight, g plant^{-1}		Leaf area, cm^2 plant^{-1}	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Compost from plant residues									
Control (Without)		204.28c	210.31c	802.58c	813.00c	243.50c	246.17c	558.75c	566.83c
Compost (faba bean)		217.35b	223.32b	878.58b	889.83b	275.92b	279.67b	591.17b	599.17b
Compost (Banana tree)		224.14a	231.11a	950.00a	962.83a	296.75a	300.67a	614.50a	621.83a
Sub main factor : Nanoparticle potassium from different sources									
Control (without)		213.33c	218.57c	859.11d	869.56c	264.78d	268.56d	580.56c	588.78c
Potassium sulphate (Nano)		214.2bc	220.71bc	870.44c	881.78b	270.22c	274.11c	584.89bc	592.89bc
Potassium citrate (Nano)		216.1ab	222.8ab	884.67b	896.33a	274.56b	277.33b	590.78ab	598.11ab
Potassium silicate (Nano)		217.47a	224.25a	894.00a	906.56a	278.67a	282.00a	596.33a	604.00a
Interaction									
Control (Without)	**Control (without)**	202.32	205.79	783.67	795.33	236.67	239.67	550.67	558.00
	Potassium sulphate (Nano)	204.41	210.74	799.33	810.33	241.67	245.00	556.00	565.00
	Potassium citrate (Nano)	204.68	210.82	808.33	818.67	245.00	246.67	562.00	569.00
	Potassium silicate (Nano)	205.72	213.89	819.00	827.67	250.67	253.33	566.33	575.33
Compost (Faba bean)	**Control (without)**	214.03	220.02	858.67	868.67	264.67	269.00	583.33	590.33
	Potassium sulphate (Nano)	213.91	220.55	867.67	877.00	273.33	277.33	585.33	594.33
	Potassium citrate (Nano)	219.52	226.32	890.67	900.67	281.00	283.67	594.00	603.33
	Potassium silicate (Nano)	221.95	226.38	897.33	913.00	284.67	288.67	602.00	608.67
Compost (Banana tree)	**Control (without)**	223.63	229.90	935.00	944.67	293.00	297.00	607.67	618.00
	Potassium sulphate (Nano)	224.12	230.83	944.33	958.00	295.67	300.00	613.33	619.33
	Potassium citrate (Nano)	224.09	231.26	955.00	969.67	297.67	301.67	616.33	622.00
	Potassium silicate (Nano)	224.73	232.47	965.67	979.00	300.67	304.00	620.67	628.00
LSD at 5%		**4.75**	**4.89**	**6.40**	**18.24**	**5.51**	**3.59**	**12.38**	**12.80**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 2 details the effects of various compost types and foliar applications of nanoparticle potassium on the chemical constituents of maize leaves in the 2023 and 2024 seasons at the period of 65 days from sowing. The data demonstrate significant differences among treatments, particularly in nitrogen (N), phosphorus (P), and potassium (K) content. For the main factor of compost, maize plants treated with banana tree compost showed the highest levels of N, P and K in both seasons, followed by those receiving faba bean compost. The control group (without compost) exhibited the lowest concentrations for all nutrients, underscoring the beneficial effects of organic amendments on nutrient accumulation in maize leaves.

Table 2. Effects of various compost types and foliar application of nanoparticle potassium from different sources on leaves chemical constituents of maize in the 2023 and 2024 seasons.

Treatments		N, %		P, %		K, %	
		1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor : Compost from plant residues							
Control (Without)		2.89c	2.94c	0.307c	0.320c	2.73c	2.85c
Compost (Faba bean)		3.22b	3.29b	0.340b	0.354b	2.89b	3.01b
Compost (Banana tree)		3.52a	3.60a	0.366a	0.381a	3.11a	3.23a
Sub main factor : Nanoparticle potassium from different sources							
Control (without)		3.15b	3.22c	0.331d	0.344c	2.85c	2.96c
Potassium sulphate (Nano)		3.18b	3.24c	0.335c	0.349b	2.89b	3.01b
Potassium citrate (Nano)		3.24a	3.30b	0.340b	0.353b	2.94a	3.06a
Potassium silicate (Nano)		3.27a	3.34a	0.346a	0.359a	2.96a	3.08a
Interaction							
Control (Without)	**Control (without)**	2.85	2.91	0.302	0.314	2.66	2.77
	Potassium sulphate (Nano)	2.88	2.94	0.303	0.316	2.72	2.84
	Potassium citrate (Nano)	2.88	2.93	0.309	0.322	2.75	2.87
	Potassium silicate (Nano)	2.93	2.99	0.314	0.327	2.78	2.90
Compost (Faba bean)	**Control (without)**	3.15	3.21	0.331	0.344	2.81	2.92
	Potassium sulphate (Nano)	3.17	3.23	0.338	0.354	2.85	2.98
	Potassium citrate (Nano)	3.28	3.35	0.344	0.358	2.95	3.07
	Potassium silicate (Nano)	3.29	3.35	0.348	0.362	2.95	3.07
Compost (Banana tree)	**Control (without)**	3.46	3.55	0.360	0.374	3.07	3.19
	Potassium sulphate (Nano)	3.50	3.56	0.364	0.378	3.10	3.22
	Potassium citrate (Nano)	3.55	3.62	0.367	0.381	3.12	3.24
	Potassium silicate (Nano)	3.58	3.66	0.375	0.390	3.14	3.27
LSD at 5%		**0.08**	**0.06**	**0.006**	**0.008**	**0.07**	**0.07**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Regarding the sub-main factor of nanoparticle potassium sources, the application of nano potassium silicate consistently resulted in the highest nutrient levels across most measurements. Nano potassium citrate followed closely, with nano potassium sulphate showing slightly lower values, and the control group (without potassium) had the lowest nutrient contents. The interaction between compost type and nanoparticle potassium treatments revealed that combinations of banana tree compost with nano potassium silicate achieved the most significant increases in nutrient concentrations.

Table 3 presents the effects of various compost types and foliar applications of nanoparticle potassium on the chlorophyll and carotene content of maize leaves during the 2023 and 2024 seasons. The data indicate significant differences in the levels of chlorophyll a, chlorophyll b, and carotene due to the studied treatments.For the main factor (compost type), plants treated with banana tree compost exhibited the highest values for all three pigments (chlorophyll a, chlorophyll b, and carotene) in both seasons, followed by those receiving faba bean compost. The control group (without compost) consistently showed the lowest pigment concentrations, suggesting that organic amendments promote higher pigment content in maize leaves.

Regarding the sub-main factor of nanoparticle potassium sources, nano potassium silicate outperformed other treatments, leading to the highest pigment concentrations across all parameters. Nano potassium citrate ranked second, followed by nano potassium sulfate, with the control group (without potassium) showing the lowest values.

The interaction between compost type and nanoparticle potassium revealed that the combination of banana tree compost with nano potassium silicate recorded the highest chlorophyll and carotene levels, further emphasizing the synergistic benefits of combining organic compost with advanced potassium sources. These results highlight the role of organic and nanoparticle potassium treatments in improving the photosynthetic capacity and overall health of maize plants.

Table 3. Effects of various compost types and foliar application of nanoparticle potassium from different sources on leaves chemical constituents of maize in the 2023 and 2024 seasons.

Treatments		Chlorophyll a, mg g^{-1}		Chlorophyll b, mg g^{-1}		Carotene, mg g^{-1}	
		1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor : Compost from plant residues							
Control (Without)		0.917c	0.953c	0.624c	0.655c	0.408c	0.416c
Compost (Faba bean)		1.034b	1.078b	0.682b	0.717b	0.448b	0.457b
Compost (Banana tree)		1.145a	1.193a	0.751a	0.789a	0.495a	0.506a
Sub main factor : Nanoparticle potassium from different sources							
Control (without)		1.008d	1.048c	0.668d	0.703c	0.438d	0.447d
Potassium sulphate (Nano)		1.024c	1.069b	0.680c	0.714b	0.446c	0.455c
Potassium citrate (Nano)		1.038b	1.083b	0.690b	0.724b	0.454b	0.463b
Potassium silicate (Nano)		1.056a	1.099a	0.704a	0.740a	0.463a	0.472a
Interaction							
Control (Without)	**Control (without)**	0.894	0.928	0.610	0.642	0.394	0.402
	Potassium sulphate (Nano)	0.908	0.944	0.619	0.649	0.402	0.410
	Potassium citrate (Nano)	0.922	0.960	0.627	0.657	0.412	0.419
	Potassium silicate (Nano)	0.943	0.980	0.639	0.670	0.423	0.432
Compost (Faba bean)	**Control (without)**	1.008	1.050	0.669	0.702	0.437	0.445
	Potassium sulphate (Nano)	1.027	1.072	0.678	0.712	0.444	0.453
	Potassium citrate (Nano)	1.040	1.085	0.685	0.718	0.451	0.460
	Potassium silicate (Nano)	1.060	1.105	0.697	0.734	0.459	0.468
Compost (Banana tree)	**Control (without)**	1.121	1.166	0.726	0.764	0.482	0.494
	Potassium sulphate (Nano)	1.138	1.190	0.741	0.779	0.493	0.502
	Potassium citrate (Nano)	1.153	1.203	0.759	0.795	0.500	0.510
	Potassium silicate (Nano)	1.167	1.213	0.776	0.815	0.506	0.516
LSD at 5%		**0.020**	**0.026**	**0.016**	**0.017**	**0.011**	**0.009**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 4. Effects of various compost types and foliar application of nanoparticle potassium from different sources on the antioxidant indicators in leaves of maize in the 2023 and 2024 seasons.

Treatments		Proline, µg.g^{-1} F.W		MDA, µmol.g^{-1} F.W		CAT, Unit mg^{-1} protein^{-1}		POX, Unit mg^{-1} protein^{-1}	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Compost from plant residues									
Control (Without)		11.00a	11.21a	13.04a	13.19a	211.92c	216.10c	68.11c	69.03c
Compost (Faba bean)		9.80b	10.00b	11.71b	11.85b	236.47b	241.10b	75.38b	76.39b
Compost (Banana tree)		8.65c	8.83c	10.41c	10.58c	253.55a	258.68a	88.23a	89.32a
Sub main factor : Nanoparticle potassium from different sources									
Control (without)		10.24a	10.46a	12.25a	12.41a	225.34d	229.59d	75.88c	76.82c
Potassium sulphate (Nano)		9.89b	10.09b	11.91b	12.07b	233.77c	238.07c	76.87b	77.92b
Potassium citrate (Nano)		9.69c	9.88c	11.48c	11.64c	236.38b	241.22b	77.60b	78.58b
Potassium silicate (Nano)		9.44d	9.64d	11.24d	11.38d	240.42a	245.62a	78.61a	79.66a
Interaction									
Control (Without)	**Control (without)**	11.33	11.56	13.43	13.59	203.82	208.18	66.82	67.65
	Potassium sulphate (Nano)	11.09	11.31	13.19	13.39	209.46	212.81	67.65	68.43
	Potassium citrate (Nano)	10.93	11.12	12.89	13.03	213.62	217.97	68.53	69.55
	Potassium silicate (Nano)	10.64	10.85	12.63	12.74	220.77	225.45	69.42	70.49
Compost (Faba bean)	**Control (without)**	10.20	10.39	12.38	12.54	223.51	227.36	73.06	74.06
	Potassium sulphate (Nano)	9.94	10.15	11.79	11.93	237.01	241.66	74.83	75.85
	Potassium citrate (Nano)	9.65	9.85	11.47	11.60	240.53	245.71	75.89	76.86
	Potassium silicate (Nano)	9.42	9.62	11.19	11.34	244.81	249.66	77.74	78.77
Compost (Banana tree)	**Control (without)**	9.19	9.42	10.94	11.08	248.70	253.23	87.76	88.73
	Potassium sulphate (Nano)	8.64	8.80	10.73	10.89	254.84	259.74	88.12	89.47
	Potassium citrate (Nano)	8.49	8.66	10.08	10.29	254.98	259.99	88.37	89.34
	Potassium silicate (Nano)	8.25	8.43	9.89	10.06	255.67	261.76	88.67	89.74
LSD at 5%		**0.23**	**0.23**	**0.26**	**0.25**	**1.84**	**5.23**	**1.69**	**1.69**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Proline, MDA and enzymatic antioxidants

Table 4 shows the effects of different compost types and foliar applications of nanoparticle potassium on proline, malondialdehyde (MDA) and enzymatic antioxidants (CAT and POX) in maize leaves during the 2023 and 2024 seasons. The data highlight significant differences across treatments in terms of antioxidant activity.

Plants receiving no compost (control) exhibited the highest proline content in both seasons, followed by those treated with faba bean compost. The lowest proline levels were observed in plants receiving banana tree compost, indicating that compost application reduces stress markers like proline. MDA, an indicator of lipid peroxidation and oxidative stress, followed a similar trend, with the control group having the highest levels, and banana tree compost-treated plants showing the lowest, suggesting reduced oxidative damage with compost application. Enzymatic antioxidants like CAT and POX were highest in plants treated with banana tree compost, followed by faba bean compost. The control group consistently showed the lowest CAT and POX activity, indicating that compost enhances the antioxidant defense system of maize plants.

Nano potassium silicate resulted in the lowest proline levels, followed by nano potassium citrate and nano potassium sulfate. The control group (no potassium application) had the highest proline content, suggesting that potassium nanoparticles help reduce stress.Similarly, nano potassium silicate led to the lowest MDA content, indicating its superior ability to mitigate oxidative stress. Nano potassium silicate also resulted in the highest CAT and POX activities, followed by nano potassium citrate and nano potassium sulfate, with the control group showing the lowest enzymatic activity.

The combination of banana tree compost and nano potassium silicate consistently yielded the lowest proline and MDA levels while achieving the highest CAT and POX enzyme activities. This combination appears to offer the most effective protection against oxidative stress, enhancing the overall antioxidant defense system in maize plants. On the contrary, the control group (without compost and nanoparticle potassium) had the highest proline and MDA levels and the lowest antioxidant enzyme activity, indicating greater susceptibility to oxidative stress.

Yield and quality parameters

Table 5 highlights the effects of different compost types derived from plant residues and foliar application of nanoparticle potassium from various sources on maize yield and its components during the 2023 and 2024 seasons, including cob weight, cob length, cob diameter, number of seeds per cob, weight of 100 grains, grain yield, biological yield (Figs 5,6) and harvest index. The results show a significant improvement in most of the studied traits due to the different treatments applied. Compost from banana trees demonstrated the best results compared to other treatments, showing the highest values of all aforementioned traits. This indicates that banana tree compost provided optimal nutrient availability for maize, leading to improved yield components. Compost from faba bean residues also resulted in substantial improvements in yield components, though not as pronounced as banana tree compost. It showed higher cob weight, cob length, cob diameter, number of seeds per cob, weight of 100 grains, grain yield, biological yield and harvest index compared to the control, highlighting the beneficial effects of organic matter in enhancing soil fertility and crop productivity.

Table 5. Effects of various compost types and foliar application of nanoparticle potassium from different sources on maize yield and its components in the 2023 and 2024 seasons.

Treatments		Weight of cob, g		Cob length, cm		Cob diameter, cm		No. of seeds cob^{-1}	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Compost from plant residues									
Control (Without)		168.52c	176.89c	16.19c	16.43c	2.83c	2.85c	277.92c	281.67c
Compost (Faba bean)		230.80b	242.82b	18.41b	18.72b	3.63b	3.70b	350.83b	355.42b
Compost (Banana tree)		259.25a	272.38a	22.33a	22.63a	4.18a	4.28a	384.83a	389.25a
Sub main factor : Nanoparticle potassium from different sources									
Control (without)		212.93d	224.26d	18.01d	18.28b	3.23c	3.30b	330.56c	335.11c
Potassium sulphate (Nano)		216.99c	227.87c	18.76c	19.12ab	3.53b	3.62a	334.11c	338.78c
Potassium citrate (Nano)		221.84b	232.46b	19.28b	19.46ab	3.77ab	3.82a	340.56b	344.33b
Potassium silicate (Nano)		226.34a	238.18a	19.86a	20.19a	3.63a	3.70a	346.22a	350.22a
Interaction									
Control (Without)	**Control (without)**	162.93	171.63	15.47	15.67	2.50	2.50	272.00	275.67
	Potassium sulphate (Nano)	165.06	173.11	15.90	16.20	3.00	3.13	273.33	278.00
	Potassium citrate (Nano)	170.33	178.51	16.50	16.70	3.10	3.07	279.33	282.33
	Potassium silicate (Nano)	175.75	184.30	16.90	17.17	2.70	2.70	287.00	290.67
Compost (Faba bean)	**Control (without)**	221.23	232.96	17.37	17.67	3.40	3.50	339.33	342.67
	Potassium sulphate (Nano)	227.38	239.00	17.97	18.47	3.50	3.50	345.33	350.67
	Potassium citrate (Nano)	235.39	246.90	18.73	18.83	3.80	3.90	356.67	362.33
	Potassium silicate (Nano)	239.21	252.40	19.57	19.90	3.80	3.90	362.00	366.00
Compost (Banana tree)	**Control (without)**	254.64	268.20	21.20	21.50	3.80	3.90	380.33	387.00
	Potassium sulphate (Nano)	258.52	271.51	22.40	22.70	4.10	4.23	383.67	387.67
	Potassium citrate (Nano)	259.79	271.98	22.60	22.83	4.40	4.50	385.67	388.33
	Potassium silicate (Nano)	264.06	277.82	23.10	23.50	4.40	4.50	389.67	394.00
LSD at 5%		**6.25**	**5.02**	**0.35**	**2.11**	**0.37**	**0.35**	**6.95**	**7.52**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Cont. Table 5

Treatments		Weight of 100 grain, g		Grain yield, ton/hectare		Biological yield, ton/hectare		Harvest index, %	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Compost from plant residues									
Control (Without)		37.33c	37.94c	3.90c	3.99c	8.72c	8.88c	44.74c	44.87c
Compost (Faba bean)		41.75b	42.48b	4.57b	4.65b	9.74b	9.94b	46.86b	46.81b
Compost (Banana tree)		42.88a	43.52a	5.30a	5.41a	10.39a	10.62a	51.01a	50.96a
Sub main factor : Nanoparticle potassium from different sources									
Control (without)		40.33b	41.03c	4.40d	4.48d	9.45c	9.63c	46.41c	46.39c
Potassium sulphate (Nano)		40.54ab	41.28b	4.54c	4.63c	9.59b	9.80b	47.19bc	47.04bc
Potassium citrate (Nano)		40.77ab	41.35b	4.63b	4.73b	9.66b	9.87b	47.74b	47.74b
Potassium silicate (Nano)		40.96a	41.60a	4.79a	4.90a	9.77a	9.96a	48.81a	49.02a
Interaction									
Control (Without)	**Control (without)**	36.91	37.51	3.74	3.83	8.43	8.56	44.40	44.73
	Potassium sulphate (Nano)	37.14	37.80	3.88	3.94	8.70	8.88	44.59	44.40
	Potassium citrate (Nano)	37.43	37.99	3.92	4.00	8.80	8.99	44.53	44.47
	Potassium silicate (Nano)	37.82	38.47	4.07	4.17	8.96	9.10	45.46	45.88
Compost (Faba bean)	**Control (without)**	41.37	42.21	4.33	4.40	9.57	9.77	45.26	45.00
	Potassium sulphate (Nano)	41.64	42.57	4.47	4.55	9.72	9.92	46.02	45.90
	Potassium citrate (Nano)	41.97	42.53	4.65	4.75	9.77	9.96	47.56	47.69
	Potassium silicate (Nano)	42.01	42.60	4.81	4.91	9.90	10.09	48.58	48.66
Compost (Banana tree)	**Control (without)**	42.71	43.36	5.13	5.22	10.35	10.55	49.58	49.45
	Potassium sulphate (Nano)	42.84	43.46	5.28	5.38	10.37	10.59	50.96	50.83
	Potassium citrate (Nano)	42.90	43.52	5.32	5.44	10.41	10.65	51.13	51.05
	Potassium silicate (Nano)	43.04	43.74	5.47	5.61	10.45	10.68	52.38	52.51
LSD at 5%		**0.87**	**0.32**	**0.09**	**0.09**	**0.19**	**0.13**	**1.48**	**1.22**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

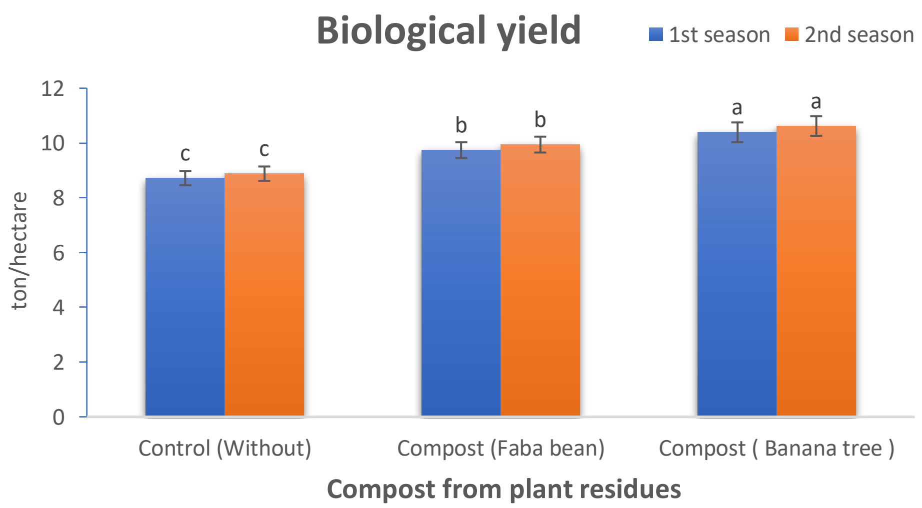

Fig. 5. Effects of various compost types on the biological maize yield in the 2023 and 2024 seasons.

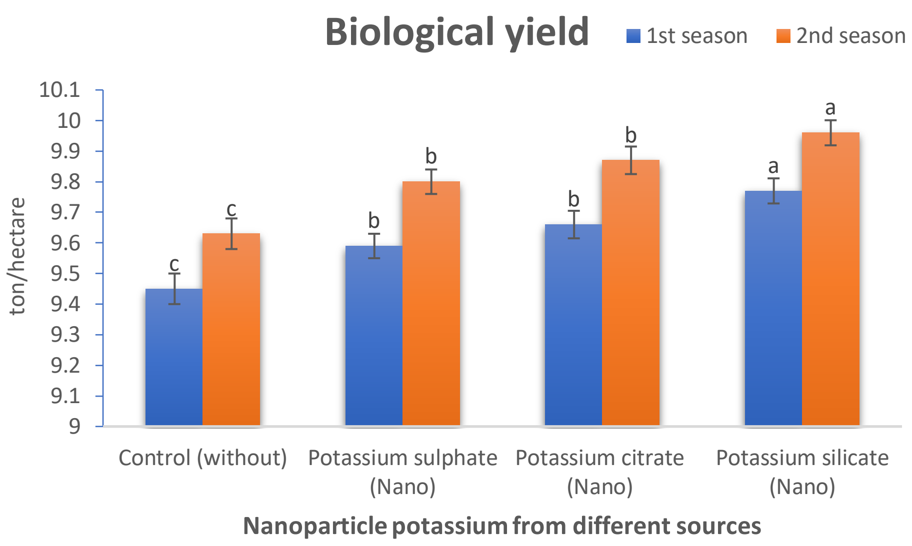

Fig 6. Effects of foliar application of nanoparticle potassium from different sources on the biological maize yield in the 2023 and 2024 seasons.

Potassium silicate (nano) consistently led to the best outcomes among the nanoparticle potassium sources, significantly improving cob weight, cob length, cob diameter, and the number of seeds per cob. It also resulted in higher grain yield and biological yield, with a superior harvest index compared to other treatments. This suggests that potassium silicate plays a key role in improving maize performance under the given conditions. Potassium citrate (nano) and potassium sulfate (nano) also showed significant improvements over the control, although their effects were slightly less pronounced compared to potassium silicate. The combination of banana tree compost with potassium silicate (nano) achieved the highest values across all measured parameters, indicating a synergistic effect between these treatments in enhancing maize growth and yield.The combination of faba bean compost with potassium silicate (nano) also produced high values but was slightly less effective than the banana tree compost combinations.

Table 6 presents the effects of various compost types and foliar application of nanoparticle potassium from different sources on maize quality parameters, including nitrogen (N), phosphorus (P), potassium (K), protein and carbohydrate content, across two seasons (2023 and 2024). Banana tree compost showed the most pronounced improvement in maize quality, leading to the highest levels of N, P, K, protein and carbohydrates in both seasons. For instance, in the second season, the N content reached 2.13%, while protein content was 12.23%, and carbohydrates were 70.33%. These results suggest that banana tree compost provided the best nutrient availability for maize, enhancing both its nutritional quality and overall composition. Faba bean compost also significantly improved maize quality compared to the control, although it was less effective than banana tree compost. It increased the protein content to 10.56% in the second season and carbohydrates to 67.88%, highlighting the benefits of organic compost in improving nutrient uptake and quality traits. Potassium silicate (nano) consistently showed the highest impact on maize quality, with the highest N (1.91% in the second season), protein (10.98%) and carbohydrates (68.07%). This demonstrates that potassium silicate plays a critical role in enhancing the nutritional content of maize, making it the most effective nanoparticle potassium source among those tested. Potassium citrate (nano) and potassium sulfate (nano) also positively affected maize quality, but their impacts were slightly lower than potassium silicate, with potassium citrate leading to 1.84% N content in the second season and potassium sulfate leading to 1.80%. The combination of banana tree compost and potassium silicate (nano) recorded the highest values across all measured parameters, with

2.22% N, 12.77% protein, and 70.34% carbohydrates in the second season, indicating a strong synergistic effect that significantly enhanced maize quality. Faba bean compost combined with potassium silicate (nano) also showed strong results, with 1.91% N, 10.98% protein, and 68.43% carbohydrates in the second season, demonstrating that this combination also improved maize quality but was slightly less effective than banana tree compost. The control treatments (without compost or nanoparticle potassium) showed the lowest values in all quality parameters, highlighting the importance of both organic compost and nanoparticle potassium in improving the nutritional quality of maize.

Table 6. Effects of various compost types and foliar application of nanoparticle potassium from different sources on maize quality in the 2023 and 2024 seasons.

Treatments		N, %		P, %		K, %		Protein, %		Carbohydrates, %	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Compost from plant residues											
Control (Without)		1.41c	1.48c	0.172c	0.179c	1.21c	1.27c	8.09c	8.50c	64.17c	64.96c
Compost (Faba bean)		1.75b	1.84b	0.195b	0.204b	1.65b	1.74b	10.05b	10.56b	67.07b	67.88b
Compost (Banana tree)		2.02a	2.13a	0.219a	0.227a	1.85a	1.95a	11.63a	12.23a	69.54a	70.33a
Sub main factor : Nanoparticle potassium from different sources											
Control (without)		1.61c	1.70c	0.191c	0.199c	1.53a	1.60b	9.27c	9.78c	66.63a	67.33a
Potassium sulphate (Nano)		1.71bc	1.80b	0.194b	0.202b	1.56a	1.64ab	9.81bc	10.36b	66.80a	67.63a
Potassium citrate (Nano)		1.77ab	1.84ab	0.196b	0.204b	1.58a	1.67ab	10.15ab	10.60ab	67.06a	67.86a
Potassium silicate (Nano)		1.82a	1.91a	0.200a	0.208a	1.62a	1.70a	10.46a	10.98a	67.23a	68.07a
Interaction											
Control	**Control (without)**	1.25	1.33	0.168	0.175	1.15	1.20	7.21	7.63	64.07	64.72
	Potassium sulphate	1.37	1.45	0.171	0.179	1.20	1.26	7.88	8.36	64.07	64.75
	Potassium citrate (Nano)	1.47	1.53	0.174	0.181	1.24	1.31	8.45	8.82	64.12	64.94
	Potassium silicate (Nano)	1.53	1.60	0.176	0.183	1.26	1.33	8.80	9.20	64.43	65.44
Compost (Faba bean)	**Control (without)**	1.64	1.73	0.192	0.200	1.61	1.69	9.43	9.93	66.38	67.12
	Potassium sulphate	1.75	1.84	0.193	0.202	1.64	1.73	10.04	10.58	66.77	67.58
	Potassium citrate (Nano)	1.79	1.87	0.194	0.202	1.65	1.75	10.27	10.75	67.53	68.41
	Potassium silicate (Nano)	1.82	1.91	0.202	0.210	1.71	1.80	10.45	10.98	67.60	68.43
Compost (Banana tree)	**Control (without)**	1.94	2.05	0.213	0.221	1.83	1.91	11.16	11.79	69.42	70.16
	Potassium sulphate	2.00	2.11	0.217	0.225	1.84	1.94	11.50	12.15	69.55	70.57
	Potassium citrate (Nano)	2.04	2.12	0.221	0.230	1.85	1.96	11.73	12.21	69.53	70.25
	Potassium silicate (Nano)	2.11	2.22	0.223	0.232	1.89	1.99	12.13	12.77	69.66	70.34
LSD at 5%		**0.19**	**0.17**	**0.005**	**0.004**	**0.18**	**0.13**	**1.07**	**0.96**	**1.48**	**3.71**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

4. Discussion

Alkaline soils often pose challenges, notably reduced nutrient availability and microbial activity, adversely impacting plant growth and yield. This study aimed to investigate how different compost types and foliar applications of nanoparticle potassium affect maize growth, quality, and stress resistance under alkaline conditions. Several scientific reasons can explain these findings, particularly the nutrient dynamics of compost, the role of nanoparticle potassium, and the interaction between organic and foliar treatments.

Effect of compost on maize

It can be said that organic compost led to improve soil structure and nutrient availability, which is critical in alkaline soils where essential nutrients may be locked in non-available forms. Compost, especially from banana trees and faba beans, significantly enhanced the performance and productivity of maize. The superiority of banana tree compost can be attributed to its rich organic matter content, which improves soil structure, increases microbial activity, and enhances nutrient availability. Banana tree compost is particularly high in potassium, nitrogen, and other essential nutrients, which directly contribute to the improved performance and productivity of maize. The breakdown of organic materials in compost releases nutrients slowly, ensuring a sustained supply of N, P, and K throughout the growing season. This aligns with previous research that emphasizes the role of compost in improving soil fertility, leading to enhanced plant growth and crop quality (**Soliman *et al.* 2023&2024**). The effectiveness of faba bean compost can be explained by the leguminous nature of faba beans, which fix atmospheric nitrogen into the soil through biological nitrogen fixation (BNF). This natural nitrogen addition contributes to the higher nitrogen content observed in maize plants treated with faba bean compost **(Krenz *et al.* 2023).** Moreover, the organic acids and enzymes produced during compost decomposition facilitate better nutrient absorption, improving maize performance and productivity (**Rashwan 2024)**.

Role of nanoparticle potassium on maize

The foliar application of nanoparticle potassium sources, particularly potassium silicate (nano), led to significant improvements in maize performance and productivity parameters. Nanoparticles possess unique properties due to their small size, high surface area, and increased reactivity, which enhances the efficiency of nutrient absorption by plants. Potassium silicate, in particular, plays a vital role in plant physiological processes, including water regulation, enzyme activation, and stress tolerance. Its high efficiency in improving nutrient uptake likely contributed to the superior growth performance and productivity observed in maize treated with potassium silicate. Potassium is essential for photosynthesis, carbohydrate synthesis, and protein formation (**Mahil and Kumar 2019**).The nanoparticle form ensures a more targeted and efficient delivery of potassium to plant cells, resulting in improved crop quality. Additionally, potassium silicate enhances plant resilience to environmental stress, further contributing to the observed improvements in the second season, which may have experienced variations in temperature or moisture conditions. Potassium citrate (nano) and potassium sulfate (nano) also positively affected maize performance and productivity but to a slightly lesser extent. Both are effective sources of potassium, with citrate providing additional organic carbon, which can improve root health and nutrient uptake, while sulfate contributes to sulfur availability, an essential element for protein synthesis (**Mahil and Kumar 2019; Farrag *et al.* 2024**).

Interaction between compost and nanoparticle potassium

The interaction between compost and nanoparticle potassium demonstrated a synergistic effect. This synergy can be attributed to the enhanced soil structure, nutrient retention, and microbial activity provided by the compost, coupled with the increased nutrient uptake efficiency due to the nanoparticle foliar application. Banana tree compost provides an ideal organic base that retains moisture and nutrients, which are then efficiently absorbed and utilized by the plant through the foliar application of nanoparticle potassium. Potassium silicate, known for improving cell wall strength and stress tolerance, further boosts nutrient assimilation and transport within the plant. This combination leads to an optimal environment for maize growth, resulting in better performance growth and productivity.

Oxidative Stress and Antioxidant Activity

The study also highlighted the effects of treatments on oxidative stress markers, with compost application significantly reducing malondialdehyde (MDA) levels. This indicates a lower degree of lipid peroxidation and oxidative damage in plants, a crucial factor for maintaining plant health under stress. The combination of banana tree compost and potassium silicate not only minimized stress markers but also enhanced enzymatic antioxidant activities (CAT and POX), providing further protection against oxidative stress (**Sahakyan *et al*. 2022; Elsonbaty and El-Sherpiny 2024)**.

Seasonal variations and consistency in results

The consistency of results across both the 2023 and 2024 seasons suggests that the treatments, particularly the combination of compost and nanoparticle potassium, offer stable improvements in maize performance and productivity. Seasonal variations, such as differences in temperature, humidity, and soil moisture, may have impacted plant nutrient uptake. However, the slow-release nature of compost nutrients and the efficiency of nanoparticle potassium ensured sustained plant performance across both seasons.

5. Conclusion

This study demonstrates that combining banana tree compost with nanoparticle potassium can significantly improve maize growth, quality, and stress tolerance in alkaline soils. Future research should explore various compost types and their interactions with nanoparticle fertilizers, focusing on long-term impacts and economic feasibility across different cropping systems. Such studies will be vital for enhancing food security and promoting sustainable agricultural practices.

Conflicts of interest

The authors have declared that no competing interests exist.

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