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RESEARCH ARTICLE

Nano-powered maize revolution: enhancing yield and sustainability through synergistic application of nano-fertilizers for food security

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Abstract

The global agricultural sector faces mounting challenges from climate change, population growth and resource depletion. This study explores the potential of nano-fertilizers to improve maize productivity in India. Field experiments were conducted during the *Kharif* seasons of 2021-22 in Karnataka. The study compared various combinations of conventional fertilizers with foliar applications of nano-nitrogen and nano-phosphorus. Results revealed significant improvements in maize yield and yield components following nano-fertilizer treatments. The highest yield (6612 kg/ha) was achieved with 75 % of the Recommended Dose of Fertilizers (RDF) plus two foliar sprays of nano-nitrogen and nano-phosphorus, surpassing conventional fertilizer application (5741 kg/ha). Nano-fertilizer treatments enhanced growth parameters, including plant height, leaf area and dry matter accumulation. Yield components such as cob length, grain weight and kernel number per cob showed notable improvements. The synergistic application of nano-fertilizers with conventional fertilizers shows promising for optimizing nutrient use efficiency and reducing environmental impact. This study underscores the promise of nano-fertilizers in transforming maize cultivation, contributing to sustainable agricultural practices by minimizing pollution and resource depletion. The findings suggest that integrating nano-fertilizers into mainstream agricultural practices could significantly contribute to food security and environmental sustainability in India.

Keywords: foliar application; food security; maize yield; nano-fertilizers sustainable agriculture; nutrient use efficiency

Introduction

Maize, a widely cultivated global crop, gaining a consistent increase in its cultivation area, mostly driven by the increasing demand for its utilization in the food and feed sectors. Maize ranks third in both production and productivity, following wheat and rice (1). Maize is commonly cultivated during the *Kharif* season; however, its adaptability to diverse climatic circumstances allows for its cultivation throughout the *Rabi* and summer seasons. This photoperiod insensitivity trait characteristic of maize enables its cultivation throughout a wide geographic range in India.

Due to the high nutrient demand for maize cultivation, the nutrient requirement of this crop cannot be adequately met only by the inherent nutrient reserves present in the soil. Nevertheless, these requirements can be augmented through applying fertilizers to the soil or by employing foliar spraying techniques on the plant's foliage. Global food production and distribution systems are facing increasing and enduring pressures due to climate change, population growth and diminishing availability of arable land and freshwater resources (2). Implementing technological advancements and substantial modifications to existing global food production processes may offer a potential solution. Nutrient management constitutes an integral component of the production management system. The success of crop production in terms of profitability hinges upon the understanding and application of appropriate nutrient quantities required at each stage of growth, as well as a comprehensive assessment of the soil's ability to supply these nutrients (3).

Presently, the utilization of agrochemicals at elevated levels is essential for contemporary agricultural practices. To achieve optimal growth and productivity, crops need synthetic chemical fertilizers; yet crop productivity or plant Nutrient Utilization Efficiency (NUE) are often not significantly improved. The nitrogen, phosphorus and potassium macronutrients exhibit low NUE values, ranging from 30–35 %, 18–20 % and 35–40 %, respectively (4). As a result, several processes, including photolysis, hydrolysis, leaching, microbial immobilization and degradation, more than half of the fertilizers applied to the fields, evaporate and fail to reach their intended locations.

The fields of nanoscience and nanotechnology have recently emerged as promising areas for the research community. Nano fertilizers are easy to get and can even be applied foliar. However, when bulk fertilizers are applied directly to the soil, nutrients are lost due to leaching, runoff, degradation and other processes. It is useful in managing the availability and release of nutrients, but this does not prevent nutrients from being lost. It's possible that the applied fertilizer won't be able to make it to where it's supposed to be in the plant system to ensure the healthiest growth and output possible for the crops. As a result of this, a foliar spray that contains nano fertilizer was created to increase the effectiveness of the crop's ability to absorb fertilizer (5).

Nano fertilizers are produced using nanotechnology, wherein they are either artificially synthesized or modified forms of conventional fertilizer components. Alternatively, they can be obtained from different vegetative or reproductive parts of plants through various chemical, physical, mechanical or biological methods. Nano fertilizers offer numerous advantages, including one of which is a notable enhancement in NUE, resulting in a three-fold rise. The utilization of chemical fertilizers can be significantly diminished by a factor of approximately 55–60, leading to a substantial reduction in their requirement (6). Additionally, crops exhibit a remarkable resilience to stress, with an improvement in tolerance by a factor of 10 to 12. The source material employed in this context is fully biodegradable, ensuring its environmental sustainability. Moreover, agricultural yields witness a notable enhancement, ranging from 18–54 %. There is an expectation that emerging nano strategies, such as the use of nano fertilizers, will exhibit more effectiveness in enhancing the utilization of fertilizers compared to conventional bulk fertilizers. Although there exists literature on the application of nano micronutrient fertilizers via foliar spraying on certain crops, the available data is insufficient to ascertain the efficacy of nano-fertilizers. Hence, the objective of this study was to evaluate the impact of nano-fertilizers on maize yield, its components and selected morphological traits.

To address the growing need for agricultural products, it is imperative to enhance crop yield, hence necessitating a reliance on fertilizers as a means of providing essential nutrients to plants. Due to the reliance on fertilizers, it is imperative to devise strategies aimed at enhancing the efficacy of their application and optimizing crop productivity. Nano fertilizers are advantageous compared to conventional fertilizers as they increase soil fertility, yield and quality parameters of the crop, they are less harmful to the environment and human health, while minimizing cost and maximizing profit. As such the use of nano fertilizers could prove to be a blessing for Indian agriculture and may pave the way for their efficient utilization, in the view of the above, it was felt appropriate to study the efficacy of conventional, nano and water-soluble fertilizers.

Materials and Methods

Field research was conducted at Shikaripura, Karnataka during the *Kharif* seasons of 2021 and 2022. The research site was located at a latitude of 14°28' N, a longitude of 75°32' E and an elevation of 603 m above sea level. The soil exhibited a sandy loam texture and possessed an acidic character, as indicated by a pH value of 6.5. The sample had a moderate level of organic carbon content, specifically measuring at 0.60 %. Additionally, the Electrical Conductivity (EC) of the sample was recorded at 0.048 dSm^{-1}. The medium availability of nitrogen, phosphorus and potassium (NPK) was seen at levels of 275, 48.24 and 198 kg ha^{-1}, respectively. The soil used in the experiment was classified as sandy loam, characterized by an average particle composition consisting of 68 % sand, 15 % silt and 17 % clay. The cumulative precipitation recorded over the crop growth period amounted to 691 mm. The average monthly maximum temperature exhibited a range of 27.5 °C in the month of July to 30 °C in the month of October. Similarly, the minimum temperature showed a range of 19.8–21.5 °C The humidity levels varied between 79–92 %. The trial was conducted using a randomized complete block design, with three replications and a total of 14 treatment combinations. The sowing of all plots was conducted manually and the desired plant population was maintained by the process of thinning the excess plants. The maize crop was planted with a plant-to-plant spacing of 30 cm and a row-to-row spacing of 60 cm. Weed management was consistently performed manually. The crop was subjected to irrigation using a furrow irrigation method. The remaining cultural practices were adhered to in accordance with established agronomic standards. During the agricultural growth period, which spans from July to October, a cumulative rainfall of 822 mm was recorded on average over a two-year period.

Experimental design and treatments

The experiment employed a Randomized Complete Block Design (RCBD) with three replications, a standard approach in agricultural field trials to account for soil heterogeneity. Fourteen treatment combinations were evaluated, T1: 100 % RDF through conventional fertilizers (POP), T2: 50 % RDN through CF's(Conventional Fertilizers) + 3 foliar spray of nano nitrogen, T3: 75 % RDN through CF's + 2 foliar spray of nano nitrogen, T4:100 % RDN through CF's + 1 foliar spray of nano nitrogen, T5: 50 % RDP through CF's + 3 foliar spray of nano phosphorus, T6: 75 % RDP through CF's + 2 foliar spray of nano phosphorus, T7: 100 % RDP through CF's + 1 foliar spray of nano phosphorus, T8:50 % RDNP through CF's + 3 foliar spray of nano nitrogen and phosphorus, T9: 75 % RDNP through CF's + 2 foliar spray of nano nitrogen and phosphorus, T10: 100 % RDNP through CF's + 1 foliar spray of nano nitrogen and phosphorus, T11: 50 % RDNP through CF's + 3 foliar spray of WSF (12:61:0), T12: 75 % RDNP through CF's + 2 foliar spray of WSF (12:61:0), T13: 100 % RDNP through CF's + 1 foliar spray of WSF (12:61:0), T14: absolute control (no fertilizer application).

Planting and crop management

Maize (variety: MAH 14-5) was manually sown with a plant-to-plant spacing of 30 cm and a row-to-row spacing of 60 cm, resulting in a plant population of approximately 55555 plants ha^{-1}. This spacing is consistent with recommendations for optimal maize yield in the region. Thinning was performed to maintain the desired plant population.

Weed management was carried out manually throughout the growing season to minimize competition for resources. Irrigation was provided using the furrow method as needed, supplemented with natural rainfall to maintain optimal soil moisture conditions for maize growth.

Fertilizer application

Conventional fertilizers were applied as urea (46 % N), single super phosphate (16 % P_2O_5) and potassium sulphate (50 % K_2O). In treatments receiving 100 % RDF through conventional fertilizers (T1, T4, T7, T10, T13), the full dose of P and K was applied during bed preparation, while N was split-applied with 50 % at bed preparation and the remaining 50 % at tassel initiation and silking stages. This split application of N is a common practice to improve nitrogen use efficiency in maize.

For treatments with reduced conventional fertilizer rates (T2, T5, T8, T11), 50 % of the RDF was applied as a basal dose. In treatments T3, T6, T9 and T12 the full dose of P and K and 50 % of N were applied as basal, with the remaining 25 % N applied at the knee-high stage (Table 1).

Nano fertilizers and water-soluble fertilizers

The nano-urea and nano-DAP used were manufactured by Indian Farmers Fertilizer Cooperative Limited (IFFCO). Nano-urea particles ranged from 20-50 nm in size, with an average of 30-40 nm and a specific surface area of 60-80 m^2/g. Nanoparticles were coated with hydrophobic silica to improve dispersion and prevent premature degradation.

Nano-DAP had similar specifications. Their small size and surface area enhance nutrient solubility and plant absorption (7–9).

The water-soluble fertilizer used had a nutrient ratio of 12:61:0 (N:P:K), applied as foliar sprays in treatments T11-T13.

Field observations

During vegetative stage after 10 days of sowing, we had taken shoot length and root length observations. At harvest, measurements were taken for plant height (in centimeters), dry matter accumulation in leaves and stem (per plant), number of leaves and leaf area per plant, cob length (in centimeters), number of cobs per plant, number of grain rows per plant, number of grains per row and 1000 grain weight (in grams) and yield.

Statistical analysis

The collected data were subjected to Analysis of Variance (ANOVA) using an F-test at a 5 % significance level (10). This statistical approach allows for the determination of significant differences among treatments. When significant differences were detected, means were separated using the Least Significant Difference (LSD) test at $p \leq 0.05$.

All statistical analyses were performed using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). The normality of data distribution was checked using the Shapiro-Wilk test and homogeneity of variances was assessed using Levene's test prior to ANOVA.

Results and Discussion

Growth parameters

Seedling length (cm) and root length (cm)

On the tenth day, five healthy seedlings were randomly chosen from each treatment to measure the length of their roots. From the collar region to the tip of the primary leaf, the seedling's length was measured. The mean seedling length was expressed in centimeters. Every plant's shoot and root length was measured using a measuring tape and the averages were noted for statistical examination (11).

Growing maize plants undergo a remarkable transformation during the early stages of germination. As the seedlings emerge from the soil, they exhibit rapid growth in both the root system and shoot structure. Measuring the root length and shoot length provides valuable insights into the overall health of the plants. The shoot length measurement serves as a valuable indicator of the plant's ability to establish itself and capture vital sunlight for photosynthesis. A well-developed shoot system enables efficient nutrient uptake, supports the growth of leaves and flowers and ultimately contributes to higher crop yield. Ten days after seedling emergence, we did not find any significant difference between different treatments, where we applied 100 % RDF with or without additional supply of nutrients, we are observing higher number seedling and root growth (12).

Shoot length and root length were measured in all the treatments, there was no significant difference in shoot and root growth between the two consecutive years after 10 days of emergence. However, a significant difference was observed in the treatment with 100 % RDF (T13), which exhibited greater seedling vigor (13), closely followed by the 75 % RDF treatment. The least shoot and root growth were recorded in the absolute control plot (T14). The results are presented in Fig. 1.

Plant height

Application of different combinations of nano fertilizers with multiple dosages can enhance the height of the plants. Plant height was significantly enhanced by the application of one spray of nano nitrogen and phosphorus along with 100 % RDF, followed by 75% RDF with two sprays of nano nitrogen and phosphorus ($p < 0.05$). The lowest plant height was recorded in the absolute control plot, while the tallest plants were observed in treatments T9 and T10. Lowest growth of the plants were observed in absolute control plots, results of water soluble fertilizers plots with 50 % and 75 % RDF (T11 & T12) shows plant height is lower than nano fertilizers applied plots, that was shown in Fig. 2. General observations showed that all treatments are performing higher with application of nano fertilizers except

Table 1. Treatment wise quantity of nutrient application summary

Treatment number	Nitrogen fertilizer		Phosphorus fertilizer	Potash fertilizer
	Basal	Top dressing	Basal	Basal
T1, T4, T7, T10, T13	50 %	50 %	100 %	100 %
T2, T5, T8, T11	50 %		50 %	100 %
T3, T6, T9, T12	50 %	25 %	75 %	100 %

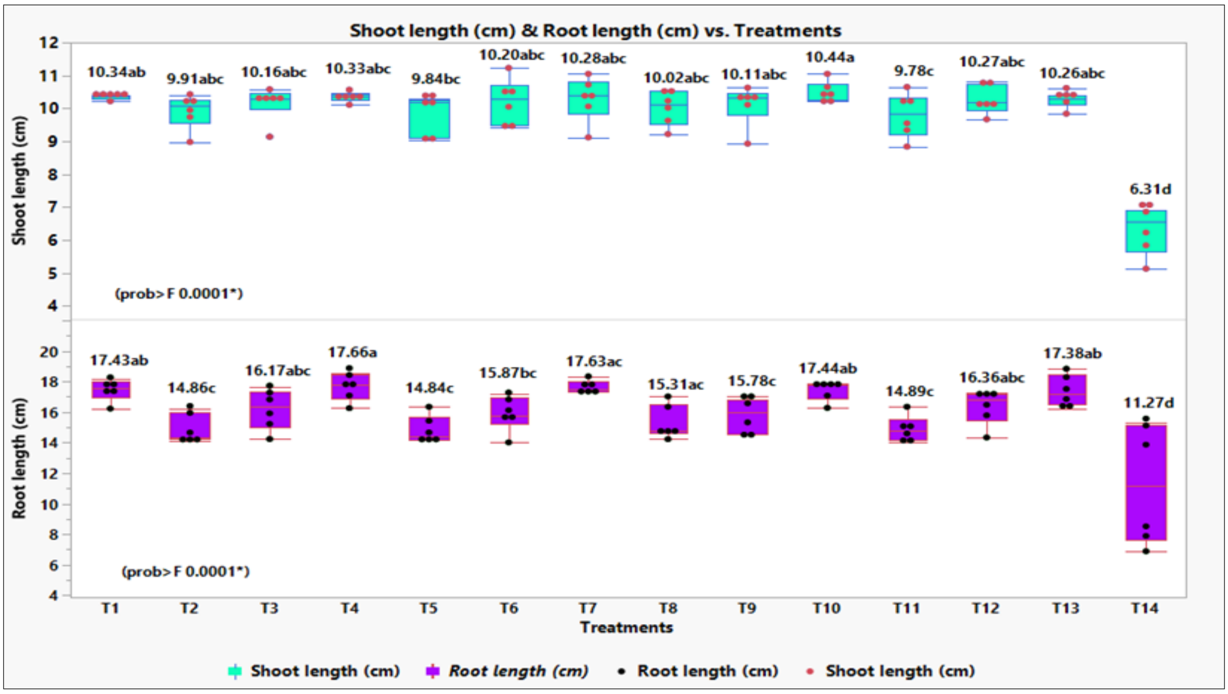

Fig. 1. Shoot and root growth by application of nano and water-soluble fertilizers.

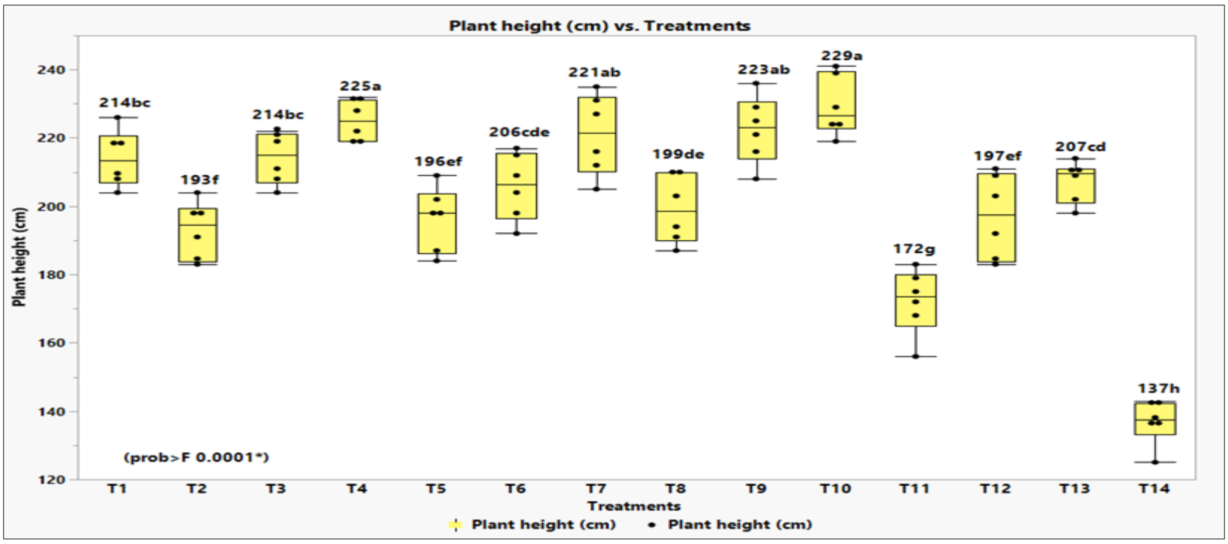

Fig. 2. Influence of plant height by application of different dosages of nano and water-soluble fertilizers.

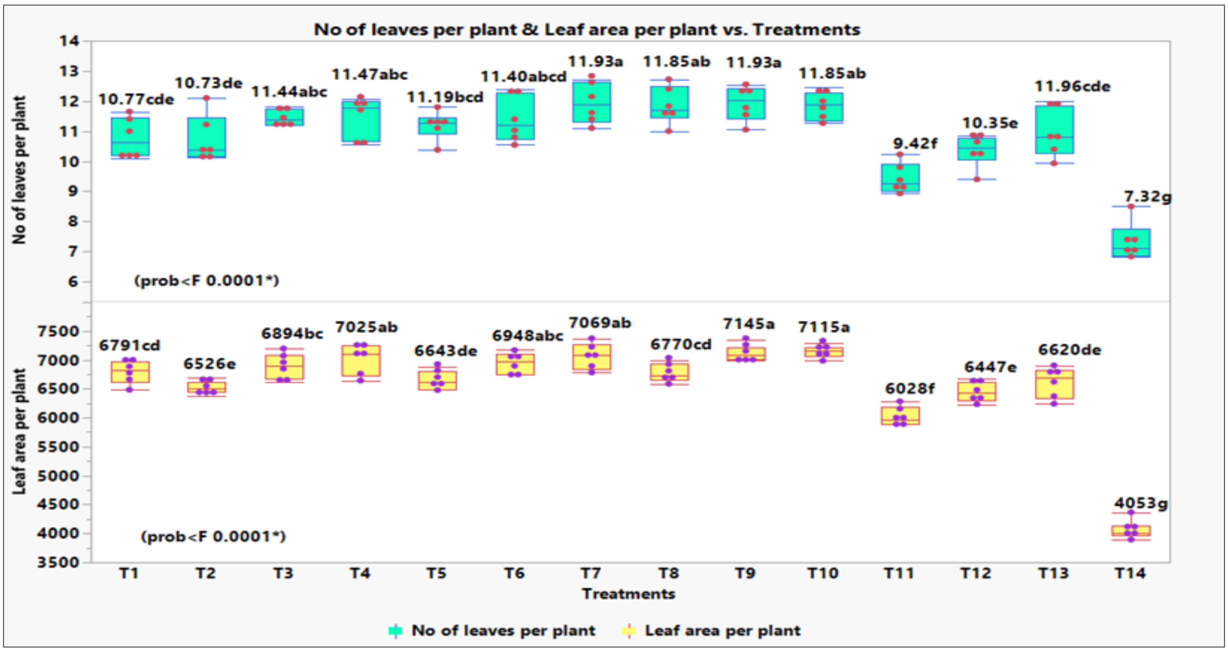

Fig. 3. Influence of number of leaves per plant and leaf area by application of different dosages of nano and water-soluble fertilizers.

water soluble fertilizer spray. These findings indicate that nano fertilizer can serve two purposes: supplying nutrients to the plant and facilitating the transportation or absorption of existing nutrients, leading to improved crop growth. A study conducted by author found similar results in maize (14).

Number of leaves and leaf area per plant

The number of leaves per plant plays a crucial role in determining the overall productivity of a crop. In the context of maize cultivation, achieving a higher number of leaves per plant can significantly impact yield, that was shown in Fig. 3. This section explores how the application of nano nutrients, specifically nano nitrogen and nano phosphorus, can stimulate leaf production and contribute to an increased number of leaves per plant meanwhile leaf area plays a vital role in the growth and development of maize plants, directly impacting important processes such as photosynthesis and nutrient absorption. Maximizing leaf area is crucial for optimizing the plant's ability to capture sunlight and essential nutrients. The application of 75 % RDF with two sprays of nano nitrogen and phosphorus significantly improved ($P < 0.05$) the number of leaves and leaf area per plant, which was statistically superiors over rest of the treatments in two years of study. Application 100 % RDF with one spray nano nitrogen and phosphorus also provide higher number of leaves and leaf area per plant (T7, T10 and T13). Foliar applications of water soluble fertilizer with 50 % and 75 % RDF in different combinations gives lower result as compared nano nitrogen and phosphorus application (T11 & T12). Nano nitrogen and phosphorus application combination performed well and higher number of leaves were observed. While significantly minimum leaf per plant and leaf area in absolute control plot without application of fertilizers (T14). The outcomes of this study were consistent with those reported in another study (15).

Dry weight of leaf, stem and cob

Dry weight of leaves (g)

This parameter measures the total dry biomass of leaves for each treatment after removing all moisture content, as presented in Table 2. Leaf dry weight is an important indicator of plant growth and photosynthetic capacity. Leaves are the primary site of photosynthesis and their biomass accumulation reflects the plant's ability to capture and convert light energy into chemical energy, treatment T11 (25.25c) has the lowest dry weight of leaves, significantly different from most other treatments. Treatments T9 (39.02ab), T10 (38.91a), T7 (37.07ab), T4 (37.55ab), T6 (36.36ab) and T13 (36.13ab) have the highest leaf dry weights and are not significantly different from each other.

Dry weight of stem (g)

The dry weight of the stem represents the total dry biomass of the plant's main structural support system. The stem serves as a conduit for water and nutrient transport, as well as a storage organ for carbohydrates and other essential compounds. Stem dry weight is often correlated with plant height, thickness and overall vigor. Treatment T14 (37.98f) has the lowest stem dry weight, significantly different from others. Treatments T9 (79.27a) and T10 (77.93a) have the highest stem dry weights, not significantly different from each other but different from the rest (16).

Cob dry weight (g)

In the context of this study, which appears to be focused on maize or corn, the cob dry weight measures the total dry biomass of the corn ears or cobs, excluding the grains or kernels. The cob is the central cylindrical structure that bears the kernels and its weight can be an indicator of the overall yield potential and resource allocation within the plant. Treatment T14 (80h) has the lowest cob dry weight, significantly different from others. Treatments T9 (220a) and T10 (217ab) have the highest cob dry weights, not significantly different from each other but different from the rest.

The improved growth is due to a high concentration of nano-fertilizers, which enhanced auxin synthesis. Auxin has the potential to induce cell division and elongation in all emerging plant parts. As a result of better plant height and growth characteristics, dry matter levels increase as crop growth progresses. Furthermore, this increase could be attributed to the fact that nonfertilizer, which are quickly absorbed by plants, may cause increased photosynthesis and a buildup of dry matter. Similar results were reported in previous studies (17–19).

Yield parameters

Rows per cob (no.)

This parameter quantifies the average number of kernel rows or ranks present on each corn cob for the respective treatments presented in Table 2. The number of rows per cob is a genetic characteristic of the maize variety, but it can also be influenced by environmental factors and cultural practices. More rows per cob generally translate into higher grain yield potential. Treatment T14 (8.17e) has the lowest number of rows per cob, significantly different from others. Treatment T10 (13.33a) has

Table 2. Dry weight and yield related parameters are influenced by application of nano and water-soluble fertilizers (N & P)

Treatments	Dry weight of leaves (g)	Dry weight of stem (g)	Cob dry weight (g)	Rows per cob (no.)	Grains per row (no.)	Kernels per cob (no.)	100 kernel weight (g)
T1	35.09ab	67.82bcd	200cd	11.33bc	27.33cd	311bc	29.99ab
T2	32.24b	52.70e	173fg	10.17d	26.17cd	266de	29.72ab
T3	35.06ab	63.94cde	199cd	11.50bc	29.33bc	337bc	30.84ab
T4	37.55ab	71.70abc	205bc	11.67bc	29.67abc	346b	31.01ab
T5	32.82b	60.84de	185ef	10.83c	26.67cde	289cd	30.04ab
T6	36.36ab	71.97abc	190cde	11.50bc	29.67bc	341bc	30.79ab
T7	37.07ab	73.05ab	208bc	11.83bc	30.67abc	364bc	30.90ab
T8	34.94ab	69.65ab	187def	11.50bc	31.33abc	361bc	30.35ab
T9	39.02ab	79.27a	220a	12.67ab	34.00a	430a	31.50a
T10	38.91a	77.93a	217ab	13.33a	33.33ab	444a	31.55a
T11	25.25c	53.67e	158g	9.00de	19.17e	155fg	28.14c
T12	31.22b	62.68cde	168fg	9.17d	22.33de	205ef	29.38
T13	36.13ab	71.16ab	203bc	11.50bc	27.83bc	320bc	30.28ab
T14	16.08d	37.98f	80h	8.17e	12.00f	109g	19.42d
P value	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*

the highest number of rows per cob followed by T9 (12.67ab), significantly different from the rest.

Grains per row (no.)

This parameter measures the average number of individual grains or kernels present in each row. Along with the number of rows per cob, the number of grains per row is a critical determinant of the final grain yield. This parameter can be influenced by various factors, including plant nutrition, water availability and growing conditions. Treatment T14 (12 f) has the lowest number of grains per row, significantly different from others. Treatment T9 (34a) has the highest number of grains per row, significantly different from the rest.

Kernels per cob (no.)

This column calculates the total number of kernels or grains present on each corn cob by multiplying the number of rows per cob by the number of grains per row. It provides a direct measure of the potential grain yield per cob, which is a key component of overall crop yield. Treatment T14 (109g) has the lowest number of kernels per cob, significantly different from others. Treatment T10 (444a) has the highest number of kernels per cob followed by T9 (430a), which is significantly different from the rest.

100-kernel weight (g)

This parameter measures the average weight of 100 individual kernels or grains for each treatment. It is an important quality trait that reflects the size and density of the grains, which can impact factors such as milling quality, nutritional value and market acceptability. Kernel weight is influenced by both genetic and environmental factors. Treatment T14 (19.42d) has the lowest 100-kernel weight, significantly different from others. Treatment T4 (31.01ab) has the highest 100-kernel weight, but not significantly different from several other treatments like T9, T10, T7, T6, T3 and T5. In summary, treatments T9 and T10 generally performed the best for yield related parameters, while T14 consistently showed the lowest values for all parameters measured. The letter notations (a, b, c, etc.) indicate which treatments are significantly different from each other for each parameter (19). The outcomes presented here are consistent with the conclusions drawn by another study (20). Water soluble fertilizers spray with 50 and 75 % RDF has not improved the yield levels, 100 % RDF with one foliar spray of water-soluble fertilizer resulted in higher yield levels compared to the bare application of 100 % RDF.

Nano nitrogen and phosphorus, particularly in the form of nano urea and DAP, has been demonstrated to enhance cell division and elongation, thereby strengthening the sink strength and promoting higher photosynthetic rates in plants. Synergistic application of nano fertilizers alongside traditional fertilizers facilitates improved nutrient translocation within the plant system, resulting in increased productivity and grain yield. Nanoparticles with dimensions less than 5 nm possess the ability to penetrate the leaf cuticles and stomatal apertures, allowing them to enter the vascular system, where their efficacy is influenced by alterations in their chemical composition and morphology, ultimately impacting the biological yield. Notably, the incorporation of nano nitrogen has been shown to augment various growth and yield attributes, as well as the final yield, in maize (*Zea mays* L.), attributable to the enhanced nutritional environment within the plant's metabolic system, which fosters higher metabolic activity and photosynthetic rates (21,22).

Yield

Based on the yield data, the highest yields were observed in treatments T9 and T10, which involved the application of combination of a nano-nitrogen and nano-phosphorus, along with conventional fertilizers. These treatments appear to be significantly different from the control (T1 and T14) and other treatments, indicating the potential benefit of using nano-fertilizers in combination with conventional fertilizers for improving maize yield (23,24), as shown in Fig. 4.

In the current study, foliar spray of nano nitrogen and phosphorus had a substantial impact on grain yield and yield characteristics (Table 2). The data showed that applying 75 % RDF + nano nitrogen and phosphorus (T9) @ 4 mL/L at knee height and tasseling was considerably superior to 100 % RDF without foliar supplementation, as were all treatments with 75 % RDF, 100 % RDF with foliar spray and the control (no nitrogen).

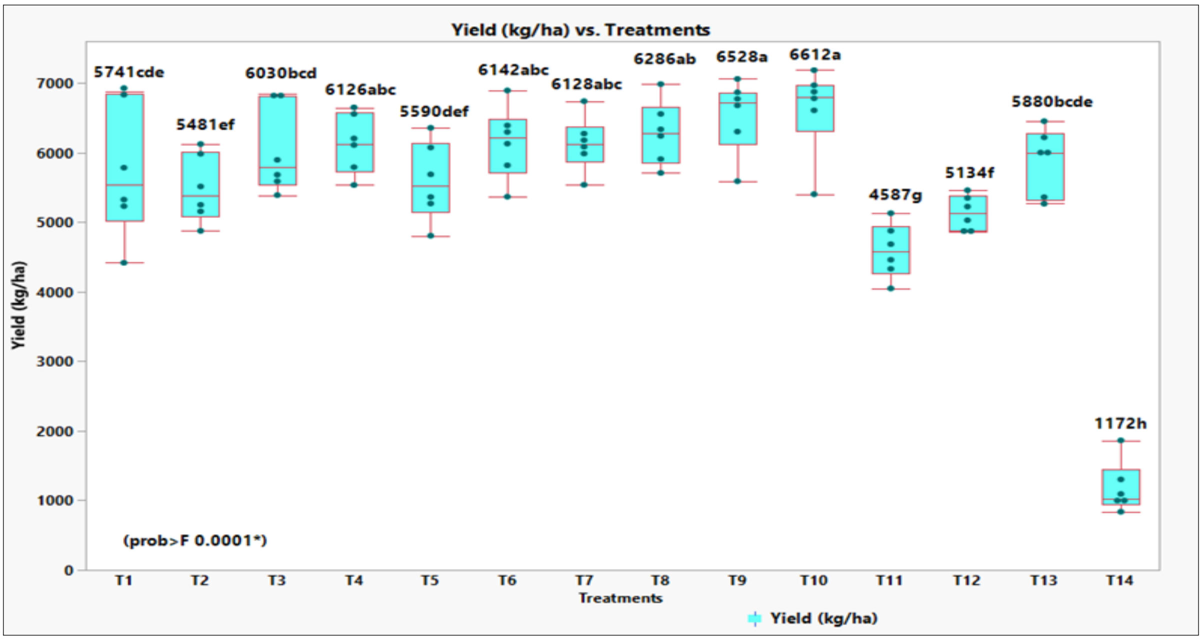

Fig. 4. Influence of nano and water-soluble fertilizers on seed yield in maize.

In this study, a statistically significant yield increase was reported with an increase in foliar spray application, in addition to the recommended nitrogen dosage; however, intensifying foliar spray from 2 to 3 could result in a statistical difference in grain yield with the appropriate amount of RDF. In comparison, the control (no nitrogen) demonstrated a much lower response in terms of grain output. The foliar application of nano-fertilizers in combination with soil-applied conventional fertilizers (Treatments T9 and T10) showed a synergistic effect, leading to significant improvements in yield. This novel approach of integrating nano-fertilizers with traditional fertilization methods could be a promising strategy for optimizing crop productivity (25,26). Nano nitrogen enhances maize growth, yield and quality. As a result, the nutritional environment in the plant metabolic system improves, resulting in higher plant metabolism and photosynthetic rates (27). The increase in grain yield could be attributed to nitrogen's positive influence on boosting source size and establishing an optimal source-sink connection (28–30).

Correlations

Correlation between yield and growth-related parameters

A statistical tool used to quantify the strength and direction of a linear relationship between two variables is the Pearson correlation coefficient. It has a range of -1 to 1, with 0 denoting no correlation, 1 denoting a perfect positive correlation and -1 denoting a perfect negative correlation, as shown in Table 3.

Explanation of correlations presented in the table

1. **Yield (kg/ha):** The diagonal element (1.000) represents the perfect correlation of yield with itself, which is expected. The yield has the strongest positive correlations with leaf area (cm^2) per plant (0.9071) and number of leaves per plant (0.8093), suggesting that higher leaf area and more leaves contribute to increased yield.
2. **Leaf area per plant:** This parameter has strong positive correlations with yield (0.9071), number of leaves per plant (0.8371), dry weight of leaves (0.8542), dry weight of stem (0.7827) and cob dry weight (0.9100). This indicates that a larger leaf area is associated with more leaves, higher biomass accumulation and increased yield and cob weight.
3. **No. of leaves per plant:** It has strong positive correlations with yield (0.8093), leaf area per plant (0.8371), dry weight of leaves (0.7691), dry weight of stem (0.7741) and cob dry weight (0.7912). This suggests that a higher number of leaves is related to increased leaf area, biomass accumulation and ultimately higher yield and cob weight.
4. **Dry weight (leaves):** This parameter exhibits strong positive correlations with yield (0.8308), leaf area per plant (0.8542), number of leaves per plant (0.7691), dry weight of stem (0.7928) and cob dry weight (0.8214). Higher leaf biomass is associated with increased yield, leaf area, number of leaves, stem biomass and cob weight.
5. **Dry weight (stem):** It has strong positive correlations with yield (0.7664), leaf area per plant (0.7827), number of leaves per plant (0.7741), dry weight of leaves (0.7928) and cob dry weight (0.8339). Higher stem biomass is related to increased yield, leaf area, number of leaves, leaf biomass and cob weight.
6. **Cob dry weight (g):** This parameter shows strong positive correlations with yield (0.8648), leaf area per plant (0.9100), number of leaves per plant (0.7912), dry weight of leaves (0.8214) and dry weight of stem (0.8339). Higher cob weight is associated with increased yield, leaf area, number of leaves and overall plant biomass.

The correlations are estimated by the Row-wise method, which means that the correlation coefficients are calculated based on the row vectors of the data matrix. The strong positive correlations observed between yield and key growth parameters, such as leaf area, number of leaves and dry weight of leaves, stem and cob, highlight the potential of nano-fertilizers to enhance overall plant growth and development. This finding aligns with recent studies that have reported the improved nutrient uptake and translocation facilitated by nano-fertilizers (31,32).

These strong positive correlations suggest that improving various plant growth parameters, such as leaf area, number of leaves and biomass accumulation, through the application of nano-fertilizers or other agronomic practices, could potentially lead to increased yield and cob weight in maize crops, shown in Table 3.

Correlation probability in yield and growth-related parameters

This section presents the p-values for testing the significance of correlations between different variables. All the p-values are less than 0.0001, indicating that the correlations between the variables (yield, leaf area per plant, number of leaves per plant,

Table 3. Correlation between yield and growth parameters

Correlation	Yield (kg/ha)	Leaf area per plant	No. of leaves per plant	Dry weight (leaves)	Dry weight (Stem)	Cob dry weight (g)
Yield (kg/ha)	1.000	0.907	0.809	0.831	0.766	0.865
Leaf area per plant	0.907	1.000	0.837	0.854	0.783	0.910
No of leaves per plant	0.809	0.837	1.000	0.769	0.774	0.791
Dry weight (leaves)	0.831	0.854	0.769	1.000	0.793	0.821
Dry weight (Stem)	0.766	0.783	0.774	0.793	1.000	0.834
Cob dry weight (g)	0.865	0.910	0.791	0.821	0.834	1.000

Table 4. Correlation probability between yield and growth parameters

Correlation probability	Yield (kg/ha)	Leaf area per plant	No. of leaves per plant	Dry weight (leaves)	Dry weight (Stem)	Cob dry weight (g)
Yield (kg/ha)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Leaf area per plant	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
No of leaves per plant	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Dry weight (leaves)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Dry weight (Stem)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Cob dry weight (g)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

dry weight of leaves, dry weight of stem and cob dry weight) are statistically significant at a very high level of confidence, details are shown in Table 4.

This correlation probability table displays the relationships between different variables related to plant characteristics. The variables included are yield (kg/ha), leaf area per plant, number of leaves per plant, dry weight of leaves, dry weight of stem and cob dry weight (g).

For example, the correlation between yield (kg/ha) and leaf area per plant is < .0001, suggesting that as the leaf area per plant increases, the yield also increases significantly. Similarly, the number of leaves per plant, dry weight of leaves, dry weight of the stem and cob dry weight all have very strong positive correlations with each other and with the yield. Overall, this correlation table demonstrates that these plant characteristics are highly interdependent, with increases in one variable being closely associated with increases in the other variables. Such strong positive correlations can provide insights into the relationships between different plant traits and their impact on yield or other important factors.

Fig. 5 shows a scatterplot matrix, which provides a visual representation of the relationships between the variables. Each panel in the matrix displays a scatterplot of two variables, with the correlation coefficient shown in the panel. The diagonal panels show the distributions of individual variables, while the off-diagonal panels show the scatterplots between pairs of variables. The scatterplot in the top-right panel shows the relationship between yield (kg/ha) and cob dry weight (g), with a strong positive correlation of 0.8648 The scatterplots generally exhibit positive linear relationships, with some variations in the strength of the relationships, as indicated by the correlation coefficients (33–35). These visualizations enable a comprehensive assessment of the interrelationships between various yield components, such as rows per cob, grains per row, kernels per cob and 100-kernel weight (36).

The color map on correlations (Fig. 6) provides a visual representation of the correlation coefficients between different parameters related to maize crop characteristics. The color scale ranges from dark red correlation coefficient of +1.0 to dark blue correlation coefficient of -1.0, with shades of red indicating positive correlations and shades of blue indicating negative correlations (37,38).

In the context of nano-fertilizer application in maize, the parameters shown in the color are influenced by the use of nano -fertilizers, particularly the application of nano-nitrogen and nano-phosphorus fertilizers has been shown to improve crop productivity by enhancing nutrient uptake and increasing the efficiency of fertilizer utilization (39).

Explanation of correlations presented in the table

1. **Yield (kg/ha):** The dark red color along the row and column for yield indicates a perfect positive correlation coefficient of +1.0 with itself.
2. **Leaf area per plant:** The dark red color in the intersection with yield suggests a strong positive correlation between leaf area per plant and yield. This could be because nano-fertilizers enhance nutrient uptake, leading to improved leaf growth and increased photosynthetic capacity, which in turn contributes to higher yields.
3. **Number of leaves per plant:** The dark red color in the intersection with yield and leaf area per plant indicates strong positive correlations, suggesting that nano-fertilizers may promote leaf development and increase the number of leaves, contributing to higher yields.
4. **Dry weight (leaves):** The dark red color at the intersection with yield, leaf area and number of leaves per plant suggests strong positive correlations. Nano-fertilizers may enhance nutrient availability, leading to increased biomass accumulation in leaves, which is associated with higher yields.
5. **Dry weight (stem):** The dark red color at the intersection with yield, leaf area, number of leaves per plant and dry weight of leaves indicates strong positive correlations. Nano-fertilizers may promote overall plant growth, including stem development, which supports higher yields.
6. **Cob dry weight (g):** The dark red color at the intersection with yield and other parameters suggests strong positive correlations. Nano-fertilizers may contribute to improved cob development and grain filling, leading to higher cob dry weights and, consequently, higher yields.

It's important to note that these correlations do not imply causation and the actual effects of nano-fertilizers on maize crop characteristics may depend on various factors, such as soil conditions, climatic conditions and agronomic practices (40).

Correlation between yield and yield related parameters

The correlation matrix for the variables, yield (kg/ha), rows per cob, grains per row, kernels per cob and 100-kernel weight are presented in Fig. 7 and Table 5. The correlation matrix quantifies the strength and direction of the linear relationships between these variables (41).

Some key observations from the correlation matrix: Yield has a strong positive correlation with grains per row (0.8261) and kernels per cob (0.7833), indicating that higher grain and kernel counts are associated with higher yields. Rows per cob has a moderate positive correlation with yield (0.6211), grains per row (0.7000) and kernels per cob (0.8768), suggesting that increasing row counts could potentially improve these yield components. Grains per row and kernels per cob have a very strong positive correlation (0.9499), which is expected as they are directly related components of the cob structure. 100 kernel weight has moderate positive correlations with yield (0.8764), grains per row (0.7673) and kernels per cob (0.7035), indicating that higher kernel weights are associated with better yield performance.

Table 5. Correlation between yield and yield related parameters

Correlation	Yield (kg/ha)	Rows per cob	Grains per row	kernels per cob	100 kernel weight
Yield (kg/ha)	1.000	0.621	0.826	0.783	0.876
Rows per cob	0.621	1.000	0.700	0.877	0.544
Grains per row	0.826	0.700	1.000	0.950	0.767
kernels per cob	0.783	0.877	0.950	1.000	0.704
100 kernel weight	0.876	0.544	0.767	0.704	1.000

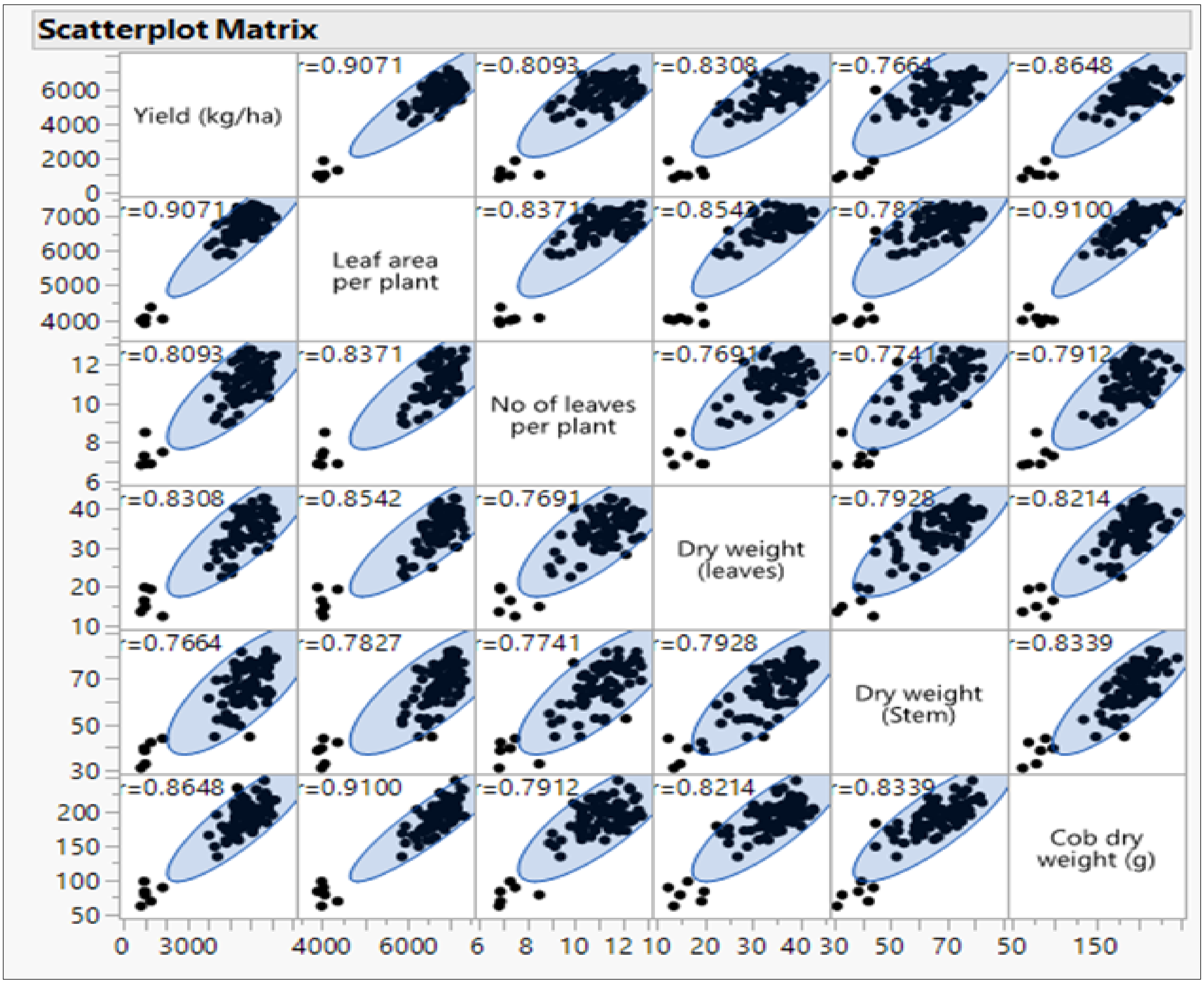

Fig. 5. Scattered plot matrix, correlation between yield and plant growth parameters.

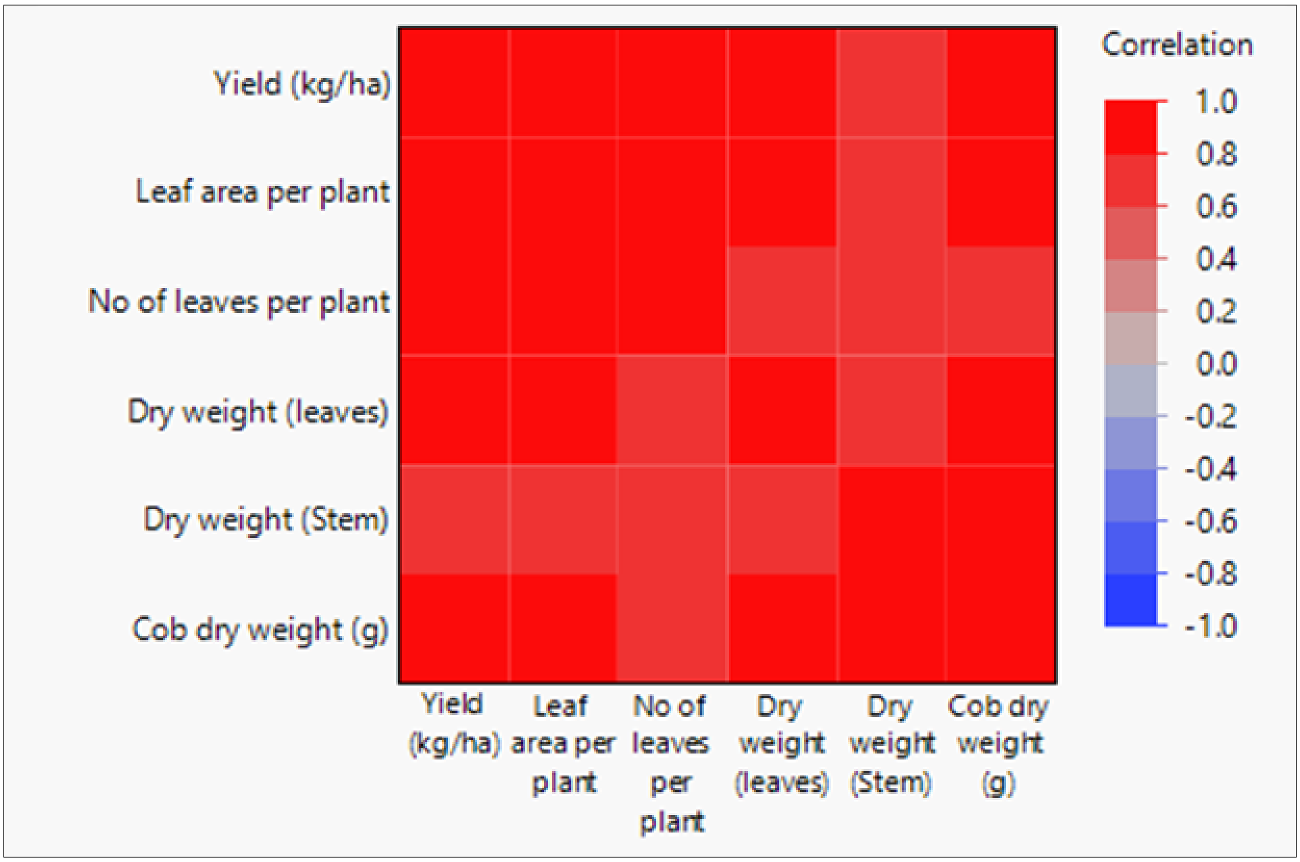

Fig. 6. Color map on correlation between yield and plant growth parameters.

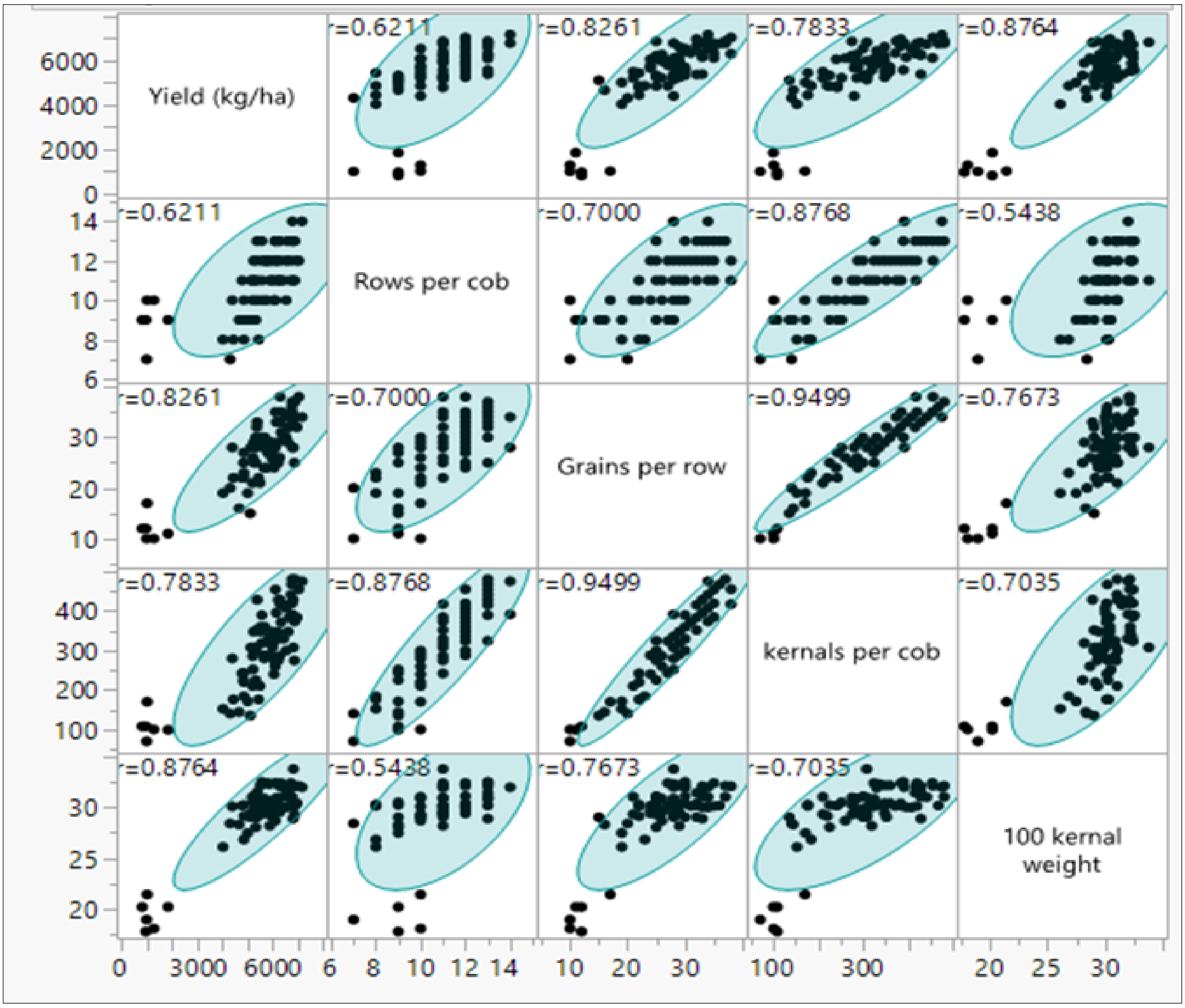

Fig. 7. Correlation between yield and yield related parameters.

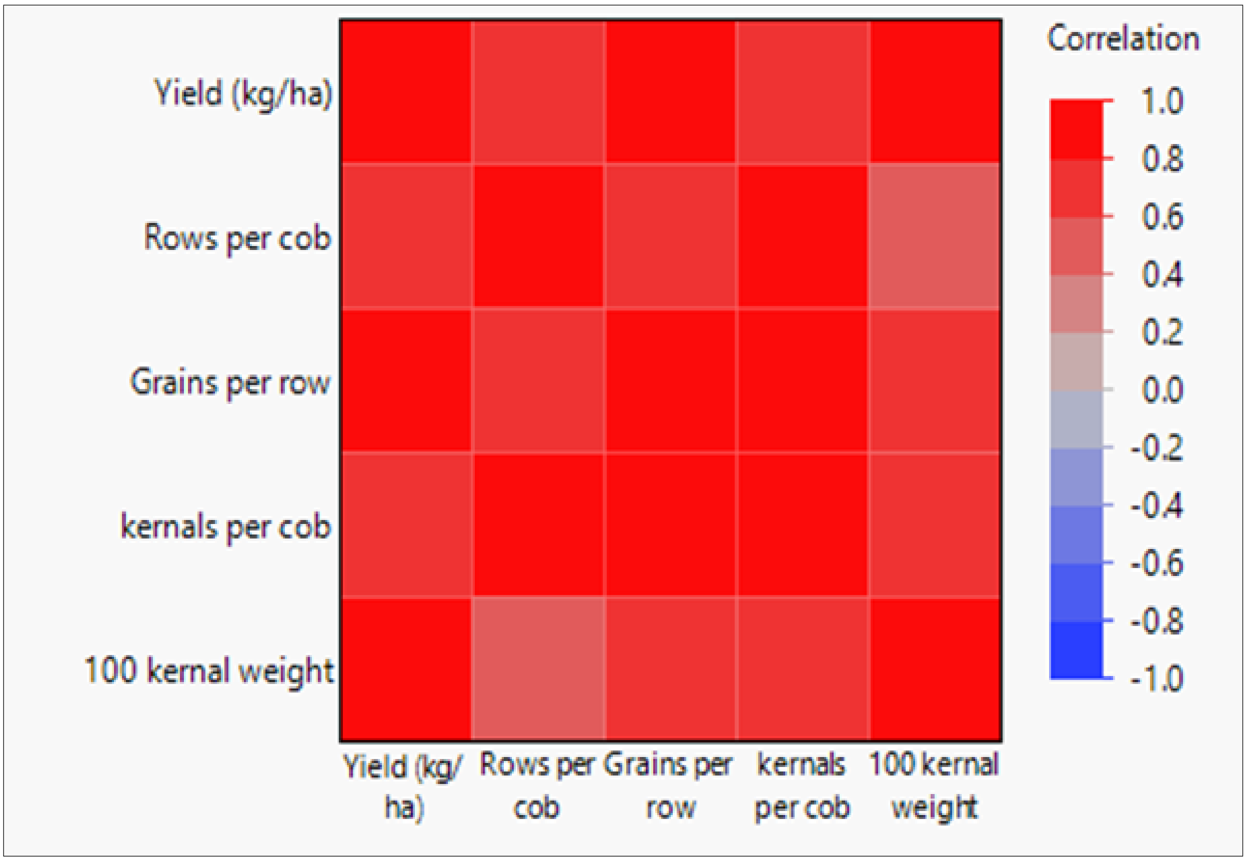

Fig. 8. Color map on correlations between yield and yield related parameters.

These correlations provide insights into the relationships between different yield components and can guide breeding strategies or agronomic practices to improve overall crop productivity. However, it's important to note that correlation does not necessarily imply causation and further experimental studies may be needed to establish causal relationships. This correlation is in line with results from other authors (42,43).

Color map on correlation representation of the correlation matrix between different yield-related parameters (Fig. 8). The color map provides a visual aid to interpret the strength and direction of correlations between the variables: yield (kg/ha), rows per cob, grains per row, kernels per cob and 100-kernel weight.

The color scale ranges from dark blue (-1.0) to dark red (1.0), representing negative and positive correlations, respectively. The intensity of the color indicates the strength of the correlation, with darker shades representing stronger correlations (either positive or negative).

The color map indicates the following observations

1. Yield (kg/ha) has a strong positive correlation (dark red) with grains per row, kernels per cob and 100-kernel weight, indicating that higher values of these components are associated with higher yields (44).
2. Rows per cob has a moderately strong positive correlation (lighter red) with yield, grains per row and kernels per cob, suggesting that increasing row counts could potentially improve yield performance.
3. Grains per row and kernels per cob exhibit a very strong positive correlation (dark red), which is expected since they are directly related components of the cob structure.
4. 100-kernel weight has a moderately strong positive correlation (lighter red) with yield, grains per row and kernels per cob, highlighting the importance of kernel size and weight in determining overall yield.

Sustainable agriculture and food security

The study highlights the potential of nanotechnology in developing innovative and sustainable fertilizer formulations that can address the challenges of low nutrient use efficiency and environmental concerns associated with conventional fertilizers. Nano-fertilizers represent a cutting-edge solution for precision agriculture, aligning with the global need for enhanced food production while minimizing environmental impacts (45,46).

The observed yield improvements with nano-fertilizer treatments contribute to the growing body of evidence supporting the use of nanotechnology in agriculture to enhance crop productivity and food security. This finding is particularly relevant in the context of increasing global population and the need for sustainable intensification of agricultural practices (47).

Future research should focus on exploring the mechanisms underlying the enhanced nutrient uptake and translocation facilitated by nano-fertilizers, as well as the potential long-term effects on soil health and ecosystem dynamics. Additionally, cost-effectiveness and practical scalability of nano-fertilizer production and application should be investigated to ensure their widespread adoption and integration into sustainable agricultural practices (48).

Conclusion

Foliar applications of nano-fertilizers, specifically nano-nitrogen and nano-phosphorus, in combination with conventional fertilizers, significantly improved maize yield and yield-related parameters compared to the application of conventional fertilizers alone or the absolute control (no fertilizer). The treatments involving 75 % RDF through conventional fertilizers, along with two foliar sprays of nano-nitrogen and nano-phosphorus (T9) and 100 % RDF through conventional fertilizers with one foliar spray of nano-nitrogen and nano-phosphorus (T10), exhibited the highest maize yield (6612 kg/ha and 6522 kg/ha, respectively) and performed significantly better than the control treatments. The application of nano-fertilizers positively influenced various growth parameters, including plant height, number of leaves, leaf area per plant and dry weight of leaves, stem and cobs, which ultimately contributed to increased yield and yield components. The controlled release and targeted delivery of nutrients facilitated by nano-fertilizers not only enhanced crop productivity but also contributed to sustainable agricultural practices by minimizing environmental pollution and resource depletion. The integration of nano-fertilizers into mainstream agricultural practices holds immense promise for achieving food security and environmental sustainability.

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Authors' contributions

BHR carried out the experiments, analyzed the data and wrote the draft manuscript. CK and VP assisted with data analysis and corrections, while HM, RHP, VVE, SRI, N and NR contributed to the preparation of the final draft. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors have no conflict of interest declare.

Ethical issues: None

AI Declaration: During the writing of the conclusion for the study, AI tools (ChatGPT) were used to draw a solid conclusion. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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