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RESEARCH ARTICLE

Sustainable nutrient management: Exploring fulvic acid, chelated zinc application methods and rates for improved Maize growth and productivity

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Abstract

The performance of maize is frequently limited by scarcity of micronutrients, especially zinc, which is essential for numerous physiological functions. The present study investigates the impact of different application methods and doses of fulvic acid (FA) and chelated zinc (Zn-EDTA) on the growth and productivity of maize (*Zea mays* L.), in response to the increasing global demand for this vital crop. This study was performed at the student farm of Lovely Professional University during the *Kharif* season of 2023-2024, utilizing a randomized block design with nine treatments, which included soil and foliar sprays of fulvic acid and Zn-EDTA at different concentrations. Essential growth parameters such as plant height, stem girth, number of leaves, leaf area, chlorophyll index, fresh and dry weight, yield attributes and yield were recorded at various growth stages. The treatment of soil fulvic acid and foliar Zn-EDTA at 2.5 kg ha^{-1} resulted in maximum plant height (152.3 cm), stem girth (2.10cm), leaf area (494.06 cm^2), chlorophyll index (48.36 SPAD), fresh and dry weight (191.5g, 86.2g), number of cobs per plant (2), rows per cob (16), grains per cob (48.33), length of cob (16.96 cm) and weight of cob (150.4 g). At the same time, the minimum values have been recorded with the sole application of 100% RDF. This study emphasizes the synergistic advantages of combining bio stimulants and micronutrients to improve maize growth and yield, providing significant insights for formulating sustainable agricultural methods that promote crop productivity and nutrient utilization efficiency.

Keywords

bio stimulants; chelates; fulvic acid; foliar application

Introduction

One of the most significant cereal crops in the world, maize (*Zea mays* L.) is used as a staple food by millions of people and as an essential raw material for products like biofuels and animal feed. The crop's importance worldwide emphasizes the necessity of ongoing advances in maize yield to fulfill rising food demands brought on by population expansion. Maize occupied 10.04mha area, 33.62 mt and 3349 kg ha^{-1} yield in India during 2022-23. Maize occupied 93.3 thousand hectares, producing 410 thousand tonnes in the Punjab State during 2022-23. The average yield was 43.93 q ha^{-1}. A complicated balance of agronomic techniques, such as the application of fertilizers and bio stimulants that improve nutrient availability and plant health, is needed to achieve the best possible maize production. Deficiencies in micronutrients, notably zinc (Zn), significantly hinder agricultural productivity, especially in alkaline calcareous soils. Consequently, Zn is commonly utilized in macronutrient fertilizers to enhance crop quality and productivity (1). The application of Zn fertilizer can enhance plant growth, flowering and biomass production (2). The application of Zn considerably boosted the number of grains per cob, grains per row, grains per ear, grain yield and yield components (3). Higher concentrations of Zn enhance maize growth and yield (4). The development of maize reproductive organs is affected by zinc fertilization during the initial growth phases. Foliar zinc fertilizers can fully recover the physiological efficiency of plants suffering from zinc deficiency (5). Zinc (Zn) is one of the micronutrients that is most important for many physiological and biochemical processes in plants, such as protein synthesis, membrane integrity and enzyme activation. Many soils have zinc deficiencies, particularly those with high pH values, calcareous soils, or soils that are subjected to heavy cropping practices. Therefore, increasing zinc availability and uptake in maize is essential for raising the crop's production and sustainability. Using chelated zinc, a form of zinc bound to organic molecules that boost its solubility and availability in the soil, is one possible way to alleviate zinc deficiency in crops. Chelated zinc is a useful remedy for zinc deficits because it is easier for plants to absorb than inorganic zinc sources (4).

Fulvic acid acts as a natural chelator of key minerals, increasing their bioavailability and enhancing nutrient uptake. The application of FA or Humic acid (HA) markedly mitigated drought effects by maintaining chlorophyll content and gas exchange, likely due to enhanced activities of antioxidant enzymes (superoxide dismutase (SOD), peroxidase (POD), catalase (CAT)) and proline levels (6). These advantageous impacts led to enhanced plant growth and grain output. FA treatment enhanced crop performance in adequately irrigated conditions. Consequently, FA can enhance crop yield under both optimal and adverse conditions (7). Moreover, humic acid diminishes water evaporation, enhances yield and its components, improves water retention and augments soil water holding capacity (8). Fulvic acid and chelated zinc are applied together to offer a synergistic method for enhancing maize production and growth. Fulvic acid increases the permeability of plant cell membranes and makes it easier for micronutrients like zinc to enter plant tissues, which improves nutrient uptake (9). Meanwhile, even in difficult soil conditions, chelated zinc makes zinc available to the plant. Nevertheless, the efficiency of these treatments could differ based on the application technique (foliar *vs.* soil), their rate of application and other factors including soil type and moisture content. There is not much information on the combined effects of fulvic acid and chelated zinc on maize development and yield, especially when it comes to varying application rates and techniques, despite the growing interest in their use in agriculture. The purpose of this study is to investigate the effects of fulvic acid and chelated zinc at varied rates and application methods (foliar and soil) on the growth and overall productivity of maize.

Materials and Methods

The study was carried out in the summer season of 2023–2024 at Lovely Professional University's student farm in Phagwara, Punjab, India. The climate at the experimental location is subtropical, with warm summers and moderate winters. These are favorable conditions for the growing of maize, especially for evaluating the results of applying nutrients and bio stimulants in actual agricultural environments. At a depth of 0 to 15 cm, soil samples were taken from five randomly chosen places inside the experimental field. Samples were mixed, allowed to dry for 48 hours and then crushed with a pestle mortar. The physico-chemical characteristics of the composite soil sample, such as pH, organic matter content and accessible nutrient levels, especially zinc, were subsequently determined through laboratory analysis. The baseline for the soil condition before the application of the treatments was provided by this analysis. Three replications of a randomized block design (RBD) were used in the experiment. To investigate the effects of fulvic acid and chelated zinc (Zn-EDTA) on maize growth and productivity, a total of nine treatment combinations in 3 replications were assessed. The following were the treatments:T_0 (Control)-100% RDF, T_1: soil application of fulvic acid @10 kg ha^{-1} at 30 and 45 DAS, T_2: soil application of Zn-EDTA @25 kg ha^{-1} at 30 and 45 DAS, T_3: foliar application of fulvic acid @1 kg ha^{-1} at 40 and 50 DAS, T_4: foliar application of Zn-EDTA @ 2.5 kg ha^{-1} at 40 and 50 DAS, T_5: soil application of fulvic acid and Zn-EDTA at 30 and 40 DAS, T_6: foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS, T_7: soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} at 30 and 45 DAS, T_8: soil application of Zn-EDTA @25 kg ha^{-1} at 30 and 45 DAS + foliar application of fulvic acid @1 kg ha^{-1} at 40 and 50 DAS. The planting material used in this study was the maize variety Pioneer P3396, which was chosen for its excellent yield potential and adaptability. To guarantee ideal growing circumstances, the planting was done with the proper spacing of 60×20cm. The experiment fertilizer schedule was set at 125:60:30 kg ha^{-1} of N, P_2O_5 and K_2O, in that order. Di-ammonium phosphate (DAP), potash and urea were the fertilizers used for phosphorus, potassium and nitrogen. 50% of the nitrogen was applied at the time of seeding and the remaining 50% was applied at 25 and 45 DAS. All the agronomic and cultural practices were followed as per the PAU package of practices that had been developed by the state agricultural university for the benefit of farmers (10). Growth and yield parameters were recorded as per standard procedures and analyzed statistically. A measuring tape was used to take frequent measurements of the height of the maize plants from the base of the plant to the tip of the main stem. For every treatment, the average height of the randomly tagged plants was measured and reported in centimeters. A leaf area meter was used to measure the leaf area. Fully formed leaves were measured to provide a sense of the plant's growth potential and photosynthetic ability. Several plants were randomly chosen from each plot to evaluate biomass output. The chosen plants were dried in an oven at 70°C for 48 hours until they reached a steady weight. The biomass was expressed as gm^{-2} and the dry weight was noted. The chlorophyll index was measured by a SPAD meter. Growth analysis in terms of CGR, RGR was measured as per Eq.1, Eq.2. The cobs from each net plot were picked and their seed weight was recorded. The yield per hectare was computed and expressed in kg ha^{-1}. A random sample of 100 seeds was obtained from each treatment, followed by counting, weighing and expressing the seed index in grams. The total number of cobs per plant and the seed count per cob were determined by averaging the quantity across each plant.

$$CGR = \frac{W2 - W1}{t2 - t1} \times 100 \quad \text{(Eq. 1)}$$

$$RGR = \frac{\ln(W2 - W1)}{t2 - t1} \times 100 \quad \text{(Eq. 2)}$$

(w_1 initial biomass, w_2 final biomass, t_1 intime, t_2 final time)

Statistical analysis

To ascertain the relevance of the treatments to metrics related to maize growth and productivity, the gathered data was subjected to analysis of variance (ANOVA). At a 5% level of significance, differences between treatment means were examined using the least significant difference (LSD). OPSTAT and OPSTAT Python beta software were used for the analysis.

Results and discussion

Effect of fulvic acid and chelated zinc application methods on Maize growth parameters:

The data presented in table 1 provide an analysis of the effects of different treatments involving fulvic acid and Zn-EDTA on plant height, stem girth, number of leaves per plant, leaf area and chlorophyll index in maize. The highest plant height (152.53 cm) was attained with a combination of soil application of fulvic acid and foliar application of Zn-EDTA. This was followed by foliar application of fulvic acid and Zn-EDTA, which produced a height of 150.03 cm. The plant height (116.53 cm) was lowest in the control treatment. The fact that fulvic acid and Zn-EDTA are both known to increase nutrient absorption and plant vigor and the increased plant height implies that their combined application had a synergistic effect.

Additionally, stem girth responded significantly to the treatments. The control treatment had the least stem girth (3.80 cm), while soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} and foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS had the highest stem girths (7.26, 6.77 cm, respectively). The enhanced stem girth observed in the treatments including the combined soil and foliar sprays of Zn-EDTA and fulvic acid emphasizes the significance of these treatments in augmenting the structural integrity and resistance of the maize plants.

The highest leaf number (11.67) was achieved by applying fulvic acid and Zn-EDTA foliar and soil in contrast, the control treatment had the lowest leaves (7.33). This increase in leaf number may be related to increased nutrient availability and generally improved plant health because fulvic acid promotes greater uptake of essential micronutrients like zinc.

A key measure of a plant's ability for photosynthesis is the leaf area. Significant differences were seen in the leaf area between treatments; soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} had the largest value (494.06 cm^2), closely followed by foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS (490.83 cm^2) and the control had the lowest leaf area (360.10 cm^2). Zn-EDTA and fulvic acid may have encouraged cell proliferation and expansion, which in turn may have promoted larger leaves for higher photosynthetic activity, which is likely the cause of the increased leaf area.

The chlorophyll index, represents the amount of chlorophyll and the photosynthetic efficiency of the plant. The use of Zn-EDTA and fulvic acid together in the treatment soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} and foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS resulted in consistent higher chlorophyll index values, suggesting a beneficial influence on chlorophyll production and overall plant health. The control group had the lowest value, which emphasizes the significance of applying micronutrients to maximize plant growth.

Table 1. Effect of fulvic acid and chelated zinc application methods on Maize growth attributes

Treatments	Plant height (cm)	Stem girth (cm)	Leaves per plant	Leaf area(cm^2)	Chlorophyll index (SPAD)	Fresh Weight (g)	RGR ($gg^{-1}day^{-1}$)	Dry weight (g)	CGR ($g\ m^{-2}day^{-1}$)
T_0	116.533^{i}	3.800^{e}	7.333^{d}	360.100^{h}	37.900^{g}	117.100^{h}	0.008^{f}	47.467^{h}	0.690^{f}
T_1	122.467^{g}	5.667^{d}	8.333^{bcd}	403.133^{f}	41.800^{e}	127.400^{f}	0.008^{f}	52.567^{f}	0.736^{f}
T_2	119.100^{h}	5.500^{d}	7.667^{cd}	400.867^{g}	39.533^{f}	120.633^{g}	0.009^{e}	49.800^{g}	0.775^{ef}
T_3	126.300^{f}	5.933^{cd}	8.667^{bcd}	416.133^{e}	41.267^{e}	130.367^{e}	0.010^{d}	54.833^{e}	0.931^{d}
T_4	128.567^{e}	5.733^{d}	8.333^{bcd}	417.117^{e}	42.367^{de}	135.967^{d}	0.009^{e}	56.233^{d}	0.872^{de}
T_5	133.233^{d}	6.000^{cd}	9.000^{abc}	441.933^{d}	42.600^{d}	146.300^{c}	0.012^{b}	67.167^{c}	1.286^{c}
T_6	150.033^{b}	6.767^{ab}	10.000^{a}	490.833^{b}	45.967^{b}	190.200^{a}	0.013^{a}	85.600^{a}	1.668^{a}
T_7	152.533^{a}	7.260^{a}	11.667^{a}	494.067a	48.367a	191.567^{a}	0.011^{c}	86.200^{a}	1.546^{a}
T_8	144.067^{c}	6.367^{bc}	9.333^{ab}	479.533^{c}	44.533^{c}	173.600^{b}	0.011^{c}	78.567^{b}	1.406^{b}
CD ($P < 0.05$)	2.333	0.534	1.725	2.074	1.234	1.929	0.001	1.326	0.110

*The means with different Letters as superscripts are significant ($P < 0.05$). The means with same letters or having common letter(s) are not significantly different. (T_0-control, T_1-soil application of fulvic acid @10kgha^{-1} at 30 and 45 DAS, T_2-soil application of Zn-EDTA @25 kgha^{-1} at 30 and 45 DAS, T_3-foliar application of fulvic acid @1 kg ha^{-1} at 40 and 50 DAS, T_4-foliar application of Zn-EDTA @2.5 kg ha^{-1} at 40 and 50 DAS, T_5-soil application of fulvic acid and Zn-EDTA at 30,40 DAS , T_6-foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS, T7-soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1}, T_8- soil application of Zn-EDTA @25 kgha^{-1} at 30 and 45 DAS + foliar application of fulvic acid @1 kg ha^{-1} at 40 and 50 DAS)

The combination of fulvic acid in the soil and Zn-EDTA foliar applied yielded the highest fresh weight of 190.20 g. The control group exhibited the lowest fresh weight, suggesting that the use of fulvic acid and Zn-EDTA played a substantial role in the accumulation of biomass. The combination of fulvic acid and Zn-EDTA, which are both known to increase the bioavailability of essential nutrients, probably allowed for improved nutrient uptake, which is why the combined treatments yielded superior results. Fresh weight and dry weight, two more reliable indicators of plant biomass, came in the same direction. Control recorded the lowest dry weight, while foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS followed with the second-highest dry weight of 85.60 g. The treatments' positive impacts on the productivity of the plants are indicated by an increase in dry weight. The significant rise in dry weight in Foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS and soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} indicates that fulvic acid and Zn-EDTA applied in combination encourage long-term growth and increased biomass accumulation.

The rate at which a plant develops in size compared to its existing biomass is indicated by its relative growth rate (RGR), an important growth metric. The highest RGR was obtained with fulvic acid and Zn-EDTA applied foliar. This was followed by fulvic acid and Zn-EDTA applied in soil, which had an RGR of 0.01239 gg^{-1} day^{-1}. The RGR for the control treatment was 0.00831 $gg^{-1}day^{-1}$. Fulvic acid and Zn-EDTA treatments had greater RGRs, especially when given in combination. This shows that these treatments improved nutrient absorption and metabolism, which in turn led to a more effective conversion of nutrients into biomass.

CGR, the biomass production per unit area changed throughout time, ranging from 1.668 $gm^{-2}day^{-1}$ to 0.690 $gm^{-2}day^{-1}$. Foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS had the highest CGR (1.668 $gm^{-2}day^{-1}$), followed by soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} (1.546 $gm^{-2}day^{-1}$) The control group had the lowest CGR (0.690 $gm^{-2}day^{-1}$). Treatments with fulvic acid and Zn-EDTA, especially the foliar sprays, increased CGR, suggesting that they accelerated the accumulation of biomass.

Increased nutrient availability and intake, which is critical for maize during its active growth stages, could be responsible for this. Conversely, fulvic acids have demonstrated the ability to enhance mineral absorption, stimulate root elongation and increase both the fresh and dry biomass of crops (11). (12) reported that FA contains many nutritional components beneficial for improving crop yields and the physicochemical and biological conditions of the soil. The findings align with those presented by (13), (14) and (15) who demonstrated that the application of Zn or FA enhanced growth, yield and its components.

Effect of fulvic acid and chelated zinc application methods on Maize yield parameters

Table 2 presents data on yield-related parameters of maize, including the number of cobs per plant, number of grains per row, number of rows per cob, length of cob and cob weight, under different treatments involving fulvic acid and Zn-EDTA applications. A plant's ability to reproduce and yield potential can be determined by counting the number of cobs it produces. The maximum number of cobs per plant was found in the soil treatment of fulvic acid with foliar Zn-EDTA, which was followed by the foliar application of fulvic acid and Zn-EDTA with 2.67 cobs. The control group had a smaller number of cobs, suggesting that the applications of fulvic acid and Zn-EDTA had a noteworthy impact on the production of cobs. The increased availability of micronutrients, which encourage reproductive growth and reduce nutrient shortages that might hinder cob development, is probably the cause of this improvement.

One of the most important factors influencing grain yield is the number of grains per row. Soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} (48.88) had the highest grains per row, followed by foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS (48.00), while the control had the fewest grains row^{-1} (38.43). Due to increased nutrient intake and metabolic activity during the reproductive stage, it is possible that the combined soil and foliar administrations of fulvic acid and Zn-EDTA boosted kernel setting, as seen by the notable increase in grain number in Soil application of fulvic acid + foliar application of Zn-EDTA and foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS.

Table 2. Effect of fulvic acid and chelated zinc application methods on Maize yield and yield attributes

Treatments	No. of cobs per plant	Rows per cob	Grains per row	Seed index (g)	Length of cob (cm)	Weight of cob (g)	Grain yield ($kgha^{-1}$)	Stover yield ($kgha^{-1}$)	HI (%)
T_0	1.000^{d}	14.800^{d}	38.433^{f}	30.733^{d}	15.513^{d}	127.167^{h}	4520.767^{h}	6119.333^{e}	42.486^{d}
T_1	1.667^{cd}	15.767^{cd}	41.967^{e}	30.783^{d}	16.287^{bcd}	135.000^{f}	4842.267^{ef}	6436.633^{d}	42.932^{cd}
T_2	2.000^{bc}	14.433^{d}	39.667^{f}	30.827^{d}	15.900^{cd}	131.833^{g}	4739.667^{g}	6504.033^{d}	42.157^{d}
T_3	1.667^{cd}	15.780^{cd}	44.167^{d}	32.640^{bc}	16.367^{bc}	137.900^{e}	4973.997^{ef}	6691.200^{c}	42.641^{d}
T_4	1.667^{cd}	16.810^{bc}	45.167^{cd}	31.983^{c}	16.480^{bc}	138.300^{e}	5086.733^{e}	6888.100^{b}	42.478^{d}
T_5	2.000^{bc}	17.610^{ab}	45.553^{cd}	31.830^{c}	16.487^{bc}	142.533^{d}	5410.987^{d}	6962.767^{b}	43.730^{bc}
T_6	2.667^{ab}	17.833^{ab}	48.003^{ab}	33.350^{ab}	17.767^{a}	148.000^{b}	5866.167^{b}	7339.467^{a}	44.420^{ab}
T_7	3.000^{a}	18.567^{a}	48.877^{a}	33.933^{a}	18.300^{a}	150.433a	6137.660^{a}	7457.167^{a}	45.149^{a}
T_8	2.333^{abc}	17.550^{ab}	46.200^{bc}	32.620^{bc}	16.757^{b}	145.867^{c}	5632.967^{c}	7449.733^{a}	43.058^{cd}
CD(p<0.05)	0.763	1.196	1.829	0.921	0.719	1.942	164.185	151.599	0.919

*The means with different Letters as superscripts are significant (P < 0.05). The means with same letters or having common letter(s) are not significantly different. (T_0-control, T_1-soil application of fulvic acid @10kgha^{-1} at 30 and 45 DAS, T_2-soil application of Zn-EDTA @25 kgha^{-1} at 30 and 45 DAS, T_3-foliar application of fulvic acid @1 kg ha^{-1} at 40 and 50 DAS, T_4-foliar application of Zn-EDTA @2.5 kg ha^{-1} at 40 and 50 DAS, T_5-soil application of fulvic acid and Zn-EDTA at 30,40 DAS , T_6-foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS, T7-soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1}, T_8- soil application of Zn-EDTA @25 kgha^{-1} at 30 and 45 DAS + foliar application of fulvic acid @1 kg ha^{-1} at 40 and 50 DAS)

The number of rows per cob ranged from 14.43 to 18.57 with the highest value observed in soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1}. Foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS (17.83 rows) and soil application of Zn-EDTA @25 kg ha^{-1} at 30 and 45 DAS + foliar application of fulvic acid @1 kg ha^{-1} at 40 and 50 DAS (17.55 rows) also showed higher values compared to the control (14.80 rows). Improved cob development is indicated by more rows per cob in the treated plants, which is important for increasing the amount of grain produced overall. Fulvic acid and Zn-EDTA appear to have positively impacted the number of rows per cob, indicating that they provided ideal conditions for the development of cobs.

Cob length is another important yield parameter. The length of cobs ranged from 15.51 cm to 18.30 cm, with the longest cobs observed in soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1}. Foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS (17.77 cm) and soil application of Zn-EDTA @25 $kgha^{-1}$ at 30 and 45 DAS + foliar application of fulvic acid @1 kg ha^{-1} at 40 and 50 DAS (16.76 cm) also showed significant improvements over the control. The longer cobs in the soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} treatment suggest that fulvic acid and Zn-EDTA promoted cell expansion and increased nutrient availability during cob formation, which in turn improved cob growth. The longer cobs in these treatments most likely contributed to the higher grain yields.

The weight of the cob is directly related to yield and grain-filling efficiency. The cob weight ranged from 127.16 g to 150.40 g with soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} showing the highest cob weight, followed closely by foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS (148.00 g). The fact that the control group exhibited the lowest cob weight suggests that fulvic acid and Zn-EDTA significantly enhanced cob size and grain filling. Soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} and foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS received fulvic acid and Zn-EDTA together, which probably improved nutrient transport and accumulation in the developing grains and produced larger cobs.

The seed index, which represents the weight of 100 grains, is an important parameter reflecting grain size and quality. Soil application of fulvic acid + foliar application of Zn-EDTA recorded the highest seed index (33.93 g), followed by foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS (33.35 g). Fulvic acid and Zn-EDTA were applied in combination in both of these treatments, suggesting an advantageous effect on grain formation. With the lowest seed index, the control group demonstrated the effectiveness of fulvic acid and Zn-EDTA in improving grain filling and weight. It is possible that fulvic acid facilitated the transfer of nutrients to the developing grains and Zn-EDTA enhanced the enzymatic processes associated with grain maturation (3, 16).

Effect of fulvic acid and chelated zinc application methods on Maize yield

Grain yield is the most crucial factor in evaluating the effectiveness of the treatments. Soil application of fulvic acid + foliar application of Zn-EDTA produced the highest grain yield (6137.66 kg ha^{-1}) followed by foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS (5866.17 kg ha^{-1}). The least quantity of grain was produced by the control. The significant increase in grain yield observed in the fulvic acid and Zn-EDTA treatments can be attributed to the increased availability and uptake of nutrients, which in turn leads to better photosynthetic efficiency and grain filling. Zn-EDTA delivered zinc, an important micronutrient for numerous metabolic processes and presumably promoted root development and nutrient absorption, leading to increased yields.

The stover yield, represents the biomass of non-grain plant parts. Soil application of fulvic acid + Foliar application of Zn-EDTA @2.5 kg ha^{-1} again recorded the highest stover yield, followed by foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS (7339.47 kg ha^{-1}) and soil application of Zn-EDTA @25 $kgha^{-1}$ at 30 and 45 DAS + foliar application of fulvic acid @1 kg ha^{-1} at 40 and 50 DAS (7449.73 kg ha^{-1}). These findings suggest that Zn-EDTA and fulvic acid treatments enhanced grain yield while simultaneously encouraging vegetative development, which increased the production of biomass. The fact that the control had the lowest biomass production indicates that the application of Zn-EDTA and fulvic acid together improved nutrient absorption and encouraged biomass formation, which in turn increased total plant growth.

The harvest index measures the way the plant distributes resources to grain production. When Zn-EDTA was applied to the soil, the harvest index varied from 42.16% to 45.15% when fulvic acid was applied to the soil together with Zn-EDTA applied foliar. Following foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS (44.42%) and soil application of fulvic acid + foliar application of Zn-EDTA @2.5 kg ha^{-1} had the greatest harvest index, suggesting that these treatments were more successful in transforming assimilates into grain. Harvest index data for the control showed a value of 42.49%, which was below the best-performing treatments but still in the range of the average. The balanced development facilitated by fulvic acid and Zn-EDTA, which guaranteed effective resource partitioning towards reproductive structures rather than excessive vegetative growth, is responsible for the better harvest index in Soil application of fulvic acid + Foliar application of Zn-EDTA @2.5 kg ha^{-1} and Foliar application of fulvic acid and Zn-EDTA at 40 and 50 DAS.

The enhancement of yield qualities can be identified as an increase in plant dry matter. An enhancement in yield and its components may be attributed to the influence of Zn and FA on plant growth, as evidenced by previous observations. Zn plays a significant role in various physiological and enzymatic processes within the plant system, facilitating the conversion of carbohydrates, protein synthesis and chlorophyll production, while also promoting numerous catalytic functions in the plant (17). The application of zinc has been found to substantially enhance yield metrics and maize yield (18). The improvement in growth characteristics resulting from Zn application can be ascribed to improved plant growth and the augmentation of photosynthetic and metabolic activities (19). This, in turn, increased various plant metabolites that facilitate cell division and elongation, due to optimal nutrient availability, alongside the accelerated growth of the internodal region and elevated synthesis of growth hormones such as IAA and the metabolism of gibberellic acid. Amino acids, vitamins, microelements and hormones are biochemical fulvic acids that can stimulate cell division, root development, nutrient absorption and enhance plant stress resistance, thereby promoting crop growth and yield (20-22).

Linear regression between growth parameters

The left plot in Fig. 1 illustrates a positive association between plant height and stem girth. As stem girth expands, plant height generally rises simultaneously. The shaded area surrounding the line denotes the confidence interval, signifying the range within which future data points are expected to reside. The middle plot in Fig. 1 illustrates a positive association between plant height and leaf area, indicating that an increase in leaf area corresponds with an increase in plant height. The correlation appears strong, as the data points are tightly clustered around the regression line. The relationship between plant height and the chlorophyll index (right plot) exhibits a positive association. Increased chlorophyll levels correlate with increased plant height. The data points are closely clustered around the regression line, indicating an accurate correlation. In all three instances, the positive correlations suggest that these characteristics (stem girth, leaf area and chlorophyll index) are likely enhancing the overall development and height of the plants. The strong linear correlations indicate that these variables are dependable predictors of plant height. Fig. 2 illustrates a robust positive association between plant height and fresh weight, as depicted in the left plot. As the biomass of the plants increases, the height of the plants sequentially improves. The data points are closely grouped around the regression line, indicating a robust and stable correlation. The middle plot in Fig. 2 demonstrates an extremely strong positive association between plant height and dry weight. As the dry mass increases, plant height correspondingly rises. The data points closely confirm to the regression line, signifying a strong linear correlation. The relationship between plant height and CGR, as depicted in the right plot of Fig. 2, demonstrates a positive association. As the plant height increases, dry mass correspondingly rises. The scatter points exhibit a marginally broader dispersion from the regression line, indicating that although a positive association exists, it may not be as robust or consistent as shown with the preceding two variables. The results are in support of the findings (23- 25).

Linear regression between yield parameters

The first plot in Fig. 3 illustrates the relationship between grain yield and the number of cobs per plant. The x-axis denotes grain yield, ranging from 4500 to 6000, while the y-axis indicates the number of cobs per plant, ranging from 1.0 to 3.0. A positive association exists between grain yield and the quantity of cobs per plant, as evidenced by the ascending regression line. The blue region denotes the confidence interval, illustrating the uncertainty of the

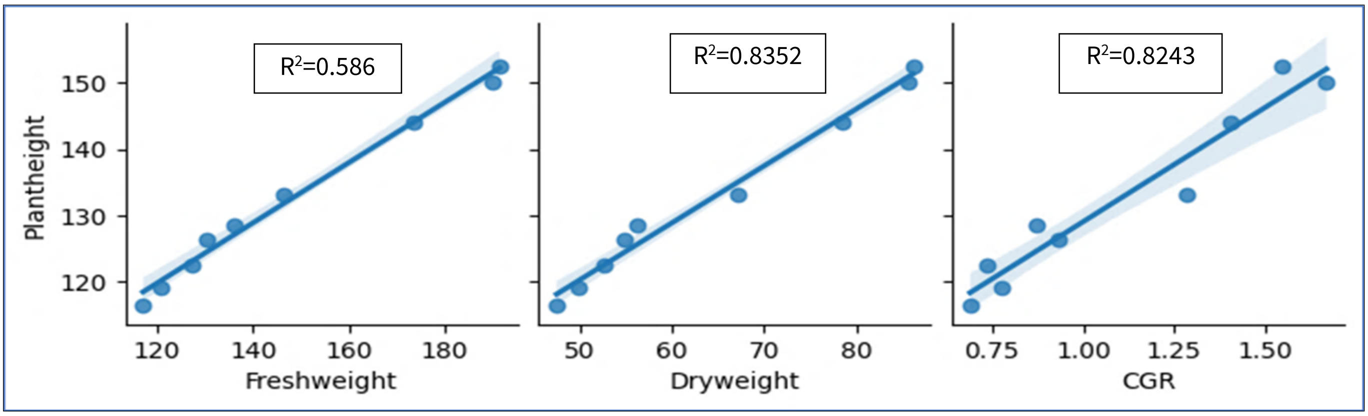

Fig. 1. The image shows three scatter plots with linear regression lines, likely representing the relationships between plant height and three different variables: stem girth, leaf area and chlorophyll index.

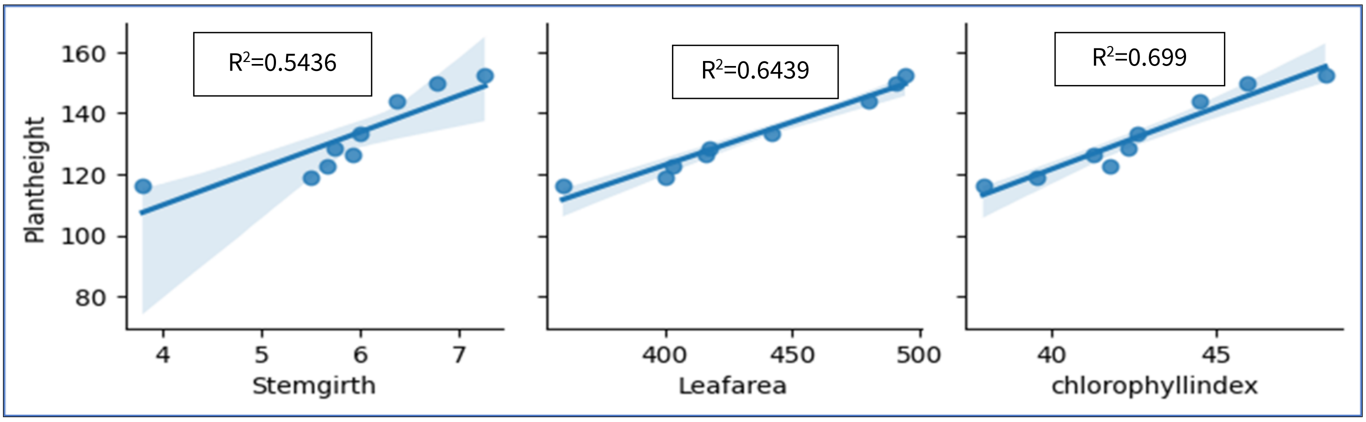

Fig. 2. The image contains three scatter plots with linear regression lines, depicting the relationships between plant height and different variables: fresh weight, dry weight and CGR.

regression model. In the second plot of Fig. 3, the x-axis denotes stover yield (varying from 6500 to 7500), while the y -axis indicates the number of cobs per plant. A positive link exists between stover yield and the quantity of cobs per plant. The regression line exhibits a comparable upward trend, while the shaded region denotes the confidence range. The final plot in Fig. 3 illustrates the relationship between the Seed Index and Cobs per Plant, with the x-axis denoting the seed index (range from 31 to 34) and the y-axis indicating the number of cobs per plant. A positive linear correlation exists between the seed index and the quantity of cobs per plant. As the seed index rises, the quantity of cobs per plant correspondingly increases, as indicated by the ascending regression line. Fig. 4 illustrates the correlation between various independent factors (on the x-axis) and Cobs per plant (on the y-axis). A positive correlation exists between the number of rows per cob and the number of cobs per plant. This indicates that plants with a greater number of rows per cob are likely to produce a higher quantity of cobs. There exists a positive correlation between the number of grains per row per cob and the number of cobs per plant, suggesting that an increase in grains per row corresponds with an increase in cobs. The length of the cob exhibits a positive correlation with the quantity of cobs per plant. Longer cobs are typically correlated with an increased number of cobs per plant. A favorable correlation exists between cob weight and the quantity of cobs per plant. Heavier cobs are typically associated with plants that yield a greater quantity of cobs. The results are in support of the findings of (26-27).

Conclusion

This study's findings indicated that the simultaneous application of fulvic acid and Zn-EDTA, especially via soil and foliar methods markedly increases maize yield by enhancing yield components, including the number of cobs per plant, grains per row, rows per cob, cob length and cob weight. The findings indicated that the application of fulvic acid and Zn-EDTA may serve as an effective agronomic strategy to enhance maize productivity, particularly in nutrient-deficient soils. The findings indicated that the simultaneous application of fulvic acid and Zn-EDTA, especially via both soil and foliar methods markedly improves seed index, grain yield, stover yield and harvest index in maize.

Future thrust of the study:

The beneficial impacts of these treatments on grain production and quality underscore the need to include organic acids and micronutrients in maize farming to enhance productivity and resource utilization efficiency. This study indicated that the use of fulvic acid and Zn-EDTA may effectively enhance maize yields, particularly in areas where nutrient availability is constrained.

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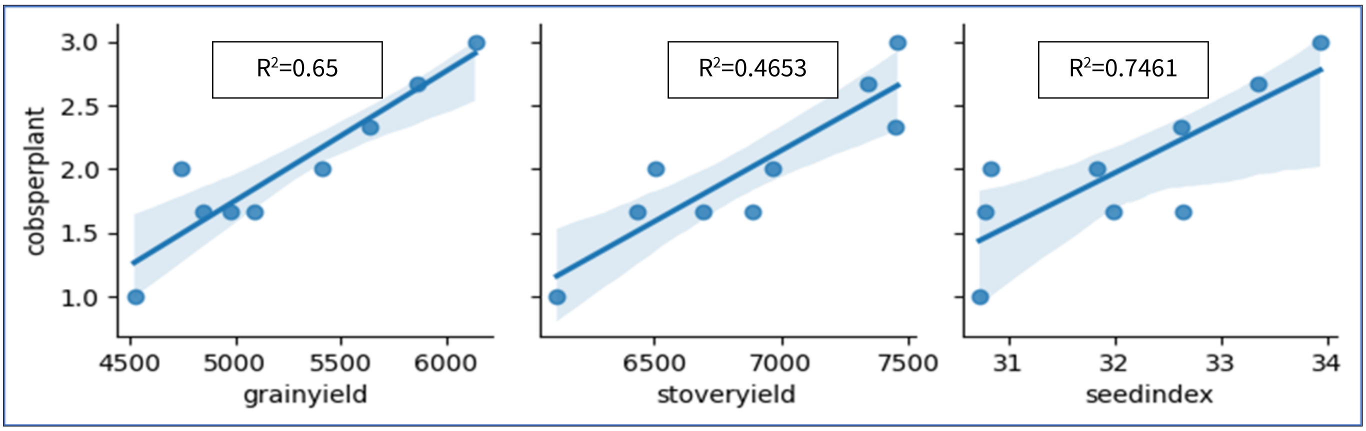

Fig. 3. All three scatter plots indicate a positive relationship between the number of cobs per plant and each of the three variables (grain yield, stover yield and seed index). The shaded areas show the uncertainty in the model predictions.

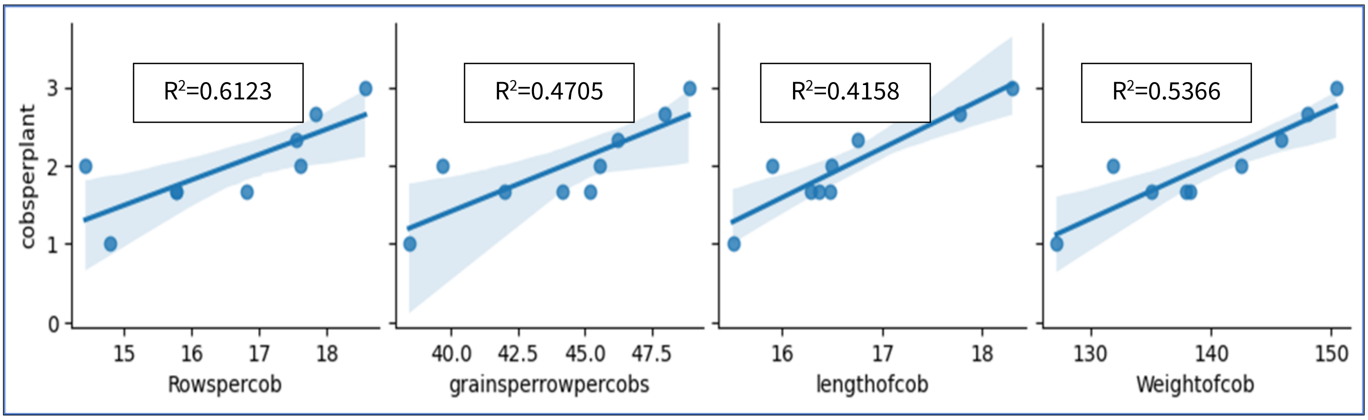

Fig. 4. This image shows a set of four scatter plots with regression lines and confidence intervals. In each scatter plot, the shaded area surrounding the regression line denotes the confidence interval, reflecting the uncertainty associated with the regression estimate. The main finding is that the variables represented on the x-axis (rows, grains, length and weight of cobs) exhibit a positive correlation with the number of cobs per plant.

Authors' contributions

All the authors contributed in writing manuscript, analyse data and final formatting of the manuscript

Compliance with ethical standards

Conflict of Interest: All authors declare that there are no commercial or financial relationships that could, in any way, lead to a potential conflict of interest.

Ethical issues: None

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