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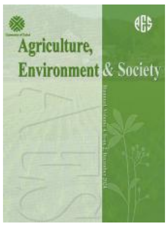

Effect of farmyard manure and zinc on quantitative and qualitative characteristics of forage corn (*Zea mays*)

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ARTICLE INFO

Article history:
Received: 27 August 2025
Accepted: 15 October 2025
Available online: 20 October 2025

Keywords:
Crude protein
Dry matter
Farmyard manure
Nanostructured zinc
Relative water content

ABSTRACT

The unique climatic features of semi-arid regions, along with inadequate soil quality characterized by low organic matter and deficiencies of essential micronutrients, have led to a forage scarcity in this area. Adding organic soil amendments with organic fertilizers and zinc nanostructured fertilizers can be crucial for boosting fodder yield. A field trial was conducted to investigate the effects of fertilizers (F_0: control, F_1: 30 t ha^{-1} farmyard manure, FYM, F_2: 8 t ha^{-1} compost, F_3: 8 t ha^{-1} vermicompost, F_4: recommended dose of chemical NPK, F_5: 50% recommended dose of NPK + 15 t ha^{-1} FYM) and zinc fertilizers (Zn_0: control, Zn_1: 30 kg ha^{-1} zinc sulfate, Zn_2: 10 kg ha^{-1} nanostructured zinc) on the growth quality performance of forage corn in the Moghan region, northwest Iran. The highest chlorophyll content and longest stems were obtained with the application of F_4+Zn_2. The greatest lateral canopy growth was observed in plants treated with F_2+Zn_2, F_4+Zn_2, and F_5+Zn_2. The highest dry matter and relative water content were achieved with the application of animal manure, conventional fertilizers, and zinc nanostructures. Applying nanostructured zinc fertilizers in addition to NPK, either alone, with FYM, or with compost, produced the maximum fresh forage yield. Analysis of forage quality components showed that the application of NPK with nanostructured zinc fertilizers significantly increased dry matter digestibility (5.67%) and crude protein (4.60%). Vermicompost use without zinc application resulted in the highest levels of water-soluble carbohydrates. The highest amounts of neutral detergent fiber were also obtained with F_1+Zn_0. The response of growth components and forage quality traits to organic fertilizer and zinc sources varied. The optimal quantitative and qualitative characteristics of forage were achieved by applying the recommended rate of NPK and 15 t ha^{-1} of FYM fertilizers together with zinc nanostructure fertilizers. The results showed that relying solely on chemical or organic fertilizers for forage corn production does not provide acceptable performance. The combined use of conventional chemical fertilizers and animal manure in forage production systems should be considered.

Highlights

- Organic soil amendment is essential in the semi-arid region under study.
- Although organic fertilizers increase yield, the combined use of animal and chemical fertilizers is preferable.
- The effectiveness of zinc micronutrient fertilizers was more evident after improving soil conditions.
- Nanostructured zinc fertilizers along with the combined use of animal manure and NPK resulted in the best forage quality of corn.

1. Introduction

The development of the livestock industry is important for providing amino acids and protein. Hence, perpetuating high nutritional value and food security in developing countries require the provision of sufficient forage crops (Sekaran et al., 2021). In the realm of forage crops, forage maize (*Zea mays* L.) plays a crucial role in meeting the

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https://doi.org/10.22034/aes.2026.551991.1116

forage needs of this expanding industry. Nevertheless, the necessary water resources for irrigation and the inadequate soil quality in the drought-prone region are the primary challenges (Jiang et al., 2024).

Maize was domesticated in Mesoamerica more than ten thousand years ago, and the dominant producing countries of maize (*Zea mays* L.) are the United States (35×10^6 ha and 390×10^6 t), China (44×10^6 ha and 289×10^6 t), Brazil (22×10^6 ha and 132×10^6 t), and South Africa with 2.5×10^6 ha cultivated land and 16×10^6 t production (Erenstein et al., 2022). Corn production in Iran during the 2023 crop year was 352,000 tonnes, with 54,000 hectares under cultivation. Also, the area under cultivation of this crop was 54,000 hectares (FAOSTAT, 2023). Maize has a C_4 photosynthetic system that produces significant yields even during hot summer periods under well-irrigated conditions with deep, permeable soils with a pH of 6–7. (Gu et al., 2025). The high photosynthetic ability of forage corn leads to increased water use efficiency compared to other forage plants with a C_3 photosynthetic system. In addition, forage corn has high sugar and starch contents and produces high biomass per unit area, and its conscious promotion can encourage farmers to cultivate it in more areas (Capstaff and Miller, 2018). Soils in semi-arid areas of Iran often are basic due to low annual rainfall, poor rainfall distribution, alkaline nature, and low leaching of carbonates in the soil. Relatively unfavorable physical and chemical conditions of the soil in semi-arid regions prevent the release of some nutrients into the rhizosphere (Spalevic et al., 2025). Organic soil amendment by improving organic matter content, adjusting pH, reducing soil compaction, improving permeability, enhancing soil water retention capacity, and increasing the cation exchange capacity can increase crop production (Mohsenpour et al., 2024). Incorporating organic matter into the soil not only enhances the availability of key nutrients like nitrogen and phosphorus but also improves the structure of soil aggregates and boosts soil fertility by promoting the activity of helpful microorganisms (Chen et al., 2024).

Livestock manures are widely available as conventional organic soil amendments for most farmers, and their use provides numerous benefits to crop production systems in both the short and long term (Abdoli et al., 2025).

The application of a decomposed mixture of collected livestock dung and urine can affect soil biota, alter the physicochemical characteristics of the soil, and ultimately increase the availability of nutrients needed for plant growth. Animal manures also can provide plants with elements such as Nitrogen, phosphorus, potassium, calcium, magnesium, iron, zinc, copper, and manganese (Köninger et al., 2021).

Compost is a natural fertilizer created through the breakdown of organic materials, such as leftover crops and animal waste, by bacteria and fungi. Using these fertilizers can enhance various physical properties of the soil, including bulk density, ventilation, compaction, soil aggregation, and promote plant growth (Goldan et al., 2023).

Vermicompost is a form of green manure produced through the breakdown processes carried out by fungi, bacteria, and different types of earthworms, particularly *Eisenia fetida* (red worms or manure worms). The presence of various decomposing microbes in the digestive systems of earthworms accelerates the release of organic acids and nutrients (Manzoor et al., 2024). Utilizing vermicompost as a fertilizer or organic soil enhancer can promote plant development by making the nutrients found in the residues available. In soils of semi-arid regions, zinc deficiency is considered a limiting factor for both the quantitative and qualitative growth of crops (Mohamadzadeh et al., 2023). Zinc is a key cofactor in over 300 important plant enzymes and all six enzyme classes. It is required for various processes during germination, vegetative growth, and the reproductive stage (Hamzah Saleem et al., 2022). Zinc is involved in processes such as the regulation of gene expression, protein biosynthesis, photosynthesis, biosynthesis of photoassimilates and carbohydrates, photomorphogenesis, source-sink relationships, and the function of biological membranes (Umair Hassan et al., 2020). In semi-arid regions, the release of this element from bedrock is very limited, and due to unfavorable soil conditions such as high pH, zinc quickly becomes unavailable in the soil. With advances in agricultural nanotechnology and the development of nanostructured fertilizers containing zinc, their efficiency has increased significantly compared to traditional and bulk fertilizers (Shoukat et al., 2025). Although the effects of different organic fertilizers have been examined in some studies, comprehensive information on the comparison of organic fertilizers and their interaction with zinc fertilizer application is still lacking. Because of the significant deficiency of soil organic matter in semi-arid areas, the insufficient understanding among farmers regarding the appropriate amounts of NPK applied during organic soil enhancement, and the limited information available on the influence of nanostructured zinc fertilizers on forage quality, additional research is essential. This study aimed to estimate the effects of traditional fertilizers and nanostructured zinc under different organic fertilizer application conditions on the development and quality of fodder corn in a drought-prone area.

2. Material and Methods

The present study conducted at a research farm in Oltan region, Moghan, in northwestern Iran (46°46′ E, 39°38′ N; altitude of 45 m) during the 2017-2018 crop year. According to agroclimatic classification, the Oltan region is temperate and semi-arid region.

Due to its low altitude, it experiences relatively warm summers and temperate winters with brief periods of sub-zero temperatures. The mean annual temperature is 14.3 ˚C, and the yearly precipitation is 375 mm.

The highest amount of rainfall occurs from November until the middle of May. The field soil was loamy clay, with an electrical conductivity of 1.84 dS m^{-1}, organic matter content of 0.69%, absorbable potassium at 276 ppm, total nitrogen 0.13%, phosphorus at 11.28 ppm, iron at 1.45 ppm, zinc at 1.09 ppm, manganese at 1.14 ppm.

Table 1. Climatological information of the Oltan region during the forage corn growing season 2018.

	February	March	April	May	June	July	August
Mean air temperature	7.6	16	19.4	26.5	29.3	33.7	32.4
Air humidity (%)	64	76	71	62	53	49	46
precipitation (mm)	78.6	56.4	48.2	61.3	28.1	9.65	1.1
Evaporation (mm)	524	45.9	129.6	242.1	267.4	286.7	251.1

The field investigation was conducted as a split-plot experiment within a randomized complete block design (RCBD) with three replications. The main factor in this experiment was the application of various organic and chemical fertilizers at 6 levels. The fertilizers studied were: F_0: control, F_1: 30 t ha^{-1} farmyard manure (FYM), F_2: 8 t ha-1 compost, F_3: 8 t ha^{-1} vermicompost, F_4: optimal dosage of chemical NPK, and F_5: 50% optimal dosage of NPK + 15 t ha^{-1} FYM. Subplots were assigned to the application of zinc-containing fertilizers at three levels (Zn_0: control, Zn_1: 30 kg ha^{-1} zinc sulfate, Zn_2: 10 kg ha^{-1} nanostructured zinc). Nanostructured zinc fertilizers were produced by Sepehr Paramis Company, Iran, by chelating zinc oxide nanoparticles with EDTA (ethylenediaminetetraacetic acid). The recommended doses were 300 kg ha^{-1} for nitrogen, 100 kg ha^{-1} for phosphorus, and 60 kg ha^{-1} for potassium.[1]. Nitrogen fertilizer was supplied from a urea source, with one-third applied at planting, one-third at the six-leaf stage, and one-third at the tasseling stage. Phosphorus and potassium were supplied from triple superphosphate and muriate of potash sources respectively, and applied as a band 2 cm beneath the seed row at planting. The corn seeds (Single Cross 407) were obtained from the Seed and Plant Certification and Registration Institute, in Karaj, Iran. Compost and vermicompost were purchased from Taisees Company, in Tehran. Farmyard manure is collected from the stables of beef cattle farms in the Moghan region and allowed to decompose for approximately 9 months before use. Some chemical properties of the organic fertilizers used are presented in Table 2.

Table 2. Chemical analysis of manure, compost, and vermicompost in terms of macronutrients, micronutrients, and organic matter.

	pH	EC	OC%	TN%	P	K	C/N	Ca	Fe	Zn	Mn
FYM	6.81	4.04	26.43	1.87	1.53	265	14.32	193.7	142.62	128	210.3
Compost	7.09	3.59	19.84	2.40	2.15	543	9.68	204.3	347	106.4	234.6
Vermicompost	7.61	5.45	17.64	3.61	1.91	819	6.31	329.4	460	159.7	301.5

The element concentration is mg kg^{-1}.EC: electrical conductivity (ds m^{-1}), OC: organic carbon, TN: total nitrogen.

The initial plowing of the land was performed with a moldboard plow in December 2017, and the boundaries of the main plots were established with dimensions of 10 ×15 meters. Organic fertilizers were applied to the main plots one month before planting and mixed with the soil to a depth of 15 cm using a cultivator. Secondary tillage was done with a furrowing hoe. The space between the ridges was set at 60 cm. On February 22, seeds were manually planted on the ridges with an in-row distance of 10 cm at a depth of 4 cm. The subplots (experimental units) were 5 × 10 meters in size and included 8 rows, each measuring 10 meters in length. Half of the zinc-containing fertilizers were applied in bands 4 cm below the seed at the seeding stage, where developing roots could easily reach them, and the other half was applied as a top dressing to the soil at the stem elongation stage. The chlorophyll content of the upper leaves was measured non-destructively at the tasseling stage using a SPAD-502 meter.

Canopy extent was determined by measuring the lateral growth of the plants on both the left and right sides with a meter at the mid-milkline stage. The plants were harvested on May 25. Fresh weight was measured using quadrat sampling methods ($1m^2$), and the plants were weighed with a digital scale.

Leaf relative water content was measured at the tasseling stage by collecting leaf samples and recording their fresh weight, turgid weight, and dry weight. Dry matter yield (DM) was determined by drying the samples at 75°C for 72 hours. To estimate the quality characteristics of the forage, dried samples were ground and 10 g from each treatment was transferred to the Research Institute of Forests and Rangelands, Iran. Forage quality characteristics including dry matter digestibility (DMD), crude protein (CP), water-soluble carbohydrates (WSC), neutral detergent fiber (NDF), and ash were determined by Near-Infrared Spectroscopy (NIRS)-8620.

Data analysis was performed using one-way ANOVA by SAS 9.4 software (SAS Institute Inc., Cary). The means comparison was performed using the LSD test. Box plots were drawn to compare means using Statistica software. Component analysis (PCA) was executed by Genstat software.

3. Results

3.1. Vegetative characteristics

The results of the variance analysis and mean comparisons of the evaluated traits are shown in Table 3. Stem length or plant height was significantly affected ($p<0.01$) by the main effects of soil amendments (F) and zinc-containing fertilizers (Zn). The tallest plants were observed under the recommended NPK dose (F_4) and the combined application of NPK + FYM (F_5). The application of all soil amendments increased plant height compared to the control. Application of zinc sulfate (Zn_1) and nanostructured zinc (Zn_2) increased plant length by 2% and 5%, respectively, compared to the control. The effect of F and Zn on chlorophyll content was significant. The highest level of this photosynthetic pigment was recorded under F_4 application, which was 25% higher than the control**.** The use of zinc-containing fertilizers significantly increased the content of this pigment compared to Zn_0. The highest canopy width growth was achieved with compost application (F_2), and the canopy width of plants grown under F_2 was 15% greater than the control. Application of Zn_2 and Zn_1 increased lateral canopy growth by 7% and 4%, respectively. Among soil amendment treatments, F_4 (NPK) and F_5 (combined NPK+FYM) had the greatest effect on this trait, increasing it by about 14% compared to F_0.

Table 3. Assessment of Zn-fertilizer effects under different soil amendment conditions on growth and forage properties of Zea mays in the Oltan region, Ardabil, Iran.

effects	PH	CC	CS	SD	MD	RWC	ASH	NDF
F_0	170.23^{e}	42.05^{c}	48.56^{d}	16.46^{d}	10.40^{f}	69.43^{d}	7.27^{f}	34.37^{b}
F_1	185.92^{c}	43.14^{c}	52.63^{c}	16.96^{c}	12.80^{a}	74.62^{a}	8.10^{c}	35.86^{a}
F_2	181.05^{d}	49.20^{b}	55.87^{a}	16.47^{d}	11.23^{e}	71.86^{c}	9.05^{a}	32.89^{c}
F_3	187.97^{bc}	44.32^{c}	54.49^{b}	18.24^{a}	11.93^{c}	72.65^{b}	7.58^{e}	32.10^{d}
F_4	195.77^{a}	52.96^{a}	55.37^{ab}	17.46^{b}	11.53^{d}	71.63^{c}	8.58^{b}	31.33^{e}
F_5	192.50^{ab}	47.18^{b}	55.62^{ab}	17.59^{b}	12.41^{b}	73.32^{b}	7.92^{d}	31.59^{de}
Zn_0	181.10^{c}	45.07^{b}	51.88^{c}	16.89^{b}	11.34^{b}	71.45^{b}	7.78^{c}	33.12^{a}
Zn_1	185.51^{b}	46.75^{a}	54.15^{b}	17.29^{a}	11.86^{a}	72.45^{a}	8.15^{b}	33.09^{a}
Zn_2	190.09^{a}	47.60^{a}	55.22^{a}	17.39^{a}	11.93^{a}	72.85^{a}	8.30^{a}	32.84^{a}
interactions								
F_0+Zn_0	163.87^{i}	39.23^{j}	47.23^{f}	15.70^{i}	10.32^{k}	68.33^{l}	7.22^{h}	32.50^{ef}
F_0+Zn_1	172.76^{hi}	42.90^{hi}	49.60^{ef}	16.5^{gh}	10.34^{k}	69.57^{k}	7.41^{fgh}	34.93^{cd}
F_0+Zn_2	174.04^{g}	44.03^{ghi}	48.83^{ef}	17.166^{ef}	10.55^{jk}	70.40^{ki}	7.19^{h}	35.67^{bc}
F_1+Zn_0	183.86^{efg}	43.40^{hi}	50.66^{de}	17.23^{def}	12.22^{cde}	73.00^{de}	7.78^{d}	37.27^{a}
F_1+Zn_1	184.03^{efg}	41.83^{ij}	54.66^{bc}	17.21^{ef}	12.89^{ab}	75.85^{a}	8.22^{c}	36.20^{ab}
F_1+Zn_2	189.86^{bcde}	44.20^{fghi}	52.56^{cd}	16.433^{gh}	13.28^{a}	75.03^{ab}	8.30^{c}	34.10^{d}
F_2+Zn_0	177.73^{fg}	47.80^{cdef}	53.37^{c}	16.20^{hi}	11.02^{hi}	71.10^{hij}	8.68^{b}	34.50^{cd}
F_2+Zn_1	180.80^{efg}	49.43^{bcd}	56.23^{ab}	16.83^{fg}	11.24^{hi}	72.73^{defg}	9.25^{a}	32.30^{ef}
F_2+Zn_2	184.55^{ef}	50.37^{abc}	58.00^{a}	16.36^{gh}	11.43^{efg}	71.77^{ghi}	9.22^{a}	31.87^{efgh}
F_3+Zn_0	185.4^{ef}	41.43^{ij}	52.60^{c}	17.84^{bcd}	11.35^{ghi}	72.70^{defg}	7.46^{efg}	31.77^{efgh}
F_3+Zn_1	186.63^{cdef}	45.67^{efgh}	54.56^{bc}	18.18^{ab}	12.38^{cd}	71.93^{efgh}	7.59^{def}	31.73^{efgh}
F_3+Zn_2	191.86^{bcd}	45.87^{defgh}	56.30^{ab}	18.69^{a}	12.05^{de}	73.33^{cd}	7.69^{de}	32.80^{e}
F_4+Zn_0	186.46^{def}	52.98^{ab}	53.57^{c}	16.93^{fg}	10.95^{ij}	70.70^{ij}	8.25^{c}	30.70^{h}
F_4+Zn_1	196.73^{ab}	53.16^{a}	54.67^{bc}	17.66^{bcde}	11.84^{ef}	71.81^{fgh}	8.22^{c}	31.57^{fgh}
F_4+Zn_2	204.10^{a}	52.75^{ab}	57.86^{a}	17.76^{bcde}	11.80^{efg}	72.38^{defg}	9.26^{a}	31.73^{efgh}
F_5+Zn_0	189.3^{bcde}	45.60^{efgh}	53.91^{bc}	17.43^{cdef}	12.19^{cde}	72.90^{def}	7.34^{gh}	32.03^{efg}
F_5+Zn_1	192.07^{bcd}	47.53^{cdefg}	55.16^{bc}	17.40^{cdef}	12.51^{bc}	72.87^{def}	8.25^{c}	31.83^{efgh}
F_5+Zn_2	196.1^{abc}	48.43^{cde}	57.81^{a}	17.93^{bc}	12.52^{bc}	74.20^{bc}	8.18^{c}	30.89^{gh}
Significance level								
F	**	**	**	**	**	**	**	**
Zn	**	**	**	**	**	**	**	ns
F×Zn	ns	ns	ns	**	*	**	**	**

F: soil amendments, F: farmyard manure. F_0: control, F_1: 30 t ha^{-1} farm yard manure, FYM, F_2: 8 t ha^{-1} compost, F_3: 8 t ha^{-1} vermicompost, F_4: recommended dose of chemical NPK, F_5: 50% recommended dose of NPK + 15 t ha^{-1} FYM, Zn: zinc fertilizers, Zn_0: control, Zn_1: 30 kg ha^{-1} zinc sulfate, Zn_2: 10 kg ha^{-1} nanostructured zinc, PH: plant length from ground level to the tip of tassel (cm), CC: chlorophyll content (SPAD unit), CS: lateral canopy growth and expansion, SD: Stem diameter near the soil surface, MD: produced dry matter (t ha^{-1}), RWC: the relative water content (%), ASH: total mineral content of forage, NDF: total cell wall content, including hemicellulose, cellulose, and lignin (%).

The effects of F and Zn on fresh forage yield were significant. Application of F4 resulted in the highest yield at 35.26 t ha^{-1}. The combined application of NPK+FYM yielded33.15 t ha^{-1} and the application of vermicompost yielded32.67 t ha^{-1} ranking second and third, respectively. The lowest production was recorded under F_0 condition with 26.84 t ha^{-1}. Application of Zn_2 and Zn_1 increased fresh forage yield by 6% and 4%, respectively. Under most soil amendment conditions, the application of nanostructured fertilizers had a greater positive effect on fresh forage yield (Figure 1).

3.2. Forage quality characteristics

Dry matter (DM)was significantly affected by the interaction effect of F ×Zn ($P < 0.05$). The lowest DM was observed under the F_0 condition (no soil amendment application). The highest DM (13.28 t ha^{-1}) was recorded with FYM + nanostructured zinc fertilizers. The application of nanostructured zinc and zinc sulfate fertilizers increased DM by 28% and 24%, respectively, compared to the control. Zinc fertilizer application under F_5 conditions also had a significant effect on increasing DM (Table 3).

Forage dry matter digestibility (DMD) evaluation indicated that zinc fertilizer application under F_0 conditions significantly DMD. Under FYM application, the highest DMD values were obtained with zinc sulfate application. Zinc application under F_2 conditions reduced DMD. Also, in plants grown with NPK, the use of nanostructured fertilizers reduced DMD by about 5% compared to the control. The highest DMD values were recorded with F_3+Zn_2, F_4+Zn_0, F_4+Zn_1, F_5+Zn_1 and F_5+Zn_2. The application of NPK fertilizer or its combined application with FYM significantly increased DMD (Figure 2).

The interaction effect of F× Zn was significant (*p<0.01*) on relative water content (RWC). The highest RWC values (75%) were obtained with the application of FYM and various fertilizers containing zinc. The application of livestock manure increased the RWC of the upper leaves by about 5% compared to the F_0 condition. Plants grown under the FYM+NPK condition ranked second place in RWC. The effects of traditional and nanostructured zinc fertilizers on RWC were largely similar with no statistically significant differences. Application of both Zn-fertilizers increased RWC compared to the control (Zn_0). Among the soil amendments F_1, F_3, and F_5 significantly increased RWC. Crude protein (CP) was affected by the interaction between F and Zn (*p<0.01*). The use of zinc sulfate and nanostructured zinc fertilizer significantly increased CP under all soil amendment conditions. The lowest percentage of CP was observed under F_0+Zn_0 (7.88), while the application of zinc sulfate and nanostructured zinc fertilizer increased this component by 0.35% and 0.74%, respectively. The use of vermicompost (F_3), NPK (F_4), and FYM+NPK (F_5) resulted in the highest CP values. The highest CP was recorded in plants grown with nanostructured zinc +NPK fertilizer (12.48%). Zinc sulfate had a greater effect on CP than nanostructured zinc fertilizers under F_1, F_3, and F_5 conditions (Figure 3).

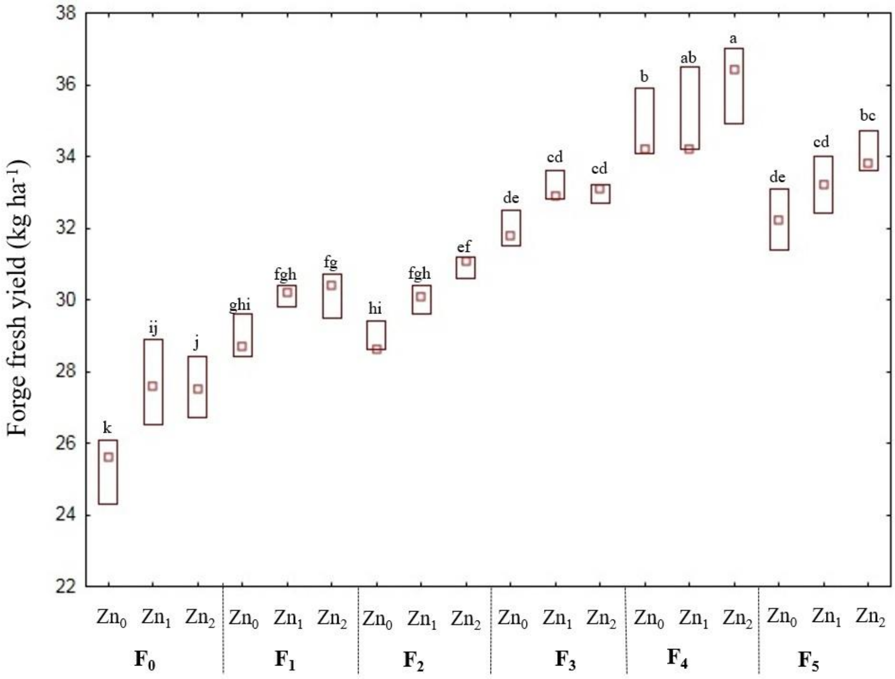

Figure 1. Mean comparisons of fresh forage yield of *Zea mays* under different soil amendment techniques and Zn fertilizer application in northwest Iran. F_0: control, F_1: 30 t ha^{-1} farm yard manure, FYM, F_2: 8 t ha^{-1} compost, F_3: 8 t ha^{-1} vermicompost, F_4: recommended dose of chemical NPK, F_5: 50% recommended dose of NPK + 15 t ha^{-1} FYM, Zn: zinc fertilizers, Zn_0: control, Zn_1: 30 kg ha^{-1} zinc sulfate, Zn_2: 10 kg ha^{-1} nanostructured zinc.

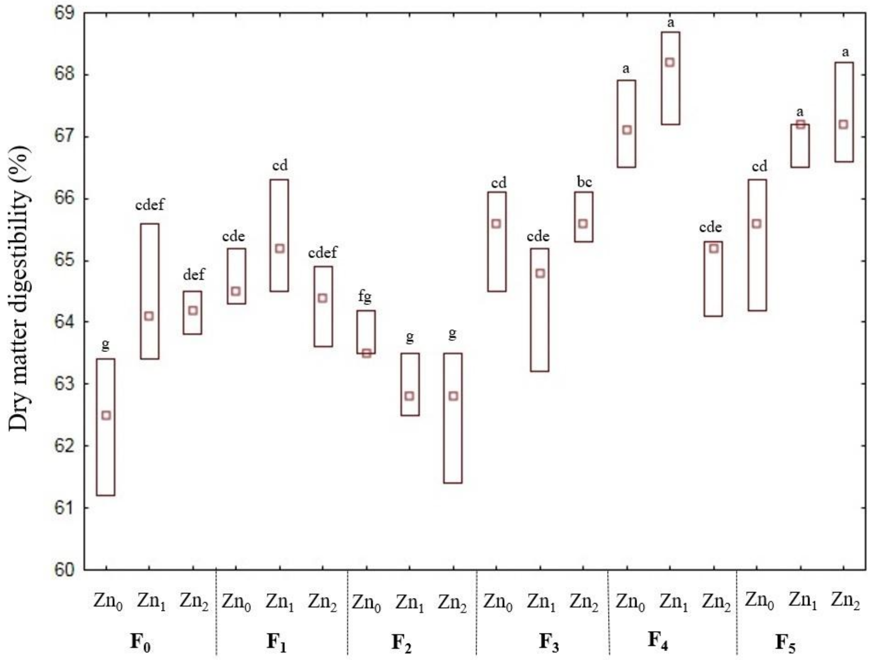

Figure 2. The influence of applying different typical organic and chemical fertilizers, along with zinc fertilizers, on the digestible dry matter content in forage corn cultivated in the Moghan area of northwest Iran. F_0: control, F_1: 30 t ha^{-1} farm yard manure, FYM, F_2: 8 t ha^{-1} compost, F_3: 8 t ha^{-1} vermicompost, F_4: recommended dose of chemical NPK, F_5: 50% recommended dose of NPK + 15 t ha^{-1} FYM, Zn: zinc fertilizers, Zn_0: control, Zn_1: 30 kg ha^{-1} zinc sulfate, Zn_2: 10 kg ha^{-1} nanostructured zinc.

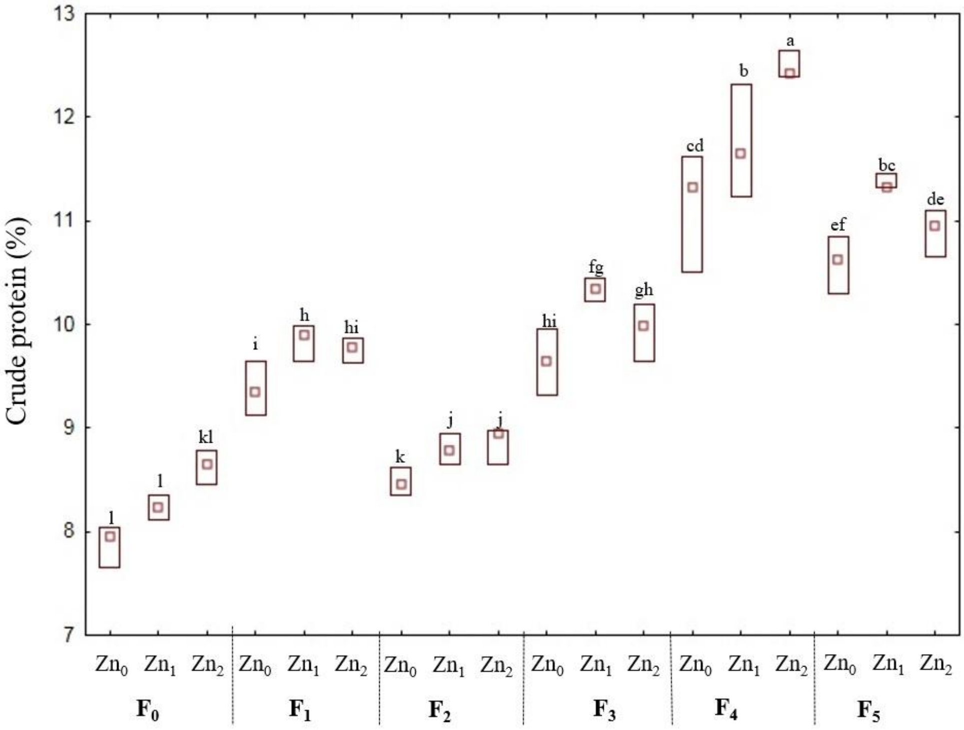

Figure 3. Evaluation of total protein content in forage corn using soil amendments and zinc-containing fertilizers in the semi-arid region of Moghan. F_0: control, F_1: 30 t ha^{-1} farm yard manure, FYM, F_2: 8 t ha^{-1} compost, F_3: 8 t ha^{-1} vermicompost, F_4: recommended dose of chemical NPK, F_5: 50% recommended dose of NPK + 15 t ha^{-1} FYM, Zn: zinc fertilizers, Zn_0: control, Zn_1: 30 kg ha^{-1} zinc sulfate, Zn_2: 10 kg ha^{-1} nanostructured zinc.

Ash or total mineral content in forage was affected by the interaction between F and Zn (*p<0.01*). The highest ash content was recorded with the application of compost and zinc-containing fertilizers (9.23%).

The lowest ash content was observed in plants grown under F_0, F_4, and F_5. Although the application of zinc-containing fertilizers increased ash content, the effect of zinc sulfate application on ash content was more pronounced. However, under FYM application, the effect of nanostructured zinc fertilizers on this component was more prominent.

Evaluation of the content of neutral detergent fibers or the total amount of structural components of the cell wall, showed that FYM application significantly increased this component. The lowest amount of NDF was obtained with the application of NPK + Zn_0 and the combined application of FYM + FYM with nanostructured zinc fertilizers. However, the effect of the main factor Zn on NDF was statistically insignificant.

Comparison of mean water-soluble carbohydrates (WSC) among different soil amendment treatments showed that the lowest WSC was recorded under F_0 conditions (25.48%). The use of soil amendments significantly increased WSC compared to the control (Figure 4). The highest WSC was obtained with the application of vermicompost (31.09%).

Application of animal manure alone or in combination with NPK fertilizer increased WSC by about 3% compared to the control. Regardless of fertilizer type, WSC increased by about 1% compared to the control. The highest WSC content was recorded in plants grown under F_3+Zn_1 and F_3+Zn_2.

3.3. Principal component analysis

Examining the correlation between traits using angular relationships and the cosine of the angles between traits showed that DM has a positive and significant relationship with RWC (Figure 5). Fresh forage yield, as a tangible economic indicator, had a positive and significant correlation with traits such as plant height, canopy width, crude protein content, dry matter digestibility percentage, and stem diameter. The characteristics highlighted in the red circle can serve as essential traits for assessing performance and quality factors. A negative and significant correlation was observed between chlorophyll content and NDF. It seems that fertilizer conditions that led to an increase in chlorophyll pigmentation in the leaves caused a significant decrease in NDF.

PCA analysis evaluating the spatial location and proximity of the combined treatments in terms of their impact on the studied traits showed that under FYM application, the effects of nanostructured and bulk fertilizers were very similar. These combined treatments resulted in the highest forage fresh yield, canopy area, plant height, and digestibility percentage (Figure 6). The highest RWC and DM values were observed in plants grown under F_1 with zinc-containing fertilizers. Compost application significantly affected the content of photosynthetic pigment chlorophyll and ash. The lowest values for most evaluated traits were found under F_0+Zn_0 conditions, which differed greatly from other combined treatments. However, the best plant performance in growth characteristics and forage quality was achieved with chemical fertilizer application. The effectiveness of vermicompost plus zinc-containing fertilizers was similar to that of F_5+Zn_0.

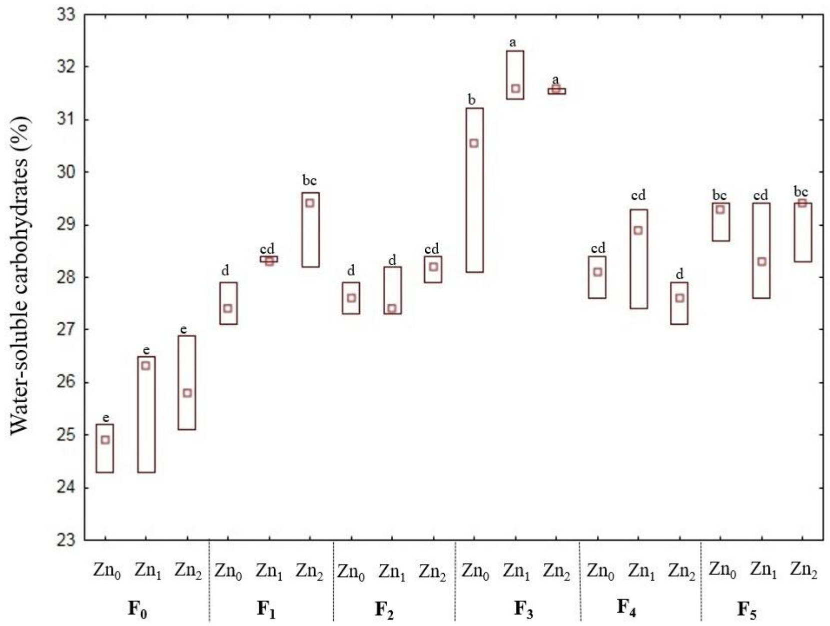

Figure 4. The effect of zinc-containing fertilizers and various physical and chemical soil amendments on water-soluble carbohydrates, including glucose, fructose, disaccharides, and polysaccharides in forage corn. F_0: control, F_1: 30 t ha^{-1} farm yard manure, FYM, F_2: 8 t ha^{-1} compost, F_3: 8 t ha^{-1} vermicompost, F_4: recommended dose of chemical NPK, F_5: 50% recommended dose of NPK + 15 t ha^{-1} FYM, Zn: zinc fertilizers, Zn_0: control, Zn_1: 30 kg ha^{-1} zinc sulfate, Zn_2: 10 kg ha^{-1} nanostructured zinc.

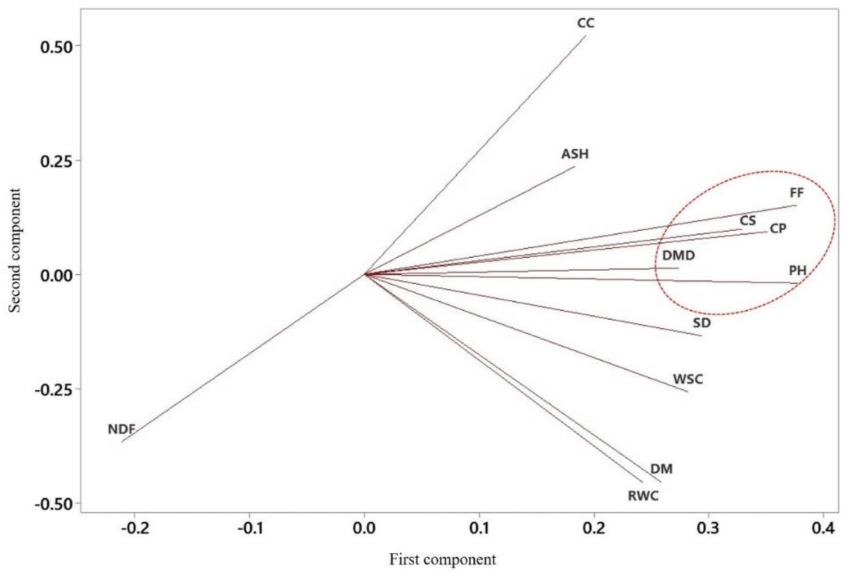

Figure 5. Principal component analysis showing the correlation between evaluated traits in forage corn grown under different fertilizer management practices. PH: plant length from ground level to tip of tassel , CC: chlorophyll content, CS: lateral canopy growth and expansion, SD: Stem diameter near the soil surface, MD: produced dry matter, RWC: the relative water content, ASH: total mineral content of forage, NDF: total cell wall content, including hemicellulose, cellulose, and lignin , FF: fresh forage yield, WSC: water-soluble carbohydrates, CP: crud protein, DM: Dry matter, NDF: Neutral detergent fibers.

4. Discussion

The study found that applying of soil amendments (F) affected all evaluated traits, with the effect of F being much stronger than that of Zn. These results indicate that the soil conditions in the region are unsuitable and have nutrient deficiencies. For successful production of forage corn, a plant that requires high inputs, soil conditions must be improved with organic amendments or chemical fertilizers. The use of NPK fertilizer significantly increased longitudinal and lateral growth as well as chlorophyll content compared to other soil amendments. These results confirm that forage corn, due to its high biomass production, cannot rely on soil amendments alone for optimal plant growth, and the use of chemical fertilizers must be considered in nutritional management. Corn, with its C_4 photosynthetic system and relatively high forage production capacity, requires significant amounts of chemical inputs and the supply of macro- and micronutrients for successful production (Grabovskyi et al., 2023).

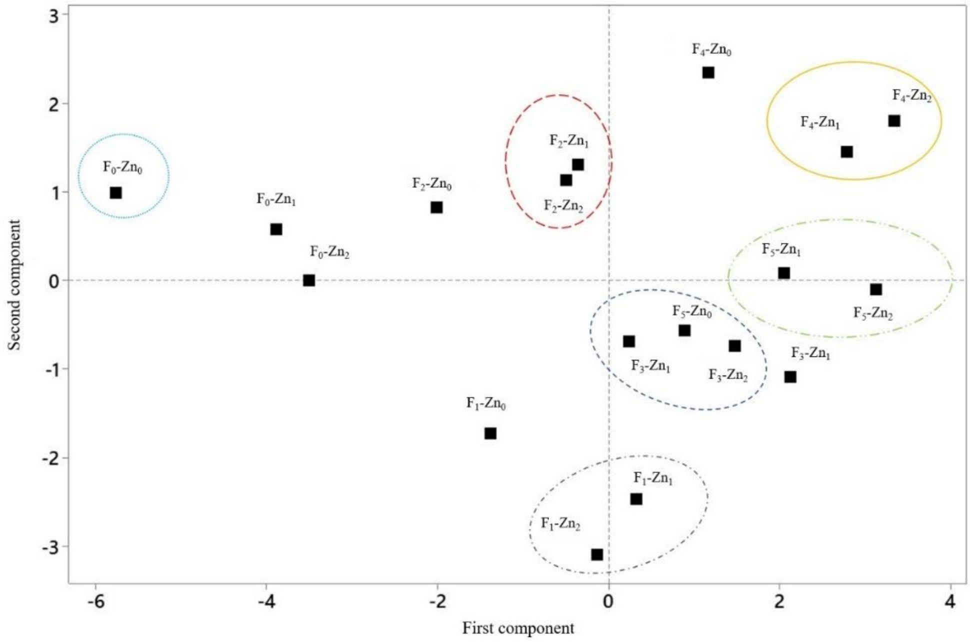

Figure 6. Monoplot generated by principal component analysis to interpret the similarities and differences among combined treatments (soil amendments and zinc fertilizer) affecting agronomic and quality traits in forage corn. F_0: control, F_1: 30 t ha^{-1} farm yard manure, FYM, F_2: 8 t ha^{-1} compost, F_3: 8 t ha^{-1} vermicompost, F_4: recommended dose of chemical NPK, F_5: 50% recommended dose of NPK + 15 t ha^{-1} FYM, Zn: zinc fertilizers, Zn_0: control, Zn_1: 30 kg ha^{-1} zinc sulfate, Zn_2: 10 kg ha^{-1} nanostructured zinc.

Chlorophyll is one of the most important plant molecules which affect by nitrogen utilization because of its chemical structure and the presence of tetrapyrrole rings. Increasing this photosynthetic pigment can enhance the rate of photosynthesis and result in greater production of photoassimilates (Guan et al., 2025).

In most growth-related traits, the effect of nanostructured zinc fertilizers was more pronounced than that of bulk zinc fertilizers (traditional zinc sulfate). This can be attributed to the gradual release of zinc oxide nanoparticles from chelating agents, reduced zinc leaching during irrigation, improved and easier absorption by the root system, its continuous availability in the rhizosphere environment, easier passage through plasma membranes, and better and enhanced translocation in the vascular system (Hanif et al., 2024). In plants, growth-related traits such as plant height, canopy width, and stem diameter are largely regulated by the ratio of phytohormones. The supply of NPK and the improvement of soil conditions through organic amendments, as well as the supply of zinc—especially via nanostructured fertilizers containing zinc—appear to provide optimal conditions for increasing the biosynthesis or preventing the degradation of growth-stimulating hormones such as auxin, cytokinin, and gibberellins s (Xing et al., 2023). Improvement of plant growth conditions ultimately lead to increased forage yield, with the highest fresh forage yield achieved through NPK application. These results indicate that despite the relatively unfavorable physical conditions in the semi-arid region studied, providing key elements for growth through chemical inputs is also a priority. Although some researchers have reported that the beneficial effects of soil amendments can be achieved through continuous application at long-term intervals (Nouraein et al., 2019; Cohen et al., 2023), the results showed that the short-term effects of organic amendments were effective in improving both the quantitative and qualitative aspects. However, continued use of organic amendments in the long term appears to lead to improved and stable yields. Evaluation of forage quality also showed that fertilizer management can significantly improve forage quality. Dry matter digestibility refers to the amount of forage consumed by livestock and its impact on meat or dairy products. The results showed that applying NPK alone, in combination with FYM, or using vermicompost, likely increased the proportion of digestible forage by improving conditions and meeting plant nutritional needs. This portion usually contains reserve carbohydrates that are easily broken down in the digestive systems of livestock. This trend was also observed for crude plant proteins. The improved availability of elements required for protein biosynthesis, especially nitrogen, likely played an important role in this effect. In addition, the key role of zinc as a cofactor in functional enzymes involved in protein biosynthesis can explain the increase in crude protein with the application of zinc-containing fertilizers. However, the effect of NPK on protein content was more pronounced than that of organic fertilizers. The application of chemical fertilizers, which provide immediate and significant amounts of nitrogen, phosphorus, and potassium, can better meet the requirements of protein biosynthesis processes. The use of vermicompost with zinc-containing fertilizers resulted in the highest percentage of WSC. Vermicompost was likely effective in increasing WSC by improving soil conditions and supplying some of the nutrients needed for the production of simple sugars, common disaccharides such as sucrose and trehalose, and some short water-soluble polymers. A higher proportion of water-soluble carbohydrates increases bacterial activity during the ensiling process, enhances the ensiling potential of forage, and improves its nutritional value (Coblentz et al., 2017). RWC is an important indicator for assessing plant water status. The results showed that the application of FYM could improve this indicator. FYM can enhance RWC by improving soil conditions such as increasing water retention capacity, improving microporosity, and facilitating water supply to the root system (Janmohammadi and Sabaghnia, 2023). Ash content in forage indicates the level of nutrients such as phosphorus, calcium, magnesium, and potassium. Ash is usually inversely related to the digestible portion of forage. However, the use of fertilizers increased the ash content in forage. This increase appears reasonable, given the significant stimulation of plant growth by fertilizers. NDF refers to the contribution of structural components of the cell wall, such as lignin, hemicellulose, and cellulose, which are considered to as slow- digesting fibrous compounds. Often, an increase in NDF leads to a decrease in dry matter and slows the rate of forage decomposition in the digestive systems of animals. The results showed that the highest amount of NDF was recorded with the use of FYM, while the lowest amount was observed with the use of NPK chemical fertilizers. Nitrogen application, by stimulating growth processes, increases the proportion of young tissues and reduces the proportion of tissues with secondary growth, thereby decreasing the amount of lignin compounds in the cell walls (Liu et al., 2016). Additionally, the use of nanostructured fertilizers containing zinc reduced NDF, which can be attributed to increased t activity of enzymes involved in the initial growth of the plant.

5. Conclusions

The use of organic soil amendments and fertilizers containing zinc had a notable impact on the growth and quality traits of forage corn. Nonetheless, the greatest plant growth was observed with NPK chemical fertilizers, either used individually or in conjunction with FYM. The results suggested that relying solely on organic fertilizers was insufficient to enhance both the quantitative and qualitative parameters. The highest yields of fresh forage, protein content, and digestibility of dry matter were recorded with NPK fertilizers and the combination of NPK along with FYM. The production of forage corn still relies to some extent on chemical fertilizers because of the large quantities produced. The combined use of FYM, NPK and nano-structured Zn can be a reasonable and effective agronomic management option for improving the quantitative and qualitative aspects of forage corn.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

References

Abdoli, H., Nasiri, Y., Janmohammadi, M., & Nouraein, M. (2025). Effect of biological and chemical fertilizers and seaweed extract application on yield, yield components, and some physiological traits of rainfed chickpea (*Saeed* cv.). *Journal of Agricultural Science and Sustainable Production, 35*(1), 1–24. https://doi.org/10.22034/saps.2024.56629.3046

Capstaff, N. M., & Miller, A. J. (2018). Improving the yield and nutritional quality of forage crops. *Frontiers in Plant Science, 9*, 535. https://doi.org/10.3389/fpls.2018.00535

Chen, Q., Song, Y., An, Y., Lu, Y., & Zhong, G. (2024). Soil microorganisms: Their role in enhancing crop nutrition and health. *Diversity, 16*(12), 734. https://doi.org/10.3390/d16120734

Coblentz, W. K., Akins, M. S., Cavadini, J. S., & Jokela, W. E. (2017). Net effects of nitrogen fertilization on the nutritive value and digestibility of oat forages. *Journal of Dairy Science, 100*(3), 1739–1750. https://doi.org/10.3168/jds.2016-12027

Cohen, J., Zolti, A., Rotbart, N., Medina, S., Green, S., & Minz, D. (2023). Short- and long-term effects of continuous compost amendment on soil microbiome community. *Computational and Structural Biotechnology Journal, 21*, 3280–3292. https://doi.org/10.1016/j.csbj.2023.05.030

Erenstein, O., Jaleta, M., Sonder, K., Mottaleb, K., & Prasanna, B. M. (2022). Global maize production, consumption and trade: Trends and R&D implications. *Food Security, 14*(5), 1295–1319. https://doi.org/10.1007/s12571-022-01288-7

FAOSTAT. (2023). *World food and agriculture: Statistical yearbook 2023*. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data/qcl

Goldan, E., Nedeff, V., Barsan, N., Culea, M., Panainte-Lehadus, M., Mosnegutu, E., & Irimia, O. (2023). Assessment of manure compost used as soil amendment: A review. *Processes, 11*(4), 1167. https://doi.org/10.3390/pr11041167

Grabovskyi, M., Kucheruk, P., Pavlichenko, K., & Roubík, H. (2023). Influence of macronutrients and micronutrients on maize hybrids for biogas production. *Environmental Science and Pollution Research, 30*(27), 70022–70038. https://doi.org/10.1007/s11356-023-27235-3

Gu, S., dos Santos Diniz, M. H., Mukhametov, A., & Kondrashev, S. (2025). Comparative study on the response of corn hybrids to different irrigation techniques and moisture levels. *Archives of Agronomy and Soil Science, 71*(1), 1–15. https://doi.org/10.1080/03650340.2025.2469900

Guan, C., Zhang, D., & Chu, C. (2025). Interplay of light and nitrogen for plant growth and development. *The Crop Journal*. Advance online publication. https://doi.org/10.1016/j.cj.2025.01.005

Hamzah Saleem, M., Usman, K., Rizwan, M., Al Jabri, H., & Alsafran, M. (2022). Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. *Frontiers in Plant Science, 13*, 1033092. https://doi.org/10.3389/fpls.2022.1033092

Hanif, S., Javed, R., Cheema, M., Kiani, M. Z., Farooq, S., & Zia, M. (2024). Harnessing the potential of zinc oxide nanoparticles and their derivatives as nanofertilizers: Trends and perspectives. *Plant Nano Biology*, 100110. https://doi.org/10.1016/j.plana.2024.100110

Janmohammadi, M., & Sabaghnia, N. (2023). Strategies to alleviate the unusual effects of climate change on crop production: A thirsty and warm future, low crop quality. *Biologija*, *69*(2), 121–133. https://doi.org/10.6001/biologija.2023.69.2.1

Jiang, C., You, Y., Lai, X., Zhang, Z., Gao, W., Ma, R., & Yang, X. (2024). Maximizing food equivalent unit yield for forage maize production without notably compromising dry matter yield and feed quality in a semi-arid region. *Industrial Crops and Products, 218*, 118942. https://doi.org/10.1016/j.indcrop.2024.118942

Köninger, J., Lugato, E., Panagos, P., Kochupillai, M., Orgiazzi, A., & Briones, M. J. (2021). Manure management and soil biodiversity: Towards more sustainable food systems in the EU. *Agricultural Systems*, *194*, 103251. https://doi.org/10.1016/j.agsy.2021.103251

Liu, J., Wu, N., Wang, H., Sun, J., Peng, B., Jiang, P., & Bai, E. (2016). Nitrogen addition affects chemical compositions of plant tissues, litter and soil organic matter. *Ecology*, *97*(7), 1796–1806. https://doi.org/10.1890/15-1683.1

Manzoor, A., Naveed, M. S., Ali, R. M. A., Naseer, M. A., Ul-Hussan, M., Saqib, M., & Farooq, M. (2024). Vermicompost: A potential organic fertilizer for sustainable vegetable cultivation. *Scientia Horticulturae*, *336*, 113443. https://doi.org/10.1016/j.scienta.2024.113443

Mohamadzadeh, M., Janmohammadi, M., Abbasi, A., Sabaghnia, N., & Ion, V. (2023). Physiochemical response of *Cicer arietinum* to zinc-containing mesoporous silica nanoparticles under water stress. *Biotechnologia*, *104*(3), 263–273. https://doi.org/10.5114/bta.2023.130729

Mohsenpour, A., Janmohammadi, M., Shekari, F., & Sabaghnia, N. (2024). Evaluation of the effect of organic soil amendments and irrigation regimes on the quantitative aspects of fatty acids in camelina seeds. *Acta Biologica Szegediensis*, *68*(2), 68–76. https://doi.org/10.14232/abs.2024.2.68-76

Nouraein, M., Skataric, G., Spalevic, V., Dudic, B., & Gregus, M. (2019). Short-term effects of tillage intensity and fertilization on sunflower yield, achene quality, and soil physicochemical properties under semi-arid conditions. *Applied Sciences*, *9*(24), 5482. https://doi.org/10.3390/app9245482

Sekaran, U., Lai, L., Ussiri, D. A., Kumar, S., & Clay, S. (2021). Role of integrated crop–livestock systems in improving agriculture production and addressing food security: A review. *Journal of Agriculture and Food Research*, *5*, 100190. https://doi.org/10.1016/j.jafr.2021.100190

Shoukat, A., Maryam, U., Pitann, B., Zafar, M. M., Nawaz, A., Hassan, W., & Mühling, K. H. (2025). Efficacy of nano and conventional zinc and silicon fertilizers for nutrient use efficiency and yield benefits in maize under saline field conditions. *Plants*, *14*(5), 673. https://doi.org/10.3390/plants14050673

Spalevic, V., Janmohammadi, M., Sabaghnia, N., & Kader, S. (2025). Adapting to climate change in semiarid regions via conservation measures: Climate-smart crop rotations of food legumes in cool seasons. *Turkish Journal of Agriculture and Forestry*, *49*(2), 242–259. https://doi.org/10.55730/1300-011X.3262

Umair Hassan, M., Aamer, M., Umer Chattha, M., Haiying, T., Shahzad, B., Barbanti, L., & Guoqin, H. (2020). The critical role of zinc in plants facing drought stress. *Agriculture*, *10*(9), 396. https://doi.org/10.3390/agriculture10090396

Xing, J., Cao, X., Zhang, M., Wei, X., Zhang, J., & Wan, X. (2023). Plant nitrogen availability and crosstalk with phytohormone signalling and their biotechnology breeding application in crops. *Plant Biotechnology Journal*, *21*(7), 1320–1342. https://doi.org/10.1111/pbi.13971