Research Article

Reaction of *Camelina sativa* L. oil profile to nano-iron and nano-zinc foliar application with farmyard manure[1]

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ABSTRACT

Climate change has intensified nutrient deficiencies in soils of semi-arid regions, largely due to low organic matter, high pH levels and harsh environmental conditions. This study investigates how the combined application of nanostructured iron and zinc micronutrients with farmyard manure influences the oil quality of *Camelina sativa* L. The experiment was based on three levels of farmyard manure application (0, 10 and 20 t ha^{-1}) and foliar sprays of nanostructured micronutrients at 300 ppm (water, nanostructured zinc and nanostructured iron). The oil extracted from the camelina seeds was analyzed for its fatty acids profile. The principal component analysis showed that the first two components explained 66 and 22 % of the total variance, respectively. Among the treatments, the combination of 10 t ha^{-1} of farmyard manure with nanostructured zinc foliar application resulted in the most notable improvement in the oil quality, significantly enhancing the levels of linolenic, oleic, docosanoic and total saturated fatty acids. It also demonstrated the strongest ability to represent and discriminate traits. Applying higher levels of manure (20 t ha^{-1}) led to a decrease in the linolenic acid content, suggesting that the excessive organic input may negatively affect the oil's nutritional profile. However, the combination of 20 t ha^{-1} of manure with nanostructured iron yielded the highest content of docosahexaenoic acid. Nanostructured zinc showed to be more effective than nanostructured iron in improving the camelina oil quality.

KEYWORDS: Fatty acid profile, nanostructured micronutrients, treatment-by-trait biplot.

RESUMO

Reação do perfil de óleo de *Camelina sativa* L. à aplicação foliar de nano-ferro e nano-zinco com esterco de curral

As mudanças climáticas intensificaram as deficiências de nutrientes nos solos de regiões semiáridas, em grande parte devido à baixa matéria orgânica, altos níveis de pH e condições ambientais adversas. Objetivou-se investigar como a aplicação combinada de micronutrientes nanoestruturados de ferro e zinco com esterco de curral influencia na qualidade do óleo de *Camelina sativa* L. Foram utilizados três níveis de aplicação de esterco de curral (0; 10; e 20 t ha^{-1}) e pulverizações foliares de micronutrientes nanoestruturados a 300 ppm (água, zinco nanoestruturado e ferro nanoestruturado). O óleo extraído das sementes de camelina foi analisado quanto ao perfil de ácidos graxos. A análise de componentes principais mostrou que os dois primeiros componentes explicaram 66 e 22 % da variância total, respectivamente. Entre os tratamentos, a combinação de 10 t ha^{-1} de esterco de curral com a aplicação foliar de zinco nanoestruturado resultou na melhoria mais notável na qualidade do óleo, aumentando significativamente os níveis de ácido linolênico, oleico, docosanoico e ácidos graxos saturados totais. Também demonstrou a maior capacidade de representar e discriminar características. A aplicação de níveis mais altos de esterco (20 t ha^{-1}) levou a uma diminuição no teor de ácido linolênico, sugerindo que o aporte orgânico excessivo pode afetar negativamente o perfil nutricional do óleo. No entanto, a combinação de 20 t ha^{-1} de esterco com ferro nanoestruturado produziu o maior teor de ácido docosahexaenoico. O zinco nanoestruturado mostrou-se mais eficaz do que o ferro nanoestruturado na melhoria da qualidade do óleo de camelina.

PALAVRAS-CHAVE: Perfil de ácidos graxos, micronutrientes nanoestruturados, biplot de caractere por tratamento.

INTRODUCTION

Camelina sativa L., native to central and eastern Europe, has a long history of cultivation for food, medicinal and biofuel purposes. Although it has been widely used for centuries, it fell into obscurity, until recent advancements in breeding and agronomic practices renewed interest among farmers (Sabaghnia et al. 2025).

The oil extracted from camelina seeds is rich in unsaturated fatty acids (about 50-60 %) which contribute to its high nutritional value (Clemente et al. 2025). However, its cultivation in semi-arid regions faces several challenges: soils in these areas often

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exhibit high pH, poor micronutrient availability, low water-holding capacity, limited microbial activity and deficiency in organic matter (Amina et al. 2025). These conditions can restrict its growth and yield, despite its promising agronomic and nutritional traits.

Organic fertilizers like manure release nutrients gradually, enhancing nutrient cycling, increasing soil organic matter and stimulating beneficial microbial activity (Rastogi et al. 2023). These effects create more favorable biological, physical and chemical conditions for plant growth. Manure also improves the soil structure by lowering its bulk density and increasing capillary pore space, what enhances its water retention capacity (Li et al. 2025). In areas with irregular rainfall and poor soil quality, animal manure has been shown to improve soil water dynamics, making crops more resilient to drought stress (Baghdadi et al. 2023). Therefore, incorporating livestock manure as an organic amendment provides a sustainable and effective approach to enhancing soil fertility and water availability, key factors in maximizing camelina growth and yield.

A study conducted in a rainfed region of northwest Iran investigated the impact of various organic amendments, including animal manure, vermicompost and biochar, on the fatty acid composition of camelina oil (Hazrati et al. 2022). The findings indicate that both foliar and soil applications of micronutrients, along with soil moisture levels, significantly influenced the oil yield and quality, particularly the balance between saturated and unsaturated fatty acids in safflower. Furthermore, the combined use of foliar-applied silicon nanoparticles and manure led to improved crop performance, when compared to untreated controls, underscoring the potential of integrated nutrient management to enhance both the quality and yield of oilseed crops in semi-arid regions (Janmohammadi & Sabaghnia, 2023).

Zinc nanoparticles have shown to enhance yield performance and improve the fatty acid profile in various crops (Azhand et al. 2025). Their application is also associated with increased seed germination, as well as improved shoot and root development (Karimi et al. 2025, Abbas et al. 2025). In tomato, zinc nanoparticles have been reported to increase plant height, chlorophyll content and overall biomass (Orfei et al. 2025). Similarly, foliar applications of zinc nanoparticles have led to increased leaf area and biomass in maize (Rizwan et al. 2019). Owing to their small size, high surface area and high reactivity, nanoparticles interact efficiently with plant tissues, enhancing nutrient uptake and improving yield quality (Zaman et al. 2025).

Iron nanoparticles have also demonstrated beneficial effects by promoting plant growth and photosynthesis. Compared to traditional iron fertilizers, nano-iron particles facilitate a better nutrient transport and more efficient iron delivery to plant leaves (Naik et al. 2025). According to Haghaninia et al. (2024), the highest oil yield and most favorable fatty acid profile were achieved using a combination of 50 % of the recommended chemical fertilizer, biological fertilizers and foliar spraying with nano-chitosan under supplemental irrigation conditions.

While earlier studies (Wang et al. 2023, Gu et al. 2024) have demonstrated that nutrient management can influence fatty acid composition in various edible oilseed crops, limited information exists regarding the impact of animal manure application under deficit irrigation on the fatty acid profile of camelina.

In Iran's semi-arid regions, camelina cultivation is often challenged by heat stress and water scarcity during the late growth stages due to declining rainfall, high evaporation rates, and increased solar radiation and air temperatures. Thus, this study was designed to evaluate the quality traits of camelina oil under levels of manure application and foliar spraying with nanostructured micronutrients of iron and zinc, in northwest Iran, in order to provide insights into how integrated nutrient and water management strategies can improve the camelina oil quality, particularly in water-limited environments.

MATERIAL AND METHODS

A field experiment was conducted in 2023 in the semi-arid, high-altitude, region of Razan, Hamadan province, located in western Iran (35º39'N, 49º03'E and altitude of 1,810 m). The region receives an average annual rainfall of 310 mm and has a mean annual temperature of 15 ºC, with average maximum and minimum temperatures of 21.3 and 5.6 ºC, respectively.

The experimental design followed a split-plot arrangement, within a randomized complete block design with three replications. The main plot factor consisted of three levels of farmyard manure (0, 10 and 20 t ha^{-1}), whereas the sub-plot treatments included the foliar application (300 ppm) of three micronutrient solutions: water (control), nanostructured iron and nanostructured zinc. Details of the chemical composition of the applied manure are presented in Table 1.

Primary soil tillage was conducted in October, followed by secondary tillage, land preparation and manure application in February. Irrigation was managed using a polyethylene pipe system equipped with a volume meter, and water was applied when the soil moisture reached 55 % of the available water capacity. Camelina seeds of the 'Soheil' cultivar were obtained from PakanBazr Co., Iran. Sowing was done manually in March, placing seeds on the top of ridges, with row spacing of 20 cm and plant spacing of 3 cm.

To determine the fatty acid profile, seed oil was extracted and subjected to transesterification. Specifically, 5 mg of extracted oil were mixed with 5 mL of 2 % methanolic sodium hydroxide and 2 mg of pentadecanoic acid (used as an internal standard), then heated in a boiling water bath for 10 min. Subsequently, 2.18 mL of methanolic boron trifluoride were added, and the mixture was refluxed for additional 2-3 min. After the reaction, 1.5 mL of hexane was added, and the sample was vigorously shaken to extract the methyl esters of the fatty acids. To facilitate phase separation and precipitate glycerol, 1 mL of saturated NaCl solution was added, and the sample was shaken again. The supernatant was collected, and 1 mL of the upper phase was transferred to a tube containing 0.5 g of anhydrous sodium sulfate to remove residual moisture. The sample was then centrifuged at 2,500 rpm for 2-5 min to complete dehydration.

The clear upper phase was injected into a gas chromatography (GC) system (Model 6890, Varian) equipped with a BPX70 silica capillary column (SGE, Austin, USA). The GC oven temperature program started at 158 ºC and increased gradually to 210 ºC, in which it was held for 20 min. The injector temperature was maintained at 230 ºC, whereas the detector temperature was set to 240 ºC. Helium was used as the carrier gas at a flow rate of 1.2 mL min^{-1}, and injections were performed in split mode. The analyzed fatty acids included linolenic (C18:3), linoleic (C18:2), eicosadienoic (C20:2), oleic (C18:1), palmitic (C16:0), erucic (C22:1), stearic (C18:0), eicosatrienoic (C20:3), arachidonic (C20:4), docosanoic (C22:0), docosahexaenoic (C22:6) and palmitoleic acid (C16:1). Additionally, the proportions of saturated fatty acids, monounsaturated fatty acids and polyunsaturated fatty acids were calculated.

A principal component analysis in a treatment-by-trait layout was performed, and the corresponding biplots were generated using the GGEbiplot software based on the following equation: $(x_{ij} - y_j)/S_j = \sum_{n=1}^{2} \lambda_n \xi_{in} \eta_{jn} + R_{ij}$, where x_{ij} is the value treatment i for trait j; y_j the average of treatments in trait j; S_j the standard error of related trait; λ_n the singular value for component n; ξ_{in} and η_{in} the obtained magnitudes for treatment i and trait j on each component; and R_{ij} the model residual item.

Table 1. Soil physical and chemical properties in the studied area and the used livestock fertilizers.

pH	EC	OC	TN	P	K
H_2O	ds m^{-1}	%		mg kg^{-1}	
6.61	4.62	28.37	1.87	1.53	192
C/N	Ca	Fe	Zn	Mn	
%	mg kg^{-1}				
14.32	193.7	142.62	128	210.3	

EC: electrical conductivity, OC: organic carbon, TN: total nitrogen.

RESULTS AND DISCUSSION

The treatment-by-trait (TT) biplot explained 53 and 26 % of the total variation in the standardized two-way dataset through the first two principal components (PC1 and PC2), respectively (Figure 1). This substantial proportion underscores the strong associations among the traits. To facilitate visual interpretation, vectors extending from the origin represent each trait, illustrating their relationships clearly. Since the TT biplot captures a significant portion of the dataset's variability, trait associations can be inferred from the cosine of the angles between their vectors: a cosine of 0º (+1) indicates a strong positive correlation, 90º (0) means no correlation, and 180º (-1) reflects a strong negative correlation. The long vectors displayed in Figure 1 indicate that most traits contributed considerably to the observed variation.

Notable positive associations observed in the TT biplot include linoleic with polyunsaturated fatty acids; docosahexaenoic with eicosadienoic acid; palmitoleic with eicosatrienoic and erucic acid; arachidonic with linolenic and monounsaturated fatty acids; and docosanoic with oleic and palmitic acid, as indicated by the acute angles between their vectors. Near-zero associations, shown by nearly perpendicular vectors, were found between linoleic and polyunsaturated fatty acids with docosanoic, oleic and palmitic acid; saturated fatty acid percentage with palmitoleic, eicosatrienoic and erucic acid; and between arachidonic, linolenic and monounsaturated fatty acids with docosanoic, oleic and palmitic acid (Figure 1).

Negative associations were also evident, such as between palmitoleic, eicosatrienoic and erucic acid with docosahexaenoic and eicosadienoic acid, and between linoleic and polyunsaturated fatty acids with arachidonic, linolenic and monounsaturated fatty acids, as reflected by the obtuse angles between their vectors (Figure 1). This visualization effectively captures the complex relationships among camelina fatty acid traits, being consistent with previous studies. For example, Rodríguez-Rodríguez et al. (2021) reported a positive link between linoleic and polyunsaturated fatty acids in camelina, and Ebrahimi et al. (2025) observed positive correlations between docosahexaenoic and eicosadienoic acid in camelina oil. However, it is important to note that the TT biplot presents associations based on the overall data structure, so these graphical interpretations may not exactly match numerical correlation coefficients, which quantify specific statistical relationships.

Figure 2 demonstrates how the TT biplot model enables the comparison of different treatments based on the measured traits, making it a useful tool

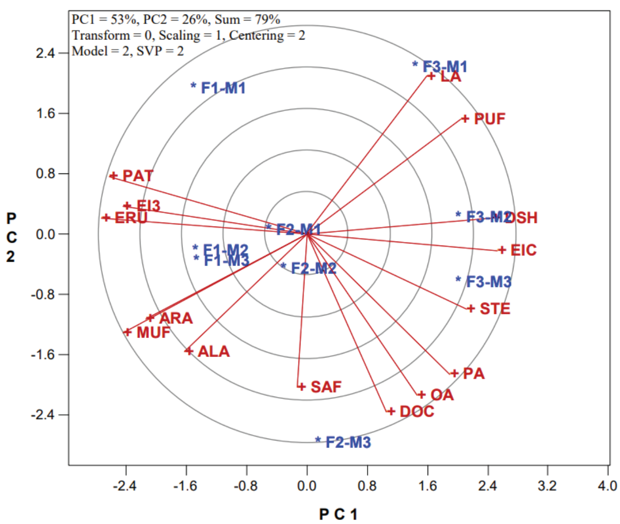

Figure 1. Ranking treatments according to traits of camelina oil profile. Treatments are: F1-M1: 0 t ha^{-1} of farmyard manure + water spray; F1-M2: 0 t ha^{-1} of farmyard manure + nanostructured iron spray; F1-M3: 0 t ha^{-1} of farmyard manure + nanostructured zinc spray; F2-M1: 10 t ha^{-1} of farmyard manure + water spray; F2-M2: 10 t ha^{-1} of farmyard manure + nanostructured iron spray; F2-M3: 10 t ha^{-1} of farmyard manure + nanostructured zinc spray; F3-M1: 20 t ha^{-1} of farmyard manure + water spray; F3-M2: 20 t ha^{-1} of farmyard manure + nanostructured iron spray; F3-M3: 20 t ha^{-1} of farmyard manure + nanostructured zinc spray. Traits are: linolenic (18:3; ALA); linoleic (18:2; LA); eicosadienoic (20:2; EIC); oleic (18:1; OA); palmitic (16:0; PA); erucic (22:1; ERU); stearic (18:0; STE); eicosatrienoic (20:3; EI3); arachidonic (20:4; ARA); docosanoic (22:0; DOC); docosahexaenoic (22:6; DSH); and palmitoleic (16:1; PAT) acids; as well as saturated fatty acid percentage (SAF); monounsaturated fatty acid (MUF); and polyunsaturated fatty acids (PUF; %).

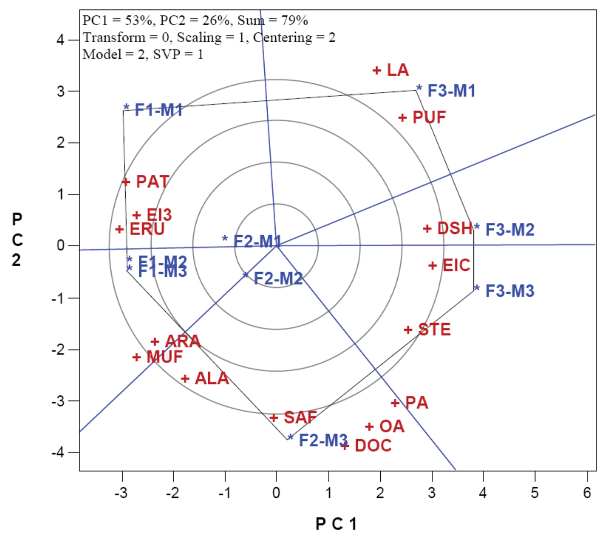

Figure 2. Presents which treatment wins which trait of camelina oil profile. Treatments are: F1-M1: 0 t ha^{-1} of farmyard manure + water spray; F1-M2: 0 t ha^{-1} of farmyard manure + nanostructured iron spray; F1-M3: 0 t ha^{-1} of farmyard manure + nanostructured zinc spray; F2-M1: 10 t ha^{-1} of farmyard manure + water spray; F2-M2: 10 t ha^{-1} of farmyard manure + nanostructured iron spray; F2-M3: 10 t ha^{-1} of farmyard manure + nanostructured zinc spray; F3-M1: 20 t ha^{-1} of farmyard manure + water spray; F3-M2: 20 t ha^{-1} of farmyard manure + nanostructured iron spray; F3-M3: 20 t ha^{-1} of farmyard manure + nanostructured zinc spray. Traits are: linolenic (18:3; ALA); linoleic (18:2; LA); eicosadienoic (20:2; EIC); oleic (18:1; OA); palmitic (16:0; PA); erucic (22:1; ERU); stearic (18:0; STE); eicosatrienoic (20:3; EI3); arachidonic (20:4; ARA); docosanoic (22:0; DOC); docosahexaenoic (22:6; DSH); and palmitoleic acid (16:1; PAT); as well as saturated fatty acid percentage (SAF); monounsaturated fatty acid (MUF); and polyunsaturated fatty acids (PUF; %).

for identifying treatments that perform best in specific areas. This visualization is especially valuable for recommending optimal fertilization strategies to camelina farmers. A hexagonal framework was used, with perpendicular lines drawn from each side to help distinguishing the leading treatments at each vertex.

The analysis revealed that the treatment 0 t ha^{-1} of farmyard manure combined with foliar spray of water as the control showed the highest levels of palmitoleic, eicosatrienoic and erucic acid, whereas the treatment 0 t ha^{-1} of farmyard manure with foliar application of nanostructured zinc exhibited the highest levels of arachidonic and monounsaturated fatty acids (Figure 2). The combination of 10 t ha^{-1} of farmyard manure with zinc foliar spray resulted in the greatest concentrations of linolenic, docosanoic, oleic, palmitic and saturated fatty acids. This indicates that applying a moderate amount of manure alongside zinc nanoparticles can significantly improve camelina oil quality, particularly by increasing the linolenic acid content. Additionally, the treatment 20 t ha^{-1} of manure with nanostructured zinc foliar spray produced high levels of stearic and eicosadienoic acid, whereas the treatment 20 t ha^{-1} of manure with water foliar spray as control yielded the highest amounts of linoleic and polyunsaturated fatty acids.

The treatment 20 t ha^{-1} of manure combined with nanostructured iron foliar spray excelled in docosahexaenoic acid content. These results suggest that applying 20 t ha^{-1} of farmyard manure together with zinc nanoparticle foliar spray is an effective strategy to optimize camelina oil quality sustainably. Camelina's adaptability to low-input conditions, requiring minimal agricultural resources, further supports its potential as a valuable oilseed crop. Its renewed interest stems from both its agronomic and physiological advantages, making it a promising candidate for sustainable agriculture. As highlighted by Alberghini et al. (2022), camelina plays an important role in diversifying and increasing oilseed crop production, contributing significantly to the long-term sustainability of agricultural systems.

Figure 3 illustrates the representativeness and discriminative ability of the various traits. In this context, the length of each trait's vector indicates its discriminative power; the longer the vector, the better the trait can differentiate among treatments. Meanwhile, the projection of a trait onto the average trait axis reflects its representativeness, with shorter distances indicating a strong ability to represent the overall pattern of traits. Notably, the saturated fatty acid percentage and docosanoic acid (22:0) stood out as having the greatest potential for both representation and discrimination, as they were located near the ideal trait position in the biplot (Figure 3). Following these, oleic (18:1), palmitic (16:0) and linolenic (18:3) acid also showed strong representativeness and discriminative power. In contrast, linoleic (18:2), palmitoleic (16:1) and polyunsaturated fatty acids exhibited limited ability in both aspects. Although the linolenic and stearic acids demonstrated strong discrimination potential due to their long vectors extending away from the plot center, their representativeness was limited because of their large projections onto the mean trait axis.

In Figure 4, the center of the circles marks the position of an ideal treatment, with its projection on the vertical mean trait axis corresponding to the longest treatment vector, and its horizontal projection set to zero, indicating minimal variability and maximum stability. Treatments with intervals closer to this ideal position are considered more optimal. Among the treatments, 10 t ha^{-1} of farmyard manure

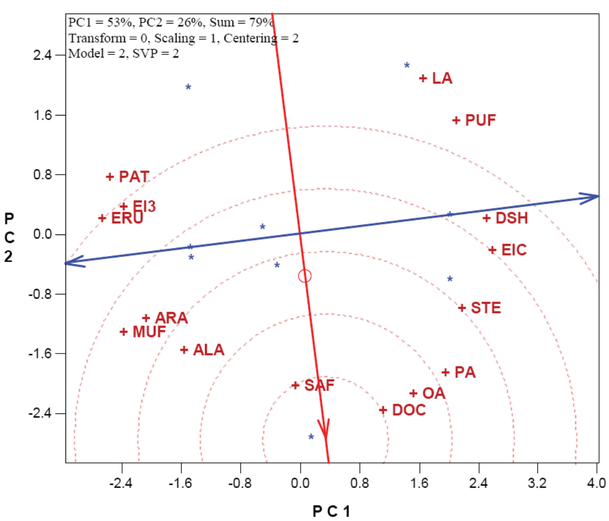

Figure 3. Ranking traits of camelina oil profile according to discriminative and representativeness capabilities. Traits are: linolenic (18:3; ALA); linoleic (18:2; LA); eicosadienoic (20:2; EIC); oleic (18:1; OA); palmitic (16:0; PA); erucic (22:1; ERU); stearic (18:0; STE); eicosatrienoic (20:3; EI3); arachidonic (20:4; ARA); docosanoic (22:0; DOC); docosahexaenoic (22:6; DSH); and palmitoleic (16:1; PAT) acid; as well as saturated fatty acid percentage (SAF); monounsaturated fatty acid (MUF); and polyunsaturated fatty acids (PUF; %).

combined with foliar spray of nanostructured zinc was closest to the ideal position, making it the most favorable choice. In contrast, the treatments 0 t ha^{-1} of farmyard manure combined with foliar spray of water as the control and 20 t ha^{-1} of farmyard manure with water spray were the farthest from this ideal point, indicating that these treatments are less suitable. The other treatments showed no significant differences and were clustered near the average axis (Figure 4). Overall, the treatment 10 t ha^{-1} of farmyard manure combined with foliar spray of nanostructured zinc exhibited the greatest ability to differentiate among the measured traits of camelina.

An evaluation of the performance of the treatment 10 t ha^{-1} of farmyard manure combined with foliar spray of nanostructured zinc for the camelina's measured traits (Figure 5) showed a strong association with docosanoic, oleic, palmitic, linolenic and saturated fatty acids. Therefore, to achieve a high linolenic acid content in camelina oil, applying 10 t ha^{-1} of farmyard manure combined with foliar spraying of nanostructured zinc is recommended.

The observed improvements in safflower yield following chemical NPK application align with findings by Rostami et al. (2022), who reported enhanced yield and oil composition in camelina with organic fertilizer use. However, nutrient requirements for camelina may vary depending on soil conditions, farming practices, cultivar selection, growth stage and environmental factors. While soil nutrient availability is crucial for production potential, environmental stresses can limit nutrient uptake and transport by reducing transpiration rates (Soares et al. 2019). Foliar application of nanostructured zinc has been shown to promote crop growth and performance by boosting antioxidant enzyme activity and improving photosynthetic yield. Similarly, Ahmed et al. (2023) reported positive effects of nanostructured zinc on trait performance in various medicinal and aromatic plants.

An analysis of linolenic acid levels across the treatments revealed that only 10 t ha^{-1} of farmyard manure combined with foliar spray of nanostructured zinc exhibited a notably high linolenic acid content,

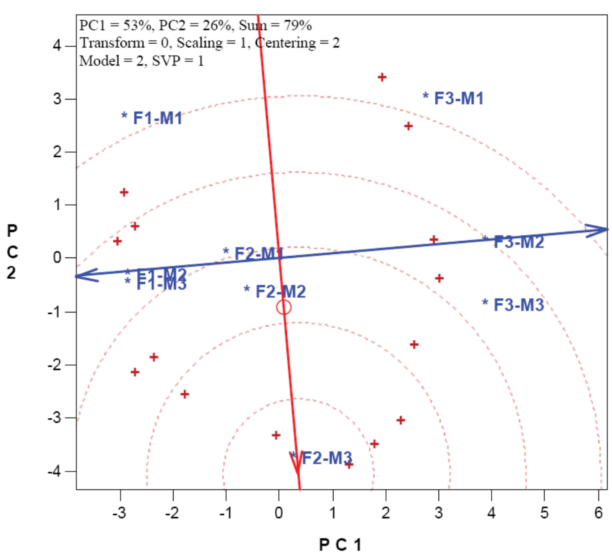

Figure 4. Ranking combinations according to traits of camelina oil profile. Treatments are: F1-M1: 0 t ha^{-1} of farmyard manure + water spray; F1-M2: 0 t ha^{-1} of farmyard manure + nanostructured iron spray; F1-M3: 0 t ha^{-1} of farmyard manure + nanostructured zinc spray; F2-M1: 10 t ha^{-1} of farmyard manure + water spray; F2-M2: 10 t ha^{-1} of farmyard manure + nanostructured iron spray; F2-M3: 10 t ha^{-1} of farmyard manure + nanostructured zinc spray; F3-M1: 20 t ha^{-1} of farmyard manure + water spray; F3-M2: 20 t ha^{-1} of farmyard manure + nanostructured iron spray; F3-M3: 20 t ha^{-1} of farmyard manure + nanostructured zinc spray.

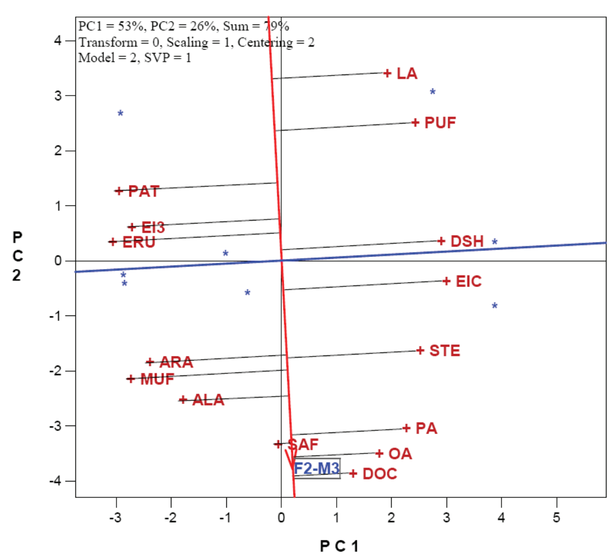

Figure 5. Ranking traits of camelina oil profile according to the F2-M3 treatment (10 t ha^{-1} of farmyard manure + nanostructured zinc spray). Traits are: linolenic (18:3; ALA); linoleic (18:2; LA); eicosadienoic (20:2; EIC); oleic (18:1; OA); palmitic (16:0; PA); erucic (22:1; ERU); stearic (18:0; STE); eicosatrienoic (20:3; EI3); arachidonic (20:4; ARA); docosanoic (22:0; DOC); docosahexaenoic (22:6; DSH); and palmitoleic (16:1; PAT) acid; as well as saturated fatty acid percentage (SAF); monounsaturated fatty acid (MUF); and polyunsaturated fatty acids (PUF; %).

followed by 0 t ha^{-1} of farmyard manure with nanostructured iron spray and 0 t ha^{-1} of farmyard manure with nanostructured zinc spray, while all other treatments showed linolenic acid levels at or below the average (Figure 6). Interestingly, treatments with the highest farmyard manure application (20 t ha^{-1}) recorded the lowest linolenic acid concentrations. Nanomaterials present a promising strategy to enhance crop performance by improving nutrient use efficiency and enabling the controlled, slow release of nutrients. This approach helps to minimize the risk of overusing growth promoters and fertilizers. In addition to boosting yield, nanomaterials contribute to improved crop quality and reduced farming costs, underscoring their potential as a sustainable tool in modern agriculture (Babu et al. 2022).

Consistently with previous research, the findings of the present study confirm that the farmyard manure application enhances crop production, whereas foliar spraying with nanostructured zinc further boosts camelina yield (Fatemeh et al. 2020, Joshi et al. 2017). Importantly, applying nanomaterials in minimal, carefully managed amounts offers an environmentally friendly and cost-effective approach, making it a practical solution for farmers aiming at sustainable agriculture.

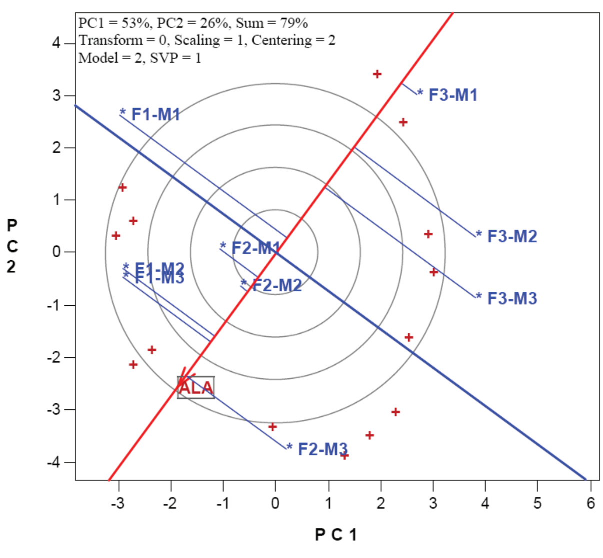

Figure 6. Ranking treatments according to the linolenic acid (ALA). Treatments are: F1-M1: 0 t ha^{-1} of farmyard manure + water spray; F1-M2: 0 t ha^{-1} of farmyard manure + nanostructured iron spray; F1-M3: 0 t ha^{-1} of farmyard manure + nanostructured zinc spray; F2-M1: 10 t ha^{-1} of farmyard manure + water spray; F2-M2: 10 t ha^{-1} of farmyard manure + nanostructured iron spray; F2-M3: 10 t ha^{-1} of farmyard manure + nanostructured zinc spray; F3-M1: 20 t ha^{-1} of farmyard manure + water spray; F3-M2: 20 t ha^{-1} of farmyard manure + nanostructured iron spray; F3-M3: 20 t ha^{-1} of farmyard manure + nanostructured zinc spray.

A proper management of nanostructured zinc application is essential to maximize its benefits, while minimizing potential risks. Studies have demonstrated that the combined application of nanostructured zinc and farmyard manure improves yield performance in maize (Singh et al. 2021), chickpea (Sabaghnia & Janmohammadi 2023) and wheat (Vishwakarma et al. 2023). As nanotechnology becomes increasingly integrated into crop production, it not only reduces fertilizer dependency, but also lowers production costs. Nanostructured zinc has shown beneficial effects on crops under environmental stress conditions (Semida et al. 2021, Ghani et al. 2022). However, despite these advantages, it is essential to acknowledge the potential risks linked to its agricultural use.

Researchers continue to investigate these risks to ensure the safe and responsible adoption of nanotechnology. Key challenges include high evaluation costs, environmental concerns and possible human health risks, which remain significant barriers to widespread implementation (Zulfiqar et al. 2019). Our findings align with previous studies indicating that nanomaterials can play a vital role in optimizing crop quality while reducing reliance on intensive agricultural inputs. To address safety concerns, the establishment of international standards for nanotechnology in agriculture is critical before large-scale commercialization and public adoption. Moreover, a careful management of nanostructured zinc release is crucial to maximize its benefits (Sabaghnia et al. 2018). While nanotechnology offers promising pathways for sustainable crop production, ongoing assessment of its environmental and health impacts is imperative (Singh & Gurjar 2022).

The application of nanostructured iron in combination with farmyard manure demonstrated a notable impact on specific fatty acid profiles in camelina oil, particularly by increasing the docosahexaenoic acid content. This finding aligns with a prior study indicating that iron nanoparticles can enhance nutrient uptake and photosynthetic efficiency, thereby improving plant growth and secondary metabolite accumulation (Naik et al. 2025). The improved docosahexaenoic acid concentration suggests that nanostructured iron may play a key role in modulating the biosynthesis pathways of long-chain polyunsaturated fatty acids, which are vital for the nutritional value and industrial applications of camelina oil.

Compared to treatments with nanostructured zinc, the foliar application of nanostructured iron showed relatively less influence on other key fatty acids such as linolenic and oleic acid. This could be attributed to differences in nanoparticle uptake mechanisms, translocation efficiency or interactions with metabolic processes specific to iron *versus* zinc. Iron's primary role in chlorophyll synthesis and electron transport during photosynthesis may indirectly affect oil biosynthesis, whereas zinc is more directly involved in enzyme activation related to lipid metabolism (Zaman et al. 2025).

Despite the promising effects of nanostructured iron on certain oil quality traits, the overall improvement in fatty acid composition was less comprehensive than observed with nanostructured zinc applications. This outcome emphasizes the need for further investigation into the optimal dosage, timing and formulation of iron nanoparticles to maximize their benefits while avoiding potential phytotoxicity or environmental concerns. Furthermore, the integration of nanostructured iron with organic amendments like farmyard manure seems to offer a synergistic effect, enhancing nutrient availability and uptake under semi-arid conditions.

Given that water scarcity and soil nutrient limitations can restrict crop yield and quality, nanostructured iron offers a promising tool for improving camelina cultivation in marginal environments. Future research should prioritize optimizing application methods, exploring various chemical forms of nanomaterials and understanding crop-specific responses to different treatments. Addressing these research gaps will enhance the effectiveness of nanostructured materials in improving crop yield and quality, ultimately contributing to more sustainable agricultural practices worldwide.

CONCLUSIONS

1. The combined application of nanostructured zinc and farmyard manure significantly enhances the camelina oil quality, notably increasing the linolenic acid content;
2. Applying 10 t ha^{-1} of farmyard manure with foliar nanostructured zinc optimally improves important traits such as docosanoic, oleic and saturated fatty acids content, leading to a superior oil composition;
3. The use of 20 t ha^{-1} of farmyard manure combined with foliar nanostructured iron results in elevated levels of docosahexaenoic acid in camelina oil;
4. Nanostructured zinc exhibits a stronger positive effect on camelina oil quality, when compared to nanostructured iron.

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