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Investigation of irrigation regimes, farmyard manure and nano-micronutrients (zinc and iron) on *Camelina sativa* L. performance

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ABSTRACT

To access the influence of irrigation regimes during application of different levels of farmyards manure (0, 10 and 20 t ha^{-1}), and foliar application of iron and zinc nano-nutrients on camelina, a field trial based on a split-split plot, was conducted in the Razan, Iran. This study utilized the treatment by trait biplot model, after significance of interactions, to assess the performance of camelina under varying micronutrient and water stress conditions, identifying the most effective treatments for improving seed yield and oil content including plant height, number of siliques per plant, seed number per silique, thousand seed weight, seed yield, harvest index, and oil percent. The biplot analysis explained 93% of the total variation, with the first two components describing for 75% and 18%. The results revealed that application of 20 t ha^{-1} farmyard manure with nano-zinc micronutrient under normal irrigation was the best-performing treatment for most yield-related traits. However, application of 10 t ha^{-1} farmyard manure with nano-zinc micronutrient under normal irrigation exhibited greater oil content from above mentioned outperformed treatment, indicating that nano-zinc applications with organic amendments enhance agronomic characteristics, oil content and yield performance. For oil content, application of 10 t ha^{-1} farmyard manure with nano-iron micronutrient under normal irrigation was the most effective treatment. The vector analysis further confirmed a positive correlation between seed yield and thousand seed weight, while height of plant indicated no relation with both seed yield and oil percentage. These findings underscore the agronomic benefits of nano-sized micronutrient fertilizers and their potential for sustainable and high-yield camelina production. Future research should explore long-term soil interactions and economic viability to further optimize nano-fertilizer applications in agriculture.

Highlights

- Application of 20 t ha^{-1} farmyard manure with nano-zinc under normal irrigation, was the best treatment for most traits.
- Using 10 t ha^{-1} farmyard manure with nano-zinc, under normal irrigation, exhibited greater oil content, indicating that nano-zinc + organic amendments enhance quality.
- For oil content, application of 10 t ha^{-1} farmyard manure, and nano-iron, under normal irrigation, was the best treatment.

1. Introduction

Camelina (*Camelina sativa* L.), an oilseed crop belonging to the Brassicaceae family, is a relatively recent addition to the list of crops that have been improved through the process of plant breeding over the past few decades. It has gained attention due to its adaptability and its potential to thrive in regions with challenging environmental conditions. Also, camelina has shown a reasonable degree of success in adapting to the regions with limited water availability (Neupane et al., 2022). This resilience makes camelina a potential crop for these areas, offering an alternative to more water-dependent crops.

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However, the situation is changing rapidly due to the ongoing climate change that is affecting regions worldwide. Recent climate changes, including higher air temperatures and reduced rainfall, have increased the difficulties faced by agriculture, especially in semi-arid and arid regions (Abdelmounaim et al., 2024). As a result, these areas are now experiencing more frequent and intense periods of drought stress, which places additional strain on agricultural productivity. The reduced availability of water resources in these regions has made it increasingly difficult for crops to thrive under normal conditions, and camelina is no exception. The effects of these climate-related changes are significant and have led to a greater urgency in understanding the adaptation mechanisms of crops like camelina in order to ensure their continued success in the face of environmental stresses (KhokharVoytas et al. 2023).

The average camelina yield is relatively low and such yield can be influenced by some factors like genetic differences, soil quality, rainfall patterns, and whether the growth of plant is limited or allowed to grow freely. It is important to note that both the quantitative traits of grain yield and the quality of the extracted oil can be significantly affected by the environmental and edaphic conditions. Despite the potential of camelina as a viable crop, statistical data on the areas dedicated to its cultivation suggest that it has yet to gain widespread adoption among farmers (Schillaci et al., 2023). Furthermore, camelina is adaptable and can be cultivated as a rainfed crop in regions that receive adequate and well-distributed rainfall throughout the growing season. This characteristic of drought tolerance positions camelina to be of increasing importance in future agricultural rotations, especially in light of climate change and the rising frequency of drought events. Another benefit of camelina is its adaptable capability to climatic conditions, allowing it to thrive in diverse environments. Additionally, camelina does not require the development of specialized machinery or equipment for its cultivation, which can reduce production costs (Pari et al. 2024). The plant has also shown the ability to produce decent yields with low fertilizer inputs, though soil conditions must meet the plant's nutritional requirements to achieve optimal growth. Given its minimal input requirements, drought tolerance, and flexibility in cultivation, camelina is poised to play an increasingly prominent role in agricultural rotations, especially as farmers seek crops that can thrive under less-than-ideal environmental conditions.

Crops are generally most vulnerable to water shortages during their reproductive stages, a critical period for yield formation. In semi-arid climates such as those found in Iran, improving water storage in the soil and implementing deficit irrigation during the vegetative growth cycle can help ensure that adequate water is available for the sensitive reproductive stages of crop development (Attia et al., 2021). This strategy was found to enhance water use efficiency, making it a promising practice for regions facing water scarcity. The positive results of limited irrigation during the vegetative growth phase can be attributed to the ability of plant to activate its drought-adaptation mechanisms, which in turn enhances its tolerance to the hot, dry periods that often occur toward the end of the growing season. This strategy not only conserves water but also improves the resilience of plant against water stress, making it a sustainable approach for optimizing camelina yield in semi-arid environments (Neupane et al. 2022).

In semi-arid regions with high temperatures and low rainfall, soils are usually poorly developed and have low fertility. They often have high pH, shallow depth, low organic matter, and low cation exchange capacity, which together create unfavorable conditions for plant growth (Ma et al., 2024). These soil characteristics limit the release and uptake of nutrients in the root zone. To improve soil quality in such environments, organic amendments are commonly used. In northwest Iran, cow manure is widely available and cost-effective. Its application improves soil structure, increases small soil pores, enhances water infiltration, and helps the soil retain more moisture (Kim et al. 2021). Micronutrient availability in semi-arid soils is strongly affected by pH, organic matter, and clay content, often leading to deficiencies. Recent advances in nanotechnology have introduced nano-fertilizers as a promising tool. Their very small size allows better absorption and more efficient movement within plants, which can improve nutrient uptake in poor soils (Singh et al., 2024). In addition, foliar application of nano-fertilizers can bypass soil limitations, offering an effective method to supply micronutrients in semi-arid agricultural systems However, despite growing importance of camelina, limited research has examined how integrated nutrient management; particularly the combined use of farmyard manure and nano-micronutrient fertilizers, can improve camelina performance under deficit irrigation in semi-arid soils. Existing studies have generally evaluated these inputs separately, leaving a clear gap in understanding their interactive effects on crop growth, yield, and stress tolerance.

2. Materials and methods

2.1. Experimental Site

A trail was performed in the semi-arid region of Razan, located in Hamedan province, in the west of Iran, 2024. The geographical coordinates of farm are 35°23′N, 49°01′E, with an elevation of 1814 meters above sea level. The average annual temperature was recorded at 11˚C, with the average rainfall of 380 mm. The soil type was identified as silty-clay loam, and some chemical properties of the soil were given in Table 1. This detailed soil profile provides essential context for the study, highlighting the initial conditions before the application of the treatments used in the experiment.

2.2. Experimental Settings

The present study was designed as a split-split plot experiment following a randomized block scheme with three replicates. The primary factor of the experiment involved two irrigation regimes: the normal irrigation (N) treatment, which involved irrigating the crops at recommended intervals based on the appearance of plant symptoms (≥ 95% field capacity in the 0-15 cm and 15-30 cm layers), before wilting and providing water up to 100% field capacity, and the water stress (S) treatment, where the water supply was limited to 60% of field capacity during irrigation. To prevent moisture leakage between the main plots, a one-meter uncultivated border was maintained. The secondary factor (sub-plots) focused on different levels of organic amendments, with three treatments: 0, 10, and 20 t ha^{-1} of decomposed animal manure, labeled as F1, F2, and F3, respectively. The third factor (sub-sub plots) examined the foliar application of nano-structured micronutrients, including a control or no application (C), nano-iron (Fe), and nano-zinc (Zn). The foliar application of nano-structured micronutrient fertilizers was carried out at a concentration of 300 ppm, applied four times in stem elongation (GS3), flower buds present and enclosed by leaves (GS50), individual flower buds visible but closed (GS55), and flowering (GS6), stages . A motorized sprayer was used to apply the solution in the early morning, ensuring thorough coverage of all plant shoots. Soil preparation began in October 2023 with initial tillage, followed by secondary tillage and the application of animal manure in February 2024. Irrigation was conducted using polyethylene pipes equipped with volume meters. Irrigation was applied when soil moisture reached 60% of available water under the full irrigation regime and 45% under deficit irrigation. Camelina variety Soheil was procured from PakanBazr Co., Iran, and manually planted on March with inter and intra-row spacings of 20×3 cm.

Table 1. Soil properties of experimental site.

N (%)	K (mg kg^{-1})	P (mg kg^{-1})	OC†	pH	EC‡ (ds m^{-1})
0.09	350	10	1.0%	7.65	1.6

†OC, organic carbon, ‡ EC, electrical conductivity

2.3. Measured Traits

From ten random samples, agronomic traits were measured. Plant height (PH), was measured from the soil surface to the tip of the main stem using a ruler or measuring tape at full maturity. Number of siliques per plant (NSP), were counted manually on the main stem and branches. Seed number per silique (SNS), was recorded from the seeds in each silique manually. The average number of seeds per silique was calculated. After harvest, seeds from each plot were cleaned and dried to constant moisture. Three samples of seeds were counted and weighed as thousand seed weight (TSW). Seeds from each plot were harvested, cleaned, and weighed as grams per unit area as seed yield (SY). Calculated as the ratio of economic yield (seed yield) to total above-ground biomass, whereas biomass was measured by harvesting all above-ground parts of the sampled plants, drying them to constant weight, and weighing. The oil percentage (OP) in the seeds of the harvested plants was determined using a Soxhlet extractor using dried and ground seed powder refluxed in n-hexane, followed by gravimetric determination of the recovered oil (Popa et al., 2019). To do this, 10 grams of camelina seeds were ground and mixed with 600 ml of hexane. After 6 hours of extraction, the solvent was separated from the oil via rotary evaporation, and the oil was stored in a refrigerator until chemical analysis.

2.4. Statistical Analysis

The biplot model based on the treatment by trait (TT) interaction was applied using the GGEbiplot application, and the analysis was performed according to the following equation:

$$\frac{m_{ij}-n_j}{SD_j} = \sum_{n=1}^{2} \lambda_n \xi_{in} \eta_{jn} + E_{ij} \quad (1)$$

where m_{ij} is the treatment i for trait j, n_j is the average of all studied treatments in each trait, SD_j is the standard deviation for each trait j, λ_n is the eigenvalue for each principal component, ξ_{in} is score for treatment i on each component, η_{jn} is score for trait j on each component, and E_{ij} is the error term. This formula is used to quantify and visualize the interaction between treatments and traits to analyze how different treatments influence various traits of interest and to identify the best treatments for optimal performance.

3. Results and Discussion

3.1. Model Fitting

The applied TT biplot model effectively captured 93% of the total variation, providing a comprehensive illustration of camelina's performance across various micronutrient treatments under both normal and drought stress conditions. Specifically, the first component explained 75% of the variation, while the second one accented 18%, collectively encompassing a substantial portion of the dataset's variability. This considerable degree of variation highlights the complex interactions among the evaluated traits across different treatments. As emphasized by Janmohammadi et al. (2016), a well-constructed biplot model should clearly delineate the primary patterns among traits, and the effectiveness of the TT biplot model relies on accurately capturing these relationships within the framework of two principal components. Additionally, reports from Sabaghnia et al. (2016) and Porkabiri et al. (2019) support current approach, indicating that two principal components are sufficient for predictive modeling when analyzing two-way data structures such as the TT biplot model. Hence, in this investigation, the interactions among treatments and traits were most effectively visualized and predicted using these two PCs.

3.2. Polygon Tool

The hexagonal representation (Figure 1) further clarifies how different treatments excel in specific traits, as the treatments positioned at each vertex denote the best or worst performers in those particular traits. Notably, the treatment N-F3-Zn, which includes normal irrigation, the application of 20 t ha^{-1} of farmyard manure, and nano-zinc micronutrient supplementation, emerged as the top-performing treatment across multiple agronomic traits. This included plant height (PH), number of siliques per plant (NSP), seed number per silique (SNS), thousand seed weight (TSW), and seed yield (SY). This finding underscores the superior efficacy of the N-F3-Zn treatment in enhancing camelina's growth and productivity under the given conditions. In addition to the superior overall performance of N-F3-Zn, specific treatments excelled in distinct quality traits. Notably, N-F2-Zn (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-zinc micronutrient) demonstrated the highest oil percentage (OP), indicating its efficacy in enhancing oil content. Meanwhile, N-F2-Fe (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-iron micronutrient) was identified as the best treatment for harvest index (HI), signifying its role in optimizing the proportion of economic yield relative to total biomass. These findings align with previous research, reinforcing the role of micronutrient application in enhancing crop performance. Azhand et al. (2024) reported that the application of zinc under water-deficit conditions could significantly improve yield performance and other agronomic and physiological traits. Similarly, Fattahi et al. (2024) observed a positive effect of organic manure on safflower seed yield, further highlighting the importance of integrated nutrient management in oilseed crops. However, not all treatments exhibited favorable outcomes. The other vertex treatments, N-F1-C (normal irrigation, 0 t ha^{-1} farmyard manure, and control fertilizer), S-F1-C (water stress, 0 t ha^{-1} farmyard manure, and control fertilizer), and S-F2-Zn (water stress, 10 t ha^{-1} farmyard manure, and nano-zinc micronutrient), did not emerge as top performers in any of the measured traits. This suggests that the absence of organic amendments or the influence of water stress conditions limited their effectiveness in enhancing camelina's agronomic and quality parameters. Despite N-F3-Zn demonstrating exceptional performance in seed yield and key yield components, it did not rank highest in oil percentage (OP). This indicates that high seed yield does not necessarily correlate with enhanced oil content, reinforcing the complexity of trait interactions in camelina. In fact, Guy et al. (2014) documented a negatively relation between yield performance and oil percent in camelina, a finding that is consistent with the present study. This inverse relationship suggests that breeding and agronomic strategies aimed at maximizing seed yield may require trade-offs when targeting improvements in oil quality.

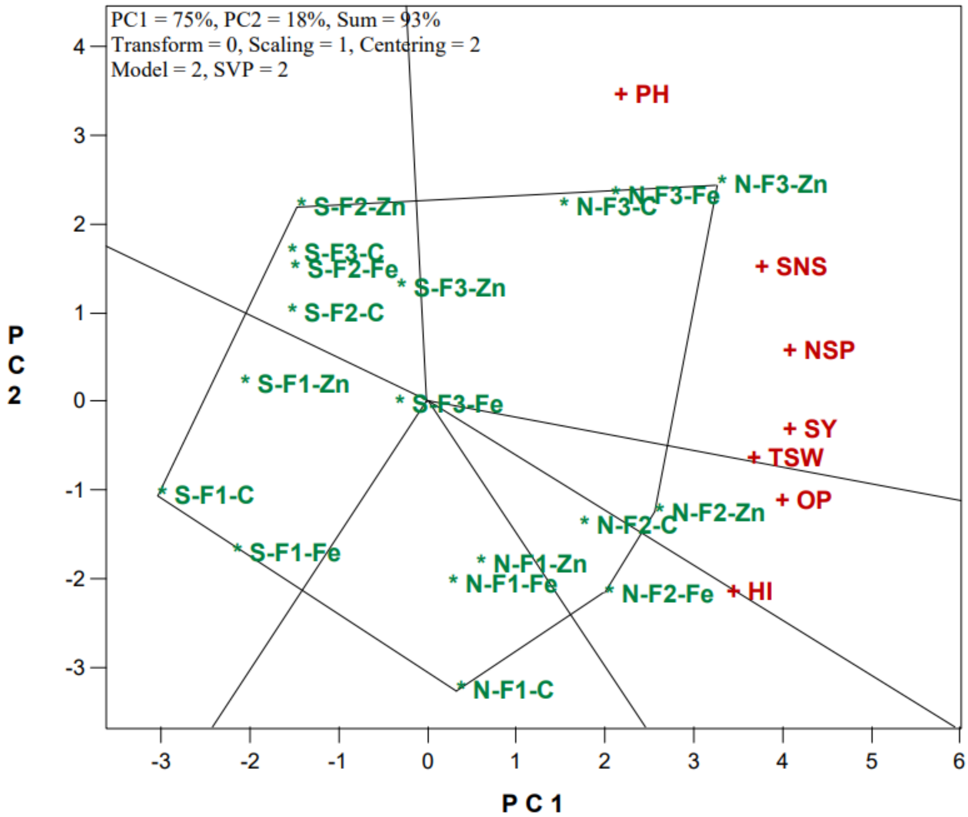

Figure 1. Which won where plot of treatment by trait biplot.

Traits are: plant height (PH), number of siliques per plant (NSP), seed number per silique (SNS), seed yield (SY), thousand seed weight (TSW), harvest index (HI), and oil percentage (OP).

Treatments are: N-F1-C (normal irrigation, 0 t ha^{-1} farmyard manure, and control or water spray), N-F1-Fe (normal irrigation, 0 t ha^{-1} farmyard manure, and nano-Fe micronutrient), N-F1-Zn (normal irrigation, 0 t ha^{-1} farmyard manure, and nano-zinc micronutrient), N-F2-C (normal irrigation, 10 t ha^{-1} farmyard manure, and control or water spray), N-F2-Fe (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-Fe micronutrient), N-F2-Zn (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-zinc micronutrient), N-F3-C (normal irrigation, 20 t ha^{-1} farmyard manure, and control or water spray), N-F3-Fe (normal irrigation, 20 t ha^{-1} farmyard manure, and nano-Fe micronutrient), and N-F3-Zn (normal irrigation, 20 t ha^{-1} farmyard manure, and nano-zinc micronutrient).

3.3. Vectors Tool

According to the vectors of traits in the TT biplot model, the cosine of the angles between vectors approximates the association between traits, while the length of each vector reflects the magnitude of variation (Figure 2). Several key relationships were identified: A strong positive association was observed among oil percentage (OP), seed yield (SY), and thousand seed weight (TSW), as indicated by their small angles Likewise, a positively relation was detected for the number of siliques per plant (NSP) and the seed number per silique (SNS), suggesting that an increase in one trait tends to correspond with an increase in the other. In contrast, plant height (PH) showed little to no association with oil percentage (OP), seed yield (SY), and thousand seed weight (TSW), as their vectors were nearly perpendicular. Similarly, plant height (PH) exhibited a negligible relationship with harvest index (HI), reinforcing its limited influence on overall biomass allocation (Figure 2). Interestingly, while seed yield (SY) displayed a moderate correlation with its components, the association was not equally strong across all yield-contributing traits. Among these, thousand seed weight (TSW) was the most strongly correlated with seed yield, whereas the number of siliques per plant (NSP) and the seed number per silique (SNS) exhibited relatively weaker correlations with seed yield. Although, these relationships are largely consistent with numerical correlation coefficients, minor discrepancies arise because the applied biplot model accounts for 93% of total variation rather than 100%. This minor limitation may introduce small estimation errors; however, as noted by Yari et al. (2018), the TT biplot procedure remains a highly reliable method for visualizing the overall structure of trait relationships, making it more practical than relying solely on numerical values.

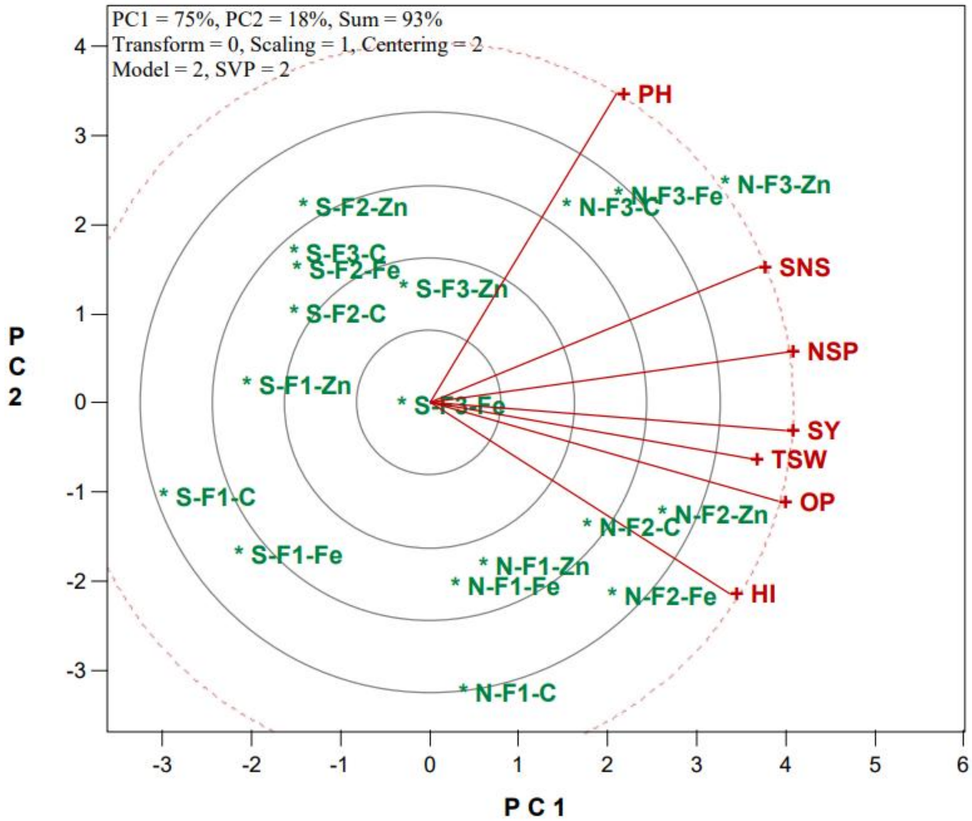

Figure 2. Vectors of traits in treatment by trait (TT) biplot model.

Traits are: plant height (PH), number of siliques per plant (NSP), seed number per silique (SNS), seed yield (SY), thousand seed weight (TSW), harvest index (HI), and oil percentage (OP).

3.4. Ideal Treatment

To identify the optimal treatment, defined as one that maximizes multiple desirable traits, the single-arrow line in the perfect-treatment biplot (Figure 3), represented the mean-trait axis. Treatments were ranked along this axis based on their overall trait performance: those on the right perform above average, while those on the left perform below average. In this analysis, N-F3-Zn (normal irrigation, 20 t ha^{-1} farmyard manure, and nano-zinc) was closest to the ideal treatment, indicating the highest overall trait performance. The next best-performing treatments were N-F3-Fe, N-F3-C, N-F2-Zn, N-F2-Fe, and N-F2-C (Figure 3). These results showed a clear trend: all normal irrigation treatments had above-average performance, whereas water-stressed treatments did not achieve superior performance across traits. This suggested that evaluating seed yield and yield components in camelina is most reliable under normal irrigation conditions, as water stress limits the plant's capacity to express its full potential. The observed benefits of micronutrients and farmyard manure under normal irrigation aligned with findings by Singh-Dhaliwal et al. (2023) and Mahto et al. (2024), who reported that combining micronutrients such as zinc and iron with farmyard manure enhances crop nutritional potential under non-stress conditions. An ideal treatment indicated strong responses across all traits, indicated by a long projection onto the mean-trait axis and a short treatment vector. Figure 3 shows that most non-water-stress treatments were near the ideal treatment, ranking highly in trait performance. Their effectiveness suggests that these treatments could be practical alternatives to conventional chemical fertilizers, supporting sustainable and nutrient-efficient crop management. These findings are further supported by Yousefzadeh et al. (2021), who reported that nano-zinc application significantly improved agronomic traits and overall yield in maize, highlighting the potential of nano-micronutrients to optimize plant growth under favorable conditions.

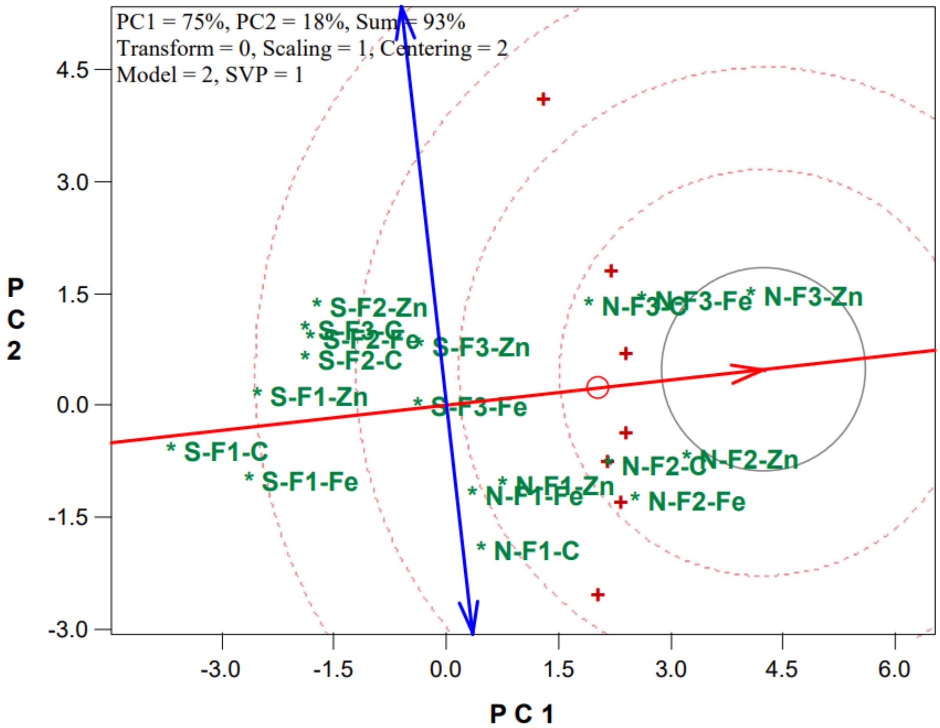

Figure 3. Perfect treatment menu of treatment by trait (TT) biplot.
Treatments are: N-F1-C (normal irrigation, 0 t ha^{-1} farmyard manure, and control or water spray), N-F1-Fe (normal irrigation, 0 t ha^{-1} farmyard manure, and nano-Fe micronutrient), N-F1-Zn (normal irrigation, 0 t ha^{-1} farmyard manure, and nano-zinc micronutrient), N-F2-C (normal irrigation, 10 t ha^{-1} farmyard manure, and control or water spray), N-F2-Fe (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-Fe micronutrient), N-F2-Zn (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-zinc micronutrient), N-F3-C (normal irrigation, 20 t ha^{-1} farmyard manure, and control or water spray), N-F3-Fe (normal irrigation, 20 t ha^{-1} farmyard manure, and nano-Fe micronutrient), and N-F3-Zn (normal irrigation, 20 t ha^{-1} farmyard manure, and nano-zinc micronutrient).

3.5. Perfect Trait

In the TT biplot model, the perfect trait represents an optimal combination of favorable treatments, effectively summarizing the most desirable trait responses across different conditions. The single-arrow line in the biplot illustrates the average-tester axis, which ranks traits based on their overall reaction to treatments. From this analysis, the number of siliques per plant (NSP) emerged as the most favorable trait, closely followed by thousand seed weight (TSW) and seed yield (SY). These traits exhibited properties similar to the ideal trait, indicating their above-average performance across treatments (Figure 4). Conversely, plant height (PH) demonstrated unfavorable performance, suggesting that it may not be a key determinant of productivity under the evaluated conditions. Given these findings, when assessing the effects of water stress, farmyard manure, and micronutrient applications in camelina, it is preferable to prioritize the measurement of the number of siliques per plant (NSP). This trait appears to be highly responsive to different treatments, making it a reliable indicator of camelina's agronomic performance under varying environmental conditions.

3.6. Seed yield

In the vector-tool analysis of the TT biplot model (Figure 5), treatments that demonstrated a strong association with the target trait of high seed yield in camelina were identified. Among these, N-F3-Zn (normal irrigation, 20 t ha^{-1} farmyard manure, and nano-zinc micronutrient) emerged as a highly effective treatment for achieving desirable seed yield performance. This suggests that its application can significantly enhance camelina seed yield under optimal conditions. However, considering its distance from the average-tester axis, which reflects some degree of variability, N-F2-Zn (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-zinc micronutrient) was found to be more desirable than N-F3-Zn. This observation implies that the use of nano-sized micronutrients in combination with farmyard manure not only improves seed yield but also enhances other agronomic characteristics, thereby supporting the broader adoption of such fertilizers in sustainable agriculture. These findings align with previous research. Azam et al. (2022) demonstrated that zinc nano-fertilizers positively influence plant growth and productivity, largely due to their ability to stimulate the activity of growth hormones. Additionally, Gangwar et al. (2023) found that nano-composites are safe for agricultural use, suggesting that nano-sized fertilizers not only boost crop production but also provide economic benefits, making them a cost-effective and sustainable alternative to conventional fertilizers.

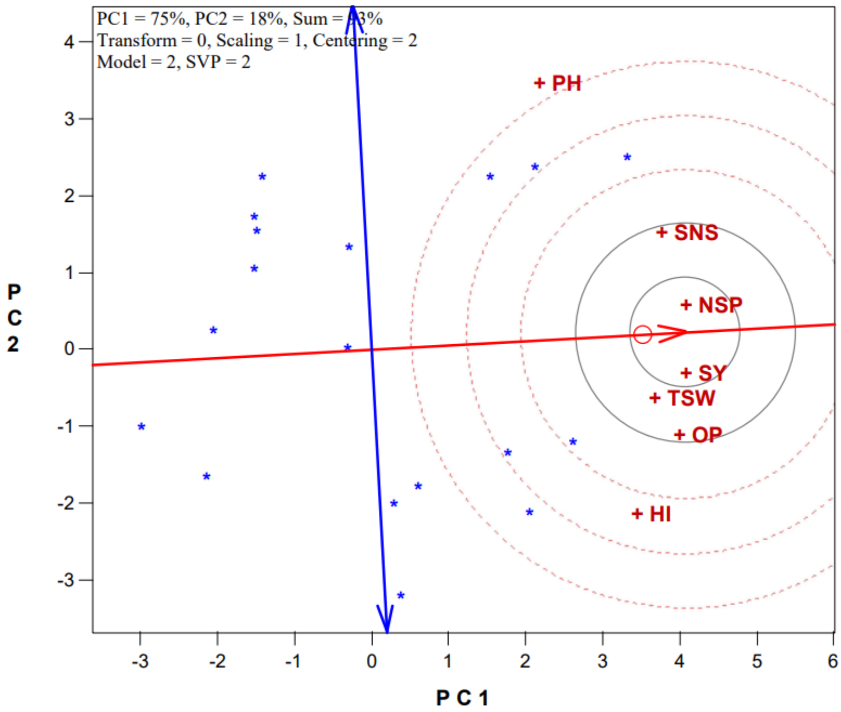

Figure 4. Perfect trait menu of treatment by trait (TT) biplot.
Traits are: plant height (PH), number of siliques per plant (NSP), seed number per silique (SNS), seed yield (SY), thousand seed weight (TSW), harvest index (HI), and oil percentage (OP).

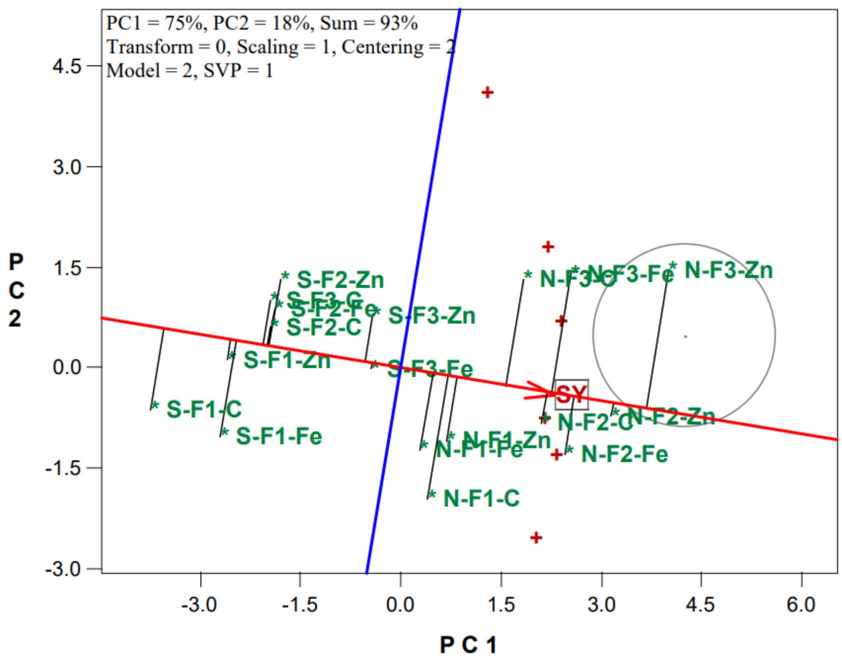

Figure 5. Examining the seed yield (SY) across treatments by trait (TT) biplot.
Treatments are: N-F1-C (normal irrigation, 0 t ha^{-1} farmyard manure, and control or water spray), N-F1-Fe (normal irrigation, 0 t ha^{-1} farmyard manure, and nano-Fe micronutrient), N-F1-Zn (normal irrigation, 0 t ha^{-1} farmyard manure, and nano-zinc micronutrient), N-F2-C (normal irrigation, 10 t ha^{-1} farmyard manure, and control or water spray), N-F2-Fe (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-Fe micronutrient), N-F2-Zn (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-zinc micronutrient), N-F3-C (normal irrigation, 20 t ha^{-1} farmyard manure, and control or water spray), N-F3-Fe (normal irrigation, 20 t ha^{-1} farmyard manure, and nano-Fe micronutrient), and N-F3-Zn (normal irrigation, 20 t ha^{-1} farmyard manure, and nano-zinc micronutrient).

3.7. Oil Percentage

In Figure 6, the focus shifts to treatments that are strongly correlated with oil percentage (OP) as the target trait. Among these, N-F2-Fe (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-iron micronutrient) was identified as the most effective treatment for enhancing oil content. This finding highlights that nano-iron application can significantly improve oil percentage, making it a preferable choice for increasing oil quality in camelina. Further supporting this conclusion, Polat et al. (2024) reported that iron (Fe) application enhances seed yield in *Brassica napus*, positively influencing key yield related traits like the siliques number per plant and the seeds number per silique. Additionally, their study found that the simultaneous application of zinc and iron significantly increased oil content, reinforcing the benefits of integrating nano-micronutrients for improved yield and oil quality.

Studies have highlighted that the adoption of nano-fertilizers significantly improves nutrient efficiency, reduces the environmental impact of fertilizers, and minimizes the risks of over-application. This advancement is crucial for achieving sustainable agricultural practices, especially in regions with limited resources. The introduction of nanotechnology has brought about a range of nanomaterials with unique biological, physical, and chemical properties. One key innovation in this area is the encapsulation of fertilizers within nanoparticles, a process that can be achieved through techniques such as embedding in nanopores, coating with thin polymer layers, and emulsifying into nano-scale droplets. These nano-fertilizers work by utilizing nano-scale delivery systems to synchronize the release of nutrients with the plant's absorption capacity, reducing the potential for fertilizer loss and degradation in the field. In terms of data analysis, the TT biplot model offers a powerful alternative to traditional numerical models. Compared to conventional approaches, the biplot method provides several advantages: (i) it presents data graphically, making it easier to identify and understand complex patterns, and (ii) it offers an interpretive framework that enables more straightforward comparisons between treatments. However, a limitation of the biplot approach is that it may not always capture the full range of variability in some datasets, meaning certain data structures might be missed. Despite this limitation, the PC1 and PC2 components of the biplot typically capture the most significant patterns in the data, ensuring the model still provides valuable insights.

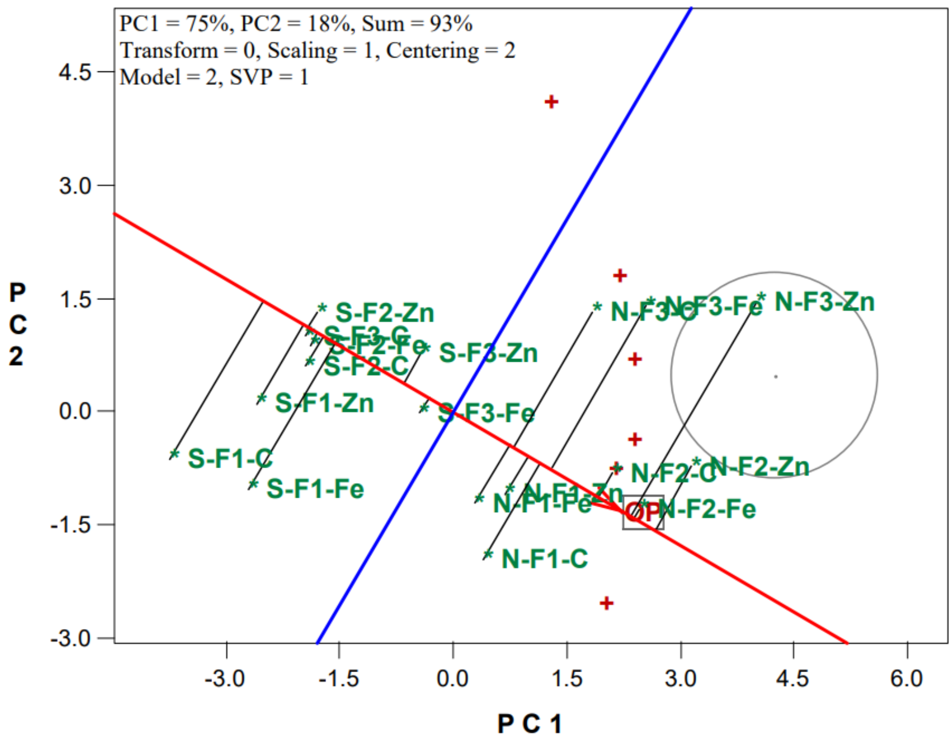

Figure 6. Examining the oil percent (OP) across treatments by trait (TT) biplot.

Treatments are: N-F1-C (normal irrigation, 0 t ha^{-1} farmyard manure, and control or water spray), N-F1-Fe (normal irrigation, 0 t ha^{-1} farmyard manure, and nano-Fe micronutrient), N-F1-Zn (normal irrigation, 0 t ha^{-1} farmyard manure, and nano-zinc micronutrient), N-F2-C (normal irrigation, 10 t ha^{-1} farmyard manure, and control or water spray), N-F2-Fe (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-Fe micronutrient), N-F2-Zn (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-zinc micronutrient), N-F3-C (normal irrigation, 20 t ha^{-1} farmyard manure, and control or water spray), N-F3-Fe (normal irrigation, 20 t ha^{-1} farmyard manure, and nano-Fe micronutrient), and N-F3-Zn (normal irrigation, 20 t ha^{-1} farmyard manure, and nano-zinc micronutrient).

The findings from this study demonstrate the potential of nano-fertilizers in improving crop productivity and sustainability. The application of nano-sized micronutrients, such as nano-zinc and nano-iron, coupled with farmyard manure, not only boosts seed yield but also improves other agronomic traits in camelina. These results are consistent with existing literature that highlights the benefits of nano-fertilizers in enhancing nutrient uptake and crop growth while reducing the risks of over-application and environmental toxicity. The use of nanoencapsulation techniques, including nanopores and polymer coatings, facilitates controlled nutrient release, reducing nutrient losses and optimizing crop uptake. This innovation aligns with sustainable farming goals, especially in resource-limited regions where efficient fertilizer use is critical for achieving higher agricultural productivity with minimal environmental impact.

The TT biplot model employed in this study indicated to be an useful menu for visualizing complex data and understanding the intricate relationships between various treatments and traits. The biplot allowed for a comprehensive interpretation of the interactions between micronutrients, farmyard manure, water stress, and their influence on yield-related traits such as seed yield, oil percentage, and thousand seed weight. The model provided a clear graphical representation that aided in identifying the best-performing treatments, particularly N-F3-Zn and N-F2-Zn, for improving camelina's seed yield. Furthermore, the N-F2-Fe treatment showed a strong correlation with oil content, reinforcing the importance of iron application in enhancing oil quality. Current result is in agreement with previous reports, such as Polat et al. (2024), which reported a positive effect of iron application on seed yield and oil content in other crops, including Brassica napus. However, the study also identified some limitations of the TT biplot model. Although the biplot was highly effective in capturing the primary patterns in the data, it could not account for all the variability in some conditions. In certain instances, the biplot did not capture finer details of the data structure, which suggests that other complementary techniques might be needed for a more complete understanding of the interactions between treatments and traits. Nevertheless, the TT biplot remains a valuable tool for visualizing complex datasets and identifying key trends, especially when numerical models might not provide the same level of interpretative insight. Finally, the study demonstrates the effectiveness of nano-fertilizers as an innovative solution for improving agricultural productivity in camelina. The findings highlight the importance of integrating nanotechnology with traditional organic fertilizers to enhance both yield and oil quality. Further research is needed to explore the impacts of nano-nutrients on soil, crop rotation, and economic viability in different agricultural contexts.

4. Conclusions

The TT biplot analysis effectively identified optimal treatments for enhancing both seed yield and oil content in camelina. N-F2-Zn (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-zinc) was the most desirable treatment for seed yield, while N-F2-Fe (normal irrigation, 10 t ha^{-1} farmyard manure, and nano-iron) significantly improved oil percentage. Treatments with high seed yield, (N-F3-Zn), did not have the highest oil content, and treatments with the highest oil percentage, (N-F2-Zn and N-F2-Fe), had moderate seed yield, so such trade-off highlighted strategies aimed at maximizing yield may need compromises in oil quality. Also, normal irrigations outperformed across most traits, because water stress limited the ability of camelina to express its potential, and both growth and quality traits were reduced, so the effectiveness of micronutrients and farmyard manure is dependent on adequate water availability.

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