doi:10.14720/aas.2024.120.4.18624 Original research article / izvirni znanstveni članek

Carthamus tinctorius L. response to nano-silicon foliar treatment under organic and inorganic fertilizer application

Naser SABAGHNIA [1], Mohsen JANMOHAMMADI [1, 2]

Received April 22, 2024; accepted November 19, 2024
Delo je prispelo 22. april 2024, sprejeto 19. november 2024

Carthamus tinctorius **L. response to nano-silicon foliar treatment under organic and inorganic fertilizer application**

Abstract: This research was studied the impacts of usage of nano-silicon in combination with various fertilizer treatments on the yield and its components of safflower. The trial evaluated the application of 0.0- and 20-mM nano-silicon in conjunction with different fertilizer treatments, including a control, 90 kg ha^{-1} NPK, and organic fertilizer at rates of 15 and 30 t ha^{-1}. Principal components approach revealed that the first two components of the treatment by trait biplot explained 66 % and 22 % of the variability, respectively. Positive correlations were observed among straw yield, achene yield, and harvest index, as well as among capitula number per plant, seed per subsidiary capitulum, and the number of the highest capitula. The polygon indicated that the NPK with 20 mM nano-silicon resulted in superior yield, whereas using 30 t ha^{-1} organic fertilizer with 20 mM nano-silicon exhibited enhanced yield components. Plant height emerged as the most representative trait, with high discrimination potential. Treatment with 30 t ha^{-1} organic fertilizer, combined with both 0.0- and 20-mM nano-silicon, was identified as the optimal treatments for discriminating among traits. The NPK plus 20 Mm nano-silicon and 30 t ha^{-1} organic manure was the best treatments.

Key words: fertilizer, organic manure, NPK, nano-silicon

Odziv žafranike (*Carthamus tinctorius* L.) na folioarno dodajanje nano-silicija pri različni uporabi organskih in anorganskih gnojil

Izvleček: Namen raziskave je bil preučiti vpliv uporabe nano silicija v kombinaciji z različnimi načini gnojenja na pridelek in njegove komponenete pri žafraniki. V poskusu so bili ovrednoteni uporaba nano silicija v odmerkih 0,0- in 20-mM v povezavi z različnimi režimi gnojenja, ki so vsebovali kontrolo, 90 kg ha^{-1} NPK in organska gnojila v odmerkih 15 in 30 t ha^{-1}. Ovrednotenje z glavnimi komponentami je odkrilo, da sta prvi komponeneti pri obravnavi lastnosti v biplotu razložili 66 % in 22 % variabilnosti. Pozitivne korelacije so bile ugotovljene med pridelkom slame, pridelkom rožk in žetvenim indeksom kot tudi med številom stranskih poganjkov na rastlino, semen na stranskih koških in številom najvišjih koškov. Obravnave so pokazale, da je gnojenje z NPK in 20 mM nano-silicija dalo najboljši pridelek medtem, ko je uporaba 30 t ha^{-1} organskega gnojila z 20 mM nano-silicija pospešila komponente pridelka. Višina rastlin se je izkazala kot najbolj reprezentativna lastnost z velikim potencialom razločevanja. Obravnava s 30 t ha^{-1} organskega gnojila, v kombinaciji z 0,0- ali 20-mM nano-silicija je bila prepoznana kot optimalno obravnavanje za prepoznavanje razlik med lastnostmi. Obravnavanje z NPK in 20 Mm nano-silicijaon ter 30 t ha^{-1} organskega gnojila se je izkazalo kot najboljše.

Ključne besede: gnojilo, organsko gnojilo, NPK, nano-silicij

1 University of Maragheh, Agriculture College, Department of Plant Production and Genetics, Iran
2 Corresponding author: sabaghnia@maragheh.ac.ir

1 INTRODUCTION

Safflower (*Carthamus tinctorius* L.) is a member of the Asteraceae and has its origins in southwest Asia. It is cultivated for multiple purposes such as vegetable oil production, forage, and medicinal applications. Safflower demonstrates the potential for acceptable yields, particularly in regions conducive to the growth of winter cereals, highlighting its versatility and underexplored possibilities (Shahrokhnia and Sepaskhah, 2017). Currently, global production estimates stand at approximately one million metric tons of safflower achenes, harvested from an area covering 1,200,000 ha, with a mean yield performance of around 830 kg ha^{-1} (FAOSTAT, 2022). In semi-arid regions, water availability is the primary restricting factor for crop cultivation, restricting the range of crops that can be grown successfully. Safflower, however, exhibits resilience to water scarcity due to its efficient deep root system and numerous fine lateral roots. This characteristic enables safflower to endure periods of moisture deficiency, a trait that sets it apart from many other crops whose performance are severely impacted by abiotic stresses like drought (Hussain et al., 2016). Safflower holds promise not only for seed production but also as a valuable forage crop in dryland cropping systems with limited water resources. Optimal forage quality is attained during the vegetative growth period when the plant has low pricks, rendering it palatable to farm animals. In such areas, the green plant of safflower can be used for feeding, contributing to livestock nutrition and overall farm productivity.

Nutrients application has a pivotal role in addressing the global imperative to enhance production and fulfill the dietary needs of an expanding population. The use of fertilizers in agriculture has a substantial effect on crop productivity as it influences traits such as phenological characteristics and root properties, which subsequently impacts physiological processes like water absorption and transpiration. (Farooq et al., 2019). However, the rates of nutrients are used vary across various environmental conditions, a variability driven by climax changes, crop types, and cropping systems. In rainfed agriculture, nutrients application is notably shaped by precipitation levels and the availability of soil moisture. In semi-arid regions, controlling the negative effects of terminal drought needs optimizing soil's capacity to capture and retain precipitation, thus it maximizes water storage for next utilization, and facilitate root penetration and proliferation (Zia et al., 2021). The widespread adoption of intensive chemical fertilizer application traces back to the Green Revolution, primarily aimed at meeting the nutrient demands of high-yielding crop varieties. Despite their advantages, chemical fertilizers are not without drawbacks. These include a heightened risk of leaching, substantial energy consumption during production, potential exposure to toxic chemicals, promotion of excessive growth, and depletion of soil moisture reserves.

Organic manure represents a viable option for field crop fertilization (Das and Avasthe, 2018). Its application can substantially enhance soil properties, leading to reduced reliance on mineral fertilizers, improved organically equilibrium, and enhanced soil moisture retention and efficiency of water usage. The application of organic fertilizers is particularly crucial in semi-arid regions of Iran, where soils are frequently subjected to intensive tillage, resulting in low organic matter content and weak structural stability (Sabaghnia and Janmohammadi, 2024). Moreover, the common practice of removing straw for animal feed further underscores the significance of organic fertilizer application (Lal et al., 2020). Organic manure has been shown to provide essential macronutrients and micronutrients necessary for plant growth, while also maintaining nutrients and promoting different aspects of fertility characteristic of soil.

Nanoparticles represent a burgeoning field of research with promising applications, particularly in agriculture, as materials for the new millennium. They interchange with corps, inducing various changes contingent upon their unique characteristics. Among these nanoparticles, nano-silicon has garnered significant attention in recent years which is abundant element in soils (Souri et al., 2021). However, the effectiveness of nano-silicon may vary among different crops or under diverse environment and climatic conditions. Despite its potential, very little research has been done to evaluate the effects of nano silicon application on safflower in semi-arid regions. Thus, this research aimed to create new insights into the effectiveness of nano-silicon on the safflower under different fertilizer management treatments.

2 MATERIALS AND METHODS

For this research, a field trial was conducted at Maragheh, Iran (37°23'N 46°14', situated in an upland semiarid region. The soil is characterized as sandy loam, with a particle size distribution showing a decreasing order of sand, silt, and clay. Soil pH was measured at 7.5, with EC of 0.51 dS m^{-1}. Organic matter content was approximately 2 g kg^{-1} and nitrogen at 0.06 % while phosphorus was at 5.7 mg kg^{-1} and potassium was at 34 mg kg^{-1}. The experimental design employed a factorial arrangement with split-plot layout, following a randomized block scheme with three replications. Fertilizer treatments were applied to the main plots: control (Con), 90 kg ha^{-1} conventional fertilizer (nitrogen, phosphorus, and potassium, NPK), 15 t ha^{-1} organic manure (OM15), and 30 t ha^{-1} organic manure (OM30). Nano-silicon (SiO_2) treatments were applied in foliar form at 0.0 Mm (N0) and 20 Mm (N20). Field preparation included plowing and disking in the autumn season, followed by manual sowing of the Esfahan variety on April 14th. Each plot measured 4.0 m in length and 3.0 m in width, comprising 12 rows spaced 0.25 m apart. Plots were rainfed and supported with supplementary irrigated practices during the seed-filling step. Organic fertilizer as cow manure was mixed in a uniform position to a depth of 15 cm, while NPK fertilizer was surface-applied after field preparation.

For the measurement of yield components and morphological traits, 10 random samples were chosen from each unit, and the following parameters were assessed: plant height (PH), the highest branch (HB), the highest capitula (HC), capitula per subsidiary branch (CSB), capitula number per plant (CNP), seed per primary capitulum (SPC), seed per subsidiary capitulum (SSC), and capitulum seed mass (CSM). Central rows of plots were manually harvested from late June to early July, with straw yield (SY) and achene yield (AY) measured, and harvest index (HI) calculated. Thousand-achene mass (TAM) was measured from three random subsamples. Principal component analysis using a treatment by trait (TT) interaction layout was conducted, and the biplot model was generated via the GGEbiplot application (Yan, 2019).

3 RESULTS AND DISCUSSION

The TT biplot elucidated 66 % to 22 % of the variation within the standardized data two-way dataset (Fig. 1), showing a relatively substantial proportion that underscores the directness of associations among the traits. However, to glean the basic structures among the traits visually, vectors are generated from the graph origin to the traits, facilitating the visualization of trait associations. Given that the TT biplot model captured a considerable magnitude of variability (about 88 %), the associations between two traits are estimated by the cosine of their vectors, with cos0°= +1, cos90°= 0, and cos180°= $^{-1}$ (Sabaghnia and Janmohammadi, 2023). The extensive variability depicted by the TT biplot model emanated from all measured traits, evident from the elongated vectors (Fig. 1). Prominent associations unveiled include: (i) positive associations among straw yield (SY), achene yield (AY), and harvest index (HI); positive associations among capitula number per plant (CNP), seed per subsidiary capitulum (SSC), and the highest capitula (HC); and positive associations among capitulum's seed mass (CSM), thousand-achene mass (TAM), capitula per subsidiary branch (CSB), and seed per primary capitulum (SPC), as depicted by acute angles. Additionally, relatively near-zero associations were observed among SY, AY, and HI with CSM, TAW, CSB, and SPC, as evidenced by the near-perpendicular vectors (Fig. 1). Thus, the TT biplot model visually delineated trait associations in safflower, aligning with findings from other researchers such as Janmohammadi et al. (2016), who reported a positively association between straw yield, achene yield, and harvest index of safflower. Similarly, Fattahi et al. (2023) noted high positive associations between capitulum's seed mass and thousand-achene mass, as well as between capitula per subsidiary branch and seed per primary capitulum. However, exact parallels should not be expected between these results and correlation coefficients because the TT biplot model explicates associations among traits based on the general structure of the data, whereas Pearson's linear simple coefficients solely elucidate the association between two traits.

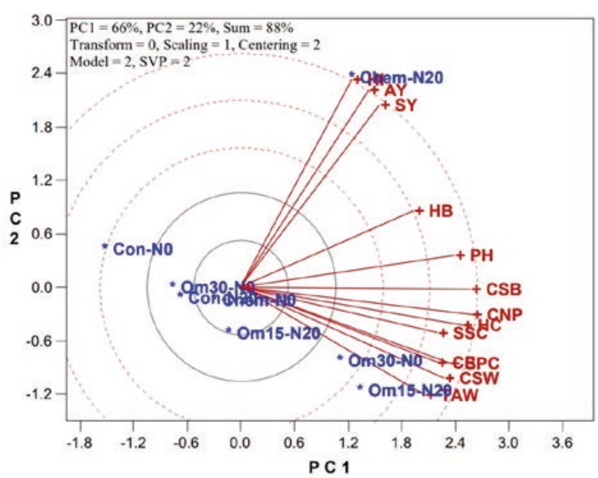

Fig. 1: Ranking entries (treatment combinations) based on testers (traits).
Treatment combinations are: control plus 0.0 Mm nano-silicon (Con-N0), control plus 20 Mm nano-silicon (Con-N20), 90 kg ha^{-1} NPK fertilizer plus 0.0 Mm nano-silicon (Chem-N0), 90 kg ha^{-1} NPK fertilizer plus 20 Mm nano-silicon (Chem-N20), 15 t ha^{-1} organic manure plus 0.0 Mm nano-silicon (OM15-N0), 15 t ha^{-1} organic manure plus 20 Mm nano-silicon (OM15-N20), 30 t ha^{-1} organic manure plus 0.0 Mm nano-silicon (OM30-N0), and 30 t ha^{-1} organic manure plus 20 Mm nano-silicon (OM30-N20).
Traits are: plant height (PH), the highest branch (HB), the highest capitula (HC), capitula per subsidiary branch (CSB), capitula number per plant (CNP), seed per primary capitulum (SPC), seed per subsidiary capitulum (SSC), capitulum's seed mass (CSW), straw yield (SY), achene yield (AY), harvest index (HI), and thousand achene mass (TAW).

Fig. 2 demonstrates how the TT biplot model can facilitate the comparison of treatment combinations based on the measured traits and identify those combinations that excel in specific aspects, thus serving as candidates for ideal fertilization practices recommended to safflower farmers. For instance, comparing Chem-N20 (NPK chemical fertilizer plus 20 Mm nano-silicon) and OM30-N20 (30 t ha^{-1} organic manure plus 20 Mm nano-silicon) revealed that Chem-N20 exhibited superior yield performance (AY), whereas OM30-N20 excelled in yield components such as CSB, CNP, SPC, SSC, and TAM (Fig. 2). Additionally, Chem-N20 showed the highest values for plant height (PH) and highest branch (HB), while OM30-N20, followed by OM30-N0 (30 t ha^{-1} organic manure plus 0 Mm nano-silicon), demonstrated high levels of the highest capitula (HC) and capitulum's seed mass (CSM).

Although, the TT biplot model may not precisely depict the averages of traits for treatment combinations, as it does not encompass all variance of the dataset, it provides insights into the underlying properties of the data structure. The polygon of the TT biplot model delineated four sections, with the remaining treatment combinations, such as Con-N0 (control plus 0 Mm nano-silicon) and OM15-N20 (15 t ha^{-1} organic manure plus 20 Mm nano-silicon), not performing optimally for any of the measured traits. Likewise, Con-N20 (control plus 20 Mm nano-silicon), Chem-N0 (NPK chemical fertilizer plus 0 Mm nano-silicon), and OM15-N0 (15 t ha^{-1} organic manure plus 0 Mm nano-silicon) were situated in unfavorable sectors or undesirable positions within favorable sectors, rendering them unsuitable candidates for advising to safflower farmers as proper fertilization practices. According to the TT biplot model (88 % in current case), if it adequately estimates the dataset, treatment combinations falling on the same section of the vertical line as AY should perform above the mean, whereas those on the opposite side should perform below the mean.

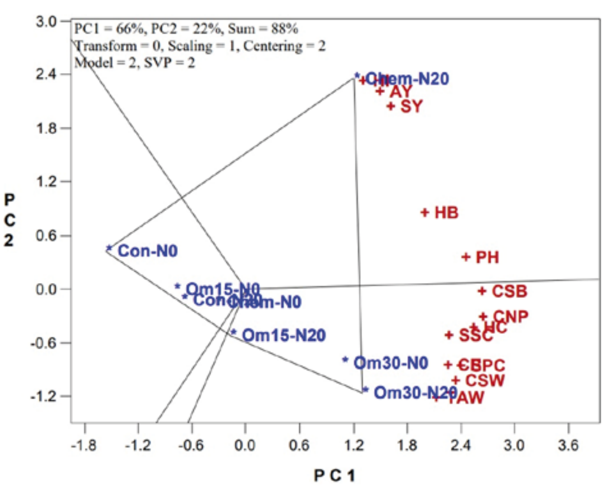

Fig. 2: Which entry (treatment combinations) wins which tester (trait).
Treatment combinations are: control plus 0.0 Mm nano-silicon (Con-N0), control plus 20 Mm nano-silicon (Con-N20), 90 kg ha^{-1} NPK fertilizer plus 0.0 Mm nano-silicon (Chem-N0), 90 kg ha^{-1} NPK fertilizer plus 20 Mm nano-silicon (Chem-N20), 15 t ha^{-1} organic manure plus 0.0 Mm nano-silicon (OM15-N0), 15 t ha^{-1} organic manure plus 20 Mm nano-silicon (OM15-N20), 30 t ha^{-1} organic manure plus 0.0 Mm nano-silicon (OM30-N0), and 30 t ha^{-1} organic manure plus 20 Mm nano-silicon (OM30-N20).
Traits are: plant height (PH), the highest branch (HB), the highest capitula (HC), capitula per subsidiary branch (CSB), capitula number per plant (CNP), seed per primary capitulum (SPC), seed per subsidiary capitulum (SSC), capitulum's seed mass (CSW), straw yield (SY), achene yield (AY), harvest index (HI), and thousand achene mass (TAM).

Fig. 3 illustrates the representative and discrimination potential of the traits, with vector length serving as a scale of discrimination potential, where a longer vector indicates a greater potential for discriminating a trait. Additionally, the stretch of a trait's projection onto the mean trait coordinate signifies its representative potential, with a shorter distance indicating a higher potential for representation of a trait. Notably, plant height (PH) exhibited the highest potential for both representative

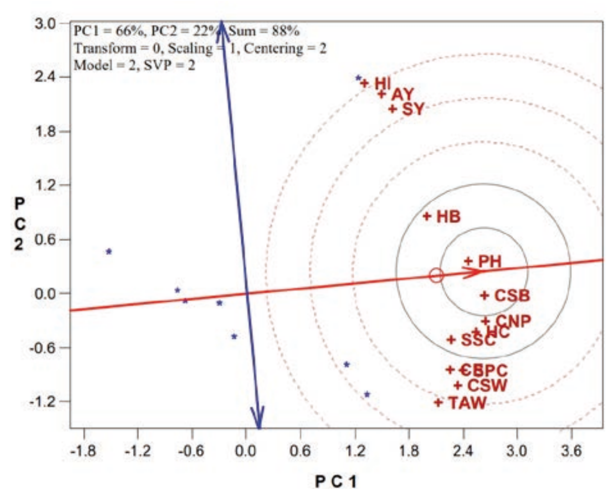

Fig. 3: Ranking testers (traits) based on discriminative and representativeness potentials.
Traits are: plant height (PH), the highest branch (HB), the highest capitula (HC), capitula per subsidiary branch (CSB), capitula number per plant (CNP), seed per primary capitulum (SPC), seed per subsidiary capitulum (SSC), capitulum's seed mass (CSW), straw yield (SY), achene yield (AY), harvest index (HI), and thousand achene mass (TAW).

and discrimination capabilities, positioned at the ideal trait location (Fig. 3).

Following PH, traits such as CSB, CNP, HC, SSC, and HB also demonstrated strong representative and discrimination potentials. Traits CSM, TAM, CSB, and SPC, as well as SY, AY, and HI, exhibited good discrimination potential, as they were positioned far from the plot center, but their representative capabilities of the trait's mean were limited due to their long projection onto the mean trait coordinate. In the future studies of safflower, using these identified traits as good indices will be useful for detection differences among treatments. In Fig. 4, the center of the circles denotes the location of an ideal treatment combination, with its projection on the vertical axis of the mean trait coordinate set to be equivalent to the largest vector among all treatment combinations. This projection on the horizontal axis of the mean trait coordinate is zero, indicating low variability and higher reliability. Thus, the closer a treatment combination's interval to this hypothetical treatment, the more optimal the treatment is. Consequently, OM30-N0 and OM30-N20, followed by Chem-N20, were the closest to the position of the ideal treatment combination. Conversely, the remaining treatment combinations, including OM15-N0, OM15-N20, Chem-N0, and Chem-N0, did not exhibit significant differences, while other treatment combinations were inferior (Fig. 4). Consequently, OM30-N0, OM30-N20, and Chem-N20 treatment combinations were capable of discriminating the differences among the measured traits of safflower.

Inspecting the performance of Chem-N20 for the measured traits of safflower (Fig. 5) revealed that straw yield (SY), achene yield (AY), and harvest index (HI) were proximate to this treatment combination. Therefore, for achieving high achene yield in safflower, the recommendation is to utilize 90 kg ha^{-1} conventional chemical fertilizer (nitrogen, phosphorus, and potassium or NPK) along with foliar application of 20 Mm nano-silicon. The observed enhancement in safflower yield performance with the use of NPK aligns with the reports of Sampaio et al. (2016), who found favorable yield outcomes with nitrogen, phosphorus, and potassium application in safflower cultivation.

However, the specific NPK requirements for safflower may vary depending on soil conditions, farming practices, cultivar selection, crop growth stage, and environmental factors. Additionally, the potential for high safflower yields is closely linked to the soil's phosphorus and potassium levels, Although, drought conditions can hinder their uptake and translocation in the crop due to reduced transpiration rates (Silva et al., 2022). Usage of nano-silicon in foliar form has shown to increase crop growth and performance by boosting the reaction of antioxidants and improving the yield of the photosynthetic system. In the research of Seyed-Sharifi et al. (2024), the application of nano-silicon under water-limited conditions led to increased safflower seed yield by augmenting total chlorophyll content and enhancing the antioxidant

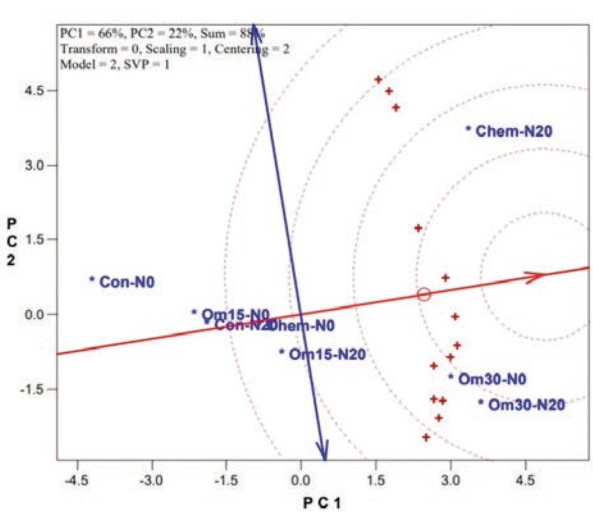

Fig. 4: Ranking entries (treatment combinations) based on testers (traits).

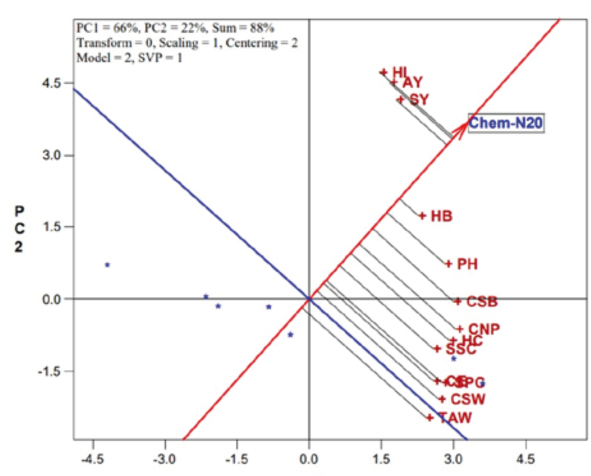

Fig. 5: Ranking traits based on the target entry (Chem-N20); 90 kg ha^{-1} NPK fertilizer plus 20 Mm nano-silicon.
Traits are: plant height (PH), the highest branch (HB), the highest capitula (HC), capitula per subsidiary branch (CSB), capitula number per plant (CNP), seed per primary capitulum (SPC), seed per subsidiary capitulum (SSC), capitulum's seed mass (CSW), straw yield (SY), achene yield (AY), harvest index (HI), and thousand achene mass (TAW).

enzymes functions and compatible osmolytes like proline and soluble sugars.

Similarly, analyzing the performance of OM30-N20 for the measured traits of safflower (Fig. 6) revealed that most yield components (CNP, SPC, SSC, CSM, and TAM), as well as the highest capitula (HC), were in close proximity to this treatment combination. Therefore, for achieving a high number of seeds and heavier seeds in safflower, the recommendation is to apply 30 t ha^{-1} organic fertilizer along with foliar usage of 20 Mm nano-silicon. The utilization of organic fertilizer has shown to enhance the yield components of safflower, is in accordance with the findings of Sudhakar et al. (2020), who found a remarkable enhance in yield performance of safflower due to the positive impacts of organic fertilizer. These impacts are attributed to the delivery of nutrients by organic fertilizer, which provides the required energy for microorganisms and aids in the degradation of organic matter, serving as an additional energy source for field microflora. Furthermore, Karchedu et al. (2023) demonstrated that usage of nano-silicon in foliar form in rice resulted in increased yield performance and zinc content. Silicon plays a significant role in improving rice quality by providing essential macronutrients, such as nitrogen, thereby contributing to enhanced yield outcomes.

Upon examining the achene yield (AY) across the studied treatment combinations, it was evident that only Chem-N20 (NPK chemical fertilizer plus 20 Mm nano-silicon) demonstrated high levels of achene yield, while all other treatment combinations fell below average for this trait (Fig. 7). Moreover, utilizing AY as the reference for evaluating the other measured traits (Fig. 8) reaffirmed the significance of straw yield and harvest index. Among the other traits, the order of importance for AY was as following list: the highest branch (HB) > plant height (PH) > capitula per subsidiary branch (CSB) > capitula number per plant (CNP) > the highest capitula (HC) > seed per subsidiary capitulum (SSC) > seed per primary capitulum (SPC) > capitulum's seed mass (CSM) > thousand-achene mass (TAM), indicating the relatively low importance of thousand-achene mass for safflower. Nanomaterials represent a novel approach to improving productivity by improving the efficiency of nutrient use and facilitating slow release of nutrients, thereby reducing the risk of overuse of growth stimulants and fertilizers (Kumar et al. 2023). Such nano-materials not only improve yield performance but also decrease farming costs, thereby playing a significant role in sustainable agriculture (Usman et al., 2020). Consistent with previous research, our findings demonstrate that nano-silicon application enhances crop production, with foliar ap-

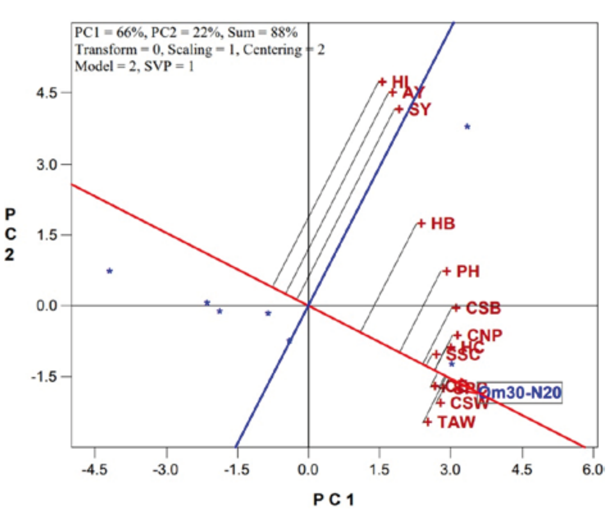

Fig. 6: Ranking traits based on the target entry (OM30-N20); 30 t ha^{-1} organic manure plus 20 Mm nano-silicon.
Traits are: plant height (PH), the highest branch (HB), the highest capitula (HC), capitula per subsidiary branch (CSB), capitula number per plant (CNP), seed per primary capitulum (SPC), seed per subsidiary capitulum (SSC), capitulum's seed mass (CSW, straw yield (SY), achene yield (AY), harvest index (HI), and thousand achene mass (TAW).

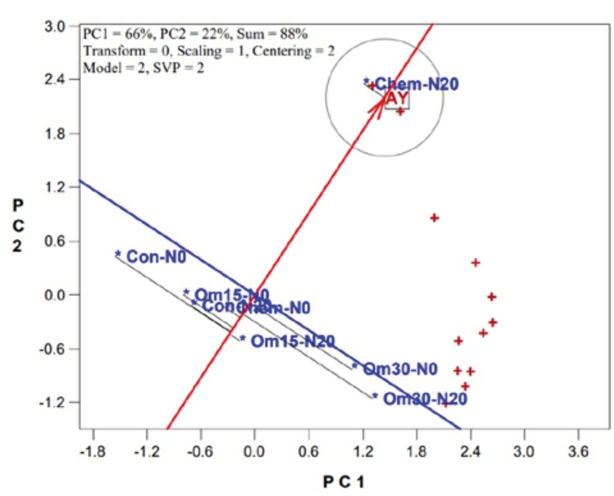

Fig. 7: Ranking treatment combinations based on the target tester AY (achene yield).
Treatment combinations are: control plus 0.0 Mm nano-silicon (Con-N0), control plus 20 Mm nano-silicon (Con-N20), 90 kg ha^{-1} NPK fertilizer plus 0.0 Mm nano-silicon (Chem-N0), 90 kg ha^{-1} NPK fertilizer plus 20 Mm nano-silicon (Chem-N20), 15 t ha^{-1} organic manure plus 0.0 Mm nano-silicon (OM15-N0), 15 t ha^{-1} organic manure plus 20 Mm nano-silicon (OM15-N20), 30 t ha^{-1} organic manure plus 0.0 Mm nano-silicon (OM30-N0), and 30 t ha^{-1} organic manure plus 20 Mm nano-silicon (OM30-N20).

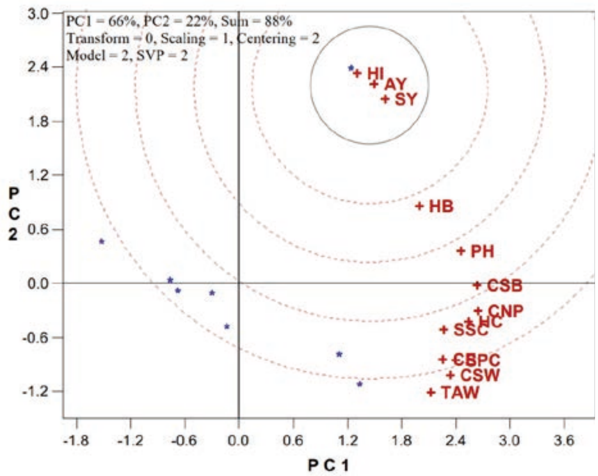

Fig. 8: Ranking traits based on the target tester AY (achene yield).
Traits are: plant height (PH), the highest branch (HB), the highest capitula (HC), capitula per subsidiary branch (CSB), capitula number per plant (CNP), seed per primary capitulum (SPC), seed per subsidiary capitulum (SSC), capitulum's seed mass (CSW), straw yield (SY), achene yield (AY), harvest index (HI), and thousand achene mass (TAW).
N0), 15 t ha^{-1} organic manure plus 20 Mm nano-silicon (OM15-N20), 30 t ha^{-1} organic manure plus 0.0 Mm nano-silicon (OM30-N0), and 30 t ha^{-1} organic manure plus 20 Mm nano-silicon (OM30-N20).

plication of nano-silicon in conjunction with chemical NPK fertilizer or organic fertilizer leading to increased safflower productivity. However, using nano-silicon and chemical fertilizers in minimal amounts presents an environmentally friendly option, promoting low-cost production within a sustainable agriculture system, and may be advisable for many farmers.

The release of nano-silicon into crops should be carefully managed to ensure effectiveness. Simultaneous use of nano-silicon and chemical NPK fertilizers has been shown to enhance yield performance in potato (Ha et al., 2019) and rice (Elekhtyar and Al-Huqail, 2023). Nanotechnology is increasingly becoming commonplace in crop production, as the use of nano-materials not only reduces fertilizer usage but also decreases production costs. Application of nano-silicon has demonstrated positive effects in crops under environmental stresses (Namjoyan et al., 2020; Hajihashemi and Kazemi, 2022). Despite the benefits of nanotechnology, it has major importance to acknowledge the potential risks related with its use in crop production. Some scientists are actively working to evaluate these risks to ensure safe and responsible usage in agriculture. However, challenges such as high evaluation costs, public environmental concerns, and human health risks remain major obstacles in this field. In other word, it is important to recognize the potential risks associated with the use of nanotechnology in agriculture, despite its many benefits, so some agronomists are assessing these risks to guarantee the biologic safety of these technologies in crop sciences. The agricultural field still faces significant barriers, including expensive evaluation and public worries about the environment, and potential risks to human health. Therefore, it is imperative to establish international standards to monitor this field before widespread public release and commercial usage.

4 CONCLUSION

The optimal fertilizer treatment for maximizing safflower yield was found to be the usage of 90 kg ha^{-1} NPK (nitrogen, phosphorus, and potassium) fertilizer, coupled with foliar application of 20 Mm nano-silicon. Conversely, for achieving high yields of safflower components, the most effective fertilizer treatment was the usage of 30 t ha^{-1} organic manure combined with 20 Mm nano-silicon foliar application. Understanding these nuances will contribute to optimizing crop yield and quality across various agricultural settings.

5 STATEMENTS

5.1 CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Naser Sabaghnia: Writing – review & editing, Supervision, Conceptualization. Mohsen Janmohammadi: Investigation, Formal analysis, Data curation.

5.2 DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

5.3 DATA AVAILABILITY

Data will be made available on request.

5.4 ACKNOWLEDGEMENT

We appreciate kind favors of Dr W. Yan (Agriculture and Agri-Food Canada) for GGEbiplot application.

6 REFERENCES

Das, S.K., Avasthe, R.K. (2018). Soil organic nutrients management through integrated approach: a policy for environment ecology. *Environmental Analysis and Ecology Studies,* 4(1), 1-8. https://doi.org/10.31031/EAES.2018.04.000579

Elekhtyar, N.M., Al-Huqail, A.A. (2023). Effect of foliar application of phosphorus, zinc, and silicon nanoparticles along with mineral NPK fertilization on yield and chemical compositions of rice (*Oryza sativa* L.). *Agriculture, 13*(5), 1061. https://doi.org/10.3390/agriculture13051061

FAOSTAT, (2022). *Food and Agricultural Organization of the United Nations.* http://faostat.fao.org [last accessed 04.21.2024].

Farooq, M., Hussain, M., Ul-Allah, S., Siddique, K.H. (2019). Physiological and agronomic approaches for improving water-use efficiency in crop plants. *Agricultural Water Management, 219*, 95^{-1}08. https://doi.org/10.1016/j.agwat.2019.04.010

Fattahi, M., Janmohammadi, M., Abasi, A., Sabaghnia, N. (2023). The effects of farmyard manure and nitrogen fertilizer on the performance of safflower. *Agrotechniques in Industrial Crops, 3*(4), 162^{-1}69. https://doi.org/10.22126/ATIC.2023.9604.1114

Ha N.M., Nguyen T.H., Wang S.L., Nguyen A.D. (2019). Preparation of NPK nanofertilizer based on chitosan nanoparticles and its effect on biophysical characteristics and growth of coffee in green house. *Research on Chemical Intermediates, 45*(1), 51e63. https://doi.org/10.1007/s11164-018-3630-7

Hajihashemi, S., Kazemi, S. (2022). The potential of foliar application of nano-chitosan-encapsulated nano-silicon donor in amelioration the adverse effect of salinity in the wheat plant. *BMC Plant Biology, 22*(1), 148. https://doi.org/10.1186/s12870-022-03531-x

Hussain, M.I., Lyra, D.A., Farooq, M., Nikoloudakis, N., Khalid, N. (2016). Salt and drought stresses in safflower: a review. *Agronomy for Sustainable Development, 36*, 1-31. https://doi.org/10.1007/s13593-015-0344-8

Janmohammadi, M., Seifi, A., Pasandi, M., Sabaghnia, N. (2016). The impact of organic manure and nano-inorganic fertilizers on the growth, yield and oil content of sunflowers under well-watered conditions. *Biologija, 62*(4). https://doi.org/10.6001/biologija.v62i4.3410

Karchedu, S., Koteodayar, G.G., Salimath, S.B., Hanchinmani, V., Marulasiddappa, D.B. (2023). Effect of zinc and silicon nanoparticles on yield, quality and economics of lowland paddy. *Environment Conservation Journal, 24*(2), 293-300. https://doi.org/10.36953/ECJ.12732363

Kumar, N., Samota, S.R., Venkatesh, K., Tripathi, S.C. (2023). Global trends in use of nano-fertilizers for crop production: Advantages and constraints–A review. *Soil and Tillage Research*, *228*, 105645. https://doi.org/10.1016/j.still.2023.105645

Lal, B., Sharma, S.C., Meena, R.L., Sarkar, S., Sahoo, A., Balai, R.C., ... Meena, B.P. (2020). Utilization of byproducts of sheep farming as organic fertilizer for improving soil health and productivity of barley forage. *Journal of Environmental Management, 269,* 110765. https://doi.org/10.1016/j.jenvman.2020.110765

Namjoyan, S., Sorooshzadeh, A., Rajabi, A. Aghaalikhani M. (2020). Nano-silicon protects sugar beet plants against water deficit stress by improving the antioxidant systems and compatible solutes. *Acta Physiologiae Plantarum, 42*, 157 (2020). https://doi.org/10.1007/s11738-020-03137-6

Sabaghnia, N., Janmohammadi, M. (2023). Influence of some nano-fertilizers on chickpeas under three irrigation strategies. *Plant Nano Biology, 4*, 100037. https://doi.org/10.1016/j.plana.2023.100037

Sabaghnia, N., Janmohammadi, M. (2024). Effect of fertilizers and planting methods on safflower fatty acid profile. *Pesquisa Agropecuária Tropical, 54,* e77864. https://doi.org/10.1590/1983-40632024v5477864

Sampaio, M.C., Santos, R.F., Bassegio, D., De Vasconselos, E.S., de Almeida Silva, M., Secco, D., Da Silva, T.R.B. (2016). Fertilizer improves seed and oil yield of safflower under tropical conditions. *Industrial Crops and Products, 94*, 589-595. https://doi.org/10.1016/j.indcrop.2016.09.041

Seyed-Sharifi, R., Seyed Sharifi, R., Khalilzadeh, R. (2024). Effects of vermicompost and nano silicon on yield and some physiological and biochemical traits of safflower (*Carthamus tinctories* L.) under irrigation withholding condition. *Environmental Stresses in Crop Sciences, 17*, 1^{-1}6. https://doi.org/10.22077/escs.2023.4884.2085

Shahrokhnia, M.H., Sepaskhah, A.R. (2017). Safflower model for simulation of growth and yield under various irrigation strategies, planting methods and nitrogen fertilization. *International Journal of Plant Production, 11*(1), 167^{-1}92. https://doi.org/10.22069/IJPP.2017.3316

Silva, D.M.R., Santos, J.C.C.D., Christensen, N., Silva, M.D.A. (2022). Potassium effect on the morphology, nutrition and production of *Carthamus tinctorius* L. under water deficiency and rehydration. *Acta Physiologiae Plantarum, 44*(11), 115. https://doi.org/10.1007/s11738-022-03454-y

Souri, Z., Khanna, K., Karimi, N., Ahmad, P. (2021). Silicon and plants: current knowledge and future prospects. *Journal of Plant Growth Regulation, 40*, 906-925. https://doi.org/10.1007/s00344-020-10172-7

Sudhakar, C., Rani, C.S., Reddy, K.K.K., Reddy, T.R., Pushpavalli, S., Rani, K.S., Padmavathi, P. (2020). Effect of organic manures and site-specific nutrient management practices (SSNM) in safflower (*Carthamus tinctorius* L.). *Journal of Oilseeds Research, 37*(1), 44-49. https://doi.org/10.56739/jor.v37i1.136385

Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S.A., Rehman, H., Ashraf, I., Sanaullah, M. (2020). Nanotechnology in agriculture: current status, challenges and future opportunities. *Science of The Total Environment*, *721*, 137778, https://doi.org/10.1016/j.scitotenv.2020.137778

Yan, W. (2019). LG biplot: a graphical method for mega-environment investigation using existing crop variety trial data. *Scientific Reports, 9*(1), 7130.https://doi.org/10.1038/s41598-019-43683-9

Zia, R., Nawaz, M.S., Siddique, M.J., Hakim, S., Imran, A. (2021). Plant survival under drought stress: Implications, adaptive responses, and integrated rhizosphere management strategy for stress mitigation. *Microbiological Research, 242*, 126626. https://doi.org/10.1016/j.micres.2020.126626