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ASSESSMENT OF NANO-SILICON APPLICATION IN CONJUNCTION WITH NPK CHEMICAL AND ORGANIC MANURE FERTILIZERS ON *Carthamus tinctorius* L.

Naser SABAGHNIA*, Yousef NASIRI*, Mohsen JANMOHAMMADI*

**Department of Plant Production and Genetics, Agriculture Faculty, University of Maragheh, Iran*
Correspondence author: Naser Sabaghnia, Department of Plant Production and Genetics, Agriculture Faculty, University of Maragheh, Iran, phone: 00984137276065, fax: 00984137276065, e-mail: sabaghnia@yahoo.com

Abstract. Silicon can significantly enhance crop productivity, especially in semi-arid areas which exhibit low organic matter content, leading to insufficient water retention and nutrient imbalances that can negatively impact crop yields. In current investigation, we assessed the positive influences of nano-silicon and various fertilizer treatments on *Carthamus tinctorius* yield and morphological traits. The treatments included the spraying of 0.0- and 20-mM nano-silicon in combination with fertilizers, including a control group, 90 kg·ha^{-1} NPK (nitrogen, phosphorus, and potassium), and organic manure at rates of 15 and 30 t·ha^{-1} which were tested at Maragheh (37°23′N; 46°14′E), Iran. Principal components (PC) analysis revealed that PC1 and PC2 described for 50% and 20% of the observed variation, respectively. A positive association was observed among straw yield, seed yield, height of the first branch, and harvest index. The NPK treatment with 20 mM nano-silicon resulted in high seed yield, while the usage of 30 t·ha^{-1} organic manure with 20 mM nano-silicon showed increased morphological and yield components. Cluster analysis of measured traits and treatment combinations generally supported the results of the PC analysis but revealed some differences, particularly in the separation of organic manure fertilizers based on consumption levels. For achieving sustainable farming goals, apply 30 t ha^{-1} of organic manure with 20 mM nano-silicon, improves biomass and yield components. This study underscores the positive impact of nano-silicon on safflower growth and emphasizes the potential benefits of its foliar application in conjunction with NPK or organic fertilizer to enhance *Carthamus tinctorius* performance in upland semi-arid regions.

Key words: cluster analysis; nanoparticles; principal components analysis; sustainable agriculture.

INTRODUCTION

The escalating global population trends underscore the urgent need to address food security challenges, particularly through enhanced food production. However, the limited availability of arable land underscores the importance of advancing breeding, improving management practices, and implementing strategies to enhance stress tolerance, all essential for achieving the necessary increase in global food production [15]. Additionally, climate change presents a significant obstacle, exerting pressure on crop yields and stability. A considerable portion of developing countries is situated in semi-arid regions characterized by unpredictable environmental conditions, rendering them particularly susceptible to stressors [29]. While soil characteristics vary widely across regions, all crops necessitate permeable soils with adequate organic content and nutrient levels for optimal growth and development [10]. Hence, achieving a balanced fertilizer application is crucial for sustainable crop production. The benefits of farmyard manure application in enhancing the biologic properties as well as physically and chemically characteristics of soil have been well-documented [41]. In semi-arid areas, the soil is typically tilled and, due to its low organic content, fertility is constrained. Previous research indicates that farmyard manure plays a vital role in increasing crop yields by providing essential macro and micronutrients necessary for crop growth and development [11].

Safflower (*Carthamus tinctorius* L.) stands out as a traditional domesticated medicinal plant well-suited to semi-arid regions. Primarily cultivated for its seed oil, safflower is also grown for its flowers, utilized for coloring or medicinal purposes in certain regions [34]. Its unique agronomic properties position *Carthamus tinctorius* as a promising oilseed crop in semi-arid areas [28]. The nutrient requirements of safflower bear resemblance to cool cereals, albeit with a longer growth period. Its deep-rooting structure enables the plant to access nutrients from lower soil depths, albeit within limited quantity and variety [35]. The application of manure enriches soil organic content, serving as a reservoir of diverse nutrients while reducing soil compaction and enhancing soil properties [4]. Certain nutrients are essential in minimal quantities, yet play pivotal roles in crucial physiological processes. Notably, manganese, iron, and zinc are crucial for safflower growth and development [5]. Manganese, for instance, has a pivotal role in physiologic functions such as photosynthetic activity and the activation of enzymes involved in nitrogen metabolism while iron contributes to chlorophyll and hormone synthesis, alongside its involvement in photosynthetic and mitochondrial processes [31]. Meanwhile, zinc serves as an essential component in enzymatic functions and protein biosynthesis, ensuring the integrity of cell membranes and maintaining growth equilibrium.

The soils of semi-arid regions are characterized by minimal organic content and encounter salinity and alkalinity challenges, exacerbating micronutrient deficiencies. The extensive use of chemical fertilizers to meet nutrient requirements presents environmental and cost concerns, while the application of organic manure offers benefits due to its positive interaction with nutrient efficiency [42]. Despite the immediate benefits of chemical fertilizers, their efficacy is contingent upon ideal soil conditions, and they pose risks such as leaching, high energy consumption, pollution, and soil moisture depletion in semi-arid regions. The adoption of diverse fertilizer types and the integration of new technological tools, such as nanotechnology, in agriculture, present promising avenues for enhancing crop production [39]. Various nano-materials have been proposed for use in crop production to enhance yield performance and serve other purposes. The foliar application of beneficial nano-materials has opened up new possibilities for integrating nanotechnology into agriculture, whereas nano-silicon, among these materials, has garnered significant attention [6]. Nanotechnology represents a promising frontier in agriculture, poised to become a significant driver of development in the future. It is believed to have the potential to enhance crop production by leveraging nano-components that stimulate physiological processes using nanoscale tools. Nanomaterials possess unique properties distinct from those observed on a bulk scale, enabling specialized applications, so they boast an increased surface area-to-volume ratio, offering greater opportunities for interaction [37]. Silicon, despite being abundant in Earth's crust, plays a crucial biological role in crops by being taken up as silicic acid, which is non-toxic even at high concentrations [8]. Its positive impacts include the induction of defense mechanisms in response to various biotic and environmental stresses. The current study was designed to assess the interaction between NPK (nitrogen, phosphorus, and potassium) chemical fertilizer, organic manure, and foliar nano-silicon application to enhance fertilizer efficiency (both chemical and organic) in *Carthamus tinctorius*. This investigation aims to offer new insights into fertilizer utilization in semi-arid areas.

MATERIALS AND METHODS

Experimental design

The experiment performed in a split-plot layout (nutrients as main plots and nano-silicon as sub-plots), based on a randomized complete block design with three replications at Maragheh (37°23′N; 46°14′E), Iran. The soil of the field was identified as sandy loam, characterized by a particle size distribution in descending order of sand, silt, and clay. Five nutritional treatments were applied to the main plots, including a control (F0), 90 kg·ha^{-1} of NPK (nitrogen + phosphorus + potassium) chemical fertilizer (NPK), 15 t·ha^{-1} of organic manure (Man15), and 30 t·ha^{-1} of organic manure (Man30). Nano-silicon was applied to the subplots as foliar spray treatment, with concentrations of 0.0 mM (Si0) and 20 mM (Si20), which are non toxic levels based on previous studies [33, 36]. Nano- silicon was provided by the Nano Pishgaman Co., Iran. The particle sizes ranged from 20 to 100 nm and specific surface area of nano-sized silicon was 180-300 m^2 × g^{-1} and the purity percent was 99.6%. Nano silicon is generally considered nontoxic to crop and, in many cases, has positive effects on crop growth and resistance to biotic and abiotic stresses [27]. The field site was located in Maragheh, Iran (37°23′N 46°14′E), characterized as an upland semi-arid area with a soil pH of 7.5 and electrical conductivity of 0.51 dS m-1. Autumn plowing followed by disking was conducted, and *Carthamus tinctorius* seeds were manually sown on April 14th based on local routine framing practices. Each plot measured 4.0 m in length and 3.0 m in width, containing 12 rows spaced 0.25 m apart. The trial was managed as rainfed cultivation but received supplementary irrigation during the seed-filling stage. Organic manure, derived from cow manure, was uniformly mixed into the soil to a depth of 15 cm, while NPK fertilizer was surface-applied after field operations. The organic content of the soil was 2.0 g·kg^{-1}, with nitrogen at 0.06%, phosphorus at 6.0 mg.kg^{-1}, and potassium at 34.0 mg·kg^{-1}.

Measured traits

The trial involved measuring the electrical conductivity (EC), canopy expansion (CG), and ground coverage (CG) traits for each experimental unit regarding the suggestion of Kouchakkhani *et al.* [22]. Additionally, ten randomly selected plant samples from each experimental unit were utilized to record the following parameters regarding the standard descriptor [14]: height of the first branch (HFB), height of the first head (HFH), stem diameter (SD), number of heads per plant (NHP), height of plant (HP), chlorophyll content (CC), heads of main branch (HMB), heads of secondary branch (HSB), seeds per main head (SMH), seeds per secondary head (SSH), main head diameter (MHD), secondary head diameter (SHD), seed weight per head (SWH), and unfilled seeds per plant (NSP). To mitigate marginal effects, center rows within each plot were manually harvested from June to July. Seed and biological yield (SY and BY) as well as straw yield (STY) were recorded, and the harvest index (HI), computed as the ratio of SY to BY, was determined based on the propose of Sabaghnia *et al.* [34]. Furthermore, the thousand seeds weight (TSW) was calculated from three randomly selected samples of each experimental unit [35].

Statistical analysis

The dataset's adherence to a normal distribution was evaluated using the Ryan-Joiner method of goodness of fit by Minitab software version 14.0 (Minitab Ins. USA). Principal component (PC) analysis was then employed to condense the associated traits into a smaller number of components, aiding in better comprehension of trait associations and treatment combinations [25]. The values of the first two PCs for both entries were plotted against each other to facilitate effective graphic representation of these associations. Furthermore, to simultaneously illustrate treatment combinations and traits in a single plot, scatter graphs were generated as biplots, capturing both aspects for enhanced visualization [43]. Hierarchical cluster analysis was utilized to categorize treatment combinations and traits based on their distance values from each other, employing squared Euclidean measure and merging by Ward's minimum variance method as proposed by Houmanat *et al.* [17]. Finally, the cutoff point for each dendrogram was determined and confirmed using the Lambda statistic of Wilk as a multivariate ANOVA model [7], ensuring the reliability of the clustering outcomes.

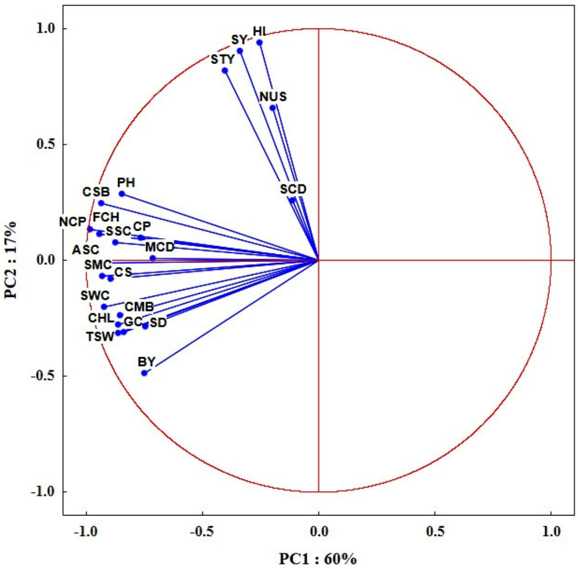

Figure 1. Plot of first two principal components indicating the interrelationships among traits of safflower.

RESULTS

Fitting principal components (PCs) indicated that the first two PCs described for 55% and 20% of the variability in traits across various fertilizer treatments (Fig. 1), collectively elucidating 75% of the variability. This substantial elucidation is advantageous as it allows for better and more reliable interpretation of the dataset. The vectors associated with the plot center indicate the relationships among traits, with the length of the vectors serving as an index of association significance, and the cosine of the angles indicating the magnitude of the associations. A closed vector angle represents a positive relation (cos 0° = +1), a right vector angle signifies no relation (cos 90° = 0), and an opposite vector angle signifies a negative relation (cos 180° = -1). From Fig. 1, it can be observed that straw yield (STY), harvest index (HI), seed yield (SY), unfilled seeds per plant (NSP), and secondary head diameter (SHD) were positively related, providing similar information regarding safflower response to fertilizers. Notably, the significance of SHD is relatively low due to its shorter vector. These traits are associated with yield properties such as harvest index, biological yield, and secondary head diameter.

Furthermore, the above-mentioned traits exhibited no correlation with biological yield (BY), canopy expansion (CG), chlorophyll content (CC), stem diameter (SD), heads of main branch (HMB), and seed weight per head (SWH), as indicated by their right vector angles (cos 90° = 0). However, they were positively correlated with closed vector angles (cos 0° = +1). These findings underscore the importance of genetic improvement projects in safflower to identify and understand the relationships among yield components and to determine suitable selection indices. This discrepancy may be related to variations in test environments, especially under rainfed conditions in semi-arid regions, where plants tend to enter the reproductive stage more quickly. However, it is important to note that direct comparisons between these results and original correlation coefficients should be made cautiously. The principal component method elucidates associations among traits based on the general structure of the data, whereas numerical correlation coefficients solely reflect the association between traits.

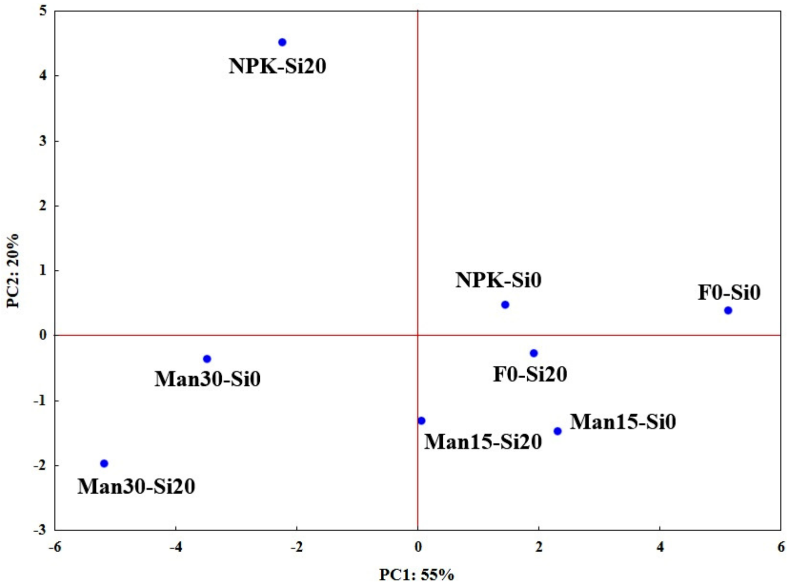

Figure 2. Plot of first two principal components for the interrelationships among treatments. Treatment combinations are: control plus 0.0 Mm nano-silicon (F0-Si0), control plus 20 Mm nano-silicon (F0-Si20), 90 kg·ha^{-1} NPK plus 0.0 Mm nano-silicon (NPK-Si0), 90 kg·ha^{-1} NPK plus 20 Mm nano-silicon (NPK-Si20), 15 t·ha^{-1} organic manure plus 0.0 Mm nano-silicon (Man15-Si0), 15 t·ha^{-1} organic manure plus 20 Mm nano-silicon (Man15-Si20), 30 t·ha^{-1} organic manure plus 0.0 Mm nano-silicon (Man30-Si0), and 30 t·ha^{-1} organic manure plus 20 Mm nano-silicon (Man30-Si20).

The PC1 effectively distinguished NPK-Si20 (90 kg·ha^{-1} NPK plus 20 mM nano-silicon), Man30-Si0 (30 t·ha^{-1} organic manure without nano-silicon), and Man30-Si20 (30 t·ha^{-1} organic manure with 20 mM nano-silicon) from the other treatment combinations (Fig. 2). This indicates that the performance of high doses of organic manure with or without nano-silicon application is comparable to the effects of chemical NPK combined with nano-silicon. However, the use of low doses of organic manure fertilizer did not significantly improve the measured traits or yield performance, suggesting that its application should be sufficiently large to be effective, especially in the short term. The PC2 further segregated treatment combinations into four distinct groups. Notably, NPK-Si20 was separated from both Man30 (0- and 20-mM nano-silicon) fertilizers and could discriminate between organic manure fertilizers and chemical NPK fertilizer. Additionally, PC2 differentiated F0-Si0 (control without nano-silicon) and NPK-Si0 (90 kg·ha^{-1} NPK without nano-silicon) from the remaining treatment combinations such as F0-Si20 (control with 20 mM nano-silicon), Man15-Si0 (15 t·ha^{-1} organic manure without nano-silicon), and Man15-Si20 (15 t·ha^{-1} organic manure with 20 mM nano-silicon). This grouping underscores the significance of nano-silicon application, as the use of 20 mM nano-silicon could distinguish between fertilizer application and non-application. Moreover, the performance of chemical NPK fertilizer was similar to non-application of fertilizer combined with nano-silicon. Furthermore, the application of nano-silicon did not significantly affect the performance of low doses of organic manure fertilizers (15 t·ha^{-1}). Thus, for better and more effective utilization of organic manure, its dosage should be increased. The increase in seed and straw yield performance of safflower under rainfed conditions in semi-arid areas is attributed to the enhancement of pigments involved in photosynthesis, thereby increasing photosynthetic efficiency in the field crops.

The scatter plot (Fig. 3), which combines treatment combinations and measured traits in a biplot, offers insights into the impact of treatments on safflower traits. NPK-Si20 treatment exhibited high values for harvest index (HI), seed yield (SY), straw yield (STY), unfilled seeds per plant (NSP), and height of first branch (HFB) traits in safflower. Conversely, Man30-Si20 treatment resulted in high values for biological yield (BY), thousand seeds weight (TSW), canopy expansion (CG), chlorophyll content (CC), stem diameter (SD), heads of main branch (HMB), and seed weight per head (SWH) traits (Fig. 3). Furthermore, Man30-Si0 treatment showed high averages for height of plant (HP), heads of secondary branch (HSB), height of first head (HFH), seeds per secondary head (SSH), number of heads per plant (NHP), seeds per main head (SMH), electrical conductivity (EC), and main head diameter (MHD), and relatively high values for the traits of Man30-Si20 treatment. However, upon inspecting the virtual polygon vertex treatments, the performance of Man30-Si0 treatment was superior to Man30-Si20 in these traits (Fig. 3). Similarly, we found NPK-Si20 to be the most effective fertilizer treatment for achieving high yield performance in safflower. Additionally, we observed that the application of high amounts of organic manure fertilizer can enhance most morphological traits and yield components. The other virtual vertex treatments, F0-Si0 and Man15-Si0, did not demonstrate any superiority over other treatment combinations in the measured traits of safflower (Fig. 3). Therefore, the application of 20 mM nano-silicon can be recommended with 90 kg·ha^{-1} NPK for conventional agriculture or with 30 t·ha^{-1} organic manure for sustainable organic agriculture.

Hierarchical clustering analysis was employed to confirm the conclusions drawn from the principal

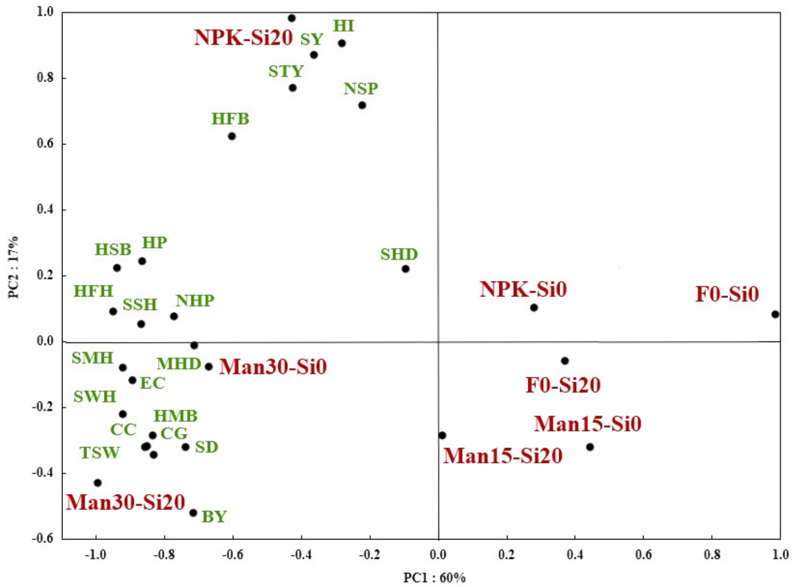

Figure 3. Biplot of first two principal components for the interrelationships among treatments and traits.

component analysis, both for categorizing traits (Fig. 4) and treatment combinations (Fig. 5). The twenty-one safflower traits clustered into three groups, a classification validated by the Lambda statistic of Wilks in multivariate ANOVA (λ=0.0032, p<0.01). In Fig. 4, Cluster-I comprised biological yield (BY), seed yield (SY), and straw yield (STY) traits, consistent with the findings of Fig. 1. In semiarid regions, higher daily temperatures prolong the development phase, leading to increased biomass and straw yield, although seed yield is more influenced [1]. Cluster-II included traits such as seed weight per head (SWH), secondary head diameter (SHD), main head diameter (MHD), heads of main branch (HMB), unfilled seeds per plant (NSP), number of heads per plant (NHP), and stem diameter (SD), while Cluster-III comprised the remaining traits related to yield components and morphological traits (Fig. 4). Although there may be some inconsistencies between PC analysis and clustering results due to the PC analysis explaining less than 100% of the total variability, the overall agreement between the two approaches was acceptable. Fertilizer treatments were categorized into four clusters via Wilks' Lambda statistic of multivariate ANOVA (λ=0.0013, p<0.01). In Fig. 5, Cluster-1 consisted of NPK-Si20; Cluster-2 included Man15-S20 and Man15-Si20; Cluster-3 comprised Man30-Si0 and Man30-Si20, and Cluster-4 consisted of F0-Si0, F0-Si20, and NPK-Si0.

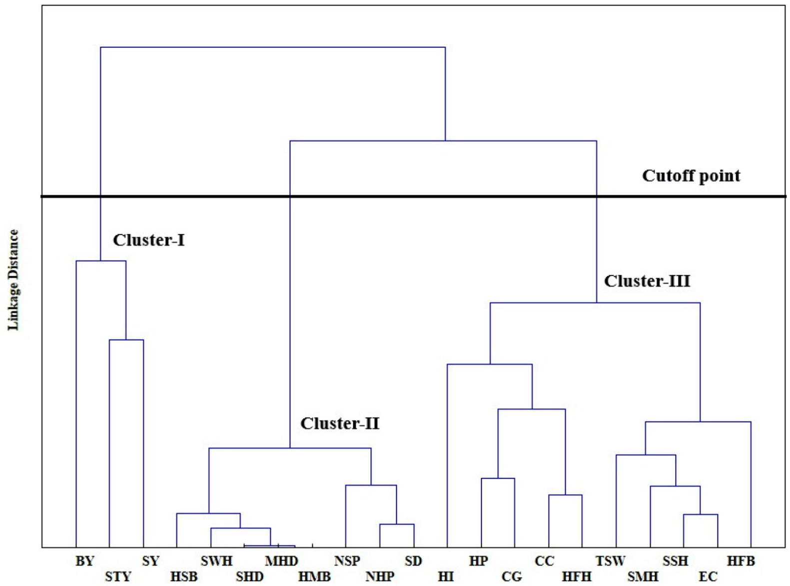

Figure 4. Dendrogram of cluster analysis indicating the classifying of measured traits of safflower.

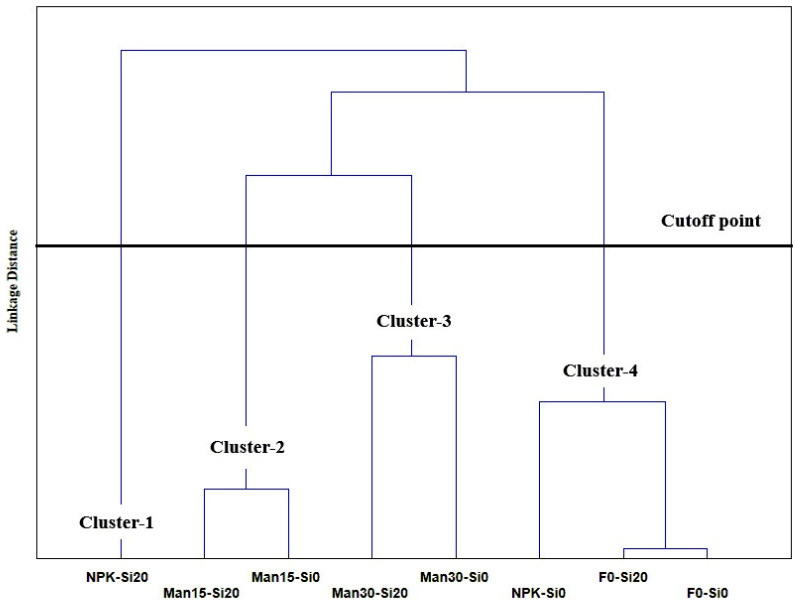

Figure 5. Dendrogram of cluster analysis indicating the classifying of treatment combinations.

Clustering of treatment combinations relatively confirmed the results of PC analysis in Fig. 2. Thus, the application of nano-silicon in conjunction with organic manure did not significantly affect safflower traits, and organic manure fertilizers were categorized based on their application amounts, with 30 $t{\cdot}ha^{-1}$ organic manure being more favorable than 15 $t{\cdot}ha^{-1}$ organic manure, resulting in higher values of morphological traits and yield components. Moreover, adding 20 mM nano-silicon to 90 $kg{\cdot}ha^{-1}$ NPK was more efficient and led to higher values in yield attributes (straw, seed, and biomass). However, using nano-silicon without any other fertilizer did not affect safflower traits, and its performance was similar to that of nano-silicon with no fertilizer usage. The influence of 90 $kg{\cdot}ha^{-1}$ NPK plus 0.0 mM nano-silicon did not show significant differences from F0-Si0 and F0-Si20, highlighting the crucial role of nano-silicon in this scenario, while the addition of 20 mM nano-silicon to NPK resulted in significant differences and identified NPK-Si20 as the best treatment combination.

DISCUSSION

It was found that that straw yield, harvest index, seed yield, unfilled seeds per plant, and secondary head diameter were positively related with yield, so genetic improvement in one of these traits may lead to an increase in other related traits, resulting in higher yield. This finding aligns with previous research by El-Bey and Kurt [13], who reported a positive relationship between yield performance and dry matter weight of *Carthamus tinctorius* plants. Similarly, Nikzad and Baydar [26] found a relationship between heads of the main branch and seed weight per head in safflower. Additionally, Koç [21] observed that seed yield was not correlated with plant height, number of branches, number of heads, and thousand seed weight in safflower genotypes across three years. These findings underscore the importance of genetic improvement projects in safflower to identify and understand the relationships among yield components and to determine suitable selection indices. Although, some researchers have reported a strong positive association between seed yield and heads of plants in safflower [12, 24], such an association was not found in this investigation. This discrepancy may be related to variations in test environments, especially under rainfed conditions in semi-arid regions, where plants tend to enter the reproductive stage more quickly. In any case, it is imperative to note that coordinate comparisons between these comes about and unique relationship coefficients ought to be made cautiously. The foremost component strategy explains affiliations among characteristics based on the common structure of the information, while numerical relationship coefficients exclusively reflect the affiliation between characteristics.

We found that the performance of high doses of organic manure with or without nano-silicon application is comparable to the effects of chemical NPK combined with nano-silicon. However, the use of low doses of organic manure fertilizer did not significantly improve the measured traits or yield performance, suggesting that its application should be sufficiently large to be effective, especially in the short term. Consequently, large-scale application of organic manure holds greater potential for effectiveness, particularly within an environmentally sustainable system [16]. The grouping of treatment according to both PC(s) underscores the significance of nano-silicon application, as the use of 20 mM nano-silicon could distinguish between fertilizer application and non-application. Moreover, the performance of chemical NPK fertilizer was similar to non-application of fertilizer combined with nano-silicon. Furthermore, the application of nano-silicon did not significantly affect the performance of low doses of organic manure fertilizers (15 $t{\cdot}ha^{-1}$). Thus, for better and more effective utilization of organic manure, its dosage should be increased. Similar findings were reported by Rashed *et al.* [32], who found that simultaneous use of organic manure fertilizer with nano-silicon was more efficient in enhancing soil fertility and improving nutrient efficiency, particularly at higher doses. The interaction between organic manure fertilizer and foliar application of nano-silicon is of high importance based on the measured traits of safflower, which is supported by the findings of Janmohammadi *et al.* [19]. The increase in seed and straw yield performance of safflower under rainfed conditions in semi-arid areas is attributed to the enhancement of pigments involved in photosynthesis, thereby increasing photosynthetic efficiency in the field crops.

Regarding the virtual polygon vertex treatments, the performance of Man30-Si0 treatment was superior to Man30-Si20 in these traits. There is ample documented evidence regarding safflower's positive response to various nutrients, especially macronutrients like nitrogen, phosphorus, and potassium [3, 23]. Similarly, we found NPK-Si20 to be the most effective fertilizer treatment for achieving high yield performance in safflower. Additionally, we observed that the application of high amounts of organic manure fertilizer can enhance most morphological traits and yield components. Organic manure contains micronutrients that improve soil organic content, thereby increasing the availability of nutrients required by the crop [11]. Similar findings of increased yield performance and yield components due to organic manure usage have been reported in okra [2], potato [9], maize [20] and onion [30].

Clustering of treatment combinations relatively confirmed the results of PC analysis. In this way, the application of nano-silicon in conjunction with natural fertilizer did not essentially influence safflower characteristics, and natural excrement fertilizers were categorized based on their application sums, with 30 $t{\cdot}ha^{-1}$ natural excrement being more favorable than 15 $t{\cdot}ha^{-1}$ natural excrement, coming about in higher values of morphological characteristics and surrender components. Additionally, including 20 mM nano-silicon to 90 kg·ha^{-1} NPK was more productive and driven to higher values in abdicate qualities (straw, seed, and biomass). Be that as it may, utilizing nano-silicon without any other fertilizer did not influence safflower characteristics, and its execution was comparative to that of nano-silicon with no fertilizer utilization. The impact of 90 kg·ha^{-1} NPK furthermore 0.0 mM nano-silicon did not appear noteworthy contrasts from F0-Si0 and F0-Si20, highlighting the pivotal part of nano-silicon in this situation, whereas the expansion of 20 mM nano-silicon to NPK brought about in noteworthy contrasts and distinguished NPK-Si20 as the finest treatment combination. Additionally, it has been revealed that sunflower yields higher performance from a combination of organic manure fertilizer with chemical fertilizers [40], suggesting that future investigations should focus on studying the interaction of organic and chemical fertilizers with nano-silicon.

Careful management of nano-silicon release into crops is crucial to ensure its effectiveness. Agreeing to Samuel *et al.* [38], the convenience of evaluating the chemical movement can be utilized for assessing the soil administration, since nearness of a critical relationship between these records and the administration hones. They moreover, emphasized that utilizing natural procedures related to edit generation caused feasible soil administration hones and the support of soil quality, so the long-term utilization of fertilization caused to the arrangement of favorable conditions for the advancement of microorganisms, in making the enzymatic potential in soil. Studies have shown that simultaneous application of nano-silicon and chemical NPK fertilizers can enhance yield performance in crops like safflower [19]. Nanotechnology is increasingly integrated into crop production, offering benefits such as reduced fertilizer usage and lower production costs. The application of nano-silicon has been found to have positive effects on crops facing environmental stresses. Despite these advantages, it's essential to acknowledge and address potential risks associated with nanotechnology in agriculture, so some scientists are actively assessing these risks to ensure safe and responsible use [18]. However, challenges such as high evaluation costs, public environmental concerns, and risks to human health remain significant hurdles in this field. Therefore, establishing international standards to monitor this domain before widespread public release and commercial utilization is essential.

The study revealed that combining NPK fertilizer with nano-silicon can significantly enhance *Carthamus tinctorius* yield performance. The optimal dosage was determined to be 90 kg·ha^{-1} NPK (nitrogen, phosphorus, and potassium) combined with 20 mM nano-silicon. Additionally, to achieve effective outcomes from organic manure fertilizer, it should be applied at higher levels, preferably up to 30 t·ha^{-1}. Further investigation is warranted to find the application of nanomaterials across crops and field conditions, with the aim of providing practical and beneficial contributions to optimizing yield performance.

Conflict of interest. There is no actual or potential conflict of interest in relation to this article.

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