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IMPACT OF NANO-FERTILIZERS ON TUBER YIELD AND MORPHOLOGICAL TRAITS OF POTATO VAR. SPIRIT IN SEMI-ARID CONDITION

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ABSTRACT: In recent years, the use of nano-fertilizers has gained attention for increasing agricultural productivity, especially in potato cultivation. This study aimed to evaluate the effects of nano, bio, and conventional fertilizers on tuber yield and key agronomical traits of the Spirit potato variety. The experiment was performed using a randomized complete block design with three replicates. Six nutritional treatments were tested: control, NPK, Mog biofertilizer, nano-chelated calcium (Nano-Ca), nano-chelated zinc + boron (Nano-Zn+B), and a complete nano-chelated fertilizer. An effective biplot approach (treatment trait) was used to visualize interactions and assess relationships among treatments, traits, and their combined effects. The first and second principal components explained 92% of the total variance. Among the measured traits; tuber weight per plant, leaf number per plant, mean tuber weight, total tuber yield, number of tubers per plant, days to flowering, dry matter content, and starch content, the complete nano-chelated fertilizer showed the highest performance. Based on the ideal treatment biplot model, this fertilizer was closest to the ideal position, performing best across all traits. It proved to be the most effective treatment for maximizing tuber yield, followed by NPK, Nano-Zn+B, and Nano-Ca treatments. This study highlights the potential of nano-fertilizers as an efficient and environmentally friendly approach to improving potato yield in semi-arid regions. The results suggest that using complete nano-fertilizers can significantly enhance agricultural practices in such areas, leading to higher yields and more efficient resource use.

KEYWORDS: nano-B, nano-Ca, nano-Zn, tuber yield, yield components

INTRODUCTION

Potato is one of the major food crops of world, grown on about 17 million hectares with a total production of 383 million *tons*. In Iran, potato cultivation spans 80,000 hectares, producing roughly 2.5 million tons annually (FAOSTAT 2023). However, potato yields are often limited by several factors, particularly low soil fertility, which is linked to poor organic matter content and restricted availability of essential nutrients. These conditions lead to declining productivity. According to Alkharabsheh *et al.* (2021), such challenges also contribute to soil erosion as well as soil degradation. To address these issues, replenishing nutrients and improving soil quality through fertilizer application is necessary (Dimkpa *et al.,* 2023). Conventional bulk fertilizers have shown limited effectiveness in maintaining high yields, as they are often associated with increased soil acidity, nutrient leaching, and deterioration of soil physical properties (Agegnehu *et al.,* 2021).

Repeated use of bulk fertilizers can further worsen soil health. As a result, alternative

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fertilization strategies, such as bio-fertilizers and the newly developed nano-fertilizers, have gained increasing attention. Studies indicate that nano-fertilizers can deliver essential nutrients more efficiently while enhancing soil quality (Sabaghnia 2015; ul Ain *et al.,* 2023). Avila-Quezada *et al.* (2022) reported that nano-fertilizers supply key nutrients; nitrogen, phosphorus, and potassium, in amounts comparable to mineral fertilizers, with added advantages over conventional bulk fertilizers.

The introducing of nanotechnology in agriculture has been relatively slow, but nano-fertilizers offer great potential to improve nutrient use efficiency. Their uptake by plants can occur through complexation, endocytosis, or ion channels, allowing more effective nutrient delivery due to their nanoscale size. This small size enables nano-fertilizers to access plant surfaces and internal transport pathways more efficiently than conventional fertilizers (Janmohammadi *et al.,* 2017b; Babu *et al.,* 2022). Silica nanoparticles have successfully delivered cargo into plant cells (Niazian *et al.,* 2021), suggesting that nano-fertilizers may have higher solubility and reactivity than their bulk counterparts. The development of nano-sized fertilizer formulations is expected to enhance fertilizer efficiency rather than hinder it. In major potato-producing regions, nutrient management is intensive and heavily reliant on chemical fertilizers (Xu *et al.,* 2022). This dependence has reduced the emphasis on crop rotation, which is important for maintaining soil fertility and nutrient balance. However, information on the interactive effects of potato cropping systems on nutrient dynamics remains limited. Among fertilizers, NPK formulations are the most widely used to increase potato yield (Xu *et al.,* 2025). Phosphorus application has been shown to improve tuber yield (Qiu *et al.,* 2022), while insufficient nitrogen results in reduced productivity (Shrestha *et al.,* 2023). Micronutrients like boron and zinc are also essential, and their deficiency can significantly lower yield (Sarkar *et al.,* 2024). Commercial application of micronutrients should focus on minimal, optimal, and efficient amounts. Nano-fertilizers have used as an alternative, providing nutrients in sufficient quantities to meet crop requirements effectively (Avila-Quezada *et al*., 2022).

Current research aimed to assess the reaction of the Spirit potato cultivar to various fertilizer types, including conventional bulk fertilizers, biofertilizers, and nano-sized fertilizers. The main objectives were to identify the most effective fertilizer and to determine the key traits that respond most positively to fertilization. The study was based on the hypothesis that nano-fertilizers can enhance potato yield more effectively than conventional fertilizers.

MATERIAL AND METHODS

The trial was conducted at the experimental field in Sarab, northwest of Iran in 47°53′ East, and 37°93′ North coordinates with elevation 1650 m. The region has a steppe climatic property, with mean yearly min and max temperatures of 2°C and 17°C, respectively. The soil of filed was classified as silty clay loam (Table 1), with a pH of 7.8 and an EC of 1.3 dS m^{-1} in the topsoil (0-0.3 m depth). The study was conducted using the Spirit potato variety, a late-medium maturity cultivar. Cultivation was done in early April and potatoes were harvested late August. Each experimental plot covered 36 m^2, consisting

Table 1. Some soil properties of experimental field (Sarab, Iran)

P (mg kg^{-1})	K (mg kg^{-1})	Fe (mg kg^{-1})	Cu (mg kg^{-1})
23	517	5.8	2.3
Zn (mg kg^{-1})	Mn (mg kg^{-1})	TNV (%)†	OC (%)‡
1.59	7.62	6.61	1.12

†TNV, Total Neutralizing Value; ‡OC, organic carbon

of eight 6-m length rows, with 0.75 m as row distance and an intra-row distance of 0.25 m between seed pieces. Irrigating of plots was performed weekly to replenish soil humidity decrease regarding the evapotranspiration of region.

The trial followed a randomized block scheme using three replicates. Six nutritional treating were evaluated: (1) control (no fertilizer application), (2) NPK chemical bulk fertilizer (20:10:5), (3) Mog biofertilizer (2 L ha^{-1}), (4) Nano-form calcium (Ca, 2 kg ha^{-1}), (5) Nano-form zinc and boron (Zn+B, 1 kg ha^{-1}), and (6) Nano-complete fertilizer (Com, 1 kg ha^{-1}). At chemical bulk fertilizer, 200 kg ha^{-1} routine NPK was used: half as a pre-plant application and the remaining half as a post-emergence in the tuber formation stage. the remained treatments were utilized via irrigation water at sowing and during the tuberization stage. Equalization is done by calculating the kg/ha of each nutrient provided by each fertilizer and adjusting the dose so all treatments supply roughly the same total nutrient amount, allowing fair comparison of nutrient source effects. The nano-chelated complete fertilizer contained 11 essential macro- and micronutrients, including nitrogen (5%), phosphorus (3%), potassium (3%), iron (5%), zinc (8%), calcium (6%), magnesium (6%), manganese (0.7%), copper (0.7%), boron (0.1%), and molybdenum (0.7%). The physicochemical properties of the Mog organic fertilizer included nitrogen (4%), potassium oxide (4%), iron (0.4%), copper (0.2%), and some enzymes (13%).

The following agronomic traits were measured: number of tubers per plant (NTP), number of leaves per plant (NL), mean tuber diameter (MTD), tuber weight per plant (TWP), mean tuber weight (MTW), tuber yield (TY, t ha^{-1}), days to tuber initiation (DIT), days to row closure (DRC), days to flowering (DF), dry matter content (DM), starch content (ST), and number of stems per plant (NS). The biplot model based on treatment-trait interaction was generated following the method of Yan (2024), with all biplots produced directly using the GGEbiplot software (Yan, 2001). This analysis visualizes the interactions between genotypes and traits, where each genotype is shown as a vector and each trait as a point. The angle between a genotype vector and a trait vector reflects the strength and direction of the interaction: smaller angles indicate a strong positive association, while larger angles indicate a weaker or no association.

RESULTS

Treatment performance in traits

The model explained 92% of the variation in the tester-standardized data, with the first and second components accounting for 80% and 12% of the variation, respectively (Figure 1). The biplot was divided into five

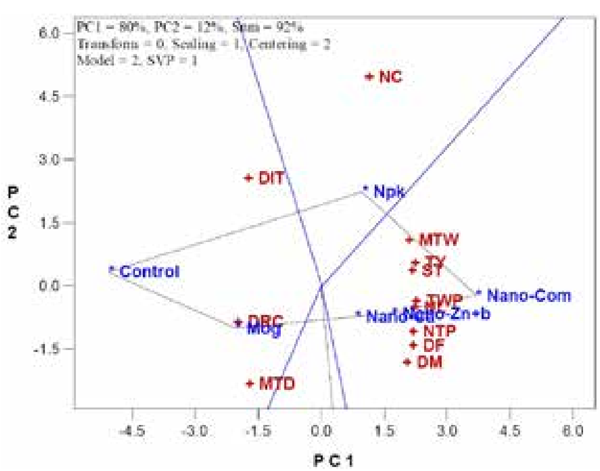

Fig. 1. Polygon-view of TT biplot showing which nano, bio and bulk fertilizer treatment had the highest values for which traits of potato.
Traits: NL, number of leaves per plant; MTD, mean tuber diameter; MTW, mean tuber weight (g); TWP, tuber weight per plant (g); TY, tuber yield (t ha^{-1}); NTP, number of tubers per plant; DIT, day to initiation of tuberization; DRC, number of the days to row closure; DF, number of days to flowering; DM, dry matter content (%); and NS, number of stems; ST, percent of starch content.

sections by five rays, with twelve traits distributed across three sections. Vertex treatments in each quadrant represented the highest-performing treatments for the respective traits. NPK treatment showed the highest performance for the number of stems (NS), while Control treatment excelled in days to tuber initiation (DIT), days to row closure (DRC), and mean tuber diameter (MTD). Nano-chelated complete fertilizer (Nano-Com) outperformed other treatments in number of leaves per plant (NL), mean tuber weight (MTW), tuber weight per plant (TWP), tuber yield (TY), number of tubers per plant (NTP), days to flowering (DF), dry matter content (DM), and starch content (ST) (Figure 1). Also, Nano-Ca and Nano-Zn+B exhibited the lowest performance across all twelve traits.

Trait correlations

Based on the angles of trait vectors in the biplot, two major correlation groups were identified (Figure 2), as Group 1 consist on

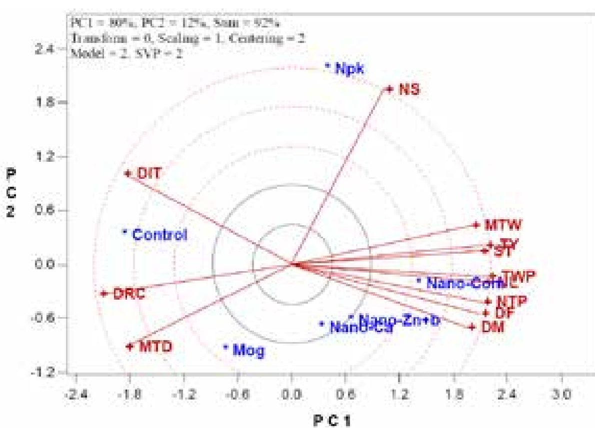

Fig. 2. Vector view of TT biplot showing the interrelationship among measured traits of potato under different nano, bio and bulk fertilizer treatments.

Traits: NL, number of leaves per plant; MTD, mean tuber diameter; MTW, mean tuber weight (g); TWP, tuber weight per plant (g); TY, tuber yield (t ha^{-1}); NTP, number of tubers per plant; DIT, day to initiation of tuberization; DRC, number of the days to row closure; DF, number of days to flowering; DM, dry matter content (%); and NS, number of stems; ST, percent of starch content.

NL, MTW, TWP, TY, NTP, DF, DM, and ST were positively correlated with each other but negatively associated with DRC and MTD. These traits had no significant association with NS. Also, Group 2 including DRC and MTD were positively correlated, while DIT was negatively associated with Group 1 traits. These relationships can be explained by source-sink dynamics. Carbon fixed during photosynthesis is either metabolized to generate energy and structural carbon for cellular growth or exported, primarily as sucrose, to other organs for development and storage compound synthesis (Janmohammadi *et al.,* 2018). Increased leaf number and leaf area index enhance the ability of plant to supply photo-assimilates, which are essential for growth. Beyond supporting actively growing sink tissues, photo-assimilates contribute to the production of growth-promoting phytohormones (Janmohammadi *et al.,* 2017a). Enhanced flow of photo-assimilates into stolons can accelerate tuberization, reducing DIT. These findings align with previous studies: Das *et al.* (2021) reported positive associations between tuber yield and NL, NTP, MTW, and DM; Asnake *et al.* (2023) indicated a strong positive correlation between tuber yield and MTW; and Gebreselassie *et al.* (2022) demonstrated that both tuber number and weight contributed to final yield, with tuber number having a greater influence.

Treatment correlations

Analysis of treatment vectors revealed that Nano-Com exhibited a significant negative correlation with the Control, while NPK showed no distinct association with either (Figure 3). Nano-Com, which contains macronutrients (NPK) and micronutrients, appears sufficient to meet the nutritional requirements of potatoes, potentially eliminating the need for other fertilizers. Other treatments showed weak or non-significant

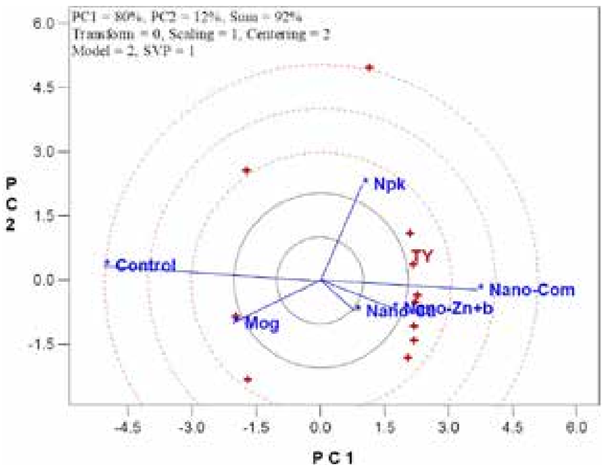

Fig. 3. Vector view of TT biplot showing the interrelationship among fertilizer treatments. TY is tuber yield (t ha^{-1}).

correlations due to their short vector lengths (Ebrahimi *et al.*, 2023).

Ideal Fertilizer

The ideal treatment, represented at the center of concentric circles (Figure 4), corresponds to the combination of superior performance across multiple traits. Nano-Com was closest to this ideal point, followed by Nano-Zn+B, Nano-Ca, NPK, and Control. While the effects of NPK and certain micronutrients (Mg, Zn, Mn) are well-documented, data on Fe, Mo, Ca, B, and Cu remain limited (Singh and Maiti, 2022).

Tuber Yield

The treatment trait biplot (Figure 5) highlighted Nano-Com as the optimal treatment for maximizing TY, followed by NPK, Nano-Zn+B, and Nano-Ca. Nano-Com not only enhanced tuber yield but also promoted other morphological traits associated with tuber development. Combined application of nano zinc plus nano boron, nano calcium, and the three primary macronutrients (N, P, and K) could further optimize productivity, suggesting that while Nano-Com is the most effective standalone treatment, integration of specific nano-fertilizers may enhance results.

Mechanistic of nano-fertilizers

Nanotechnology in agriculture offers innovative strategies to increase productivity while minimizing environmental impact. Nano-fertilizers increased efficiency of nutrients uptake and decreased nutrient loss by optimizing delivery, maintaining soil structure, and mitigating pollution (Babu *et al.*, 2022). The biplot method proved valuable

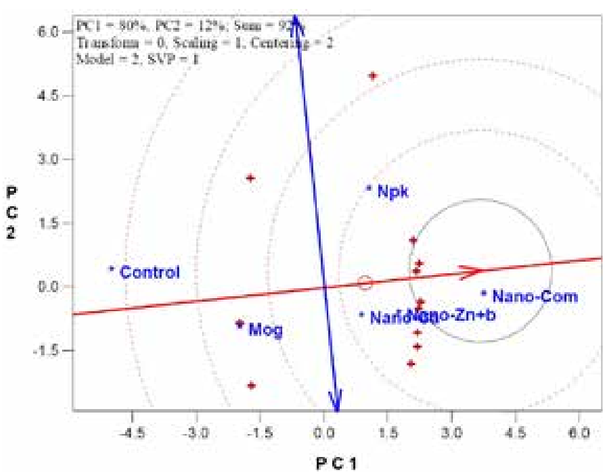

Fig. 4. Ideal entry view of TT biplot, showing the relationships of different nano, bio and bulk fertilizer treatments with ideal entry (treatment) in potato.

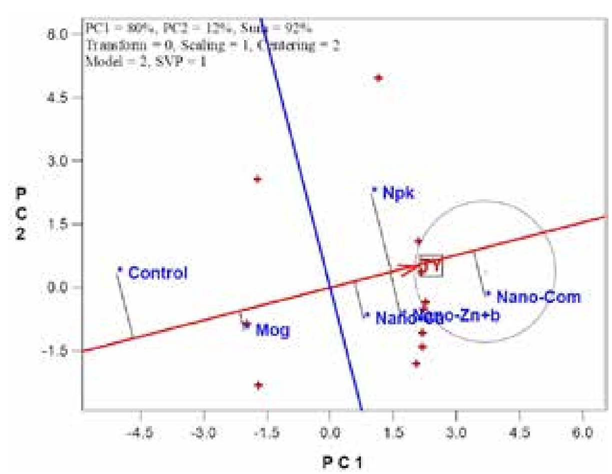

Fig. 5. Vector view of TT biplot, showing the relationships of different nano, bio and bulk fertilizer treatments with tuber yield (TY) of potato. TY is tuber yield (t ha^{-1}).

for assessing treatment trait interactions, allowing simultaneous evaluation of multiple traits (Yan and Rajcan 2002). In semi-arid regions, such as northwest Iran, low soil fertility makes balanced nutrition critical. Soils are often inadequate for meeting crop nutrient requirements using only macronutrients or micronutrients, and biological/enzymatic fertilizers tend to underperform due to insufficient nutritional thresholds (Nikitin *et al.,* 2022). A complete nano-fertilizer, providing all essential nutrients in nano-sized forms, demonstrated superior performance by enhancing vegetative growth, increasing source strength, and stimulating photoassimilate production.

Physiological considerations

The higher performance of Nano-Com can be attributed to its ability to supply a broad spectrum of macro- and micronutrients critical for photosynthesis, protein synthesis, stress response, and tuber development (Noulas *et al.,* 2023). Nutrient synergy, particularly the interaction of NPK with Fe, Zn, and B, likely improved nutrient uptake, metabolic processes, and yield (Fan *et al.*, 2021). Nitrogen increases vegetative growing and photosynthesis, while phosphorus maintains root developing and energy transfer process, but potassium controls water balance and stress tolerance, while Zn and Fe enhance enzyme activity, cell wall stability, and hormone regulation (Dhaliwal *et al.*, 2022). Nano-Ca and Nano-Zn+B also improved specific traits such as tuber weight, dry matter, and starch content, but their effects were less pronounced than Nano-Com due to a more limited nutrient profile (Seleiman *et al.,* 2020; Vera-Maldonado *et al.,* 2024).

Practical advises

The results indicated that Nano-Com is the most promising fertilizer for improving potato yield and quality, particularly in nutrient-poor, semi-arid soils. Complete nano-fertilizers offer a sustainable strategy for increasing crop yield performance, reducing nutrient losses, and mitigating environmental pollution. Adoption of a holistic nutrient management approach, emphasizing nutrient synergy and balanced nutrition, can improve crop performance not only for potatoes but also for other nutrient-sensitive crops. Next investigations should focus on improving application rates and extending evaluations to other crops to maximize agricultural sustainability and productivity.

DISCUSSION

In semi-arid regions, such as the test site in northwest Iran, low soil fertility makes balanced nutrition a critical factor for crop production. The inherent properties of these soils are often insufficient to meet crop nutrient requirements with only macronutrients or micronutrients. Furthermore, the unfavorable physical and chemical conditions of semi-arid soils limit the effectiveness of biological and enzymatic fertilizers, as microbial activity depends on minimum nutrient thresholds that are frequently absent in these environments (Nikitin *et al.,* 2022). The application of a complete nano-fertilizer; providing all essential macronutrients and micronutrients in nano-sized forms, demonstrated superior performance. This indicates that in semi-arid regions, supplying a full complement of nutrients is crucial, as synergistic interactions among them can enhance overall nutrient efficiency. The superior effect of the complete nano-fertilizer in this study is likely due to its ability to strengthen source-sink relationships, promoting vegetative growth, increasing sink capacity, and enhancing the production of photo-assimilates.

This study aimed to evaluate the impact of various fertilizers on the growth and yield of the Spirit potato variety, with a particular focus on nano-fertilizer applications. Results revealed significant effects of fertilizer treatments on key growth traits, including tuber yield, dry matter content, starch content, and several morphological characteristics. Among all treatments, the complete nano-fertilizer; containing nanoparticles of essential macro- and micronutrients, produced the most substantial positive effect on tuber yield. These results highlight the importance of balanced nutrition in promoting high crop productivity, especially in semi-arid regions with prevalent nutrient limitations. The observed increase in tuber yield under complete nano-fertilizer treatment can be attributed to more efficient nutrient uptake facilitated by the nano-sized particles. Previous researches have reported that nano-fertilizers enhance nutrient use efficiency by enhancing uptake through plant roots, particularly under conditions where traditional fertilizers are less effective (Pudhuvai *et al.,* 2024; Shoukat *et al.,* 2025). The tiny size and great surface area of nanoparticles allow them to penetrate plant cell walls and interact more efficiently with plant tissues, preparing a more balanced nutrient supply.

The superior performance of the complete nano-fertilizer also stems from its ability to supply a broad spectrum of nutrients needed for several physiologic processes, like photosynthesis, protein synthesis, and stress response. Balanced nutrient provision is particularly critical in semi-arid areas, where soil fertility is low and nutrient imbalances can limit optimal plant growth (Noulas *et al.,* 2023). By delivering a complete range of nutrients in nanoparticle form, the treatment stimulated vegetative growth, enhanced photosynthesis, and increased tuber formation and yield. An important finding of current research is the role of nutrient synergy in the complete nano-fertilizer. Nutrients interact with one another in complex ways rather than acting in isolation. The synergistic effects of macronutrients (NPK) with micronutrients like iron, zinc, and boron likely contributed to the improved plant performance. This synergy enhances nutrient uptake, metabolic activity, and ultimately, yield (Fan *et al.,* 2021). The addition of micronutrients such as zinc and iron further enhances metabolism, increases stress resilience, and boosts overall productivity (Dhaliwal *et al.,* 2022). Supplying all these nutrients in nanoparticle form ensures a well-rounded nutritional profile, translating into improved tuber yield.

Although, the complete nano-fertilizer was the most effective, other treatments such as Nano-Ca (nano chelated calcium) and Nano-Zn+B (nano chelated zinc and boron) also improved tuber yield and related traits, albeit to a lesser extent. Nano-Ca enhanced the number and weight of tubers, likely due to its role in strengthening cell walls and promoting root development (Seleiman *et al.,* 2020). Nano-Zn+B improved dry matter and starch content, reflecting the importance of zinc and boron in enzyme activity, cell wall stability, and hormone regulation (Vera-Maldonado *et al.,* 2024). However, these single-nutrient applications could not match the effectiveness of the complete nano-fertilizer. The biplot analysis for treatment trait interactions proved valuable for visualizing fertilizer performance across multiple traits. It highlighted that the complete nano-fertilizer consistently outperformed other treatments in key traits such as leaf development, tuber weight per plant, and starch content. Current findings indicated the capability of complete nano-fertilizers to increase potato yield and quality, particularly in nutrient-poor, semi-arid soils.

The obtained results have significant implications for semi-arid regions like northwest Iran, whereat soil fertility limits crop productivity. Complete nano-fertilizers offer a sustainable strategy for increasing yields while minimizing nutrient loss and environmental impact. By ensuring efficient nutrient uptake and balanced nutrition, their application could improve potato yields, food security, and farmer livelihoods. Current study emphasized the importance of a fertilizer managing that considers nutrient interactions. Traditional fertilization often focuses on individual nutrients, whereas the complete nano-fertilizer demonstrates that balanced, synergistic nutrient delivery yields the best results. This approach can benefit not only potatoes but also other crops grown in nutrient-limited environments. Supplying a full complement of nutrients in nanoparticle form presents a promising solution to the challenges of low soil fertility and environmental stress. Future research should optimize nano-fertilizer application rates and explore their potential across other crops to further enhance agricultural sustainability and productivity.

CONCLUSION

The study demonstrated that fertilizer type influences growth, tuber yield, and quality of the Spirit potato variety under semi-arid conditions. The complete nano-chelated fertilizer, containing macro-(N, P, K) and micronutrients (Zn, Fe, B, Ca, Mn, Cu) in nanoparticle form, performed better than the other fertilizers across important traits, like leaf number, tuber weight per plant, tuber yield, dry matter, and starch content. The enhanced performance of above treatment is attributed to its balanced nutrient provision, improved source-sink relationships, and synergistic interactions between macro- and micronutrients, which collectively increase nutrient uptake, photosynthesis, and tuber development. Nano-Ca and Nano-Zn+B also improved specific traits such as tuber weight, dry matter, and starch content, but their effects were less pronounced due to their limited nutrient profiles, while NPK improved stem number but was less effective than Nano-Com in enhancing tuber yield and quality. Based on the results, the recommended quantity for effective nano-fertilizer application is 150 kg ha^{-1} of the complete nano-chelated fertilizer, split into three equal applications at vegetative, flowering, and tuber initiation stages. This regimen ensures balanced nutrient supply throughout the growth cycle, maximizing tuber yield and quality while minimizing environmental nutrient losses. Finally, complete nano-chelated fertilizer provided a sustainable and efficient nutrient management strategy for potato cultivation in nutrient-poor, semi-arid soils. Its application can improve productivity, support food security, and serve as a model for integrating complete nano-fertilizers in other nutrient-sensitive crops.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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