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Original Article

Influence of Nano NPK via Foliar Spray Versus Soil-Applied NPK on Nutrient Uptake and Productivity of Lettuce (Lactuca sativa L)

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ABSTRACT

Modern agriculture must boost food output sustainably, as conventional fertilizers cause soil damage, water pollution, and nitrate buildup in crops. In response, nano-fertilizers, especially those formulated with nitrogen, phosphorus, and potassium (nano NPK) are emerging as a more efficient and environmentally friendly alternative. This study explored how foliar-applied versus soil-applied nano NPK affects the growth, yield, and nutrient content of lettuce (Lactuca sativa L.), a fast-growing leafy vegetable with high nutrient demands. A greenhouse experiment was carried out during the 2022–2023 season at the Bakrajo Technical Institute using a randomized block design. Lettuce plants were treated with different concentrations of nano NPK via foliar sprays (0, 2, 4, and 6 g/L) and compared to soil applications of conventional NPK (30, 60, and 90 g per plant). Throughout the season, data were collected on plant growth, leaf traits, chlorophyll content, moisture, and nutrient levels. The results showed that moderate foliar applications of nano NPK, especially at 4 g/L, significantly boosted plant height, root development, total weight, and chlorophyll levels, often performing as well as or better than higher doses of conventional fertilizers. Additionally, nano treatments helped reduce nitrate buildup in leaves and maintained higher moisture content, which is valuable for fresh-market quality. On the other hand, soil-applied NPK was more effective at increasing dry matter and potassium uptake. These results reveal that nano NPK if applied in the correct dose and with the appropriate application technique, can promote the growth of healthier crops with fewer disadvantages to the environment.

1. Introduction

The production of more foods with fewer resources while causing little disturbance to nature has become a major challenge for agriculture in recent times. While such fertilizers have increased yields, the misuse of fertilizers in the real sense of the word has also caused adverse effects like soil degradation, water contamination, nutrient imbalance, and greenhouse emissions (Zhang et al., 2015; Aied et al., 2025). Among the most promising approaches are nano fertilizers and specially nano-formulated nitrogen, phosphorous, and potash (Nano NPK) fertilizers, which have drawn interest

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owing to their distinctive characteristics and potential applications in the complete transformation of crop nutrition (Liu & Lal, 2015; Kumar et al., 2025).

Plant nutrients in the nano form are, in essence, nutrient particles engineered at the nanoscale, usually smaller than 100 nanometers, to exhibit increased reactivity, solubility, and bioavailability as compared to conventional fertilizers (Chhipa, 2017; Tofiq et al., 2021). These properties help maximize nutrient delivery to target sites as well as reduce loss by leaching or volatilization, thereby raising nutrient uptake by plants (Dimkpa & Bindraban, 2018). Foliar application of nano-NPK fertilizers, whereby nutrients are applied directly to the leaves, has demonstrated ample potential in increasing crop production, especially for fast-growing and nutrient-demanding crops like lettuce (Lactuca sativa L.) (Subramanian et al., 2015; Helaly et al., 2021).

Lettuce, having a short cycle of growth and characterized by its high-water content, is among the most consumed leafy vegetables (Mahmood & Abdel, 2018). Being shallow-rooted and quick in its nutrient demands, lettuce is hence very quick to respond to fertilization (Ahmed et al., 2024). On the side, it is quite sensitive to the form, method, and time of nutrient application. Synergistically, the ability of nano NPK to release nutrients directly and efficiently, especially through the foliar route, can transform traditional methods of lettuce nutrition management. There are reports that confirm the application of nano fertilizers through foliar spray as beneficial to the leaf vegetables by enlarging leaf area, biomass, chlorophyll content, and quality parameters (Tarafdar et al., 2014; Uresti-Porras, 2021; Semenova et al., 2024).

Nevertheless, it is essential to acknowledge that foliar nutrients provide rapid responses and limited soil interaction, whereas nano NPK administration via soil is particularly effective in promoting root development and microbial interactions within the rhizosphere (Rastogi et al., 2017). The essence of the argument centers on the inquiry: which application method, foliar or soil, is superior for enhancing nutrient uptake and improving output, particularly in actual agricultural settings? Prior research indicates that the efficacy of nano NPK fertilizers is contingent upon administration methods, plant species, and environmental circumstances (Duhan et al., 2017; Kah et al., 2018).

If nano fertilizers can maintain or even increase yields with lesser fertilizer application, then the environmental benefits may become very pronounced. With the potential to reduce fertilizer input by 30–50% without dropping in productivity (Al-Khayri et al., 2023; Rajashekar and Armstrong, 2024; Lata et al., 2025).

The need for designing better fertilization technologies is becoming the soul of modern-day agriculture, with ever-increasing input costs and concerns for climate change dictating new paradigms for food production (Usman et al., 2020). In the case of lettuce, being very important in many local and global markets, it provides an excellent opportunity to study new fertilization technologies.

Studying the comparative effects of foliar versus soil nano NPK is beyond a mere technical sphere; it instigates progress toward a sustainable future for nutrient management. Nano NPK, if delivered most efficiently, can, therefore, be implemented in agricultural systems to lessen their ecological risks while improving economic gains. The research is intended to study the effect of application methods of Nano NPK fertilizer (foliar and soil) on nutrient uptake, performance, growth, and yield of lettuce (Lactuca sativa L.).

2. Material and Methods

The field experiment was established during the growing season of 2022-2023 in the greenhouses at Bakrajo Technical Institute, which is a part of the Sulaimani Polytechnic University. It is located at an altitude of 838 m.a.s.l. (Abdullah et al., 2015). The area is known for its temperate climate, with moderate temperatures and relative humidity.

Table 1. Soil traits of experimental site: Site

Properties	Sand gKg^{-1}	Silt gKg^{-1}	Clay gKg^{-1}	EC dsm^{-1}	pH	N $mgKg^{-1}$	Available p $mgKg^{-1}$	Soluble K^{+} (mM.L-1)
Sample	121.3	457.6	421.1	0.34	7.1	0.14	31.2	0.29

The soil analysis was conducted by the Directorate of the Agricultural Research Center in Sulaimaniyah.

Before planting, the soil was analyzed, as presented in Table 1.

2.1 Plant Material, Land Preparation, and Cultivation

After germination and early growth, hybrid lettuce seedlings (Lactuca sativa L., cultivar Pito ZADEN) were transplanted on October 20, 2022, and planted along rows with a spacing of 40 cm between individual plants and 60 cm between rows. Weeds were controlled through manual hoeing and hand weeding as needed. The plants were regularly monitored throughout the growing season, and pest management measures were applied equally across all treatments whenever necessary. Harvesting took place between January 10 and January 20.

The experiment relied on drip irrigation, which was applied one day prior to transplanting to moisten the soil. Irrigation scheduling was based on prevailing weather conditions, with the aim of maintaining adequate moisture levels in the root zone.

The experimental layout consisted of four blocks (replicates), each comprising seven treatments. For this treatment evaluation, five plant samples from the various treatments were randomly chosen for data collection. The field data were recorded during the cultivation period based on visual observations and measurements pertaining to growth and yield parameters for research purposes.

2.2 Experimental Design

The study included two main factors:

1. Nano foliar fertilization with balanced NPK (20-20-20) at four concentrations:

- Control (no application)
- Low concentration (2 g/L)
- Medium concentration (4 g/L)
- High concentration (6 g/L)

2. Soil application of a balanced NPK fertilizer (20-20-20) was carried out using four different concentrations:

- A low concentration (T1) of 30 g/plant.
- A medium concentration (T2) of 60 g/plant.
- A high concentration (T3) of 90 g/plant.

The experiment was designed as a 4 × 4 factorial arrangement within a Randomized Complete Block Design (RCBD) with four replicates.

2.3 Application of Treatments

Foliar application of Nano NPK (20-20-20) fertilizer began in the third week after transplanting. Subsequent foliar sprays were applied in the fifth and seventh weeks, with a two-week interval between each application. A manual hand sprayer was used for all foliar treatments to ensure even coverage.

In addition, soil application of the conventional balanced NPK (20-20-20) fertilizer was conducted biweekly for a total duration of six weeks. This approach was applied consistently across the designated soil-treated plots to evaluate the effectiveness of different application methods.

2.4 Data Collection and Measurements

Data collection was performed at the time of harvest. The following morphological and physiological parameters were recorded:

- Plant height (cm)

- Chlorophyll content (spad)
- Head diameter (cm)
- Stem diameter (mm)
- Leaf width (cm)
- Leaf length (cm)
- Leaf surface area(cm2)
- Number of outer leaves
- Number of inner leaves
- Leaf moisture content (%)
- Root length (cm)
- Root fresh weight (g)
- Fresh leaf weight (g)
- Total plant weight (g)

In addition to growth-related traits, the following chemical analyses were conducted to evaluate nutrient uptake:

- Nitrogen (N)(%)
- Phosphorus (P) (%)
- Potassium (K) (%)
- Nitrate content (NO_3^-)(%)

2.5 Statistical Analysis

All recorded data were subjected to analysis of variance (ANOVA) appropriate for the RCBD design, as described by Stell et al. (1980). To compare treatment means, the Least Significant Difference (LSD) test was employed at a 5% level of significance.

3. Results and Discussion

The data from Table 2 reveal clear differences in how lettuce growth traits respond to foliar-applied Nano NPK compared to soil-applied conventional NPK. These findings reflect how nutrient delivery methods and concentrations can influence physiological growth patterns and overall plant development.

Root length appeared to benefit most under the nano control treatment (14.91 cm) and the highest conventional NPK dose (90 gm, 14.5 cm), while the 60 gm treatment showed a significantly shorter root length (12.58 cm). This suggests that moderate or well-regulated nutrient availability can promote optimal root elongation. In contrast, excessive soil-applied nutrients may reduce root expansion, possibly due to feedback inhibition mechanisms. Nanoparticles are known to enhance nutrient absorption and movement within the plant, which could explain the better root performance at lower concentrations (Khodakovskaya et al., 2012).

Concerning the root fresh weight, the maximum values were recorded in the treatments with 60 gm NPK and 2 gm nano (43.53 g and 41.43 g, respectively), with 6 gm nano showing a significant drop down to 30.50 g. This apparently signifies that low doses of nanoparticles could boost root biomass formation, just as do the high dosages of conventional fertilizers. Yet, a higher nanoparticle concentration could be counterproductive due to the emergence of toxicity or nutrient imbalance (Abbasirad & Ghotbi-Ravandi, 2025).

The stem diameter followed quite a similar trend. The 30 gm and 60 gm NPK treatments produced the thickest stems, on par with the nano control. But 2 gm nano treatment resulted in thinner stems (21.02 mm), indicating that at this dose the nutrients might not have been adequate to stimulate proper stem development. Such variation in the response corresponds with reports indicating the necessity of a judicious optimization of the nano-fertilizer dose due to its narrow window range of efficacy (Rastogi et al., 2017).

Plant height was generally taller in the nano treatments, particularly at 4 gm and 6 gm, as well as in the nano control. These plants grew over 33 cm tall and exceeded the 30 gm NPK group in performance (30.08 cm). This may be due to the faster and more efficient nutrient transportation by

Table 2. Influence of Nano NPK via Foliar Spray Versus Soil-Applied NPK on Some Growth Traits of Lettuce.

Treatments		Root Length (cm)	Root fresh Weight (g)	Stem diameter (mm)	Plant Hight (cm)	Head diameter (cm)	Total plant Weight (g)
Nano particles	Control	14.91 a	35.53 ab	26.98 a	33.57 a	39.60 a	484.00 a
	2 gm	13.38 ab	41.43 ab	21.02 b	32.80 ab	38.80 a	420.00 ab
	4 gm	14.20 ab	33.83 ab	24.58 ab	35.20 a	36.40 ab	402.00 ab
	6 gm	13.26 ab	30.50 b	25.88 ab	35.28 a	33.00 b	378.00 b
NPK	30 gm	13.88 ab	39.93 ab	28.46 a	30.08 b	38.00 ab	434.00 ab
	60 gm	12.58 b	43.53 a	28.60 a	32.70 ab	40.40 a	490.00 a
	90 gm	14.50 ab	37.38 ab	24.58 ab	32.30 ab	41.20 a	478.00 a
LSD		1.627	8.334	3.515	2.666	3.55	69.69

Similar letters in the same column indicate no significant differences (P>0.05).

nanoparticles, resulting in the accelerated shoot growth (Zhao et al., 2020).

In terms of head diameter, the highest values belonged to the nano control and 60 gm NPK groups, with sizes beyond 39 cm. However, at the 6 gm nano dose, the head size significantly declined to 33 cm, indicating that going beyond the threshold nanoparticle concentration level could impair the head development. This may be related to oxidative stress or a hormonal imbalance triggered from overexposure to nanoparticles (Raliya et al., 2015).

The weighted total plant production ranged in tandem with the dose-dependent effects. The highest call yield included 60 gm NPK (490 g) and nano control (484 g), with the 90 gm NPK also performing well. But at the 6 gm level, plant weight was decreased drastically (378 g), confirming that, when in excess, nano-fertilization actually harms biomass accumulation rather than helping it. These findings are consistent with studies advocating for low, precisely managed nano-nutrient applications to avoid antagonistic effects and ensure safe, effective use (Solanki et al., 2015).

Taken together, the results demonstrate that low doses of foliar-applied nano NPK can match or even exceed the performance of traditional, soil-applied fertilizers in key lettuce growth parameters. Yet, the outcomes also highlight the importance of precision. Over-application of nanoparticles appears to reverse these benefits, underscoring the need for proper dosage calibration in nano fertilizer use (Servin et al., 2015).

The results in Table 3 reflect how differently lettuce plants respond to nano NPK applied via foliar spray compared to conventional NPK delivered through soil, specifically in terms of production traits such as leaf dimensions, leaf weight, and leaf count.

Across treatments, leaf width did not show any statistically significant differences ($P > 0.05$), with values ranging narrowly between 9.62 cm and 10.7 cm. Although the 90 gm NPK treatment recorded the highest width (10.7 cm), this was not significantly different from the nano treatments. This outcome suggests that leaf width may be relatively stable under varied nutrient sources and may not be the most sensitive trait to distinguish treatment efficiency. However, the consistent width across nano-treated plants also implies their adequacy in sustaining leaf development (Solanki et al., 2015).

On the other hand, leaf area exhibited notable variation. The 60 gm NPK treatment produced the largest leaf area (5.556 cm^2), significantly greater than all nano treatments and even the conventional 30 and 90 gm groups. In contrast, nano treatments, particularly at 2 gm and 4 gm doses, showed markedly lower leaf areas (2.822 and 2.908 cm^2). This may indicate that while nano-fertilizers can support linear growth (length and width), they might be less effective in promoting expansive leaf surface area—possibly due to the limited nutrient reservoir from foliar application compared to soil availability. Leaf area is directly related to photosynthetic capacity and is often enhanced when nutrient availability is continuous and systemic, as occurs in soil-based applications (Bielczynski et al., 2017).

Interestingly, leaf length remained statistically similar across all treatments, ranging from 23.26 to 25.6 cm. This trait, much like leaf width, appears relatively insensitive to the nutrient source and method of delivery. It's possible that length is governed more by genetic factors or water status than by macronutrient input (Rastogi et al., 2017).

Wet leaf weight followed a slightly different pattern. While the 90 gm and 60 gm NPK treatments yielded the highest values (299.77 g and 296.04 g, respectively), these were not significantly different from nano or other conventional treatments. Even the nano control produced a relatively high wet leaf weight (285.07 g). These results highlight that foliar nano-NPK can sustain competitive leaf biomass production, particularly under moderate applications. Such efficiency is likely due to enhanced nutrient uptake at the foliar level, where nanoparticles penetrate cuticles and enter cells more efficiently than bulk particles (Khodakovskaya et al., 2012).

Looking at the number of outer leaves, the highest values were found in the nano control and 90 gm NPK treatments (16.6 and 16.4, respectively), although these did not significantly differ from most other treatments. However, the 30 gm NPK group showed a significantly lower number (12.6), suggesting that inadequate soil-based nutrient availability can constrain outer leaf development. Nano-fertilizers sprayed onto the foliage, even at lower doses, tend to maximize the growth of the outer leaves, possibly by making sure that the necessary N and K needed for leaf initiation and expansion are absorbed in time (Raliya et al., 2015). Regarding the number of inner leaves, the very high figures were observed in treatments with 60 gm and 90 gm of NPK (both 16.4), and the lowest number of inner leaves was with the 6 gm nano (12.2), which may suggest either diminishing returns or some slight toxicity imposed by the higher doses of nano. Quite an opposite reaction in inner leaf number under the 6 gm nano treatment signifies that perhaps higher foliar concentrations might not effectively penetrate or could induce some local foliar stress, as was reported by Servin et al. (2015). In contrast, the balanced action of the nano control and 2–4 gm treatments would support the concept of using the lower doses of nanoparticles to assist internal leaf formation without burdening the system.

These results highlight that foliar nano-NPK fertilizers are effective in sustaining many of the key yield-related traits in lettuce, such as leaf length, width, and wet weight, but may be less effective for traits heavily influenced by nutrient continuity, like leaf area and inner leaf proliferation. Conventional soil NPK, particularly at higher doses, remains superior for boosting total leaf expansion and density. This supports the idea of integrating nano-fertilization with conventional methods for optimized productivity and sustainability in leafy vegetables.

The findings in Table 4 provide insight into how the method and concentration of fertilizer application—whether nano-based via foliar spray or conventional NPK through soil—affect physiological content in lettuce plants. The measured traits include moisture content, dry matter percentage, and chlorophyll concentration, which are essential indicators of plant health, nutrient assimilation, and photosynthetic efficiency.

Starting with moisture content, the highest values were recorded in the nano treatments, particularly at 4 gm (52.68%) and in the nano control group (52.58%), with no significant difference between them. These were notably higher than all conventional NPK treatments, especially the 30 gm and 60 gm doses, which showed significantly reduced moisture contents (31.28% and 32.36%, respectively).

Table 3. Influence of Nano NPK via Foliar Spray Versus Soil-Applied NPK on Some Production Traits of lettuce

Treatments		Traits					
		leaf width (cm)	Leaf Area (cm)	leaf length (cm)	Wet leaf wt. (g)	Number of outer leaves	Number of inner leaves
Nano particles	Control	10.24 a	4.51 b	25.33 a	285.06 a	16.60 a	14.80 ab
	2 gm	10.44 a	2.82 e	25.38 a	240.58 a	15.00 ab	13.80 ab
	4 gm	9.94 a	2.90 de	24.78 a	242.52 a	14.00 ab	13.40 ab
	6 gm	10.60 a	3.57 cd	25.60 a	237.85 a	15.00 ab	12.20 b
NPK	30 gm	9.68 a	4.20 bc	23.26 a	250.76 a	12.60 b	15.40 ab
	60 gm	9.62 a	5.55 a	23.90 a	296.03 a	13.80 ab	16.60 a
	90 gm	10.70 a	4.17 bc	25.06 a	299.76 a	16.40 ab	16.40 a
LSD		1.314	0.494	1.766	49.417	2.944	2.886

Similar letters in the same column indicate no significant differences (P>0.05).

This suggests that nano-fertilizers—when foliar-applied—help retain water within plant tissues more effectively than soil-applied NPK. The likely mechanism is the enhanced stomatal regulation and improved osmotic balance triggered by the small size and controlled release of nano-nutrients (Raliya et al., 2015). By contrast, soil-applied bulk fertilizers may lead to excessive salt buildup or osmotic stress, contributing to reduced water retention in tissues (Shalaby et al., 2016).

In terms of dry matter content, the inverse trend was observed. The 30 gm and 60 gm NPK treatments recorded the highest dry matter percentages (68.72% and 67.64%, respectively), significantly surpassing all nano treatments. This is expected, as reduced water content often leads to concentration of structural and metabolic solids. These results imply that while nano-NPK helps maintain tissue hydration, it may not contribute as significantly to structural biomass accumulation compared to traditional soil-based fertilization. However, from a fresh-market perspective, moisture-rich lettuce is often preferred for texture and weight (Solanki et al., 2015).

Looking at chlorophyll content, one of the key indicators of photosynthetic capacity and leaf vitality, the highest values were observed in the nano control (22.70), 4 gm nano (21.70), and 6 gm nano (22.12) treatments. These were significantly higher than the 30 gm NPK treatment (14.92) and slightly higher than the 60 gm and 90 gm NPK treatments. This strongly supports the potential of nano-fertilizers to enhance pigment synthesis and photosynthetic activity. Nanoparticles, particularly when absorbed via leaf surfaces, can improve nitrogen use efficiency and magnesium availability—both critical for chlorophyll biosynthesis (Khodakovskaya et al., 2012; Zhao et al., 2020).

Interestingly, while the 2 gm nano treatment showed slightly reduced chlorophyll levels (16.58), this may suggest an insufficient nutrient load to fully support pigment development at that dose. In contrast, mid-to-high nano dosages (4–6 gm) seemed to strike the right balance, enhancing chlorophyll while maintaining optimal moisture. This trend aligns with prior findings indicating that moderate nanoparticle concentrations can stimulate photosynthetic gene expression, whereas too little or too much can disrupt metabolic balance (Rastogi et al., 2017).

Taken together, these results illustrate a complementary picture: Nano-fertilizers appear to support better hydration and chlorophyll accumulation, making them ideal for maintaining physiological quality and freshness in leafy vegetables like lettuce. Meanwhile, soil-applied

Table 4. Influence of Nano NPK via Foliar Spray Versus Soil-Applied NPK on Some Plant Content of Lettuce.

Treatments		Traits		
		Moisture %	Dry matter %	Chlorophyll content (spad)
Nano particles	Control	52.584 a	44.970 b	22.700 a
	2 gm	46.894 a	52.926 b	16.580 bc
	4 gm	52.682 a	47.318 b	21.700 a
	6 gm	50.664 a	49.336 b	22.120 a
NPK	30 gm	31.280 b	68.720 a	14.920 c
	60 gm	32.364 b	67.636 a	19.340 ab
	90 gm	48.672 a	51.328 b	21.700 a
LSD		9.998	8.201	2.747

Similar letters in the same column indicate no significant differences (P>0.05).

conventional NPK is more effective in increasing dry matter, which may be advantageous for yield-focused production systems. The evidence supports the idea of tailored fertilization strategies—possibly integrating both nano and conventional fertilizers—to meet specific production goals (Servin et al., 2015).

The data in Figure 1 offer insights into how different fertilization methods—foliar-applied nano NPK versus soil-applied conventional NPK—affect the mineral nutrient accumulation in lettuce, specifically focusing on nitrate (NO_3^-), potassium (K), phosphorus (P), and nitrogen (N). These nutrients are essential for plant metabolism, growth, and quality, and their distribution within plant tissues reflects both nutrient availability and uptake efficiency.

Starting with nitrate (NO_3^-) content, the lowest values were recorded in the nano control and 2 gm nano treatment (0.223 and 0.200, respectively), while significantly higher nitrate levels were observed in the 4–6 gm nano treatments and all NPK treatments (0.273–0.302). This suggests that lower doses of nano NPK reduce nitrate accumulation, which is considered beneficial from a food safety perspective. High nitrate levels in leafy vegetables like lettuce are often linked to health risks in humans, such as methemoglobinemia (blue baby syndrome) and potential carcinogenic effects (Santamaria, 2006). The efficient nutrient use associated with nano-fertilizers may reduce nitrate assimilation without compromising plant growth (Liu & Lal, 2015).

In terms of potassium (K) content, a striking difference was observed. All nano treatments and most conventional NPK treatments showed relatively low K concentrations (0.072–0.120), except for the 60 gm NPK treatment, which had a significantly higher value (0.542). This suggests that soil-applied potassium at sufficient dosage ensures better systemic uptake, likely due to its higher mobility in soil water compared to foliar uptake efficiency. On the other hand, foliar-applied nanoparticles may require surface modification or formulation improvement to enhance potassium delivery (Subramanian et al., 2015).

For phosphorus (P) content, values ranged narrowly from 0.458 to 0.509, with no significant differences among most treatments. The 60 gm NPK dose slightly outperformed others (0.509), which may reflect the sustained release of phosphorus from soil granules over time. However, the nano treatments—especially at 4 and 6 gm—maintained phosphorus levels on par with conventional fertilizers. This suggests that nanoscale phosphorus delivery is effective in maintaining adequate P levels, thanks to better leaf cuticle penetration and improved phloem mobility (Dimkpa & Bindraban, 2018).

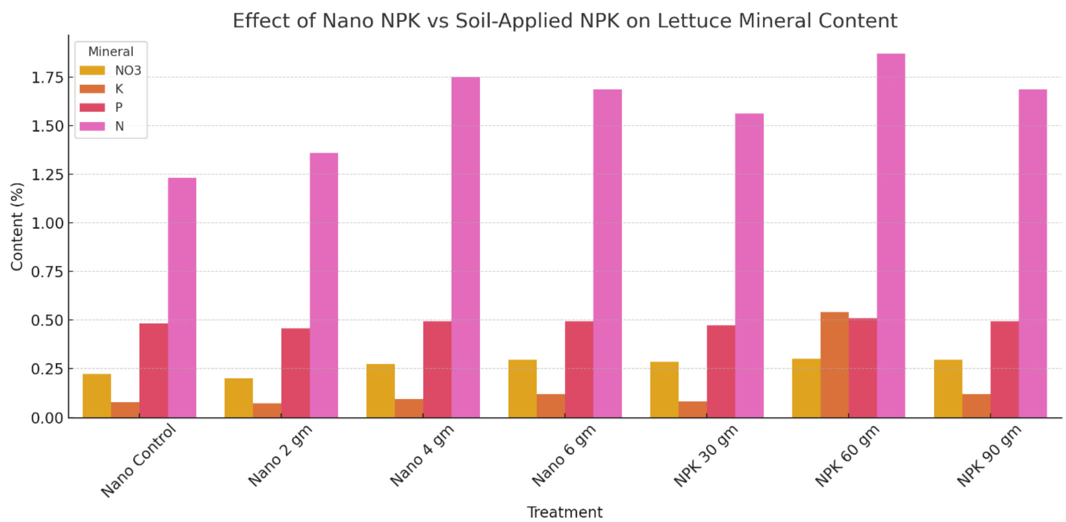

Figure 1. Influence of Nano NPK via Foliar Spray Versus Soil-Applied NPK on Plant Mineral Content of Lettuce

The most prominent trend was observed in total nitrogen (N) content. The lowest N values appeared in the nano control and 2 gm nano treatment (1.233 and 1.360), while nitrogen increased significantly at higher nano doses (1.687–1.750) and peaked at 60 gm NPK (1.873). These results reflect a dose-dependent response in both delivery systems. High nitrogen content is generally correlated with increased protein synthesis and vegetative growth. The 4 gm nano treatment provided nitrogen levels comparable to high-dose conventional fertilizers, which indicates that moderate foliar application of nano-NPK is sufficient to meet nitrogen demands without risking over-fertilization (Parisi et al., 2015).

Together, these results confirm the potential of nano NPK—especially at 4–6 gm doses—for improving nitrogen and phosphorus content efficiently while also reducing nitrate accumulation, a clear advantage from a consumer safety standpoint. However, for potassium uptake, conventional soil fertilization (particularly at 60 gm) remains more effective, likely due to the systemic movement and root uptake preference of K^+ ions in plants (Wang et al., 2021). Therefore, a combined approach or formulation refinement may be necessary to maximize the mineral balance in leafy crops.

4. Conclusion

This investigation has shown that foliar application of nano NPK fertilizers, notably at the 4 g/L concentration, could greatly increase lettuce growth, yield, and physiological quality while reducing nitrate accumulation. In comparison to the soil-applied NPK fertilizers, nano fertilizers exhibited positive effects on height, chlorophyll content, and moisture retention of plants, thus contributing to fresh-market quality and environmental sustainability. However, soil-applied NPK fertilizers performed better than nano fertilizers in the enhancement of dry matter and uptake of potassium, especially at the 60 g dose. The authors conclude that, therefore, an integrated or site-specific fertilization system that utilizes the advantages of both nano and conventional fertilizers can boost nutrient use efficiency and, in turn, promote sustainable crop production systems.

Conflict of interest

The authors declare that there is no conflict of interests.

CRediT authorship contribution statement

Conceptualization, methodology, writing—original draft preparation, **Nigar Majeed Abdalrahman**; data curation, writing—review, and editing, **Hawar Ali Maruf**; formal analysis, data curation, **Sazan Fathi Sharif**; writing—review and editing, **Niyan Jalal Qadir**. All authors have read and agreed to the published version of the manuscript.

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References

Abdulla, A. R., Ahmed, J. O. & Mahmood, S. Q. (2015): Comparisons of six hybrids corn (Zea mays L.), in terms of yields and components in Sulaimania. American Eurasian Journal of Agriculture & Environmental. Sciences, 15(5), pp.848-852.

Abbasirad, S. & Ghotbi-Ravandi, A. A. (2025): Toxicity of copper oxide nanoparticles in barley: induction of oxidative stress, hormonal imbalance, and systemic resistances. BMC Plant Biology, 25, pp.1–16.https://doi.org/10.1186/s12870-025-06213-6

Ahmed, G. O., Halshoy, H. S., Mahmood, C. H. & Hama, J. R. (2024): Titanium nanoparticle and humic acid applications improve seed germination, growth development, and phytochemical contents of lettuce (Lactuca sativa) plants. BioNanoScience, 14, pp.4930–4941. https://doi.org/10.1007/s12668-024-01545-3

Aied, K. Y., Farhan, M. J. & Ghassan, J.Z. (2025): Effect of vermicompost tea addition methods on growth and yield of lettuce (Lactuca sativa). Tikrit Journal for Agricultural Sciences, 25, pp. 201–208. https://doi.org/10.25130/tjas.25.2.17

Al-Khayri, J. M., Rashmi, R., Surya Ulhas, R., Sudheer, W. N., Banadka, A., Nagella, P., Aldaej, M. I., Rezk, A. A.-S., Shehata, W. F. & Almaghasla, M. I. (2023): The role of nanoparticles in response of plants to abiotic stress at physiological, biochemical, and molecular levels. Plants, 12, pp. 292. https://doi.org/10.3390/plants12020292

Bielczynski, L. W., Łącki, M. K., Hoefnagels, I., Gambin, A. & Croce, R. (2017): Leaf and plant age affects photosynthetic performance and photoprotective capacity. Plant Physiology, 175, 1634–1648. https://doi.org/10.1104/pp.17.00904

Chhipa, H. (2017): Nanofertilizers and nanopesticides for agriculture. Environmental Chemistry Letters, 15, pp.15–22. https://doi.org/10.1007/s10311-016-0600-4

Dimkpa, C. O. & Bindraban, P. S. (2018): Nanofertilizers: New products for the industry? Journal of Agricultural and Food Chemistry, 66, pp. 6462–6473. https://doi.org/10.1021/acs.jafc.7b02150

Duhan, J. S., Kumar, R., Kumar, N., Kaur, P., Nehra, K. & Duhan, S. (2017): Nanotechnology: The new perspective in precision agriculture. Biotechnology Reports, 15, pp.11–23.https://doi.org/10.1016/j.btre.2017.03.002.

Helaly, A. A., Ashmawi, A. E., Mohammed, A. A., El-Abd, M. T. & Nofal, A. S. (2021): Effect of soil application of nano NPK fertilizers on growth, productivity and quality of lettuce (Lactuca sativa). Al-Azhar Journal of Agricultural Research, 46, pp.91–100.https://doi.org/10.21608/ajar.2021.218559

Kah, M., Kookana, R. S., Gogos, A. & Bucheli, T. D. (2018): A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. Nature Nanotechnology, 13, pp.677–684.https://doi.org/10.1038/s41565-018-0131-1

Khodakovskaya, M. V., Kim, B. S., Kim, J. N., Alimohammadi, M., Dervishi, E. & Cernigla, C. E.

(2012): Carbon nanotubes as plant growth regulators: effects on tomato growth, reproductive system, and soil microbial community. Small, 9, pp.115–123. https://doi.org/10.1002/smll.201201225

Kumar, S., Sharma, Y., Khandelwal, V., Rawat, K. & Patil, A. (2025): Applications of nanotechnology in fertilizers: a review study. Sustainable Chemistry for the Environment, 67, pp. 100247. https://doi.org/10.1016/j.scenv.2025.100247

Lata, S., Yadav, A., Kumar, P., & Joshi, A. K. (2025). Nanofertilizers for Sustainable Crop Production Under Changing Climate: A Global Perspective. In Smart Technologies in Sustainable Agriculture (pp. 23-62). Apple Academic Press.

Liu, R. & Lal, R. (2015): Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Science of the Total Environment, 514, pp.131–139. https://doi.org/10.1016/j.scitotenv.2015.01.104

Mahmood, C. H. & Abdel, C. G. (2018): Response of imbibing lettuce (Lactuca sativa var. longifolia) cv. Marul seeds to boron levels and mulching on head folding, bitterness, and quality of produced seeds. Sulaimani Journal for Pure and Applied Sciences, 1, pp.468–482. https://doi.org/10.17656/jzs.10694

Parisi, C., Vigani, M. & Rodríguez-Cerezo, E. (2015): Agricultural nanotechnologies: what are the current possibilities. Nano Today, 30, pp.100829. https://doi.org/10.1016/j.nantod.2019.100829

Raliya, R., Tarafdar, J. C. & Biswas, P. (2015): Enhancing the mobilization of native phosphorus in the arid soil using zinc nanoparticles: an approach to overcome phosphorus deficiency for sustainable agriculture. International Journal of Biological Sciences, 11, pp.1134–1143. https://doi.org/10.7150/ijbs.12244

Rajashekar, C. B. & Armstrong, B. (2024): Effect of titanium dioxide nanoparticles on growth and biomass accumulation in lettuce (Lactuca sativa). American Journal of Plant Sciences, 15, pp.1–13.https://doi.org/10.4236/ajps.2024.151001

Rastogi, A., Zivcak, M., Sytar, O., Kalaji, H. M., He, X., Mbarki, S. & Brestic, M. (2017): Impact of metal and metal oxide nanoparticles on plant: a critical review. Frontiers in Chemistry, 5, pp.78.https://doi.org/10.3389/fchem.2017.00078

Santamaria, P. (2006): Nitrate in vegetables: toxicity, content, intake and EC regulation. Journal of the Science of Food and Agriculture, 86, pp.10–17. https://doi.org/10.1002/jsfa.2351

Servin, A., Elmer, W., Mukherjee, A., De la Torre-Roche, R., Hamdi, H., White, J. C. & Bindraban, P. S. (2015): A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. Journal of Nanoparticle Research, 17, pp.92.https://doi.org/10.1007/s11051-015-2907-7

Semenova, N.A., Burmistrov, D.E., Shumeyko, S.A. & Gudkov, S.V. (2024): Fertilizers Based on Nanoparticles as Sources of Macro- and Microelements for Plant Crop Growth: A Review. Agronomy, 14(8), pp.1646. https://doi.org/10.3390/agronomy14081646

Shalaby, T. A., Bayoumi, Y., Abdalla, N., Taha, H., Alshaal, T., Shehata, S. & El-Ramady, H. (2016): Nanoparticles, soils, plants and sustainable agriculture. Nanoscience in Food and Agriculture, 1, pp.283–312.https://doi.org/ 10.1007/978-3-319-39303-2_10

Solanki, P., Bhargava, A., Chhipa, H., Jain, N. & Panwar, J. (2015). Nano-fertilizers and their smart delivery system. In Nanotechnologies in Food and Agriculture (pp. 81–101). https://doi.org/10.1007/978-3-319-14024-8_4

Stell, R., Torrie J. & Dickey D. (1980). Principles and procedures of statistics: A biometrical approach. New York: MacGraw-Hill. https://trove.nla.gov.au/work/9171434/version/49088515.

Subramanian, K. S., Manikandan, A., Thirunavukkarasu, M., & Rahale, C. S. (2015). Nano-fertilizers for balanced crop nutrition. In M. Rai, C. Ribeiro, L. Mattoso, & N. Duran (Eds.), Nanotechnologies in food and agriculture (pp. 69–80). Springer. https://doi.org/10.1007/978-3-319-14024-7_4

Tarafdar, J. C., Raliya, R., Mahawar, H. & Rathore, I. (2014): Development of zinc nanofertilizer to enhance crop production in pearl millet (Pennisetum americanum). Agricultural Research, 3, pp.257–262.https://doi.org/10.1007/s40003-014-0113-y

Tofiq, G. S., Hamakhan, A. M., Qadir, N. J., Hassan, I. A. & Mohammed, B. R. (2021): The effects of mature and immature chicken manure on the growth and yield of lettuce plant (Lactuca sativa L.). Tikrit Journal for Agricultural Sciences, 21, pp.33–39.https://doi.org/ 10.25130/tjas.21.4.5

Uresti-Porras, J. G., Cabrera-De-La Fuente, M., Benavides-Mendoza, A., Sandoval-Rangel, A., Zermeno-Gonzalez, A., Cabrera, R. I. & Ortega-Ortíz, H. (2021): Foliar application of zinc oxide nanoparticles and grafting improves the bell pepper (Capsicum annuum L.) productivity grown in NFT system. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 49, pp.12327–12327.https://doi.org/10.15835/nbha49212327

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

Wang, Y., Chen, Y. F. & Wu, W. H. (2021): Potassium and phosphorus transport and signaling in plants. Journal of Integrative Plant Biology, 63, pp. 34–52.https://doi.org/10.1111/jipb.13053

Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P. & Shen, Y. (2015): Managing nitrogen for sustainable development. Nature, 528, pp.51–59.https://doi.org/10.1038/nature15743

Zhao, L., Peng, B., Hernandez-Viezcas, J. A., Rico, C. M., Peralta-Videa, J. R. & Gardea-Torresdey, J. L. (2020): CeO_2 and ZnO nanoparticles change the nutritional qualities of cucumber (Cucumis sativus). Journal of Agricultural and Food Chemistry, 68, pp.1960–1967.https://doi.org/10.1021/acs.jafc.9b07820.

