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Precision nano-fertilization as a strategy to enhance growth and sweetener accumulation in stevia under arid sandy soil conditions

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ABSTRACT

The escalating demand for natural, low-calorie sweeteners has elevated *Stevia rebaudiana* as a strategic crop of economic and nutritional importance. Optimizing agronomic practices, particularly fertilization strategies, is crucial for enhancing both biomass and steviol glycoside content. This two-season field study aimed to assess the effects of nano-fertilizer applications, including nano-NPK, nano-ZnO, and nano-Fe_2O_3, on the growth, nutrient uptake, and sweetener profile of Stevia cultivated in the sandy soils of Giza, Egypt. Results revealed that the integrated nano-fertilizer treatment (T5: nano-NPK + ZnO + Fe_2O_3) significantly improved plant height, biomass accumulation, nutrient assimilation, and concentrations of stevioside and rebaudioside A compared to conventional fertilization. These enhancements are attributed to the superior solubility, controlled release, and higher bioavailability of nano-formulations, which enhanced nutrient use efficiency under the leaching-prone, low-retentive conditions of sandy soils. This study affirms the agronomic potential of nano-fertilizers in sustainable, high-value crop production systems.

1. Introduction

The rising global demand for natural, non-caloric sweeteners has elevated *Stevia rebaudiana* Bertoni as a crop of considerable agricultural and commercial importance. Native to Paraguay and belonging to the *Asteraceae* family, *S. rebaudiana* produces high-intensity sweet compounds, chiefly stevioside and rebaudioside A, which are 200-300 times sweeter than sucrose (Yadav *et al.*, 2011). These glycosides are heat-stable, non-fermentable, and safe for individuals with diabetes or those following calorie-restricted diets, making Stevia an attractive alternative to artificial sweeteners.

Emerging research in medicinal and aromatic crops supports the potential of nano-fertilizers to improve yield and secondary metabolite accumulation. For instance, Rafiq *et al.* (2024) reported enhanced essential oil production in fennel, Singh *et al.* (2025) demonstrated improved metabolite content in peppermint, and Ali *et al.* (2025) showed higher bioactive compound yields in basil. However, equivalent validation in Stevia remains absent. Global cultivation of Stevia has expanded substantially, driven by health awareness and demand for plant-based functional ingredients. Achieving high biomass and sweetener yield, however, depends strongly on agronomic practices, with nutrient management being a pivotal factor regulating glycoside biosynthesis and productivity (Ghosh *et al.*, 2021; Lemus-Mondaca *et al.*, 2012). Advanced nutrient delivery approaches such as nano-fertilization are being increasingly recognized for improving nutrient use efficiency and supporting sustainable crop performance across diverse agro-ecological systems (Hamed *et al.*, 2025).

Effective nutrient management is essential not only for promoting vegetative growth but also for enhancing the accumulation of secondary metabolites in Stevia. Macronutrients like nitrogen (N), phosphorus (P), and potassium (K), along with micronutrients such as zinc (Zn) and iron (Fe), play integral roles in photosynthetic function, enzymatic regulation, and chlorophyll synthesis, all of which influence steviol glycoside production (Nazir *et al.*, 2024; Ahmadirad *et al.*, 2024; Muhammad *et al.*, 2025).

Nonetheless, conventional fertilization methods often fail to deliver optimal results in sandy soils due to their inherently low cation exchange capacity, limited nutrient-holding ability, and high susceptibility to leaching. These soil limitations frequently lead to nutrient inefficiencies, increased environmental losses, and reduced crop productivity. As a result, the integration of nanotechnology in fertilizer development has emerged as a compelling alternative, particularly in sandy and arid regions where nutrient management is inherently challenging.

Nano-fertilizers, by virtue of their nanoscale dimensions, enhanced solubility, and large surface area, offer numerous advantages over conventional fertilizers. These include improved nutrient absorption, targeted delivery, and prolonged release dynamics, facilitating more efficient uptake through both foliar and root systems (Gerami *et al.*, 2024). Research has demonstrated their potential to boost nutrient use efficiency, increase photosynthetic activity, and enhance both primary and secondary metabolite accumulation in various crops. Although nano-fertilizers have been tested in cereals and sugar crops such as maize and sugarcane (Raliya *et al.*, 2015; Liu & Lal, 2015) and in some medicinal plants like fennel and peppermint (Rafiq *et al.*, 2024; Singh *et*

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al., 2025), no published field studies have evaluated their performance in *Stevia rebaudiana* under sandy, nutrient-leaching soils.

Despite these promising attributes, nano-fertilizer application in *Stevia rebaudiana* remains underexplored, particularly under arid climates and sandy soils such as those in Egypt. Most existing studies are limited to greenhouse or hydroponic conditions, leaving a significant gap in field-based validation. To address this, the present study conducted a two-season field trial to evaluate the effects of nano-fertilizers on the growth, nutrient uptake, and sweetener accumulation of Stevia cultivated under sandy soil conditions.

2. Materials and Methods

2.1 Experimental site and soil properties

Field experiments were conducted during the summer seasons of 2023 and 2024 at the experimental farm, Agricultural Research Center (ARC), Giza, Egypt in Giza, Egypt (Latitude: 30.021° N, Longitude: 31.2103° E). The site is characterized by sandy-textured soils with inherently low fertility and limited nutrient retention capacity. A pre-sowing soil analysis (0-30 cm depth) revealed a pH of 7.6, electrical conductivity (EC) of 1.1 dS/m, and organic matter content of 0.43%. Available nitrogen, phosphorus, and potassium levels were 42 mg/kg, 5.8 mg/kg, and 110 mg/kg, respectively. Soil texture was determined using the hydrometer method and confirmed as sandy.

2.2 Plant material and cultivation practices

Stevia rebaudiana cv. Sugar High seedlings were sourced from a certified horticultural nursery in Egypt. Transplanting was carried out on March 15, 2023, for the first season, and March 17, 2024, for the second season, using 30-day-old seedlings. Each experimental plot measured 2 m × 2 m and was arranged in rows with 30 cm plant spacing and 60 cm row spacing, accommodating 20 plants per plot. Standard cultural practices were applied across all treatments as recommended. Harvesting occurred on August 10, 2023, and August 12, 2024.

2.3 Nano-fertilizer sources and treatment structure

All nano-fertilizers employed in this study were procured from the Central Laboratory for Agricultural Climate (CLAC), Giza, Egypt. Both transmission electron microscopy (TEM) imaging and energy dispersive X-ray spectroscopy (EDS) analysis were conducted specifically for the nano-fertilizers synthesized and applied in this study, to validate their morphology, elemental composition, and ensure consistency with nanoscale delivery criteria. Nanoparticle size distribution was analyzed from TEM images using ImageJ software. This method has been widely employed for accurate nanoparticle size determination and statistical analysis (Jabbar *et al.*, 2022). The application of ImageJ for nanoscale structural analysis has also been demonstrated in materials science studies, confirming its suitability for particle size assessment (Hashim *et al.*, 2018).

Representative micrographs (Fig. 1) depict the structural features of the nano-fertilizers:

- **Nano-ZnO** displayed irregularly clustered particles with diameters ranging between 23.06 and 27.6 nm.
- **Nano-Fe_2O_3** particles were predominantly spherical with slight agglomeration, exhibiting a mean size range of approximately 30.4 to 34.2 nm.

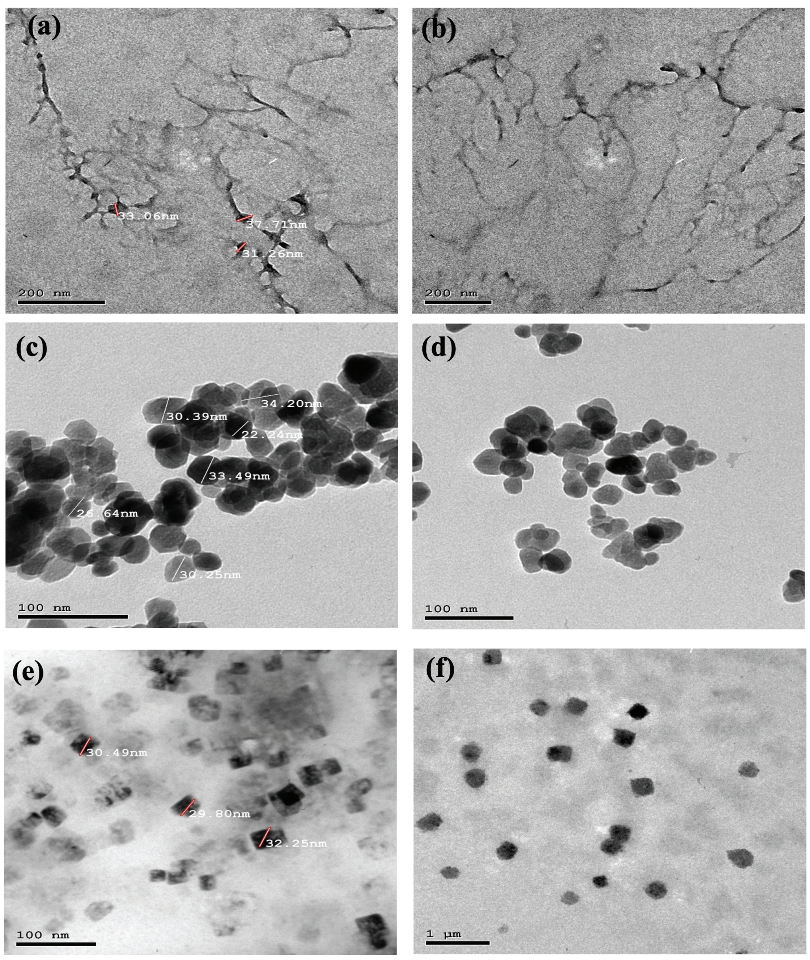

Fig. 1. Morphological and dimensional characterization of hybrid nanostructures via TEM; panels (a & b): Surface topography of nano-ZnO particles, panels (c & d): Nano-Fe_2O_3 particles, and panels (e & f): nano-NPK particles.

- **Nano-NPK** particles appeared well-dispersed, primarily cubic or rounded in shape, with average dimensions of 30-32 nm; larger aggregates up to 1 µm were occasionally observed.

All nano-formulations maintained a consistent nanometric size distribution below 100 nm, aligning with the physicochemical criteria for efficient nutrient uptake via foliar and root absorption. These structural properties make them well-suited for application in low-retention sandy soils. The elemental composition of each nano-fertilizer was validated through EDS, confirming the formulations as follows: Nano-ZnO (40 ppm Zn), Nano-Fe_2O_3 (50 ppm Fe), and Nano-NPK (20:20:20 NPK).

Experimental design and fertilizer treatments

The experiment followed a split-plot in Randomized Complete Block Design (RCBD) with six fertilization treatments and three replicates:

- T1 – Control: 100% recommended dose of conventional NPK (600 kg/ha of granular NPK 20:20:20)
- T2 – 100% nano-NPK (foliar application of 20:20:20 nano-formulation at 2 g/L)
- T3 – Nano-ZnO foliar application at a concentration of 40 ppm Zn (2 mL/L of ZnO nanoparticle suspension)
- T4 – Nano-Fe_2O_3 foliar application at 50 ppm Fe (2 mL/L of Fe_2O_3 nanoparticle suspension)
- T5 – Combined nano-fertilizer treatment: nano-NPK (2 g/L) + nano-ZnO (40 ppm) + nano-Fe_2O_3 (50 ppm)
- T6 – Integrated treatment: 50% conventional NPK (300 kg/ha of NPK 20:20:20) + 50% nano-NPK (1 g/L).

Treatment T5 (combined nano-NPK + nano-ZnO + nano-Fe_2O_3) was included to evaluate the maximum synergistic potential of a fully nano-based system. In contrast, Treatment T6 integrated nano-fertilizers with conventional NPK to test a partial substitution strategy, assessing whether a hybrid approach could achieve comparable agronomic gains while minimizing chemical inputs. This comparison supports practical scalability for growers transitioning to nano-based fertilization.

The application rates of nano-fertilizers used in this study were determined based on a combination of prior literature, preliminary greenhouse screening trials, and alignment with agronomically relevant nutrient thresholds. Specifically, the selected concentrations 40 ppm for Nano-ZnO, 50 ppm for Nano-Fe_2O_3, and the equivalent macro-nutrient content for Nano-NPK (20:20:20) were informed by published studies demonstrating efficacy in enhancing nutrient use efficiency and crop performance without inducing phytotoxicity (e.g., Raliya *et al.*, 2015; Khan *et al.*, 2020). These concentrations were validated through pilot trials under controlled conditions to ensure optimal physiological response in *Stevia rebaudiana* under sandy soil stress.

All foliar nano-fertilizer treatments were applied uniformly at 30, 60, and 90 days after transplanting using a calibrated handheld pressure sprayer to ensure consistent coverage across all treatments.

2.4 Data collection and measured parameters

The following traits were evaluated throughout the growing cycle and at final harvest:

- Plant Height (cm): Measured from the soil surface to the apex using a ruler
- Leaf Number: Total number of leaves per plant counted manually
- Leaf Area (cm^2): Determined using a leaf area meter
- Fresh Biomass (g/plant): Total fresh weight of whole plants
- Dry Biomass (g/plant): Samples oven-dried at 70°C to constant weight
- Leaf Yield (g/plant): Total harvested leaf weight
- Leaf Dry Matter (%): determined by first recording the fresh weight of the harvested leaves using an electronic balance. The samples were then oven-dried at 70 °C until a constant weight was achieved. The dry matter content was calculated using the following formula:

  Leaf Dry Matter % =Dry weight/Fresh weight × 100

- Nutrient Uptake: Leaf tissues were digested with H_2SO_4-H_2O_2; nitrogen was determined by the Kjeldahl method, phosphorus by spectrophotometry, potassium by flame photometry, and Zn/Fe by atomic absorption spectrophotometry
- Stevioside and Rebaudioside A (mg/g): Quantified by HPLC (Agilent 1200 series) following methanolic extraction and filtration.

2.5 Statistical analysis

All experimental data from the 2023 and 2024 seasons were subjected to analysis of variance (ANOVA) using MSTAT-C software (Michigan State University, 1991) in an RCBD. Prior to conducting ANOVA, data were screened to ensure compliance with parametric assumptions, including normality and homogeneity of variances. Means were separated using the L.S.D. (Least Significant Difference) test at the 5% probability level ($p \le 0.05$). Standard errors (SE) were also calculated for each trait to quantify variability among replications and are presented alongside the mean values in the tables.

3. Results and Discussion

This two-season field investigation assessed the comparative performance of six fertilizer treatments on the growth, yield, nutrient partitioning, and sweetener accumulation in *Stevia rebaudiana* cultivated under sandy soil conditions. All treatments were significantly different ($p \le 0.05$) across the examined traits, underscoring the pronounced effect of nano-fertilizer applications on physiological and agronomic performance compared to conventional fertilization.

3.1 Vegetative growth attributes

Across both seasons, T5 (Combined nano-fertilizer treatment) emerged as the most effective treatment in promoting vegetative growth. It significantly outperformed all other treatments in plant height, number of leaves, and leaf area. In the first season (Table 1), T5 (combined nano-fertilizers) consistently produced the tallest plants, largest leaf number, and expanded leaf area, outperforming the conventional control (T1) across both seasons (Fig. 2). Nano-fertilizers play a pivotal role in regulating the physiological and biochemical processes of crops by enhancing nutrient availability and uptake efficiency. This improved nutrient dynamics stimulates key metabolic activities and promotes meristematic functions, leading to increased apical growth and expanded photosynthetic area. These effects are primarily mediated through enhanced cell division, chlorophyll biosynthesis, and leaf expansion, driven by hormone-regulated growth responses. (Schmidt *et al.*, 2020; Acharya *et al.*, 2024; Nazir *et al.* 2024; Ali *et al.*, 2024; Muhammad *et al.*, 2025).

3.2 Biomass accumulation and leaf yield

Fresh and dry biomass accumulation responded positively to nano-fertilizer applications, with T5 again exhibiting the highest performance. Nano-fertilizer applications enhanced fresh and dry biomass, with T5 recording the highest values (Figs. 3 and 4). The substantial increase in biomass and leaf yield under nano-Fe_2O_3 and nano-NPK treatments highlights the role of Fe in enzyme activation and enhanced metabolic

Table 1.
Effects of different nano-fertilizer treatments on vegetative growth parameters of Stevia rebaudiana during the 2023 and 2024 growing seasons.

Fertilizer treatment	No. of Leaves ± SE		Leaf area (cm^2) ± SE	
	1st season	2nd season	1st season	2nd season
T1	30.47 ± 0.92	30.38 ± 0.92	176.45 ± 4.97	184.49 ± 1.69
T2	36.01 ± 1.66	35.52 ± 1.39	207.58 ± 7.06	211.61 ± 6.12
T3	38.01 ± 1.24	38.49 ± 1.55	231.37 ± 11.53	235.05 ± 6.87
T4	38.92 ± 0.72	40.31 ± 0.79	230.87 ± 3.30	246.92 ± 12.15
T5	47.31 ± 0.20	44.29 ± 1.29	281.05 ± 7.06	266.40 ± 4.89
T6	33.14 ± 1.26	32.81 ± 2.04	198.76 ± 9.10	204.93 ± 1.93
L.S.D $_{at\ 5\%}$	2.19	2.90	15.49	13.56

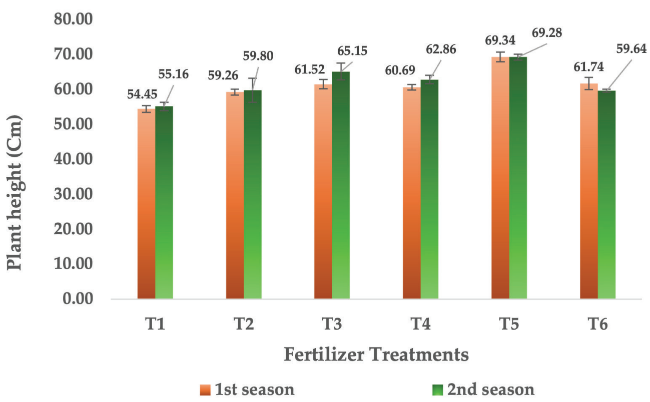

Fig. 2. Effect of nano-fertilizer treatments on plant height (cm) of *Stevia rebaudiana* during the first and second seasons. Error bars represent standard error (SE), L.S.D values at 5% (2.73 and 3.83) for 1st and 2nd seasons, respectively.

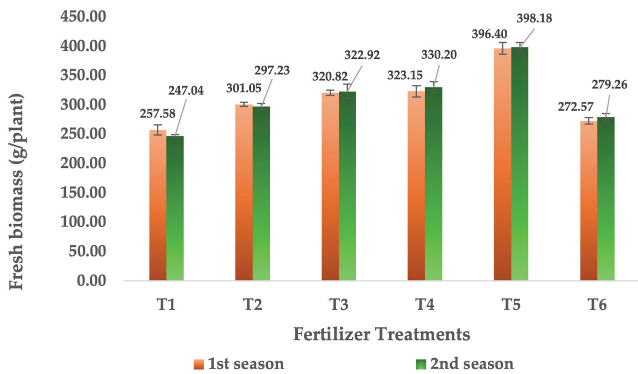

Fig. 3. Influence of nano-fertilizer applications on fresh biomass (g/plant) of *Stevia rebaudiana* in both seasons. Error bars represent standard error (SE), L.S.D values at 5% (15.17 and 16.81) for 1st and 2nd seasons, respectively.

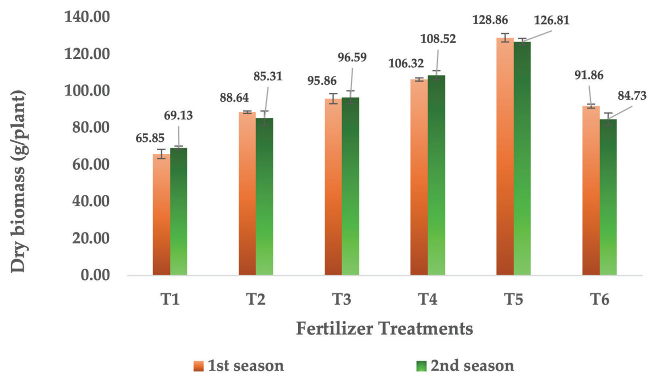

Fig. 4. Dry biomass (g/plant) response of *Stevia rebaudiana* to different nano-fertilizer treatments across two seasons. Error bars represent standard error (SE), L.S.D values at 5% (3.83 and 5.70) for 1st and 2nd seasons, respectively.

flux, while nano-NPK improves nutrient partitioning and source–sink balance (Bhardwaj *et al.*, 2022; Akhter *et al.*, 2025).

3.3 Leaf dry matter percentage

The superior leaf dry matter percentage (LDM%) (Table 2) observed in T5 reflects enhanced photosynthate accumulation and improved water-use efficiency in sandy soils, likely facilitated by nano-enabled delivery of Fe and N, which improve carbon fixation and assimilate storage (Reddy *et al.*, 2024; Singh *et al.* 2025; Muhammad *et al.*, 2025).

Table 2.
Impact of nano-fertilizer treatments on biomass production, leaf yield, and dry matter percentage of *Stevia rebaudiana*.

Fertilizer treatment	Leaf yield (g/plant) ± SE		Leaf dry matter % ± SE	
	1st season	2nd season	1st season	2nd season
T1	205.64 ± 3.81	194.89 ± 3.83	24.72 ± 0.56	25.11 ± 0.10
T2	243.93 ± 6.39	248.76 ± 9.33	28.50 ± 0.56	26.88 ± 0.58
T3	276.78 ± 2.97	278.18 ± 5.60	28.36 ± 0.12	29.44 ± 0.60
T4	283.87 ± 2.60	281.59 ± 7.54	31.27 ± 0.87	29.36 ± 0.48
T5	363.44 ± 0.94	346.24 ± 7.24	33.42 ± 0.26	35.30 ± 0.90
T6	223.62 ± 4.33	242.32 ± 5.77	27.66 ± 0.51	26.76 ± 1.29
L.S.D at 5%	8.00	13.46	1.08	1.60

3.4 Nutrient uptake efficiency

Nutrient uptake efficiency followed a similar trend. Nitrogen content in T5-treated plants reached 29.3 mg/g versus 20.4 mg/g in T1. Phosphorus and potassium uptake were also highest under T5, at 6.9 mg/g and 47.2 mg/g respectively. Macro- and micronutrient uptake was maximized under T5 (Figs. 5-9). The synergistic effect of nano-NPK with Fe and Zn enabled more efficient assimilation, owing to the higher mobility and foliar penetration of nanoparticles, which enhance root-to-shoot translocation and nutrient bioavailability (Ali *et al.*, 2025; Dimkpa *et al.*, 2017).

3.5 Sweetener content (Stevioside and Rebaudioside A)

Steviol glycosides (stevioside and rebaudioside A) were significantly enhanced under nano-fertilizer treatments, particularly T5 (Table 3). Mechanistically, Zn acts as a cofactor for glycosyltransferases that catalyze glycoside biosynthesis, while Fe enhances chlorophyll-driven

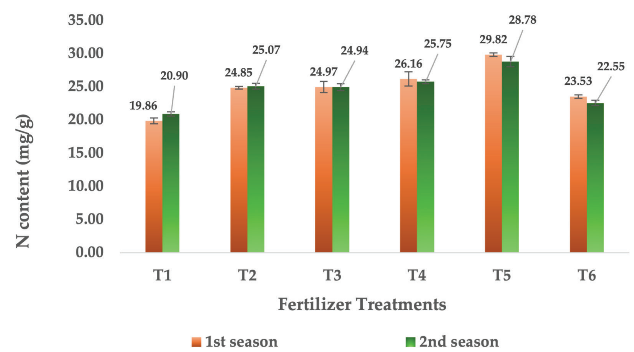

Fig. 5. Effect of nano-fertilizer treatments on nitrogen content in Stevia leaves during 2023 and 2024 growing seasons. Bars represent standard error (SE), L.S.D values at 5% (1.27 and 1.01) for 1st and 2nd seasons, respectively.

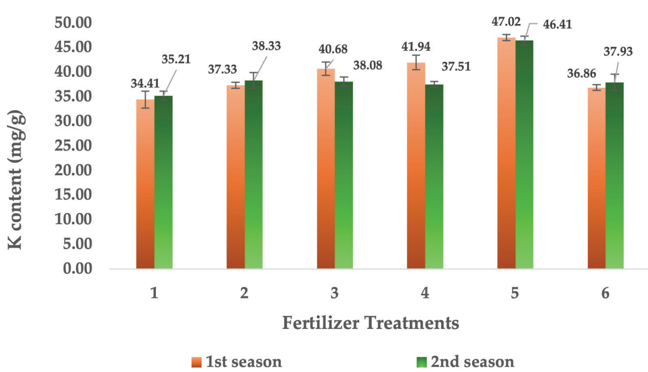

Fig. 6. Effect of nano-fertilizer treatments on potassium (K) uptake in *Stevia rebaudiana* leaves during 2023 and 2024 growing seasons. Bars represent standard error (SE), L.S.D values at 5% (2.46 and 2.38) for 1st and 2nd seasons, respectively.

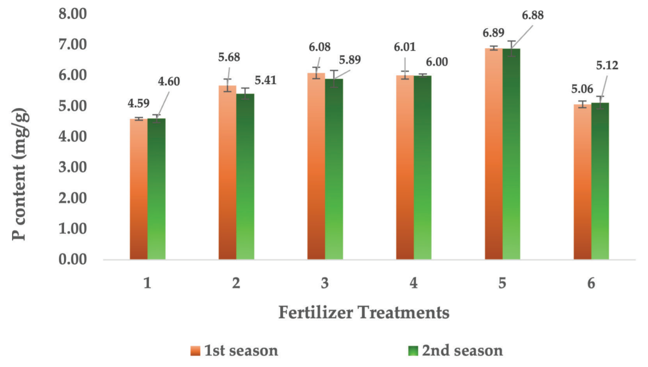

Fig. 7. Effect of nano-fertilizer treatments on phosphorus (P) concentration in *Stevia rebaudiana* leaves during 2023 and 2024 growing seasons. Bars represent standard error (SE), L.S.D values at 5% (0.27 and 0.39) for 1st and 2nd seasons, respectively.

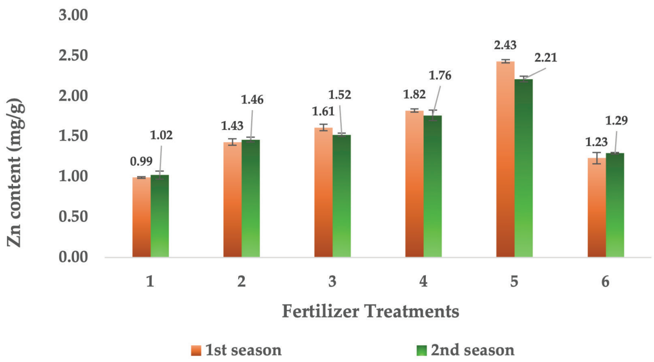

Fig. 8. Effect of Nano-ZnO and combined nano-fertilizer applications on foliar Zinc (Zn) content in *Stevia rebaudiana* leaves during 2023 and 2024 growing seasons. Bars represent standard error (SE), L.S.D values at 5% (0.08 and 0.08) for the 1st and 2nd seasons, respectively.

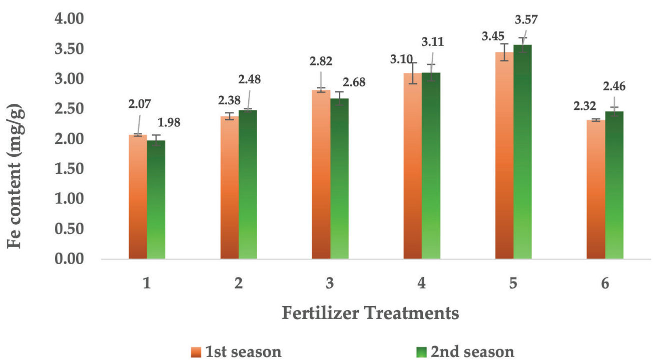

Fig. 9. Effect of varying nano-fertilizer treatments on iron (Fe) concentration in leaves of *Stevia rebaudiana* during 2023 and 2024 growing seasons. Bars represent standard error (SE), L.S.D values at 5% (0.19 and 0.20) for 1st and 2nd seasons, respectively.

Table 3.
Influence of nano-fertilizer applications on Stevioside and Rebaudioside A concentrations in *Stevia rebaudiana* leaves.

Fertilizer treatment	Stevioside (mg/g) ± SE		Rebaudioside A (mg/g) ± SE	
	1st season	2nd season	1st season	2nd season
T1	31.44 ± 0.49	30.02 ± 0.70	19.92 ± 0.51	20.12 ± 0.18
T2	34.40 ± 1.39	34.90 ± 1.10	26.01 ± 0.87	25.49 ± 0.21
T3	38.61 ± 0.95	39.31 ± 1.26	28.42 ± 1.27	27.91 ± 0.67
T4	39.85 ± 0.26	40.26 ± 1.99	30.64 ± 2.04	29.58 ± 0.49
T5	47.84 ± 2.01	48.89 ± 2.54	35.70 ± 1.35	33.94 ± 0.48
T6	32.58 ± 0.32	33.14 ± 0.45	23.69 ± 0.73	23.40 ± 0.22
L.S.D at 5%	2.26	3.04	2.49	0.85

carbon fixation, thereby increasing precursor availability. Nano-NPK contributes by improving carbohydrate partitioning, jointly stimulating secondary metabolite pathways (Puscaselu *et al.*, 2019; Djéssica *et al.*, 2022; Rafiq *et al.*, 2024; Akhter *et al.*, 2025).

3.6 Integrated assessment

The combined nano-fertilizer treatment (T5) consistently delivered superior outcomes across vegetative growth, biomass accumulation, nutrient uptake, and steviol glycoside synthesis, underscoring the central role of synergistic nutrient interactions at the nanoscale. This performance is attributable to the unique properties of nanoparticles, including high surface area, enhanced solubility, and controlled release, which facilitate greater foliar absorption and more efficient translocation compared to bulk fertilizers (Dimkpa *et al.*, 2017; Raliya *et al.*, 2015).

The observed improvements in growth attributes are linked to nutrient-mediated physiological processes. Zinc nanoparticles act as cofactors for enzymes such as glycosyltransferases and dehydrogenases, promoting metabolic activity and secondary metabolite biosynthesis (Puscaselu *et al.*, 2019; Rafiq *et al.*, 2024). Iron contributes to chlorophyll development and photosynthetic efficiency, thereby increasing precursor availability for both biomass and glycoside accumulation (Schmidt *et al.*, 2020; Reindinger *et al.*, 2012). In parallel, nano-NPK enhances nitrogen assimilation and carbohydrate partitioning, stimulating source-sink relationships and assimilate allocation (Bhardwaj *et al.*, 2022; Nazir *et al.*, 2024). Together, these mechanisms explain the consistent superiority of combined nano-treatments.

A notable finding was the significant enhancement of steviol glycoside concentration. This is consistent with previous reports that Zn and Fe nanoparticles stimulate enzymatic pathways of secondary metabolism and upregulate glycosylation reactions involved in stevioside and rebaudioside A biosynthesis (Djéssica *et al.*, 2022; Khan *et al.*, 2020). The agronomic implication is that nano-fertilizers not only increase yield but also improve crop quality and economic value, particularly for high-value crops such as *Stevia rebaudiana*. In *Stevia rebaudiana*, steviol glycoside biosynthesis depends on both photosynthetic carbon fixation and glycosyltransferase-mediated glycosylation reactions (Puscaselu *et al.*, 2019). Nano-fertilizers facilitate nutrient entry through stomata, cuticular pores, and root apoplastic/symplastic pathways (Dimkpa & Bindraban, 2017), thereby enhancing chlorophyll biosynthesis (via Fe), carbohydrate metabolism (via NPK), and enzyme activation (via Zn). This physiological synergy explains the higher stevioside and rebaudioside A accumulation observed under T5.

The environmental sustainability dimension is also crucial. Sandy soils are characterized by poor nutrient retention and high leaching losses. The nano-formulations applied here reduced nutrient losses through gradual release and improved uptake efficiency, which aligns with the broader goals of sustainable agriculture and reduced agrochemical pollution (Dimkpa & Bindraban, 2018; Liu & Lal, 2015). These outcomes suggest that nano-enabled fertilization can simultaneously address productivity and environmental challenges in marginal soils. The superior performance of nano-fertilizers can be attributed to their high solubility, gradual release, and enhanced bioavailability (Liu & Lal, 2015). These properties ensured a steady nutrient supply during critical growth phases, preventing stress-induced fluctuations common in sandy soils. In Stevia, this stability supported continuous photosynthesis and substrate flow into glycosyltransferase pathways, thereby stimulating stevioside and rebaudioside A accumulation (Djéssica *et al.*, 2022).

While nano-fertilizers demonstrated improved nutrient use efficiency and reduced leaching in sandy soils, potential long-term ecological impacts should be considered. Reports indicate that nanoparticles may accumulate in soil and alter microbial communities, with possible transfer into food chains (Wang *et al.*, 2024; Mubeen *et al.*, 2023). Multi-season and multi-site studies are therefore required to confirm their environmental safety.

Finally, the inclusion of T6 (50% nano + 50% conventional NPK) highlights the potential for transitional adoption strategies. Although less effective than T5, T6 outperformed the conventional control, indicating that even partial substitution with nano-formulations enhances productivity and sustainability. This approach may be particularly attractive for smallholders in resource-limited settings, where gradual adoption reduces costs while maintaining yield improvements (Ali *et al.*, 2024; Akhter *et al.*, 2025; Muhammad *et al.*, 2025).

Collectively, these findings provide strong evidence that integrated nano-macro and nano-micronutrient strategies enhance plant growth, yield, secondary metabolism, and sustainability under sandy soil conditions. By combining agronomic, biochemical, and environmental benefits, nano-fertilization represents a climate-smart solution for Stevia production in arid regions.

4. Conclusion

This field investigation provides strong evidence that nano-fertilizers enhance the productivity and biochemical quality of *Stevia rebaudiana* grown in sandy soils. The combined application of nano-NPK, nano-ZnO, and nano-Fe_2O_3 (T5) consistently delivered the greatest improvements across agronomic and physiological traits, including nutrient uptake and steviol glycoside accumulation, while individual nano-nutrient treatments (T2-T4) also outperformed conventional NPK fertilization. These results highlight the potential of nano-agronomic approaches to improve fertilizer use efficiency, reduce environmental losses, and support the sustainability of Stevia cultivation in arid environments.

However, as the findings are based on two seasons at a single experimental site, caution is warranted in generalizing the outcomes. Future multi-location and long-term studies are recommended to validate scalability, environmental safety, and economic feasibility of nano-fertilizer adoption in medicinal crop systems.

CRediT authorship contribution statement

Lamy HAMED: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation, Supervision, Project administration. **Eman EMARA**: Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization, Visualization, Validation, Investigation.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work presented in this paper.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors confirm that there was no use of Artificial Intelligence (AI)-Assisted Technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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