Growth Response and Productivity of Red Radish to Foliar Application of Amino Acid-Based Organic Fertilizer and Nano NPK Fertilizer

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Abstract

A field experiment was conducted at the experimental fields of the Department of Horticulture and Landscape Design, College of Agriculture, Al-Qasim Green University, during the winter season of 2025–2026. The primary objectives were to evaluate the effectiveness of varying concentrations of an amino acid-based organic fertilizer and a nano NPK fertilizer in enhancing vegetative growth efficiency, improving yield, and elevating qualitative yield indicators of red radish (*Raphanus sativus* L.).The experiment comprised two main factors: the first was the organic fertilizer applied at four concentration levels (0, 1, 2, and 3 $mL \cdot L^{-1}$), coded as A_1, A_2, A_3, and A_4, respectively; the second was the nano NPK fertilizer applied at three levels (0, 1.5, and 3 $g \cdot L^{-1}$), coded as B_1, B_2, and B_3. The experiment was conducted according to a randomized complete block design (RCBD) as a two-factor factorial arrangement with three replicates, aiming to identify the optimal interaction between the two treatments.Results revealed a significant positive effect of organic fertilizer on all traits studied, with values increasing progressively with concentration. The 3 $mL \cdot L^{-1}$ treatment demonstrated clear and significant superiority over the other concentrations in most indicators. Similarly, the nano NPK fertilizer significantly improved all traits examined, and the 3 $g \cdot L^{-1}$ level elicited the highest response in the majority of measured parameters.A highly significant interaction response was observed for all indicators under the combined treatments. The interaction treatment (A4B3) exhibited marked superiority in vegetative growth indicators, recording the highest values for leaf number and chlorophyll content. This improvement was reflected in yield traits, where the same treatment recorded the highest values for fresh weight of shoot system, fresh weight of roots, and dry weight of roots, compared with the

ISSN 2072-3857

control. With respect to chemical measurements, the interaction between the highest fertilization levels (A4B3) maximized macronutrient uptake efficiency, yielding the highest values for nitrogen percentage, phosphorus percentage, and potassium percentage, in addition to enhanced carbohydrate and total protein accumulation. Regarding total soluble solids (TSS), the treatments (A1B3), (A2B3), (A3B3), and (A2B2) achieved the highest recorded values.These results indicate that the treatment (A4B3) was the most effective, contributing substantially to the improvement of growth efficiency and enhancement of yield quality in red radish.

Keywords: red radish, Raphanus sativus, amino acid, nano fertilizer, foliar application, growth, carbohydrates.

1 - Introduction

Radish (*Raphanus sativus* L.) is an economically important crop belonging to the family Brassicaceae (Cruciferae). It is believed to have originated in central-western China and the Indian subcontinent (ul Haq et al., 2012). Radish is cultivated primarily for its fleshy taproot, and it ranks among the most widely grown root vegetable crops globally. Its uses, however, extend beyond roots to include leaves, sprouts, and seed pods, which are consumed as leafy vegetables or oilseed crops depending on culinary traditions (Swaamy, 2023). Radish roots are recognized as a nutritious, low-calorie food choice; per 100 g of fresh weight, they provide 94% water and approximately 20 kcal, as well as carbohydrates, proteins, and minerals including calcium and phosphorus, and vitamins A, B-complex, C, E, and K. These constituents make radish effective in skin hydration and body temperature regulation (Matar, 2021; Kanash, 2023; Kurina et al., 2021).

In a comprehensive investigation, Geny et al. (2025) reported that radish leaves contain bioactive compounds including flavonoids, glucosinolates, and polysaccharides, which exhibit a broad spectrum of biological activities encompassing acetylcholinesterase inhibition, anticancer, anti-inflammatory, antimicrobial, anti-obesity, and anti-ulcer properties, in addition to their roles in reducing blood pressure and improving intestinal motility.

ISSN 2072-3857

The foliar application of biostimulants and amino acids represents a promising avenue warranting further investigation (Peña Calzada et al., 2022). Organic nitrogen fertilizers contribute effectively to increasing dry matter accumulation and nutrient content in crops, and improve the utilization of nitrogen fertilizers, chlorophyll content, and stress resistance at equivalent nitrogen application rates; organic fertilizers can enhance the quality and use efficiency of nitrogen fertilizers (Ren et al., 2022).

Peña-Calzada et al. (2025) reported that foliar application of growth biostimulants exerted a positive effect on radish growth and productivity, particularly at a concentration of 1.5 $mL \cdot L^{-1}$, increasing total chlorophyll content, total ammonium nitrogen, leaf lipid content, and leaf diameter, resulting in a 21% increase in crop yield compared with the control treatment. Furthermore, foliar application of growth biostimulants at 1.2 $mL \cdot L^{-1}$ increased total dry weight, chlorophyll content, leaf lipid content, and leaf area, as well as yielding a 10% improvement in productivity.

With respect to nano-fertilization, nanoparticles can enhance plant resistance to biotic and abiotic stresses, potentially reducing production costs and alleviating environmental pressures (Babu et al., 2022). Moreover, foliar application of nanomaterials has been shown to increase stem length, root length, fresh weight, and dry matter content of radish grown in intercropping with peas by 7–8%, 27–41%, and 50–60%, respectively; nanomaterial application also differentially influenced pigments such as chlorophyll a and b, carotenoids, free amino acid concentrations, soluble sugars, flavonoids, and phenolic compounds (Shafiq et al., 2023).

In light of the documented efficacy of organic and nano-fertilizers in improving growth and productivity of vegetable crops, and given the increasing need for more efficient and sustainable fertilization strategies, this study was designed to investigate the effect of both fertilizer types on red radish. The study aimed to evaluate the potential of organic and nano-fertilizers in improving the productivity and quality of red radish, as these fertilizer types possess promising potential in enhancing plant .

Despite the economic importance of red radish, intensive conventional chemical fertilization poses environmental risks and often results in low nutrient use efficiency. Furthermore, there is a limited understanding and a lack of comprehensive studies exploring the potential of combining amino acid-based organic fertilizers with nano-

ISSN 2072-3857

NPK fertilizers to enhance both vegetative growth and phytochemical traits in this crop. Therefore, this study was undertaken to address this knowledge gap.

growth efficiency. To achieve this, three principal objectives were pursued:

1. To evaluate the effect of amino acid-based organic fertilizer on the vegetative and root characteristics of red radish.
2. To elucidate the effect of nano NPK fertilizer concentration levels on plant growth and yield.
3. To study the interaction between the two treatments to identify the optimal combined level that achieves maximum productivity and qualitative yield in this crop.

2. Materials and Methods

2.1 Experimental Site

This experiment was conducted at the Department of Horticulture and Landscape Design, College of Agriculture, Al-Qasim Green University, during the winter season of 2025–2026, in the open-field plots affiliated with the Department. Red radish (cv. Cherry Bell) seeds were used to study the improvement of growth and qualitative yield of red radish through foliar application of nitrogen-based organic fertilizer and nano NPK fertilizer.

2.2 Land Preparation and Experimental Design

The soil was ploughed prior to planting, then levelled and prepared as raised beds of specified dimensions. The experiment was conducted as a two-factor factorial arrangement using a randomized complete block design (RCBD) with three replicates, each comprising 12 experimental units. The land was divided into raised beds of 1 m width per experimental unit, with 50 cm spacing between experimental units, 75 cm between beds, and 25 cm margins on all sides to facilitate agricultural operations and minimize inter-treatment interference.

2.3 Planting

Red radish seeds (cv. Cherry Belle) sourced from Pop Vriend Seeds, the Netherlands, were sown on 23 December 2025 directly in the open field by broadcasting at a rate of 3 g per experimental unit The broadcasting method was adopted to achieve a uniform plant density and ensure homogeneous seed distribution across the small experimental units, which aligns with local commercial practices for root crop production.

All agronomic practices including irrigation and weed control were carried out as required. Drip irrigation was the system employed throughout the experiment.

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2.4 Experimental Factors

Factor A — Amino Acid-Based Organic Fertilizer: The organic fertilizer used was the commercial formulation "CIFAMIN BK" (produced by Siffa Shifo S.r.l., Italy). It is an organic nitrogen fertilizer enriched with amino acids, boron, and manganese. The chemical composition of CIFAMIN BK consists of: 8% Total Nitrogen (N) (with 8% organic N derived from biological origin), 20% Organic Carbon (C), 0.01% Water-soluble Boron (B), 0.1% Water-soluble Manganese (Mn), and 0.01% Water-soluble Zinc (Zn). The treatments were applied at four concentration levels:

A1: Control (no application); A2: 1 $mL·L^{-1}$; A3: 2 $mL·L^{-1}$; A4: 3 $mL·L^{-1}$.

Factor B — Nano NPK Fertilizer: The nano fertilizer used was the commercial formulation "SPECIAL FERT" (utilizing Sparkling Nano Technology, produced under UKFC British standards by United Kingdom Fertilizers Company). It is a high-potassium water-soluble nano NPK fertilizer with a formulation ratio of 10-10-36. The chemical composition comprises: 10% Organic Nitrogen (N), 10% Organic Phosphorus (P_2O_5), and 36% Organic Potassium (K_2O) The treatments were applied at three concentration levels based on the manufacturer's recommendation.

B1: Control (no application); B2: 1.5 $g·L^{-1}$ (manufacturer's recommendation); B3: 3 $g·L^{-1}$

2.5 Measurements

The measurements were recorded on February 23, 2026….

2.5.1 Vegetative Growth and Yield Indicators

Leaf number ($leaves·plant^{-1}$): Leaves were counted on randomly selected plants within each experimental unit and the mean was calculated. Relative chlorophyll content (SPAD) Measured using a SPAD-502 Chlorophyll Meter (Minolta, Japan). The measurements were taken from five fully expanded leaves per plant, selecting five random plants from each experimental unit, and the average value was recorded

(Minolta, Japan). Fresh weight of shoot system ($g·plant^{-1}$): Five plants were randomly harvested per experimental unit; shoots were separated from roots and weighed. Fresh weight of root system ($g·plant^{-1}$): Roots of five plants were washed thoroughly to remove soil residue, dried of surface moisture, and weighed. Dry weight of root system ($g·plant^{-1}$): Roots of five plants per unit were washed and oven-dried at 70°C until constant weight was achieved, then weighed.

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2.5.2 Chemical Measurements

Total nitrogen percentage (%): Determined using the Micro-Kjeldahl method as described by Page et al. (1982). Briefly, 10 mL of the digested sample was transferred and 10 mL of 40% NaOH solution was added. Distillation was carried out and the liberated ammonia was collected in a flask containing 10 mL of 2% boric acid with a mixed indicator (Methyl Red and Bromocresol Green). The collected ammonia was then titrated with 0.005 N HCl, and the total nitrogen percentage was calculated from the volume of acid consumed. Phosphorus percentage (%): Determined using the ammonium molybdovanadate colorimetric method (Al-Sahaf, 1989). The reagent was prepared by dissolving 22.5 g ammonium molybdate in 400 mL distilled water (Solution A) and 1.25 g ammonium metavanadate in 300 mL hot distilled water (Solution B); Solutions B and A were combined, cooled, and 250 mL concentrated HNO_3 was added carefully before the volume was made up to 1 L. For analysis, 5 mL of the digested sample and 5 mL of reagent were combined and the volume was completed to 50 mL with distilled water; absorbance was measured at 410 nm after 30 minutes. Potassium percentage (%): Determined using a flame photometer (Al-Sahaf, 1989) with automatic calibration provided by the manufacturer.

2.5.3 Qualitative Yield Characteristics

Total carbohydrate percentage (%): Estimated by the phenol–sulfuric acid method (Hedge and Hofreiter, 1962). A 0.2 g sample was treated with 25 mL of 1 N perchloric acid in a water bath at 60°C for 30 minutes. After filtration, 1 mL of filtrate was diluted to 10 mL. One millilitre of the diluted solution was mixed with 5% phenol and 5 mL concentrated H_2SO_4; absorbance was read at 490 nm using a spectrophotometer, and concentrations were derived from a glucose calibration curve. Total protein percentage (%): Calculated from the total nitrogen percentage using the factor 6.25, according to the method of Gresser and Parsons (1979): Protein % = N% × 6.25. Total soluble solids, TSS (%): Measured by hand refractometer (Al-Ani, 1985) on juice extracted from radish roots at room temperature.

3. Results and Discussion

3.1 Vegetative Growth and Yield Indicators

3.1.1 Leaf Number (leaves·plant^{-1})

The data recorded in Table 1 reveal significant differences in leaf number in response to the fertilization treatments studied. Liquid organic fertilizer treatments increased leaf

ISSN 2072-3857

number progressively; the 3 $mL \cdot L^{-1}$ concentration achieved the highest leaf count of 9.15 $leaves \cdot plant^{-1}$, compared with the control which recorded the lowest value of 7.56 $leaves \cdot plant^{-1}$. With regard to nano-fertilizer, the 3 $g \cdot L^{-1}$ level was significantly superior, recording the highest mean leaf number of 8.81 $leaves \cdot plant^{-1}$, while the control registered the lowest value of 7.70 $leaves \cdot plant^{-1}$. The interaction treatment (a4b3) produced the highest mean leaf number of 9.53 $leaves \cdot plant^{-1}$, whereas the control interaction (a1b1) yielded the lowest value of 6.70 $leaves \cdot plant^{-1}$.

Table 1. Effect of organic and nano NPK fertilizer and their interaction on leaf number ($leaves \cdot plant^{-1}$) in red radish.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 $g \cdot L^{-1}$ (b2)	3 $g \cdot L^{-1}$ (b3)	Organic Mean
a1 Control	6.70	7.80	8.20	7.56
a2 1 $mL \cdot L^{-1}$	7.23	7.73	8.60	7.85
a3 2 $mL \cdot L^{-1}$	8.10	8.60	8.93	8.54
a4 3 $mL \cdot L^{-1}$	8.80	9.13	9.53	9.15
Nano Mean	**7.70**	**8.31**	**8.81**	
LSD (0.05): A×B = 0.35 B = 0.17 A = 0.20				

3.1.2 Relative Chlorophyll Content (SPAD Units)

The results presented in Table 2 indicate significant differences in relative chlorophyll content in response to the fertilization levels studied. The liquid organic fertilizer at 3 $mL \cdot L^{-1}$ was significantly superior, yielding the highest mean of 38.25 SPAD units, compared with the control which recorded the lowest mean of 32.92 SPAD units. The nano-fertilizer at 3 $g \cdot L^{-1}$ likewise recorded the highest chlorophyll content of 37.08 SPAD units, while the control registered the lowest value of 33.63 SPAD units. The interaction treatment (a4b3) produced the highest relative

ISSN 2072-3857

chlorophyll content of 39.02 SPAD units, whereas the control (a1b1) recorded the lowest value of 28.22 SPAD units.

Table 2. Effect of organic and nano NPK fertilizer and their interaction on relative chlorophyll content (SPAD units) in red radish leaves.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 g·L^{-1} (b2)	3 g·L^{-1} (b3)	Organic Mean
a1 Control	28.22	35.08	35.45	32.92
a2 1 mL·L^{-1}	34.84	36.13	35.77	35.58
a3 2 mL·L^{-1}	33.98	37.17	38.08	36.41
a4 3 mL·L^{-1}	37.49	38.23	39.02	38.25
Nano Mean	**33.63**	**36.65**	**37.08**	
LSD (0.05): A×B = 1.41 B = 0.70 A = 0.81				

3.1.3 Fresh Weight of Shoot System (g·plant^{-1})

The data in Table 3 reveal a pronounced and significant effect of fertilization treatments on shoot fresh weight. The liquid organic fertilizer at 3 mL·L^{-1} recorded the highest mean fresh weight of 19.52 g·plant^{-1}, compared with the control which recorded the lowest value of 14.05 g·plant^{-1}. Application of nano-fertilizer at 3 g·L^{-1} produced a significant increase, recording the highest mean of 19.58 g·plant^{-1}, while the control registered the lowest value of 13.99 g·plant^{-1}. The interaction (a4b3) was significantly superior, recording the highest shoot fresh weight of 22.25 g·plant^{-1}, whereas the control interaction (a1b1) produced the lowest mean of 11.02 g·plant^{-1}.

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Table 3. Effect of organic and nano NPK fertilizer and their interaction on fresh weight of shoot system (g·plant^{-1}) in red radish.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 g·L^{-1} (b2)	3 g·L^{-1} (b3)	Organic Mean
a1 Control	11.02	13.84	17.28	14.05
a2 1 mL·L^{-1}	13.05	17.91	18.88	16.61
a3 2 mL·L^{-1}	15.63	16.73	19.90	17.42
a4 3 mL·L^{-1}	16.25	20.06	22.25	19.52
Nano Mean	**13.99**	**17.14**	**19.58**	
LSD (0.05): A×B = 1.19 B = 0.59 A = 0.68				

3.1.4 Fresh Weight of Root System (g·plant^{-1})

The results in Table 4 indicate a clear and significant response in root fresh weight to the different fertilization levels. The liquid organic fertilizer at 3 mL·L^{-1} achieved the highest mean root fresh weight of 45.69 g·plant^{-1}, compared with the control which recorded the lowest mean of 31.76 g·plant^{-1}. The statistical data show that the nano-fertilizer at 3 g·L^{-1} produced a significant increase in root weight, recording the highest value of 44.43 g·plant^{-1}, while the control yielded the lowest value of 30.30 g·plant^{-1}. The interaction treatment (a4b3) achieved the highest root fresh weight of 53.44 g·plant^{-1}, whereas the control (a1b1) recorded the lowest value of 22.33 g·plant^{-1}.

Table 4. Effect of organic and nano NPK fertilizer and their interaction on fresh weight of root system (g·plant^{-1}) in red radish.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 g·L^{-1} (b2)	3 g·L^{-1} (b3)	Organic Mean
a1 Control	22.33	33.80	39.13	31.76
a2 1 mL·L^{-1}	29.17	35.30	41.47	35.31
a3 2 mL·L^{-1}	32.22	40.76	43.66	38.88
a4 3 mL·L^{-1}	37.46	46.17	53.44	45.69
Nano Mean	**30.30**	**39.01**	**44.43**	
LSD (0.05): A×B = 2.32 B = 1.16 A = 1.34				

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3.1.5 Dry Weight of Root System (g·plant^{-1})

The results in Table 5 reveal significant differences in root dry weight in response to the fertilization treatments. Application of organic fertilizer at 3 mL·L^{-1} produced the highest root dry weight of 3.08 g·plant^{-1}, while the control recorded the lowest value of 2.22 g·plant^{-1}. The nano-fertilizer at 3 g·L^{-1} likewise produced a clear and significant improvement, recording the highest dry weight value of 3.10 g·plant^{-1} compared with the control which recorded the lowest value of 2.12 g·plant^{-1}. The binary interaction between organic and nano-fertilizer treatment (a4b3) was significantly superior, yielding the highest mean root dry weight of 3.74 g·plant^{-1}, while the control interaction (a1b1) recorded the lowest value of 1.56 g·plant^{-1}.

Table 5. Effect of organic and nano NPK fertilizer and their interaction on dry weight of root system (g·plant^{-1}) in red radish.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 g·L^{-1} (b2)	3 g·L^{-1} (b3)	Organic Mean
a1 Control	1.56	2.36	2.74	2.22
a2 1 mL·L^{-1}	2.04	2.47	2.90	2.47
a3 2 mL·L^{-1}	2.26	2.85	3.05	2.72
a4 3 mL·L^{-1}	2.62	2.89	3.74	3.08
Nano Mean	**2.12**	**2.64**	**3.10**	
LSD (0.05): A×B = 0.32 B = 0.16 A = 0.18				

3.2 Chemical Measurements

3.2.1 Nitrogen Percentage (%)

The laboratory results recorded in Table 6 indicate clear and significant effects of the fertilization treatments on nitrogen absorption efficiency in leaves. The organic fertilizer at 3 mL·L^{-1} recorded the highest nitrogen percentage of 5.41%, surpassing the control which registered the lowest value of 3.97%. With regard to nano-fertilizer, significant differences were observed at the 3 g·L^{-1} level, which recorded the highest leaf nitrogen content of 5.47%, while the lowest value of 3.69% was recorded in the untreated control. The interaction treatment (a4b3) produced the maximum response for this trait, recording the highest nitrogen percentage of 6.03%, whereas the control interaction (a1b1) recorded

ISSN 2072-3857

the lowest nitrogen percentage of 3.17%.

Table 6. Effect of organic and nano NPK fertilizer and their interaction on nitrogen percentage (%) in red radish leaves.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 g·L⁻¹ (b2)	3 g·L⁻¹ (b3)	Organic Mean
a1 Control	3.17	3.92	4.84	3.97
a2 1 mL·L⁻¹	3.37	4.24	5.24	4.28
a3 2 mL·L⁻¹	3.65	5.11	5.79	4.85
a4 3 mL·L⁻¹	4.58	5.64	6.03	5.41
Nano Mean	**3.69**	**4.72**	**5.47**	
LSD (0.05): A×B = 0.03 B = 0.01 A = 0.02				

3.2.2 Phosphorus Percentage (%)

The results in Table 7 reveal significant differences in leaf phosphorus content of red radish in response to the different treatments. The organic fertilizer at 3 mL·L⁻¹ was significantly superior, recording the highest mean phosphorus content of 0.5248%, compared with the control which recorded the lowest mean of 0.5103%. The nano-fertilizer at 3 g·L⁻¹ similarly produced the highest leaf phosphorus value of 0.5259%, while the control registered the lowest value of 0.5072%. The interaction (a4b3) achieved the highest phosphorus accumulation of 0.5320%, whereas the control (a1b1) recorded the lowest value of 0.5020%.

Table 7. Effect of organic and nano NPK fertilizer and their interaction on phosphorus percentage (%) in red radish leaves.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 g·L⁻¹ (b2)	3 g·L⁻¹ (b3)	Organic Mean
a1 Control	0.5020	0.5096	0.5193	0.5103
a2 1 mL·L⁻¹	0.5043	0.5130	0.5236	0.5136
a3 2 mL·L⁻¹	0.5073	0.5220	0.5286	0.5193
a4 3 mL·L⁻¹	0.5153	0.5273	0.5320	0.5248
Nano Mean	**0.5072**	**0.5180**	**0.5259**	
LSD (0.05): A×B = 0.0014 B = 0.0007 A = 0.0008				

ISSN 2072-3857

3.2.3 Potassium Percentage (%)

The results in Table 8 reveal significant differences in leaf potassium concentration in response to the fertilization levels. The organic fertilizer at 3 $mL \cdot L^{-1}$ was significantly superior, recording the highest potassium percentage of 3.558%, while the control registered the lowest value of 3.423%. Application of nano-fertilizer at 3 $g \cdot L^{-1}$ produced a clear increase in leaf potassium content, yielding the highest value of 3.570%, compared with the control which recorded the lowest value of 3.390%. The interaction treatment (a4b3) achieved the highest potassium percentage of 3.643%, whereas the control interaction (a1b1) recorded the lowest value of 3.343%.

Table 8. Effect of organic and nano NPK fertilizer and their interaction on potassium percentage (%) in red radish leaves.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 $g \cdot L^{-1}$ (b2)	3 $g \cdot L^{-1}$ (b3)	Organic Mean
a1 Control	3.343	3.423	3.503	3.423
a2 1 $mL \cdot L^{-1}$	3.363	3.433	3.533	3.443
a3 2 $mL \cdot L^{-1}$	3.393	3.520	3.603	3.505
a4 3 $mL \cdot L^{-1}$	3.463	3.570	3.643	3.558
Nano Mean	**3.390**	**3.486**	**3.570**	
LSD (0.05): A×B = 0.008 B = 0.004 A = 0.004				

3.3 Qualitative Yield Characteristics

3.3.1 Total Carbohydrate Percentage in Leaves (%)

The results in Table 9 reveal significant differences in total leaf carbohydrate content in response to the fertilization treatments. The organic fertilizer at 3 $mL \cdot L^{-1}$ was significantly superior, recording the highest mean carbohydrate content of 4.98%, compared with the control which registered the lowest mean of 3.62%. The nano-fertilizer at 3 $g \cdot L^{-1}$ likewise recorded the highest leaf carbohydrate value of 5.06%, while the lowest mean of 3.41% was recorded in the control. The interaction (a4b3) produced the maximum carbohydrate accumulation in leaves of 5.62%, while the control (a1b1) recorded the lowest value of 2.94%.

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Table 9. Effect of organic and nano NPK fertilizer and their interaction on total carbohydrate percentage (%) in red radish leaves.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 g·L⁻¹ (b2)	3 g·L⁻¹ (b3)	Organic Mean
a1 Control	2.94	3.62	4.31	3.62
a2 1 mL·L⁻¹	3.20	3.94	4.96	4.03
a3 2 mL·L⁻¹	3.34	4.64	5.38	4.45
a4 3 mL·L⁻¹	4.19	5.14	5.62	4.98
Nano Mean	**3.41**	**4.33**	**5.06**	
LSD (0.05): A×B = 0.03 B = 0.01 A = 0.02				

3.3.2 Total Protein Percentage in Leaves (%)

The results in Table 10 reveal significant differences in leaf protein percentage. The organic fertilizer at 3 mL·L⁻¹ produced the highest mean protein percentage of 33.86%, surpassing the control which registered the lowest value of 24.86%. The nano-fertilizer at 3 g·L⁻¹ was significantly superior, recording the highest mean protein percentage of 34.22%, compared with the control which registered the lowest value of 23.08%. The binary interaction (a4b3) was significantly superior, yielding the highest protein percentage of 37.70%, while the control interaction (a1b1) recorded the lowest value of 19.80%.

Table 10. Effect of organic and nano NPK fertilizer and their interaction on total protein percentage (%) in red radish leaves.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 g·L⁻¹ (b2)	3 g·L⁻¹ (b3)	Organic Mean
a1 Control	19.80	24.52	30.25	24.86
a2 1 mL·L⁻¹	21.08	26.50	32.74	26.77
a3 2 mL·L⁻¹	22.81	31.93	36.18	30.30
a4 3 mL·L⁻¹	28.64	35.24	37.70	33.86
Nano Mean	**23.08**	**29.55**	**34.22**	
LSD (0.05): A×B = 0.24 B = 0.12 A = 0.14				

ISSN 2072-3857

3.3.3 Total Soluble Solids, TSS (%)

The results in Table 11 reveal significant differences in TSS percentage in red radish roots. The organic fertilizer at 1 mL·L^{-1} recorded the highest mean TSS of 3.66%, significantly surpassing the control which registered the lowest mean of 3.11%. The nano-fertilizer at 3 g·L^{-1} was significantly superior in TSS, recording the highest value of 3.91%, while the control registered the lowest value of 2.91%. Regarding the interaction effect, the treatments (a1b3), (a2b3), (a3b3), and (a2b2) jointly achieved the highest TSS value of 4.00%, whereas the control (a1b1) recorded the lowest value of 2.33%.

Table 11. Effect of organic and nano NPK fertilizer and their interaction on total soluble solids (TSS %) in red radish roots.

Nano-fertilizer Organic fertilizer	Control (b1)	1.5 g·L^{-1} (b2)	3 g·L^{-1} (b3)	Organic Mean
a1 Control	2.33	3.00	4.00	3.11
a2 1 mL·L^{-1}	3.00	4.00	4.00	3.66
a3 2 mL·L^{-1}	3.33	3.33	4.00	3.55
a4 3 mL·L^{-1}	3.00	3.66	3.66	3.44
Nano Mean	**2.91**	**3.50**	**3.91**	
LSD (0.05): A×B = 0.61 B = 0.30 A = 0.35				

3.4 General Discussion

The significant effect of organic fertilizer across all indicators presented in Tables 1–11 can be attributed to the content of this extract in certain nutrients, notably nitrogen, which plays a pivotal role in increasing cell number and size, thereby expanding leaf area through its involvement in amino acid formation, including tryptophan—the precursor to auxin biosynthesis (Al-Najjar and Tawfiq, 1981).

The significant increase in chlorophyll content can be explained by the nitrogen content of the organic extract, which contributes to chlorophyll molecule synthesis through the supply of the amino acid glutamate—a participant in porphyrin biosynthesis, the fundamental building block of chlorophyll (Marschner, 1995).

The significant increases observed with organic fertilizer foliar application in vegetative growth and yield indicators (Tables 1–5) are consistent with findings of researchers

ISSN 2072-3857

who have used organic extracts and biostimulants; foliar application of these materials improves photosynthetic efficiency and promotes shoot growth. This is attributed to the richness of organic materials in amino acids and nutrients that support cell division (Al-Tufayli, 2023; Mehdawe et al., 2023).

The results in Tables 9, 10, and 11 demonstrate clear and significant superiority of the organic fertilizer at 3 $mL \cdot L^{-1}$ in qualitative yield characteristics—total carbohydrate percentage, total protein percentage, and total soluble solids. This improvement is attributed to the role of foliar organic fertilizer application in increasing TSS levels by providing additional quantities of soluble sugars and organic acids, which raise osmotic concentration, thereby improving the water status of cells and enhancing the accumulation of metabolic products in storage organs (Stevenson, 1994).

The increase in protein content within plant cells is attributed to the fact that the organic nitrogen made available from foliar application enters directly into the metabolism and synthesis of amino acids and into structural and enzymatic proteins within tissues, supporting the structural integrity of the plant (Mengel and Kirkby, 2012). In the same context, the increase in total carbohydrate content is explained by the role of humic substances present in the organic fertilizer, which stimulate photosynthetic enzyme activity and enhance CO_2 fixation efficiency, ultimately maximizing carbohydrate accumulation in various plant tissues (Chen and Aviad, 1990).

With respect to nano-fertilization, the nano NPK fertilizer also exerted a significant and pronounced effect in improving vegetative growth, yield, and chemical composition as evidenced in Tables 1–11. The nano-fertilizer at 3 $g \cdot L^{-1}$ was significantly superior in qualitative yield characteristics—total soluble solids, total protein, and total carbohydrates—as shown in Tables 9, 10, and 11. This elevation is attributed to the role of nanotechnology in improving ion transport across cell membranes within the vacuoles of storage tissues, thereby increasing their content of sugars and total dissolved solids. With respect to protein content, this is attributable to the role of nanoparticles in improving the availability of nitrogen and sulfur—the fundamental structural elements of proteins—while simultaneously activating nitrate reductase and fixation enzymes (Nair et al., 2010).

This study is consistent with Rostami et al. (2015), who reported that application of nano-potassium fertilizer at increasing concentrations to tomato plants produced a

ISSN 2072-3857

significant increase in vegetative characteristics and yield traits proportional to the concentration of applied fertilizer.

The superiority observed in carbohydrate qualitative indicators upon nano-potassium fertilizer application is attributed to the vital role of this element in stimulating photosynthetic efficiency and regulating stomatal movement, which positively reflects on the translocation of metabolic products to the roots. Furthermore, these treatments contribute to providing the base carbohydrate material required for the synthesis of secondary and medicinal compounds such as glucosinolates (Amran and Abbass, 2022).

Across all indicators studied, the interaction results confirmed the comprehensive superiority of the treatment (a4b3): combined foliar application of organic and nano-fertilizer provides the plant with nutrients ready for direct absorption through the leaves, bypassing any constraints imposed by saline soils, thereby ensuring a rapid and continuous supply that stimulates cell elongation and division (Brady and Weil, 1996).

4. Conclusions

1. The study revealed a high-level physiological synergism when combining organic and nano-fertilization: organic nitrogen acts as a structural substrate while nanoparticles function as an energy catalyst, collectively improving all indicators studied.
2. The results confirmed the superiority of nano-fertilizers across all indicators studied, contributing to the maintenance of a stable nutritional status within radish leaves and preventing nutrient depletion at advanced growth stages.
3. Integrated fertilization enhanced the sink efficiency of roots in attracting metabolic products, as reflected in the significant increases in carbohydrate content, protein content, and total soluble solids, thereby elevating the marketability and nutritional value of the crop.
4. The interaction between the organic and nano-fertilizer treatment (a4b3) represents the optimal nutritional equilibrium point for red radish, ensuring maximum productive capacity while maintaining the highest standards of qualitative output.

ISSN 2072-3857

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Received: 2025 | Accepted: 2026 | Al-Qasim Green University — College of Agriculture

ISSN 2072-3857