

International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(8): 996-1003
www.biochemjournal.com
Received: 10-05-2026
Accepted: 13-06-2026

Alok Kumar
Student (M.Sc.) Institute of
Agricultural Science,
university of Calcutta,
Kolkata, West Bengal, India

Dr. Pinaki Acharya
Associate Professor, Institute of
Agricultural Science,
university of Calcutta,
Kolkata, West Bengal, India

Sanat Kumar Meher
Research Scholar, Institute of
Agricultural Science,
university of Calcutta,
Kolkata, West Bengal, India

Effect of foliar application of nanonutrients on growth, yield and quality in radish (*Raphanus sativus* L. cv. Japanese white)

Alok Kumar, Pinaki Acharya and Sanat Kumar Meher

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i8Sl.9561>

Abstract

A field investigation on the “Effect of Foliar Spray of Nano Nutrient on Growth, Yield and Quality of Radish (*Raphanus sativus* L. cv. Japanese white)” was carried out in randomized block design having 21 treatments and 3 replicates during Rabi season of 2022-23 at Agricultural Experiment Research Farm of Calcutta University, Baruipur, South 24 Parganas, West Bengal. The treatments comprised of foliar spray of different Nano nutrients. With the combinations 1 (IFFCO Nano Urea: 3 ml, IFFCO Nano DAP: 5ml and IFFCO Nano ZnO: 1ml) and combination 2 (IFFCO Nano Urea: 5ml, IFFCO Nano DAP: 10ml, IFFCO Nano ZnO: 2ml). Among the Growth parameters the treatments, T₂₁ (Control-having 100% of RDF with a NPK ratio of 75:50:100 kg/ha) recorded significantly higher in number of leaves per plant (8.88 cm), leaf length (20.55 cm), leaf area (55.66 cm²) compared to other treatments at 30 DAS while, T₂₀ [Nano DAP C₂ + Nano Urea C₂ + Nano ZnO C₂ + (25%N + 25% P + 100% K of RDF as basal fertilizer Application)] recorded maximum plant height (45.62), leaf length (27.74 cm), number of leaves (14.02 cm) and leaf area (77.67 cm²) at 60 DAS. All treatments differed significantly with respect to yield parameters. Among the treatments, T₂₀ recorded significantly higher root length per plant (17.88 cm), edible root weight (102.64 g), leaf weight (74.58 g), diameter (3.63 cm), plant yield per ha (315.45 kg), dry weight root of plant (8.64 g) and total fresh weight of plant weight (177.22 g) over other treatments while minimum yield attributes were recorded in T₃ [Nano Urea C₂ + (25%N + 100%P + 100% K of RDF as basal fertilizer Application)]. The results pertaining to quality parameters revealed that maximum TSS (6.590Brix), protein (0.77%), beta carotene (3.53%) and carbohydrate (4.81%) were recorded significantly in T₂₀ over other treatments. Maximum net return of Rs.1, 01261.21/ha, and B:C Ratio value (2.79) was obtained in treatment T₂₀ followed by T₁₉. Results obtained in present investigation, suggests that to obtain higher and profitable yield of radish cv. Japanese white, the crop may be foliar sprayed with a combination spray of Nano DAP C₂ + Nano Urea C₂ + Nano ZnO C₂ having 25% N + 25%P + 100% K of RDF as Basal fertilizer application followed by the next best combination spray of Nano DAP C₂ + Nano Urea C₂ + Nano ZnO C₁ coupled with 25% N + 25% P + 100% K of RDF as Basal fertilizer. Our findings are of the view that nano fertilizers may help the farmers to shorten the harvest time, reduce leaching losses and ground water contamination of soil based applied fertilizers. However, its success will lie on the acceptability by the farmers, easy availability and innovations, environmental parameters at the site like wind velocity, radiation hours etc. and finally the cost-benefit ratio.

Keywords: Nano fertilizers, radish, growth, yield

Introduction

Agriculture serves as the backbone of the Indian economy, providing livelihoods to a significant portion of the country's population. With the global population continuously increasing, there is a pressing need to boost agricultural productivity in a sustainable manner. This can be accomplished either by bringing more land under cultivation or, more preferably, by enhancing crop yields through improved nutrient management practices. In recent years, nano-fertilizers have emerged as a promising and innovative alternative to traditional chemical fertilizers. Nanotechnology has demonstrated considerable potential in vegetable production by improving seed germination, enhancing seedling vigour, reducing both abiotic and biotic stresses, and ultimately increasing yield and quality of produce. These developments have established nanotechnology as an important tool for achieving sustainable and precision agriculture.

Corresponding Author:
Alok Kumar
Student (M.Sc.) Institute of
Agricultural Science,
university of Calcutta,
Kolkata, West Bengal, India

Radish (*Raphanus sativus* L.), a member of the Brassicaceae family, is one of the most widely cultivated and popular root vegetables grown across tropical, subtropical, and temperate regions of the world. It can be grown as both an annual and biennial crop depending on the purpose. Although primarily a cool-season crop, Asiatic varieties show better tolerance to higher temperatures than European types. In areas with mild climatic conditions, radish can be cultivated throughout the year except during extreme summer months. Radish holds significant importance as a dietary component worldwide. Its crisp, tuberous roots are commonly consumed raw in salads or cooked as a vegetable, imparting a characteristic pungent flavour that stimulates appetite. The tender leaves are also used as a leafy vegetable. Medicinally, radish is valued for its beneficial effects on liver and gallbladder function. Different parts of the plant, including roots, leaves, flowers, and pods, exhibit antimicrobial properties and have been traditionally used to manage urinary disorders, piles, and digestive problems. Nutritionally, radish roots are a good source of vitamin C (15-40 mg per 100 g fresh weight) and several essential minerals. The young leaves are particularly rich in vitamins A and C, along with important trace elements such as manganese, silicon, and iodine. The continuous and excessive use of chemical fertilizers has raised serious global concerns due to its negative impacts on soil health, environmental quality, and produce safety. Issues such as soil degradation, nutrient imbalances, groundwater pollution, and declining crop quality have prompted a shift towards more sustainable and precision-based nutrient management approaches. In this context, nano-fertilizers offer a smart and efficient solution. Owing to their ultra-small particle size, high surface area, and controlled-release mechanisms, nano-fertilizers significantly improve nutrient use efficiency while minimizing losses and environmental hazards. Nano-urea, developed by IFFCO and approved under the Fertilizer Control Order (FCO) in India, has shown superior performance compared to conventional urea. It facilitates better nitrogen availability, promotes vegetative growth, enhances flowering and fruit retention, and improves important quality attributes such as total soluble solids. Likewise, phosphorus plays a critical role in root development, while potassium regulates key physiological processes including photosynthesis, stomatal regulation, enzyme activation, and water-use efficiency. Zinc acts as a cofactor for numerous enzymes and is essential for hormone synthesis, protein formation, and overall plant metabolism. The distinctive properties of nanoparticles such as high reactivity, tunable characteristics, and targeted delivery make nano-fertilizers highly effective for modern nutrient management. They function as efficient carriers that enhance nutrient uptake, reduce dosage requirements, and lower environmental risks. Several studies conducted worldwide during 2020-2026 have consistently reported that nano-fertilizers (including Nano Urea, Nano DAP, and Nano ZnO) improve nutrient efficiency, crop productivity, and produce quality while reducing the overall cost of cultivation. In recent times, consumer demand for high-quality, nutrient-rich vegetables has increased significantly. However, there is still limited scientific information available on the foliar application of nano-nutrients for improving growth, yield, and quality in

radish. Globally, China leads in radish production, while India has witnessed steady growth in radish cultivation. During 2024-25, India produced approximately 3.2-3.5 million tonnes of radish. West Bengal is among the major radish-producing states, with an area of about 39-41 thousand hectares and production ranging between 557-574 thousand tonnes during the same period, contributing substantially to the national output.

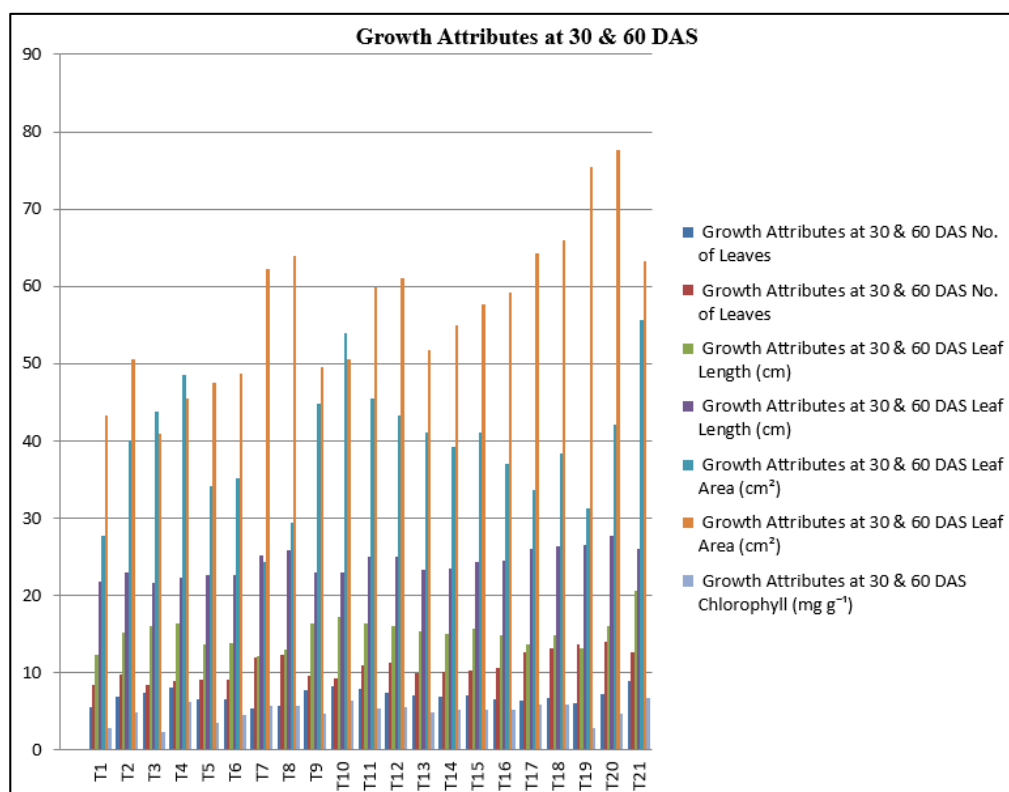
Materials and Methods

The present field experiment was conducted to assess the effect of foliar application of nano-nutrients on growth, yield, and quality parameters of radish at the Agricultural Experimental Research Farm, Institute of Agricultural Science, University of Calcutta, Baruipur, South 24 Parganas, West Bengal. The experiment was laid out in a Randomized Block Design (RBD) with three replications. The net plot size was 1 m × 1 m (1 m²). Healthy, disease-free seeds of radish variety Japanese White were used for the study. Seeds were sown at a recommended spacing of 20 cm × 10 cm. The study consisted of 21 treatments involving different combinations of nano-fertilizers applied as foliar sprays. The nano-nutrient combinations used were: Combination 1 (C₁): IFFCO Nano Urea (3 ml) + IFFCO Nano DAP (5 ml) + IFFCO Nano ZnO (1 ml) Combination 2 (C₂): IFFCO Nano Urea (5 ml) + IFFCO Nano DAP (10 ml) + IFFCO Nano ZnO (2 ml) The treatments were as follows: T₁: Nano DAP (C₁) + 25% N + 25% P + 100% K of RDF as basal application T₂: Nano DAP (C₂) + 25% N + 25% P + 100% K of RDF as basal application T₃: Nano Urea (C₁) + 25% N + 100% P + 100% K of RDF as basal application T₄: Nano Urea (C₂) + 25% N + 100% P + 100% K of RDF as basal application T₅: Nano DAP (C₁) + Nano ZnO (C₁) + 25% N + 25% P + 100% K of RDF as basal T₆: Nano DAP (C₁) + Nano ZnO (C₂) + 25% N + 25% P + 100% K of RDF as basal T₇: Nano DAP (C₂) + Nano ZnO (C₁) + 25% N + 25% P + 100% K of RDF as basal T₈: Nano DAP (C₂) + Nano ZnO (C₂) + 25% N + 25% P + 100% K of RDF as basal T₉: Nano Urea (C₁) + Nano ZnO (C₁) + 25% N + 100% P + 100% K of RDF as basal T₁₀: Nano Urea (C₁) + Nano ZnO (C₂) + 25% N + 100% P + 100% K of RDF as basal T₁₁: Nano Urea (C₂) + Nano ZnO (C₁) + 25% N + 100% P + 100% K of RDF as basal T₁₂: Nano Urea (C₂) + Nano ZnO (C₂) + 25% N + 100% P + 100% K of RDF as basal T₁₃: Nano DAP (C₁) + Nano Urea (C₁) + Nano ZnO (C₁) + 25% N + 25% P + 100% K of RDF as basal T₁₄: Nano DAP (C₁) + Nano Urea (C₁) + Nano ZnO (C₂) + 25% N + 25% P + 100% K of RDF as basal T₁₅: Nano DAP (C₁) + Nano Urea (C₂) + Nano ZnO (C₁) + 25% N + 25% P + 100% K of RDF as basal T₁₆: Nano DAP (C₁) + Nano Urea (C₂) + Nano ZnO (C₂) + 25% N + 25% P + 100% K of RDF as basal T₁₇: Nano DAP (C₂) + Nano Urea (C₁) + Nano ZnO (C₁) + 25% N + 25% P + 100% K of RDF as basal T₁₈: Nano DAP (C₂) + Nano Urea (C₁) + Nano ZnO (C₂) + 25% N + 25% P + 100% K of RDF as basal T₁₉: Nano DAP (C₂) + Nano Urea (C₂) + Nano ZnO (C₁) + 25% N + 25% P + 100% K of RDF as basal T₂₀: Nano DAP (C₂) + Nano Urea (C₂) + Nano ZnO (C₂) + 25% N + 25% P + 100% K of RDF as basal T₂₁: Control (100% RDF with N:P:K ratio of 75:50:100 kg/ha applied as basal).

Results and Discussion

Table 1: Mean Value Table for Growth attributing character of radish at 30 DAS and 60 DAS among the treatment:-

Sl. No.	No of leaves		Leaf Length (cm)		Leaf rea(cm ²)		Chlorophyll of leaves (mg g ⁻¹)
	30 DAS	60 DAS	30 DAS	60 DAS	30 DAS	60 DAS	
T ₁	5.46*	8.423*	12.30*	21.743*	27.74*	43.227*	2.85*
T ₂	6.90*	9.847*	15.15*	23.047*	40.00*	50.523*	4.903*
T ₃	7.44*	8.473*	16.00*	21.653*	43.83*	40.837*	2.337*
T ₄	8.03*	8.967*	16.40*	22.367*	48.52*	45.413*	6.157*
T ₅	6.50*	9.043*	13.66*	22.633*	34.12*	47.533*	3.510*
T ₆	6.55*	9.123*	13.80*	22.717*	35.21*	48.727*	4.537*
T ₇	5.37*	11.933	12.11*	25.133	24.33*	62.257	5.663
T ₈	5.74*	12.38*	12.95*	25.817	29.46*	63.95*	5.750*
T ₉	7.82*	9.6*	16.29*	22.93*	44.87*	49.557*	4.640*
T ₁₀	8.25*	9.19*7	17.14*	22.967*	53.92*	50.49	6.447*
T ₁₁	7.98*	10.99*7	16.31*	24.98*	45.44*	59.843*	5.317*
T ₁₂	7.42*	11.283	15.99*	25.043	43.26*	60.98*	5.473*
T ₁₃	7.13*	9.973*	15.40*	23.28*	41.04*	51.667*	4.910*
T ₁₄	6.89*	10.04*	14.97*	23.44*	39.20*	55.037	5.130*
T ₁₅	7.14*	10.34*	15.63*	24.377*	41.16*	57.587	5.160*
T ₁₆	6.63*	10.697*	14.90*	24.57*	37.10*	59.233*	5.207*
T ₁₇	6.47*	12.65	13.60*	26.013	33.67*	64.263*	5.803*
T ₁₈	6.73*	13.227	14.92*	26.387*	38.43*	65.9	5.933
T ₁₉	6.12*	13.677	13.13*	26.527*	31.30*	75.363	2.817*
T ₂₀	7.17*	14.023	15.97	27.74*	42.06*	77.677	4.780*
T ₂₁	8.88*	12.593	20.55	25.973	55.6	63.26	6.807*
C.D.	0.1	1.196	1.51	0.294	0.31	4.327	0.271
SE(m)	0.04	0.521	0.53	0.102	0.11	1.508	0.095
C.V.	0.87	8.375	6.05	0.732	0.47	4.597	3.303



Plant Height (cm)

Plant height at 60 DAS was significantly influenced by the foliar application of nano-nutrients. The maximum plant height (45.62 cm) was recorded in treatment T₂₀ [Nano DAP (C2) + Nano Urea (C2) + Nano ZnO (C2) + 25% N + 25% P + 100% K of RDF as basal application]. This was followed by T₁₉ (43.93 cm), T₁₈ (41.97 cm), and T₁₇ (41.51 cm). The minimum plant height (33.56 cm) was observed in T₃ [Nano

Urea (C1) + 25% N + 100% P + 100% K of RDF as basal]. Most treatments recorded significantly higher plant height compared to the control, except T₈, T₁₇, and T₁₈. The increase in plant height under higher concentrations of nano-nutrients, particularly in T₂₀, can be attributed to the enhanced availability of nitrogen supplied through both Nano Urea and Nano DAP. Nitrogen plays a crucial role in promoting cell division, cell elongation, and metabolic

activities, leading to improved vegetative growth and better assimilation of photosynthates. These findings are in agreement with the results of Tripathi *et al.* (2017)^[24] and Baloch *et al.* (2014)^[7] in radish.

Number of Leaves per Plant

The number of leaves per plant was significantly affected by different nano-nutrient combinations. At 30 DAS, the control treatment (T₂₁) recorded the highest number of leaves (8.88), followed by T₁₀, T₄, and T₁₁. At 60 DAS, the maximum number of leaves (14.02) was observed in T₂₀ [Nano DAP (C2) + Nano Urea (C2) + Nano ZnO (C2) + 25% N + 25% P + 100% K of RDF as basal], followed by T₁₉ (13.68), T₁₈ (13.23), and T₁₇ (12.65). The lowest number of leaves was recorded in T₁ (5.46) at 30 DAS and T₃ (8.42) at 60 DAS. The improvement in leaf number may be due to the timely and efficient supply of nutrients through nano-fertilizers, which enhanced the photosynthetic rate and accumulation of metabolites. Similar observations were reported by Lakra *et al.* (2017)^[15] and Dash *et al.* (2018)^[9] in radish. Nanoparticles are known to modulate gene expression, thereby influencing various physiological and biochemical pathways that support improved plant growth and development.

Leaf Area (cm²)

Leaf area was significantly influenced by the application of different nano-nutrient combinations at both 30 and 60 DAS. At 30 DAS, the maximum leaf area (55.60 cm²) was recorded in the control treatment (T₂₁), followed by T₁₀ (53.92 cm²) and T₄ (48.52 cm²). The minimum leaf area (27.74 cm²) was observed in T₁. At 60 DAS, the highest leaf area (77.68 cm²) was recorded in T₂₀, followed by T₁₉ (75.36 cm²), T₁₈ (65.90 cm²), and T₁₇ (64.26 cm²). The lowest leaf area at 60 DAS was recorded in T₃ (40.84 cm²). Treatments T₇, T₈, T₁₁, T₁₂, T₁₆, and T₁₇ were statistically at par with the control. The substantial increase in leaf area under combined application of Nano Urea and Nano DAP

(especially in T₂₀) indicates a strong synergistic effect of nano-nutrients on vegetative growth. These results are consistent with the findings of Nofal *et al.* (2021)^[17], who reported significant improvement in leaf area and vegetative biomass in cabbage with higher doses of nano-nitrogen. The foliar application schedule (30 and 45 DAS) likely contributed to the enhanced leaf expansion during the later growth stage.

Leaf Length (cm)

At 30 DAS, the maximum leaf length (20.55 cm) was recorded in the control (T₂₁), followed by T₁₀ (17.14 cm) and T₄ (16.40 cm). The minimum leaf length (12.30 cm) was observed in T₁. At 60 DAS, the highest leaf length (27.74 cm) was recorded in T₂₀ [Nano DAP (C2) + Nano Urea (C2) + Nano ZnO (C2)], followed by T₁₉ (26.53 cm) and T₁₈ (26.39 cm). The minimum leaf length (21.65 cm) was recorded in T₃. Treatments T₇, T₈, T₁₂, and T₁₇ showed non-significant differences with the control, while T₁₉ and T₁₈ were at par with each other.

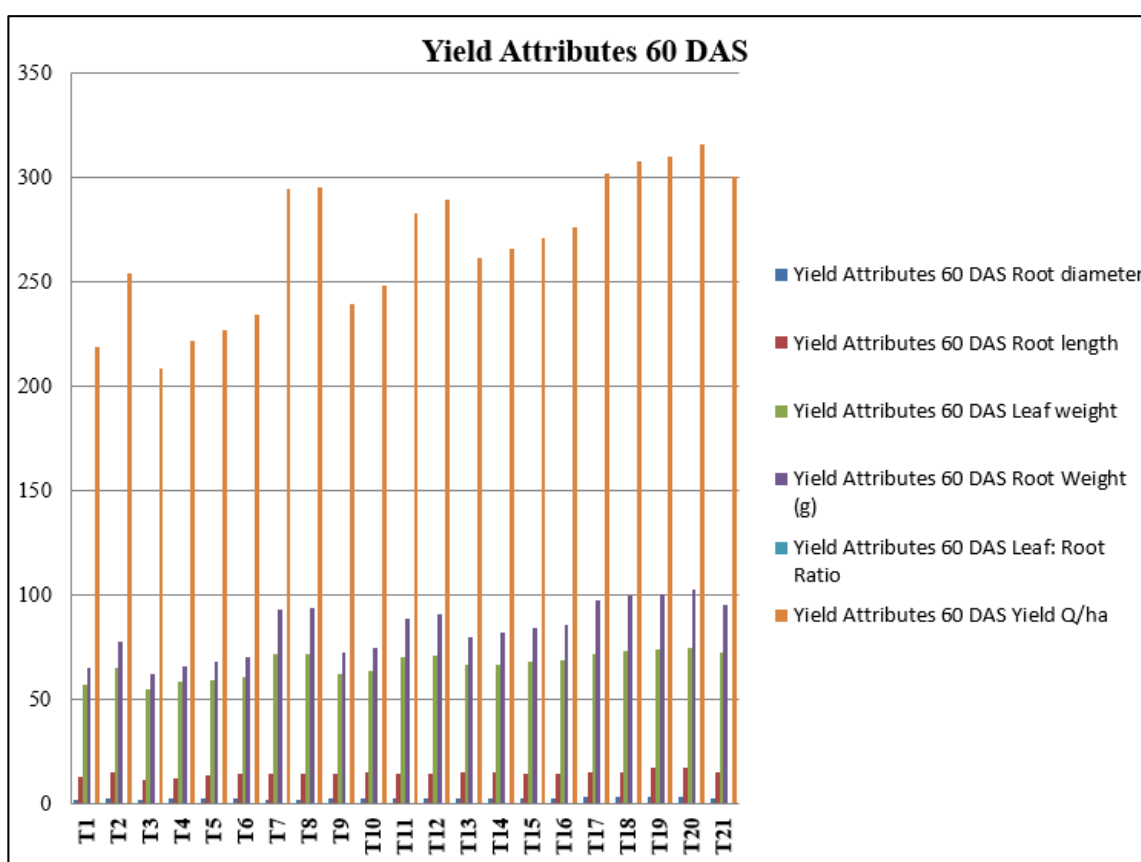
Chlorophyll Content (mg g⁻¹)

Chlorophyll content in radish leaves was significantly influenced by nano-nutrient treatments at both growth stages. At 30 DAS, the highest chlorophyll content (6.81 mg g⁻¹) was recorded in the control (T₂₁), followed by T₁₀ (6.45 mg g⁻¹). The lowest value was observed in T₃ (2.34 mg g⁻¹). At 60 DAS, the maximum chlorophyll content (5.80 mg g⁻¹) was recorded in T₁₇, while T₂₀ also showed comparatively high values. The minimum chlorophyll content was recorded in T₃. The improvement in chlorophyll content with nano-nutrient application may be attributed to the role of zinc and nitrogen in chlorophyll biosynthesis and enzyme activation. These observations are supported by the findings of Abbasifar *et al.* (2020)^[1] in basil and Babaei *et al.* (2017)^[6] in wheat, who reported enhanced chlorophyll content with the application of nano-zinc and nano-nitrogen fertilizers.

Table 2: Effect of Foliar spray of Nano nutrients on yield parameters of radish.

Treatments		Yield Attributes 60 DAS					
		Root diameter	Root length	Leaf weight	Root Weight (g)	Leaf: Root Ratio	Yield Q/ha
T ₁	Nano DAPC1 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	2.46*	12.977*	57.41*	65.283*	0.880*	218.36*
T ₂	Nano DAPC2 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	2.88*	15.123*	65.333*	77.433*	0.844*	254.04*
T ₃	Nano Urea C 1 + (25% N + 100% P + 100% K of RDF as Basal fertilizer Application)	2.36*	11.907*	55.18*	61.95*	0.892*	208.433*
T ₄	Nano Urea C 2 + (25% N + 100% P + 100% K of RDF as Basal fertilizer Application)	2.68*	12.643*	58.313*	66.19*	0.881*	221.543*
T ₅	Nano DAP C1 + Nano ZnO C1 + (25% N + 25% P + 100% K of RDF as Basal fertilizer)	2.77*	13.977*	59.253*	68.08*	0.871*	226.583*
T ₆	Nano DAP C1 + Nano ZnO C2 + (25%N + 25% P + 100% K of RDF as Basal fertilizer)	2.78*	14.313*	60.917*	70.63*	0.863*	234.083*
T ₇	Nano DAP C2 + Nano ZnO C1 + (25% N + 25% P + 100% K of RDF as Basal fertilizer)	2.12	14.797*	71.65	93.347*	0.768*	293.597*
T ₈	Nano DAP C2 + Nano ZnO C2 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	2.17*	14.583*	71.903	93.747*	0.767*	294.773
T ₉	Nano Urea C 1 + Nano ZnO C1 + (25% N + 100% P + 100% K of RDF as Basal fertilizer Application)	2.80*	14.647*	62.26*	72.293*	0.862*	239.43*
T ₁₀	Nano Urea C 1 + Nano ZnO C2 + (25% N + 100% P + 100% K of RDF as Basal fertilizer Application)	2.85*	15.057*	64.147*	75.147*	0.854*	247.863*
T ₁₁	Nano Urea C 2 + Nano ZnO C1 + (25% N + 100% P + 100% K of RDF as Basal fertilizer Application)	3.03	14.81*	70.093	88.657*	0.791*	282.487*
T ₁₂	Nano Urea C2 + Nano ZnO C2 + (25% N + 100% P + 100% K of RDF	3.06	14.847*	71.353	90.98*	0.785*	288.86*

	as Basal fertilizer Application)						
T ₁₃	Nano DAP C1 + Nano Urea C 1 + Nano ZnO C1 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	2.91*	15.277	66.823*	79.94*	0.836*	261.153*
T ₁₄	Nano DAP C1 + Nano Urea C 1 + Nano ZnO C2 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	2.93	15.453	66.947*	82.25*	0.814*	265.483*
T ₁₅	Nano DAP C1 + Nano Urea C 2 + Nano ZnO C1 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	2.95*	14.753*	67.953*	84.35*	0.806*	271.013*
T ₁₆	Nano DAP C1 + Nano Urea C 2 + Nano ZnO C2 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	2.99*	14.717*	69.18	85.983*	0.805	276.113*
T ₁₇	Nano DAP C2 + Nano Urea C1 + Nano ZnO C1 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	3.24	15.497	72.213	97.42*	0.742	301.843
T ₁₈	Nano DAP C2 + Nano Urea C 1 + Nano ZnO C2 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	3.28	15.583*	73.5**	99.51*	0.739	307.863
T ₁₉	Nano DAP C2 + Nano Urea C2 + Nano ZnO C1 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	3.41*	17.397*	73.743	100.153*	0.737	309.43*
T ₂₀	Nano DAP C2 + Nano Urea C2 + Nano ZnO C2 + (25% N + 25% P + 100% K of RDF as Basal fertilizer Application)	3.63*	17.88	74.583*	102.64*	0.727	315.453*
T ₂₁	Control (RDF)	3.197	15.377	72.837*	95.84	0.76	300.153*
	C.D	0.165	0.202	2.216	1.071	0.023	5.557*
	SE(m)	0.58	0.07	0.772	0.373	0.008	1.937
	C.V.	3.352	0.82	1.999	0.775	1.736	1.254



Root Length (cm)

Root length was significantly influenced by the foliar application of different nano-nutrient combinations. The maximum root length (17.88 cm) was recorded in T₂₀ [Nano DAP (C2) + Nano Urea (C2) + Nano ZnO (C2) + 25% N + 25% P + 100% K of RDF as basal application]. This was followed by T₁₉ (17.39 cm), T₁₈ (15.58 cm), and T₁₇ (15.49 cm). The minimum root length (11.90 cm) was observed in T₃ [Nano Urea (C1) + 25% N + 100% P + 100% K of RDF as basal]. Treatments T₁₃, T₁₄, and T₁₇ were statistically at par with the control. The increase in root length under higher nano-nutrient doses, especially in T₂₀, may be attributed to better nutrient availability and uptake. Nitrogen, phosphorus, and potassium serve as fundamental components for the synthesis of various metabolites,

enzymes, and co-enzymes, which enhance photosynthetic efficiency and improve the translocation of carbohydrates to the roots. These findings are in agreement with the results of Chang and Chang (2000) [8] and Ahmed *et al.* (2004) [3] in radish, turnip, and onion.

Root Weight (g)

Fresh root weight was significantly affected by the application of nano-nutrients. The highest root weight (102.64 g) was recorded in T₂₀ [Nano DAP (C2) + Nano Urea (C2) + Nano ZnO (C2) + 25% N + 25% P + 100% K of RDF as basal], followed by T₁₉ (100.15 g) and T₁₈ (99.51 g). The lowest root weight (61.95 g) was observed in T₃. All treatments showed significant differences over the control. The improvement in root weight can be ascribed to

enhanced nutrient uptake, which promoted greater production of photosynthates, increased leaf number, and larger plant biomass, ultimately resulting in higher dry matter accumulation in the roots. These observations are consistent with the findings of Baloch *et al.* (2014)^[7] and Kiran *et al.* (2016)^[14] in radish.

Root Diameter (cm)

Root diameter was significantly influenced by nano-nutrient treatments. The maximum root diameter (3.63 cm) was recorded in T₂₀, followed by T₁₉, T₁₈, and T₁₇. The minimum root diameter (2.36 cm) was observed in T₃. Treatment T₂₁ (control) was statistically at par with T₈, while several other treatments (T₂, T₉, T₁₀, T₁₃, T₁₄, T₁₅, and T₁₆) also showed comparable performance. The increase in root diameter under combined nano-nutrient application indicates improved translocation of photosynthates from leaves to roots. Nano-fertilizers, due to their small particle size and high reactivity, facilitate better nutrient absorption and transport, leading to superior root development. The combination of Nano DAP, Nano Urea, and Nano ZnO at higher concentrations proved most effective in enhancing root morphological traits compared to the control.

Leaf Weight (g per plant)

Leaf fresh weight per plant varied significantly due to different nano-nutrient combinations. The maximum leaf weight (74.58 g) was recorded in T₂₀, followed by T₁₉ (73.74 g), T₁₈ (73.50 g), and T₁₇ (72.21 g). The minimum leaf weight (55.18 g) was observed in T₃. Most treatments recorded significantly higher leaf weight than the control, except T₇, T₈, T₁₁, T₁₂, T₁₆, and T₁₇. The higher leaf weight in T₂₀ may be due to repeated foliar application of nano-nutrients coupled with favourable climatic conditions such as lower temperature and short-day length, which promoted vigorous vegetative growth. Similar improvements in leaf

biomass with nano-zinc application have been reported by Zagzog and Gad (2017)^[26] in mango.

Leaf: Root Weight Ratio

The leaf to root weight ratio was calculated by dividing leaf fresh weight by root fresh weight. The maximum leaf:root ratio (0.892) was recorded in T₃ [Nano Urea (C1) + 25% N + 100% P + 100% K of RDF as basal]. The minimum ratio (0.727) was observed in T₂₀ [Nano DAP (C2) + Nano Urea (C2) + Nano ZnO (C2) + 25% N + 25% P + 100% K of RDF as basal]. A lower leaf:root ratio in T₂₀ indicates greater partitioning of assimilates towards root development rather than leaves, resulting in higher root yield. This shift in biomass allocation is desirable for root crops like radish. The variation in ratio across treatments was also influenced by prevailing environmental conditions during the growing period. These findings align with the results of Rasha *et al.* (2019)^[19], who observed significant changes in leaf and fruit parameters in grapes with nano-zinc application.

Yield (q/ha)

Total root yield (q/ha) was significantly influenced by the application of different nano-nutrient combinations. The highest yield (315.15 q/ha) was recorded in T₂₀, followed by T₁₉, T₁₈, and T₁₇. The lowest yield (208 q/ha) was observed in T₃. Most treatments performed significantly better than the control, except T₈ and T₁₇. The superior performance of T₂₀ can be attributed to the synergistic effect of nano-nutrients, which enhanced overall plant growth, photosynthetic efficiency, and assimilate translocation to the roots. Nano-fertilizers improve nutrient use efficiency and support better metabolic activity, leading to higher root yield. These results are in conformity with the findings of Ramesh *et al.* (2020)^[18] in black gram and earlier studies by Chang and Chang (2000)^[8] and Ahmed *et al.* (2004)^[3] in radish and other root crops.

Effect of foliar application of nano-nutrients on quality attributes of radish at 60 DAS

Treatment	Root Dry Matter (g)	Protein (%)	Carbohydrate (%)	Beta Carotene (µg/mg)	TSS (°Brix)
T ₁	5.13*	0.403*	1.87*	2.127*	4.033*
T ₂	5.85*	0.467*	2.717*	3.363*	5.067*
T ₃	4.39*	0.337*	1.553*	2.03*	3.633*
T ₄	5.32*	0.427*	2.013*	2.423*	4.307*
T ₅	5.50*	0.433*	2.113*	2.87*	4.657*
T ₆	5.62*	0.457*	2.303*	3.067*	4.757*
T ₇	6.85*	0.61*	3.74*	4.157*	5.69*
T ₈	7.24*	0.617*	4.01*	4.303*	5.947*
T ₉	5.78*	0.46*	2.45*	3.167*	4.967*
T ₁₀	5.81*	0.46*	2.6*	3.217*	5.057*
T ₁₁	6.20*	0.583*	3.42*	3.86*	5.44*
T ₁₂	6.64*	0.607*	3.547*	3.91*	5.44*
T ₁₃	5.92*	0.477*	2.85*	3.363*	5.09*
T ₁₄	5.97*	0.493*	2.96*	3.463*	5.217*
T ₁₅	6.01*	0.527*	3.12*	3.513*	5.277*
T ₁₆	6.08*	0.557*	3.26*	3.76*	5.34*
T ₁₇	7.94	0.677*	4.343*	5.197*	6.25*
T ₁₈	8.49*	0.70*	4.477*	6.087*	6.37*
T ₁₉	8.55*	0.717*	4.66*	6.63*	6.54*
T ₂₀	8.65*	0.77*	4.887*	7.273*	6.59*
T ₂₁	7.76	0.637	4.123	4.233	6.067
CD (5%)	0.334	0.038	0.163	0.629	0.181
SE(m)	0.12	0.013	0.23	0.219	0.063
CV (%)	3.128	4.181	8.83	9.725	2.058

Note: * = Significant difference from control at 5% level of significance.

Root Dry Matter Content (g)

Root dry matter content was significantly influenced by the foliar application of nano-nutrients. The highest root dry matter (8.65 g) was recorded in T₂₀ [Nano DAP (C2) + Nano Urea (C2) + Nano ZnO (C2) + 25% N + 25% P + 100% K of RDF as basal application]. This treatment was statistically at par with T₁₉ (8.55 g) and T₁₈ (8.49 g). The lowest root dry matter content (4.39 g) was observed in T₃. Most treatments recorded significantly higher dry matter accumulation than the control (T₂₁), except T₁₇. The improvement in dry matter accumulation under combined nano-nutrient application may be attributed to enhanced enzymatic activities and better hormone synthesis, particularly auxin, facilitated by nano-zinc along with efficient supply of nitrogen and phosphorus through nano-urea and nano-DAP. These results are in line with the findings of Vafa *et al.* (2015) [25], who reported increased dry matter production in savory plants with nano-zinc application due to its role in enzyme activation and improved carbohydrate and protein metabolism.

Carbohydrate Content (%)

Carbohydrate content in radish roots was significantly affected by different nano-nutrient combinations. The maximum carbohydrate content (4.89%) was recorded in T₂₀, followed by T₁₉ (4.66%) and T₁₈ (4.48%). The minimum carbohydrate content (1.55%) was observed in T₃. Most treatments showed significantly higher values compared to the control. Zinc plays a vital role in photosynthesis, chlorophyll synthesis, and starch formation through the activation of the enzyme carbonic anhydrase. The combined application of nano-zinc with nano-nitrogen sources likely improved carbohydrate synthesis and its translocation to the roots. These observations are consistent with the findings of Sharifi *et al.* (2016) [21] and Rasha *et al.* (2019) [19], who reported enhanced carbohydrate content in different crops with the application of nano-zinc fertilizers.

Total Soluble Solids (°Brix)

Total soluble solids (TSS) content in radish roots showed significant variation due to nano-nutrient treatments. The highest TSS (6.59 °Brix) was recorded in T₂₀, which was significantly superior to the control. The lowest TSS value (3.63 °Brix) was observed in T₃. The increase in TSS under T₂₀ may be due to improved photosynthetic efficiency, higher assimilate production, and better translocation of sugars to the roots resulting from balanced and efficient supply of nano-nutrients. These findings are in agreement with the results of Abd El-Rahman *et al.* (2022) [2] and Davarpanah *et al.* (2016) [10], who reported enhanced TSS and sugar content in crops with the application of nano-nitrogen and nano-zinc fertilizers.

Protein Content (%)

Protein content in radish roots was significantly influenced by the application of nano-nutrients. The highest protein content (0.77%) was recorded in T₂₀, followed by T₁₉ (0.72%) and T₁₈ (0.70%). The lowest protein content (0.34%) was observed in T₃. Since nitrogen is a major structural component of proteins and amino acids, the slow and targeted release of nitrogen from nano-urea, along with the supportive effect of nano-DAP and nano-ZnO, likely promoted protein synthesis in the roots. These results are supported by the findings of Astanah *et al.* (2021) [5],

Manikandan and Subramanian (2016) [16], and Sharma *et al.* (2022) [22], who observed increased protein content with the application of nano-nitrogen fertilizers in various crops.

Beta Carotene Content (µg/mg)

Beta carotene content in radish roots differed significantly among the treatments. The maximum beta carotene content (7.27 µg/mg) was recorded in T₂₀, followed by T₁₉ and T₁₈. The minimum value (2.03 µg/mg) was observed in T₃. The improvement in beta carotene content under higher nano-nutrient doses may be attributed to enhanced photosynthetic activity and better nutrient balance, which supported the biosynthesis of pigments. These observations are consistent with the findings of Sharaf-Eldin (2022) [20], who reported significant enhancement in β-carotene content with combined application of nano-nitrogen fertilizers.

References

1. Abbasifar A, Shahrabadi F, Valizadeh Kaji B. Effects of green synthesized zinc and copper nano-fertilizers on the morphological and biochemical attributes of basil plant. *Journal of Plant Nutrition*. 2020;43(8):1104-1118.
2. Abd El-Rahman MA, El-Sayed AA, El-Gazzar IA. Effect of nano-fertilizers on growth, yield and fruit quality of date palm. *Journal of Horticultural Science & Ornamental Plants*. 2022;14(2):78-89.
3. Ahmed F, Sarwar S, Khan BM. Effect of different combinations of NPK fertilizers on the growth and yield of turnip (*Brassica rapa* L.) at the northern areas of Pakistan. *Pakistan Journal of Soil Science*. 2004;23(3-4):43-48.
4. Alloway BJ. *Zinc in Soils and Crop Nutrition*. 2nd ed. Brussels: International Zinc Association; 2008.
5. Astanah T, Mohammadi A, Gholami M. Effects of nano-chelated nitrogen and urea fertilizers on growth, yield and protein content of wheat (*Triticum aestivum* L.). *Journal of Plant Nutrition*. 2021;44(12):1785-1797.
6. Babaei K, Seyed Sharifi R, Pirzad A, Khalilzadeh R. Effects of bio fertilizer and nano Zn-Fe oxide on physiological traits, antioxidant enzymes activity and yield of wheat (*Triticum aestivum* L.) under salinity stress. *Journal of Plant Interactions*. 2017;12(1):381-389.
7. Baloch PA, Uddin R, Nizamani FK. Effect of nitrogen, phosphorus and potassium fertilizers on growth and yield characteristics of radish (*Raphanus sativus* L.). *Journal of Agriculture and Environmental Sciences*. 2014;14(6):565-569.
8. Chang L, Chang J. Effect of potassium on yield quality of radish (*Raphanus sativus* L.). *Journal of Hebei Agricultural University*. 2000;23(2):20-24.
9. Dash SK, Pathak M, Tripathy L, Barik S. Studies on effect of integrated nutrient management on growth and yield attributes in radish (*Raphanus sativus* L.) and its residual effect in coriander (*Coriandrum sativum* L.) in radish-coriander cropping sequence. *Journal of Pharmacognosy and Phytochemistry*. 2018;8(1):319-322.
10. Davarpanah S, Tehranifar A, Davarynejad G, Abadía J, Eshghi S. Effects of foliar nano-nitrogen and zinc fertilizers on pomegranate (*Punica granatum* L.) fruit yield and quality. *Scientia Horticulturae*. 2016;211:125-130.

11. Elhindi K, El-Hendawy S, Abdel-Salam E, Elgorban A, Ahmed M. Impacts of fertigation via surface and subsurface drip irrigation on the growth rate, yield and flower quality of *Zinnia elegans*. *Brigantia*. 2016;75(1):96-107.
12. Greenwood DJ, Stone DA, Martinets TV. Dynamic model for the effects of soil P and fertilizer P on crop growth, P uptake and soil P in arable cropping: Experimental test of the model for field vegetables. *Annals of Botany*. 2001;88(2):293-306.
13. Jadhav PB, Patel DJ, Kireeti A, Patil NB, Dekhane SS, Harad NB, *et al.* Effect of different levels of vermicompost on growth and yield of radish cv. Local variety. *International Journal of Research and Review*. 2014;1(2):29-31.
14. Kiran M, Jilani MS, Waseem K, Sohail M. Effect of organic manures and inorganic fertilizers on growth and yield of radish (*Raphanus sativus* L.). *Pakistan Journal of Agricultural Resources*. 2016;29(4):363-372.
15. Lakra AS, Prasad D, Deepanshu VM, Shabi M. Effect of nitrogen and phosphorus on growth and yield of radish (*Raphanus sativus* L.) cv. Pusha Chetki under shade net condition. *The Pharma Innovation Journal*. 2017;6(11):768-770.
16. Manikandan A, Subramanian KS. Zeolite-based nano-nitrogen fertilizer on growth and productivity of maize (*Zea mays* L.). *International Journal of Agricultural Sciences*. 2016;8(12):2785-2789.
17. Nofal AS, Ashmawi AE, Mohammed AA, El-Abd MT, Helaly AA. Effect of soil application of nano NPK fertilizers on growth, productivity and quality of lettuce (*Lactuca sativa*). *Al-Azhar Journal of Agricultural Research*. 2021;46:91-100.
18. Ramesh T, Rathika S, Sangeetha S, Satheesh S, Ponpradeepa M, Pavithra A. Enhancement of black gram productivity through foliar spray of nutrients and growth hormones: A review. *International Journal of Current Microbiology and Applied Sciences*. 2020;9(12):1-11.
19. Rasha EA, El-Sayed MA, El-Mogy MM. Effect of nano-zinc application on growth, yield and fruit quality of grapevines. *Journal of Plant Production*. 2019;10(11):1025-1032.
20. Sharaf-Eldin MA. Nano-nitrogen fertilization strategies for improving growth, yield and quality of vegetable crops. *Journal of Soil Science and Plant Nutrition*. 2022;22(3):3124-3137.
21. Sharifi RS, Khalilzadeh R, Pirzad A. Effect of zinc application on growth and some physiological characteristics of barley under water stress. *Journal of Plant Nutrition*. 2016;39(5):702-712.
22. Sharma S, Kumar V, Singh R. Effect of foliar nano-nitrogen application on growth, yield and quality of pearl millet. *Indian Journal of Agronomy*. 2022;67(4):456-462.
23. Thapa U, Mohanto B, Chattopadhyay SB, Ghanti P. Growth and yield of some cultivars of radish (*Raphanus sativus* L.) with nitrogen levels. *Environment & Ecology*. 2003;21(4):836-838.
24. Tripathi AK, Ram RB, Rout S, Kumar A, Patra SS. Studies on the effect of nitrogen levels and spacing on quality traits of radish (*Raphanus sativus* L.) cv. Kashi Sweta. *International Journal of Chemical Studies*. 2017;5(6):537-540.
25. Vafa ZS, Nadian H, Heidari M. Effect of nano-zinc fertilizer on growth parameters and some biochemical traits of savory (*Satureja hortensis* L.). *Journal of Medicinal Plants*. 2015;14(4):67-78.
26. Zagzoug OA, Gad MM, Hafez NK. Effect of nano-chitosan on vegetative growth, fruiting and resistance of malformation of mango. *Trends in Horticultural Research*. 2017;7(1).