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Effect of seed priming by nano-urea and nano-zinc on the growth, yield and quality of radish (*Raphanus sativus* L.)

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Abstract

Nanotechnology is an emerging field of science with a variety of applications in various disciplines, including agriculture. Recently some nano-fertilizers are available in the market, which may be highly effective in improving crop productivity in a more economical manner than the conventional fertilizers. The present investigation was carried out to evaluate the impact of seed priming using urea and zinc, when applied in the form of nano-fertilizers on the growth, quality and yield related attributes in radish. Field experiment on radish (White Plus-F_1 Hybrid) was carried out during the *rabi* season of 2022-2023 in the Horticultural Farm of the Faculty of Agricultural Sciences, DAV University, Jalandhar in randomised block design (RBD) comprising twelve treatments *viz*., T_1 (Control), T_2 (NPK *i.e*., 100% recommended dose), T_3 (Nano-Urea *i.e*., 100%), T_4 (Nano-Urea *i.e*., 50%), T_5 (Nano-Zinc *i.e*., 100%), T_6 (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%), T_7 (Nano-Urea *i.e*., 50% + Nano-Zinc *i.e*., 100%), T_8 (NPK *i.e*., 100% recommended dose + Nano-Zinc *i.e*., 100%), T_9 (NPK *i.e*., 100% recommended dose + Nano-Urea *i.e*., 100%), T_{10} (NPK *i.e*., 100% recommended dose + Nano-Urea *i.e*., 50%), T_{11} (NPK *i.e*., 100% recommended dose + Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%) and T_{12} (NPK *i.e*., 100% recommended dose + Nano-Urea *i.e*., 50% + Nano-Zinc *i.e*., 100%) with three replications each. The results showed that the seed priming application of Nano-Urea (100%) along with NPK minimised the days to 50% germination. It was also observed that Nano-Urea (100%) along with NPK increased leaf length and leaf area and further the combination of both Nano-Urea (100%) and Nano-Zinc (100%) recorded the highest plant height, number of leaves per plant and the leaf width. Among, the root yield of radish, the highest root diameter, root weight, root yield per hectare, root yield per plot, fresh weight of plant and dry weight of plant were recorded in the combined application of Nano-Urea (100%) and Nano-Zinc (100%). Whereas, the maximum root length of radish was recorded with the combined application of NPK and Nano-Urea (100%). Among the quality attributes, the combination of both Nano-Urea (100%) and Nano-Zinc (100%) recorded the highest TSS and ascorbic acid. The chlorophyll content, carotenoid content, total protein content, total flavonoid content and total phenolic content were recorded highest, when NPK was applied in combination with the seed priming of 100% Nano-Urea. The analysis of yield economics suggested that the maximum gross income, net income and benefit-cost ratio was there in case of treatment T_6 (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%), which was significantly higher than all other treatments.

Keywords: Radish, nano-fertilizers, nano-urea, nano-zinc, seed priming, benefit-cost ratio, growth parameters, randomised block design

Introduction

Radish (*Raphanus sativus* L.) is a major root vegetable of the family Brassicaceae (2n=2x=18) that is widely cultivated in both tropical and temperate regions of the world (Kumar *et al*., 2021; Singh *et al*., 2018) [1-2]. It is also known as Mooli and its major edible part is the root, although the whole plant is edible (Kumar *et al*., 2022) [3]. The radish is generally considered as a root vegetable used in salads (Alam *et al*., 2010) [4]. Depending on the cultivar, the length can range from 2.5-90 cm (Sharma *et al*., 2019) [5]. The stems can be either hollow or simple, expanding outward towards anthesis and can grow up to one metre in hight (Ridley *et al*., 2009) [6]. The leaves are simple, alternate or cauline, sometime lobed, petiolate and exstipulate with the reticulate venation (Kushwah *et al*., 2019) [7]. Radish is low in calories and high in vitamin C, protein, carbs, fat, minerals and fibre (Singh and Nath, 2012) [8]. Further, the presence of volatile isothiocyanates causes the distinctive pungent flavour of radish (Bose *et al*., 2001) [9]. Radish contains antioxidants such as cytokinin and other antioxidants that also protect the human body against cancer (Harborne and Baxter, 1993) [10]. It is also used in homeopathy to treat neurological issues, headaches, insomnia and persistent diarrhoea

(Kumar *et al.*, 2014) [11]. There are several kinds of radish, including white radish, red radish, radish black and many others (Naderi *et al.*, 2012) [12]. Punjab Safed Mooli-2 (2015), Punjab Pasand (1997), Pusa Himani (1995), Pusa Chetki (1988) and Japanese White (1962) are some improved radish varieties (Lanna, 2018) [13] under cultivation.

Both Europe and Western Asia are considered as the center of origin of radish (Patel *et al.*, 2023) [14]. The first evidence of radish usage in human nutrition dates to approximately 2700 BC in ancient Egypt (George and Evans 1981) [15]. It is grown both under tropical and temperate regions of the world (Patel *et al.*, 2023) [14]. Radish is one of the oldest vegetables in India (Ridley *et al.*, 2008) [16] and is grown over 0.204 million hectares with an annual production of 3.107 million tons (NHB, 2022) [17].

Global food production has expanded as the world's population has grown (Wallace, 2000) [18]. To increase food production, it is essential to use advanced technologies in agriculture (Davis *et al.*, 2017) [19]. The term 'nano' is derived from the Greek word 'nanos', which means 'dwarf' (Maheswari *et al.*, 2022) [20]. Nanotechnology makes use of nanomaterials, which are generally tiny in size (1-100 nm) and imparts their distinct properties and advantages (Kumar *et al.*, 2021) [1]. Recently, excessive use of chemical fertilizers has resulted in a number of serious environmental issues, such as heavy metal accumulation in soil and plant systems (Savci, 2012) [21]. Therefore, it is necessary to use modern ideas for fertilizing the vegetable crops to increase food production. Nanotechnology is one such modern technology, which has the potential to change the pattern of the utilization of chemical fertilizers (also the dosage), including several other scientific fields (Chen and Yada, 2011 [22]; Prasad *et al.*, 2014) [23]. Nanotechnology offers a new opportunity for improving fertilizer application, because of the increased surface area of nano-materials, which can lead to a higher reactivity and faster dissolution kinetics (Mastronardi *et al.*, 2015) [24]. The use of nano-fertilizers is one of the most important applications of nanotechnology, which enhances the plant's capacity to absorb nutrients (Mousavi, 2007 [25]; Srilatha, 2011 [26] and Ditta, 2012) [27]. Nano-fertilizers are the modified or manufactured forms of traditional fertilizers (Mahanta *et al.*, 2019) [28] or extracted from different vegetative or reproductive parts of the plant by different physical, chemical, biological or mechanical methods (Kumar *et al.*, 2021) [1]. With the help of nanotechnology, nano-fertilizers are used to improve the plant productivity, soil fertility and quality of the agricultural produce (Qureshi *et al.*, 2018 [29]; DeRosa *et al.*, 2010) [30]. Nano-fertilizers can be applied to the soil or to the leaves, they so can be absorbed through the roots or leaves (Hong *et al.*, 2021) [31]. When applied as a foliar spray, they can be absorbed by leaf stomata and transferred to other plant parts via the phloem (Ebbs *et al.*, 2016) [32]. Depending on the physiology of plants and various absorption, transport and distribution methods, the uptake and translocation of these particles may differ from plant to plant (Odzak *et al.*, 2014) [33]. However, if these nano-fertilizers are used as a seed priming agent, they will hydrate and directly enter the seeds to improve germination and seedling emergence in many crops. They can directly enter the seeds and promote plant growth at the early stages of their establishment (Hong *et al.*, 2021) [31]. For successful crop establishment seed priming could play a vital role in crop production. Heydecker introduced the concept of seed priming in 1973 (Mal *et al.*, 2019) [34]. Nano-priming (seed priming with nano-agents) can be applied to seeds to protect them during storage, to improve germination, germination synchrony, and plant growth, and to increase crop tolerance to abiotic or biotic stress conditions, which can help to reduce the number of pesticides and fertilizers required (Malik *et al.*, 2021) [35]. New studies showed that seed nano-priming can activate many genes during germination, particularly those associated with plant stress tolerance (Mahakham, 2017) [36]. The use of nanotechnology for seed priming is a new field of study, although preliminary research has given promising results (Malik *et al.*, 2021) [35]. When compared to chemical fertilizer requirements and costs, nano-fertilizers are more cost-effective and are required in smaller quantities (Rameshaiah *et al.*, 2015) [37]. So, nano-fertilizers may increase the efficiency of nutrient uptake, enhance yield and nutrient content in the edible parts and also minimize its accumulation in the soil.

Materials and Methods

The field experiment was carried out during the *rabi* season of the year 2022-23 at the experimental farm of the Faculty of Agricultural Sciences, DAV University, Sarmastpur, Jalandhar (Punjab).

Plant material

Plant material, *i.e.*, radish *cv*. White plus F_1 hybrid

Nano-fertilizers and fertilizers

Nano-fertilizers *i.e.*, Nano-Urea (IFFCO) and Nano-Zinc (Geolife), Commercial fertilizers *i.e.*, NPK (IFFCO).

Experiment design

The experiment was laid out in randomised block design (RBD) comprising twelve treatments (Table 1) with three replications each.

Field preparation

The experiment field was prepared by ploughing to fine tilth with a disc plough and subsequently, light ploughing was done with a cultivator. A basal application of 25 kg N, 12 kg P_2O_5, per hectare in the form of Urea and SSP was applied after appropriate plot delineation, wherever required. The light irrigation was given immediately after sowing and then the irrigation was given at an interval of 10-12 days during the winter depending upon the moisture condition of the experimental plot. The radish crop was harvested at physiological maturity by lifting the whole plant. The roots in the net plot were harvested separately from each treatment then cleaned and weighed.

Table 1: Treatment details

Treatment No.	Treatment details
T_1	Control
T_2	NPK (100% recommended dose)
T_3	Nano-Urea (100%)
T_4	Nano-Urea (50%)
T_5	Nano-Zinc (100%)
T_6	Nano-Urea (100%) + Nano-Zinc (100%)
T_7	Nano-Urea (50%) + Nano-Zinc (100%)
T_8	NPK + Nano-Zinc (100%)
T_9	NPK + Nano-Urea (100%)
T_{10}	NPK + Nano-Urea (50%)
T_{11}	NPK + Nano-Urea (100%) + Nano-Zinc (100%)
T_{12}	NPK+ Nano-Urea (50%) + Nano-Zinc (100%)

Seed-priming treatment

Nano-Urea and Nano-Zinc was given through seed priming method at the concentrations of 2.5 g per liters (100%) for Nano-Zinc, 30 ml per liter (100%) for Nano-Urea and 15 ml per liters (50%) for Nano-Urea. The treated seeds were sown directly on ridges with a depth of 2 cm and a distance of 60 cm apart with 10 cm spacing between plants.

Collection of experimental data

During the first week, following sowing, morphological observations were taken at different stages. Five plants were randomly selected from each plot and tagged. All observations were recorded from these plants. All observations *viz*. days to 50% germination, plant height, number of leaves per plant, leaf length, leaf width and leaf area were recorded from these plants. After 60 days of planting, yield measurements were taken from each treatment, excluding rows and plants. On the basis of net plot size, the various observations were recorded. Various observations *viz*. root length, root diameter, root weight, plant fresh weight, plant dry weight, root yield per plot, and root yield per hectare were recorded. Different quality parameters (*viz*. TSS, ascorbic acid, chlorophyll content, carotenoid content, *etc*.) were also measured.

Total soluble solids

Total soluble solids were recorded by using a digital hand refractometer (Erma Hand Refractometer 0-32°Brix).

Ascorbic acid

Ascorbic acid was determined by using 2, 6 dichlorophenol-indophenol titration method (Rekha *et al*., 2012) [38]. The results were expressed as (mg/100 g) of sample and was estimated using the formula:

$$\text{Ascorbic acid} = \frac{\text{Titre value} \times \text{dye factor} \times \text{volume made up}}{\text{Aliquot of extract taken} \times \text{weight of sample}} \times 100$$

Pigment composition

The chlorophyll content of leaves was determined at 45 days and 60 days after sowing. The representative fresh leaf samples were taken. Take the supernatant and then, observations were taken at 645 nm for chlorophyll A and at 663 nm for chlorophyll B. Total chlorophyll, chlorophyll A and chlorophyll B content was calculated by the formulae and expressed in mg g^{-1} fresh weight of leaves (Arnon, 1949) [39]. The results were expressed in mg/g fresh weight of leaves and was calculated by the formula:

Total Chlorophyll (mg/g) tissue = 20.2 (A_{645}) + 8.02 (A_{663})
Chlorophyll A (mg/g) tissue = 12.7 (A_{663}) + 2.69 (A_{645})
Chlorophyll B (mg/g) tissue = 22.9 (A_{645}) - 4.68 (A_{663})

The carotenoid content of leaves was determined at 45 days and 60 days after sowing. The representative fresh leaf samples were taken. Take the supernatant and then, observations were taken 480 nm and 510 nm (Kapoor *et al*., 2014) [40]. The results were expressed in mg/g fresh weight of leaves and was calculated by the formula:

Carotenoid (mg/g) tissue = 7.6 (A_{480})-1.49 (A_{510})

Protein content

The protein content was estimated as described by (Sharma *et al*., 2011) [41]. The total protein content of leaves was determined by the method of Bradford, 1976 taking bovine serum albumin (BSA) as standard. The standard curve was plotted between different known concentrations of BSA and absorbance was recorded at 595 nm.

Total phenolic content

Total phenolic content was analysed by using Singleton's method (Singleton *et al*., 1999) [42] treating aqueous plant extract with 0.5 ml Folin and Ciocalteu's (F-C) reagent and 2 ml sodium carbonate (20% w/v). This reaction mixture was incubated at room temperature for approximately 1 hour and the absorbance was measured at 650 nm.

Total flavonoid content

Total flavonoid content was determined by using Ardekani (Ardekani *et al*., 2011) [43]. This reaction was mixed well and kept in a dark room for 1 hr and then absorbance was recorded at 510 nm.

Statistical analysis

The data collected was subjected to Analysis of Variance (ANOVA) in RBD with Fisher's test to find the critical difference (CD) among different treatment means using OPSTAT to check the significant differences among treatments at $p \leq 0.05$.

Yield economics

Economic components of different treatments were worked out, separately. Cost of cultivation (Rs. /ha) of different treatments was calculated by considering all the expenses incurred in the cultivation of experimental crop and added with common cost due to various operations and inputs used. Accordingly, cost of cultivation was calculated for each treatment combination (Zangenesh *et al*., 2010) [44]. Gross returns (Rs. /ha) were calculated by multiplying total tuber yield separately under various treatment combinations with their existing market price (Verma *et al*., 2011) [45]. Net return (Rs. /ha) was calculated by deducting the cost of cultivation from the gross return of the individual treatment combination (Umesh *et al*., 2014) [46]. The benefit-cost ratio was calculated by dividing the net return by the cost of cultivation of the individual treatment combination (Mohammadi *et al*., 2008) [47].

$$\text{Benefit-cost ratio} = \frac{\text{Net returns}}{\text{Cost of cultivation}}$$

Results

The results for various growth, yield and quality attributes are presented below under the appropriate sections.

Growth attributes

The effect of seed priming by Nano-Urea and Nano-Zinc fertilizers on various growth parameters *viz*., days to 50% germination, plant height, number of leaves per plant, leaf length, leaf width and leaf area are presented in table 2. All the observations of plant height, number of leaves per plant, leaf length, leaf width and leaf area were recorded after 60 days, except days to 50% germination. To record any significant differences in the above traits among different treatments, the analysis of variance was performed and the values of critical difference were recorded for each trait.

Days to 50% germination

The observations regarding germination were made daily, until 50% germination was achieved (Table 2). The minimum days to 50% germination (3.33 days) was observed in the treatment T_9, which however was statistically at par (not significantly different, $p \leq 0.05$) with the treatment T_3 and T_{11} (3.66 days for both). Whereas, the maximum days to 50% germination (9.66 days) were observed in the treatment T_1, which was significantly higher than all the treatments.

Plant height (cm)

Significant differences in plant height at 60 DAS was observed among the different treatments (Table 2). Maximum plant height (28.42 cm) was observed in the treatment T_6, which was significantly higher than all the treatments. Whereas, the minimum plant height (18.16 cm) was observed in the treatment T_1. It was however, statistically at par with the treatment T_2 (18.87 cm) and the treatment T_4 (19.00 cm).

Number of leaves per plant

Significant differences in the number of leaves per plant at 60 DAS was observed among the different treatments (Table 2). It was observed that the maximum number of leaves (21.73) in the treatment T_6, which was however, statistically at par with the treatment T_3 (20.40), T_4 (20.66), T_7 (20.53), T_8 (21.26), T_9 (20.46), T_{11} (20.66) and T_{12} (20.66). Whereas, the minimum number of leaves (19.46) was found in the treatment T_1, which was however, statistically at par with the treatment T_2 (19.30), T_5 (19.93) and T_{10} ((19.93).

Leaf length (cm)

Significant differences in leaf length at 60 DAS was observed among the different treatments (Table 2). The maximum leaf length (23.28 cm) was observed in the treatment T_9, which was however, statistically at par with the treatment T_6 (22.71 cm) and T_{11} (21.96 cm). Whereas, the minimum leaf length (19.63 cm) was found in the treatment T_5. It was however, statistically at par with the treatment (19.84 cm), T_3 (20.24 cm), T_4 (19.97 cm), T_8 (20.81 cm), T_{10} (20.52 cm) and the treatment T_{12} (19.82 cm).

Leaf width (cm)

Significant differences in leaf width at 60 DAS was observed among the different treatments (Table 2). The maximum leaf width (7.72 cm) was observed in the treatment T_6, which was however, statistically at par with the treatment T_9 (7.13 cm) and T_{11} (7.08 cm). Whereas, the minimum leaf width (5.31cm) was found in the treatment T_1, which was however, statistically at par with the treatment T_3 (5.84 cm) and the treatment T_2 (5.96 cm).

Leaf area (cm$^{2)}$

Significant differences in leaf area at 60 DAS was observed among the different treatments (Table 2). The maximum leaf area (183.33 cm^2) was observed in the treatment T_6, which was significantly higher than all the treatments. Whereas, the minimum leaf area (105.58 cm^2) was found in the treatment T_1, which was however, statistically at par with the treatment T_2 (127.26 cm^2), T_4 (124.64 cm^2), T_5 (123.99 cm^2) and the treatment T_{12} (127.73 cm^2).

Table 2: Effect of nano-urea and nano-zinc on the growth attributes of radish

Treatment	Days to 50% germination	Plant height (cm)	No. of leaves per plant	Leaf length(cm)	Leaf width(cm)	Leaf area(cm^2)
T_1	9.66	18.16	19.46	19.84	5.31	105.58
T_2	7.33	18.87	19.30	21.10	5.96	127.26
T_3	3.66	22.28	20.40	20.24	5.84	128.75
T_4	5.00	19.00	20.66	19.97	6.23	124.64
T_5	7.33	21.54	19.93	19.63	6.32	123.99
T_6	3.35	28.42	21.73	22.71	7.72	183.33
T_7	5.33	23.48	20.53	21.26	6.56	139.46
T_8	7.33	23.42	21.26	20.81	6.44	134.09
T_9	3.33	23.66	20.46	23.28	7.13	159.02
T_{10}	4.33	22.84	19.93	20.52	6.75	138.49
T_{11}	3.66	23.90	20.66	21.96	7.08	151.12
T_{12}	5.33	22.71	20.66	19.82	6.54	127.73
SE (m) ±	0.33	1.06	0.45	0.48	0.25	7.63
CD @ 5% ($p \leq 0.05$)	0.98	3.14	1.33	1.43	0.74	22.52

Where, CD Critical difference calculated using Fisher's least significant difference (Fisher's LSD) at 5% level of significance
SE (m) ± Standard error of mean

Yield attributes

The effect of seed priming by Nano-Urea and Nano-Zinc fertilizers on various yield parameters of radish were recorded after 60 days *viz.*, root length, root diameter, root weight, fresh weight of plant, dry weight of plant, root yield per plot and root yield per hectare are presented in (Table 3 and 4).

Root length (cm)

The effect of Nano-Urea and Nano-Zinc fertilizers on root length is presented in (Table 3). Maximum root length (25.26 cm) was observed in the treatment T_9, which was however, statistically at par with the treatment T_6 (24.75 cm). Whereas, the minimum root length (16.63 cm) was observed in the treatment T_1, which was however, statistically at par with the treatment T_5 (17.70 cm).

Root diameter (cm)

The effect of Nano-Urea and Nano-Zinc fertilizers on root diameter is presented in (Table 3). The maximum root diameter (3.69 cm) was observed in the treatment T_6, which was significantly higher than all the treatments. Whereas, the minimum root diameter (2.32 cm) was observed in the treatment T_8 (2.32 cm), which was however, statistically at par with the treatment T_1 (2.53 cm) and the treatment T_5 (2.53 cm).

Root weight (g)

The effect of Nano-Urea and Nano-Zinc fertilizers on root weight is presented in (Table 3). The maximum root weight (119.35 g) was observed in the treatment T_6, which was significantly higher than all the treatments. Whereas, the minimum root weight (88.62 g) was observed in the treatment T_1, which was however, statistically at par with the treatment T_2 (96.01 g), T_4 (95.54 g), T_8 (92.78 g) and T_{10} (95.26 g).

Table 3: Effect of nano-urea and nano-zinc on the yield attributes of radish

Treatment	Root length (cm)	Root diameter (cm)	Root weight (cm)
T_1	16.63	2.53	88.62
T_2	19.75	2.87	96.01
T_3	21.92	3.07	108.30
T_4	19.85	2.87	95.54
T_5	17.70	2.23	96.99
T_6	24.75	3.69	119.35
T_7	22.14	2.87	104.00
T_8	21.34	2.32	92.78
T_9	25.26	3.02	110.74
T_{10}	20.02	2.82	95.26
T_{11}	21.97	3.04	100.74
T_{12}	22.38	2.80	97.47
SE (m) ±	0.69	0.08	2.62
CD @ 5% ($p \leq 0.05$)	2.05	0.25	7.74

Where, CD Critical difference calculated using Fisher's least significant difference (Fisher's LSD) at 5% level of significance
SE (m) ± Standard error of mean

Fresh weight of plant (g)

The effect of Nano-Urea and Nano-Zinc fertilizers is presented in (Table 4). Maximum fresh weight of plant (208.51 g) was observed in the treatment T_6, which was statistically at par with the treatment T_9 (200.19 g). Whereas, the minimum fresh weight of plant (130.8 g) was observed in the treatment T_1, which was significantly lower than all the treatments.

Dry weight of plant (g)

The effect of Nano-Urea and Nano-Zinc fertilizers on dry weight of plant is presented in (Table 4). Maximum dry weight of plant (45.28 g) was observed in the treatment T_6, which was statistically at par with the treatment T_9. Whereas, the minimum dry weight of plant (16.44 g) was observed in the treatment T_1, which was significantly lower than all the treatments.

Root yield per plot (kg)

The effect of Nano-Urea and Nano-Zinc fertilizers on root yield per plot is presented in (Table 4). Maximum root yield per plot (4.01 kg) was observed in the treatment T_6 (Nano-Urea *i.e.*, 100% + Nano-Zinc *i.e.*, 100%), which was statistically at par with the treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 100%) (3.79 kg), T_{11} (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 100% + Nano-Zinc *i.e.*, 100%) (3.68 kg), T_7 (Nano-Urea *i.e.*, 50% + Nano-Zinc *i.e.*, 100%) (3.64 kg), T_{10} (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 50%) (3.58 kg) and the treatment T_{12} (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 50% + Nano-Zinc *i.e.*, 100%) (3.38 kg). Whereas, the minimum root yield per plot (1.26 kg) was observed in the treatment T_1 (Control), which was however, statistically at par with the treatment T_2 (NPK *i.e.*, 100% recommended dose) (1.80 kg).

Root yield per hectare (q/ha)

The effect of Nano-Urea and Nano-Zinc fertilizers on root yield per hectare is presented in (Table 4). Maximum root yield per hectare (66.91 q/ha) was observed in the treatment T_6 (Nano-Urea *i.e.*, 100% + Nano-Zinc *i.e.*, 100%), which was statistically which was statistically at par with the treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 100%) (63.25 q/ha), T_{11} (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 100% + Nano-Zinc *i.e.*, 100%) (6.141 q/ha), T_7 (Nano-Urea *i.e.*, 50% + Nano-Zinc *i.e.*, the treatment 100%) (60.68 q/ha), T_{10} (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 50%) (59.82 q/ha) and the treatment T_{12} (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 50% + Nano-Zinc *i.e.*, 100%) (56.36 q/ha). Whereas, the minimum yield per hectare was observed in the treatment T_1 (Control) (21.05 q/ha), which was statistically at par with the treatment T_2 (NPK *i.e.*, 100% recommended dose) (30.11 q/ha).

Table 4: Effect of nano-urea and nano-zinc on the yield attributes of radish

Treatment	Fresh weight of plant (g)	Dry weight of plant (g)	Root yield per plot (kg)	Root yield per hectare (q/ha)
T_1	130.80	16.44	1.26	21.05
T_2	143.11	23.29	1.80	30.11
T_3	185.75	38.92	2.83	47.25
T_4	175.22	25.03	2.36	39.46
T_5	176.22	22.15	2.39	39.84
T_6	208.51	45.28	4.01	66.91
T_7	187.09	39.54	3.64	60.68
T_8	158.65	27.18	3.11	51.91
T_9	200.19	45.40	3.79	63.25
T_{10}	177.48	27.96	3.58	59.82
T_{11}	197.18	37.97	3.68	61.41
T_{12}	182.96	37.44	3.38	56.36
SE (m) ±	3.09	1.52	0.30	5.056
CD @ 5% ($p \leq 0.05$)	9.12	4.49	0.89	14.92

Where, CD Critical difference calculated using Fisher's least significant difference (Fisher's LSD) at 5% level of significance
SE (m) ± Standard error of mean

Quality attributes

The effect of seed priming by Nano-Urea and Nano-Zinc fertilizers on various quality parameters of radish *viz.*, TSS, ascorbic acid, carotenoids, total chlorophyll, chlorophyll A, chlorophyll B, proteins, flavonoids and phenolics are presented in (Table 5) and (Table 6).

TSS (°Brix)

The maximum TSS (6.59°B) was recorded in the treatment T6, which was statistically at par with the treatment T7 (6.46°B), T3 (6.32°B), T4 (6.27°B), T9 (6.14°B), T10 (6.25°B) and the treatment T11 (6.52°B) (Table 5). Whereas, the minimum TSS (4.32°B) was observed in the treatment T1, which was significantly lower than that of any other treatment.

Ascorbic acid (mg/g FW)

The maximum ascorbic acid (17.57 mg/g FW) was observed in the treatment T_6, which was however, statistically at par with the treatment T_7 (16.94 mg/g FW) and the treatment T_8 (17.22 mg/g FW) (Table 5). Whereas, the minimum ascorbic acid (11.44 mg/g FW) was observed in the treatment T_1, which was significantly lower than that of any other treatment.

Protein content (µg/g FW)

Maximum protein content (0.226 µg/g FW) was observed in the treatment T_9, which was however, statistically at par with the treatment T_2 (0.225 µg/g FW), T_3 (0.225 µg/g FW), T_{11} (0.224 µg/g FW) and T_{12} (0.223 µg/g FW) (Table 5). However, the minimum protein content was observed (0.205 µg/g FW) in the treatment T_1, which was significantly lower than all the treatments.

Chlorophyll (mg/g FW)

The maximum content of chlorophyll A at 30 DAS was observed (0.46 mg/g FW) in the treatment T_9, which was statistically at par with the treatment T_5 (0.36 mg/g FW) and the treatment T_6 (0.45 mg/g FW) (Table 5). Whereas, the minimum content of chlorophyll A was observed (0.16 mg/g FW) in the treatment T_{10}, which was however, statistically at par with the treatment T_1 (0.20 mg/g FW), T_2 (0.22 mg/g FW), T_3 (0.25 mg/g FW), T_4 (0.18 mg/g FW) and the treatment T_8 (0.26 mg/g FW). The maximum content of chlorophyll A at 60 DAS was observed in the treatment T_9 (0.44 mg/g FW), which was statistically at par with the treatment T_6 (0.40 mg/g FW) (Table 5). However, the minimum content of chlorophyll A was observed (0.18 mg/g FW) in the treatment T_1, which was however, statistically at par with the treatment T_2 (0.25 mg/g FW), T_3 (0.24 mg/g FW), T_4 (0.26 mg/g FW), T_5 (0.27 mg/g FW), T_7 ((0.19 mg/g FW), T_8 (0.28 mg/g FW), T_{10} (0.22 mg/g FW) and the treatment T_{12} (0.26 mg/g FW).

The maximum content of chlorophyll B at 30 DAS was observed in the treatment T_9 (0.71 mg/g FW), which was significantly higher than all the treatments. However, the minimum content of chlorophyll B was observed (0.34 mg/g FW) in the treatment T_{12}, which was significantly lower than all the treatments (Table 5). The maximum content of chlorophyll B at 60 DAS was observed in the treatment T_9 (0.74 mg/g FW), which was however, statistically at par with the treatment T_2 (0.56 mg/g FW), T_4 (0.55 mg/g FW), T_6 (0.68 mg/g FW) and the treatment T_{11} (0.67 mg/g FW). However, the minimum content of chlorophyll B was observed in the treatment T_1 and T_8 (0.36 mg/g FW in both), which was however, statistically at par with the treatment T_3 (0.44 mg/g FW), T_5 (0.45 mg/g FW), T_7 (0.41 mg/g FW), T_{10} (0.37 mg/g FW) and the treatment T_{12} (0.38 mg/g FW).

The maximum content of total chlorophyll at 30 DAS was observed in the treatment T_9 (1.12 mg/g FW), which was however, statistically at par with the treatment T_3 (0.82 mg/g FW), T_6 (1.08 mg/g FW) and the treatment T_{11} (1.07 mg/g FW) (Table 5). However, the minimum content of total chlorophyll was observed (0.07 mg/g FW) in the treatment T_2, which was significantly lower than all the treatments. The maximum content of total chlorophyll at 60 DAS was observed in the T_9 (1.14 mg/g FW), which was however, statistically at par with the treatment T_{11} (1.09 mg/g FW) and T_6 (Table 5). However, the minimum content of total chlorophyll was observed (0.54 mg/g FW) in the treatment T_1, which was statistically at par with the treatment T_2 (0.82 mg/g FW), T_3 (0.69 mg/g FW), T_4 (0.81 mg/g FW), T_5 (0.73 mg/g FW), T_7 ((0.61 mg/g FW), T_8 (0.64 mg/g FW) and T_{10} (0.59 mg/g FW).

Table 5: Effect of nano-urea and nano-zinc on quality attributes *viz.*, (TSS, ascorbic acid, protein content, chlorophyll A, chlorophyll B and total chlorophyll) of radish

Treatment	TSS (Brix)	Ascorbic acid (mg/g FW)	Protein content (µg/g FW)	Chlorophyll A (mg/g FW)		Chlorophyll B (mg/g FW)		Total chlorophyll (mg/g FW)	
				30 DAS	60 DAS	30 DAS	60 DAS	30 DAS	60 DAS
T_1	4.32	11.44	0.205	0.20	0.18	0.44	0.36	0.63	0.54
T_2	5.28	14.41	0.225	0.22	0.25	0.47	0.56	0.07	0.82
T_3	6.32	15.58	0.225	0.25	0.24	0.51	0.44	0.82	0.69
T_4	6.27	15.10	0.212	0.18	0.26	0.40	0.55	0.63	0.81
T_5	5.76	16.17	0.211	0.36	0.27	0.42	0.45	0.71	0.73
T_6	6.59	17.57	0.220	0.45	0.40	0.64	0.68	1.08	1.09
T_7	6.46	16.94	0.217	0.29	0.19	0.49	0.41	0.76	0.61
T_8	5.69	17.22	0.216	0.26	0.28	0.45	0.36	0.69	0.64
T_9	6.14	16.38	0.226	0.46	0.44	0.71	0.74	1.12	1.14
T_{10}	6.25	15.97	0.216	0.16	0.22	0.43	0.37	0.64	0.59
T_{11}	6.52	16.31	0.224	0.33	0.35	0.68	0.67	1.07	1.09
T_{12}	5.94	16.28	0.223	0.33	0.26	0.34	0.38	0.62	0.65
SE (m) ±	0.16	0.27	0.001	0.03	0.04	0.06	0.08	0.10	0.10
CD @ 5% ($p \leq 0.05$)	0.48	0.81	0.002	0.10	0.14	0.02	0.23	0.31	0.29

Where, CD Critical difference calculated using Fisher's least significant difference (Fisher's LSD) at 5% level of significance
SE (m) ± Standard error of mean

Carotenoids (mg/g FW)

The maximum content of carotenoid at 30 DAS was observed in the treatment T_9 (0.40 mg/g FW), which was significantly higher than all the treatments (Table 6). Whereas, the minimum content of carotenoid was observed (0.10 mg/g FW) in the treatment T_2, which was however, statistically at par with the treatment T_1 (0.11 mg/g FW).

The maximum content of carotenoid at 60 DAS was observed in the treatment T_9 (0.52 mg/g FW), which was significantly higher among all the treatments (Table 6). Whereas, the minimum content of carotenoid was observed (0.17 mg/g FW) in the treatment T_2, which was however, statistically at par with the treatment T_1 (0.24 mg/g FW), T_3 (0.22 mg/g FW), T_4 (0.19 mg/g FW), T_5 (0.22 mg/g FW), T_8 (0.18 mg/g FW) and the treatment T_{10} (0.22 mg/g FW).

Total phenolic content (mg/g FW of Gallic acid eq.)

The maximum content of total phenolic at 30 DAS (0.229 mg/g FW of Gallic acid eq.) were observed in the treatment T_3 and T_9, which were however, statistically at par with the treatment T_2 (0.227 mg/g FW of Gallic acid eq.) T_4 (0.228 mg/g FW of Gallic acid eq.), T_5 (0.228 mg/g FW of Gallic acid eq.) and the treatment T_8 (0.228 mg/g FW of Gallic acid eq.) (Table 6). Whereas, the minimum content of total phenolic was observed (0.225 mg/g FW of Gallic acid eq.) in the treatments T_6 and T_7, which were however, statistically at par with all the treatments T_1, T_{10}, T_{11} and T_{12} (0.226 mg/g FW of Gallic acid eq.).

The maximum content of total phenolic at 60 DAS (0.228 mg/g FW of Gallic acid eq.) were observed in the treatment T_3 and T_9, which were however, statistically at par with the treatment T_{11} (0.227 mg/g FW of Gallic acid eq.) (Table 6). Whereas, the minimum content of total phenolic was observed (0.222 mg/g FW of Gallic acid eq.) in all the treatments T_1, T_5, T_7 and T_8, which was however, statistically at par with the treatment T_2 (0.223 mg/g FW of Gallic acid eq.) and the treatment T_4 (0.0.223 mg/g FW of Gallic acid eq.).

Total flavonoid content (mg/g FW of Catechin eq.)

The maximum content of total flavonoid at 30 DAS (0.235 mg/g FW of Catechin eq.) was observed in the treatment T_6, which was significantly higher than all the treatments (Table 6). Whereas, the minimum content of total flavonoid was observed (0.197 mg/g FW of Catechin eq.) in the treatment T_1, which was significantly lower than all the treatments. The maximum content of total flavonoid at 60 DAS (0.230 mg/g FW of Catechin eq.) was observed in the treatment T_9, which was however, statistically at par with the treatment T_{11} (0.229 mg/g FW of Catechin eq.) (Table 6). Whereas, the minimum content of total flavonoid was observed (0.197 mg/g FW of Catechin eq.) in the treatment T_1, which was significantly lower than all the treatments.

Table 6: Effect of nano-urea and nano-zinc on quality attributes *viz.*, (Carotenoids, total phenolic content, total flavonoid content) of radish

Treatment	Carotenoids (mg/g FW)		Total phenolic content (mg/g FW of Gallic acid eq.)		Total flavonoid content (mg/g FW of Catechin eq.)	
	30 DAS	60 DAS	30 DAS	60 DAS	30 DAS	60 DAS
T_1	0.11	0.24	0.226	0.222	0.197	0.197
T_2	0.10	0.17	0.227	0.223	0.224	0.224
T_3	0.19	0.22	0.229	0.228	0.229	0.227
T_4	0.30	0.19	0.228	0.223	0.230	0.225
T_5	0.27	0.22	0.228	0.222	0.224	0.227
T_6	0.35	0.37	0.225	0.225	0.235	0.227
T_7	0.27	0.24	0.225	0.222	0.225	0.227
T_8	0.31	0.18	0.228	0.222	0.225	0.225
T_9	0.40	0.52	0.229	0.228	0.226	0.230
T_{10}	0.35	0.22	0.226	0.225	0.224	0.215
T_{11}	0.33	0.30	0.226	0.227	0.228	0.229
T_{12}	0.20	0.32	0.226	0.226	0.226	0.227
SE (m) ±	0.016	0.025	0.001	0.002	0.001	0.001
CD @ 5% ($p \leq 0.05$)	0.048	0.073	0.002	0.001	0.003	0.002

Where, CD Critical difference calculated using Fisher's least significant difference (Fisher's LSD) at 5% level of significance
SE (m) ± Standard error of mean

Yield economics

The data obtained on the yield economics of radish as influenced by the application of Nano-Urea and Nano-Zinc fertilizers are represented in (Table 7). The gross income (Rs 267640 ha^{-1}) net income (Rs. 210148 ha^{-1}) and benefit-cost ratio (B: C ratio) (Rs. 3.65525 ha^{-1}) were observed maximum in the treatment T_6 (Nano-Urea *i.e.*, 100% + Nano-Zinc *i.e.*, 100%), which was higher than all the treatments. Whereas, the minimum gross income (Rs. 84200 ha^{-1}), net income (Rs. 27624 ha^{-1}) and benefit-cost ratio (B: C ratio) (Rs. 0.48826 ha^{-1}) were observed in the treatment T_1 (Control).

Table 7: Effect of nano-urea and nano-zinc on the yield economics of radish

Treatments	Cost of cultivation (Rs/ha)	Gross returns (Rs/ha)	Net returns (Rs/ha)	B: C ratio
T_1	56576	84200	27624	0.48826
T_2	61356	120440	59084	0.96297
T_3	57152	189000	131849	2.30697
T_4	56864	157843	100976	1.77575
T_5	56916	159360	102444	1.79992
T_6	57492	267640	210148	3.65525
T_7	57204	242720	185516	3.24306
T_8	61696	207640	145944	2.36553
T_9	61932	253000	191068	3.08512
T_{10}	61644	239280	177636	2.88164
T_{11}	62272	245640	183368	2.94463
T_{12}	61984	225440	163456	2.63706

Discussion

Recently, several novel applications of nanomaterials are emerging in different fields of science including agriculture. Application of both micro- and macro-nutrient fertilisers in their nano-particle formulations can be an important technique to gradually and carefully release the necessary nutrients in ecologically safe manner (Naderi and Abedi, 2012) [48]. When materials are reduced to the nanoscale, their physical, chemical and biological properties are altered (Mazaherinia *et al*., 2010) [49]. In an experiment conducted to investigate the impact of Nano-Carbon on the growth of tobacco, it was observed that it boosted plant height and also increased leaf area (Liang *et al*., 2013) [50]. The use of nanoparticles containing micro and macro-nutrients in agriculture, may lead to the increased yields (Reynolds, 2002) [51]. Since the nutrient losses from agricultural fields as a result of leaching (NO_3) and gaseous emissions (NH_3 and N_2O) are considered as the main sources of environmental pollution and also the causes of climate change (Kumar *et al*., 2021) [1]; nano-fertilizers may with controlled release of nutrients, deliver the correct amount of nutrients that crops need in the right proportion and increase the yield (EI-Ghamry *et al.*, 2018) [52]. Because traditional fertilisers frequently provide nutrients to plants in chemical forms that are not completely accessible to them (Liu and Lal, 2015) [53]. As a result, replacing traditional fertilisers with nano-fertilizers is advantageous, since they release nutrients into the soil continuously and in a more controlled manner reducing the water pollution thereof (Rehana *et al*., 2022) [54]. Different methods for nano-fertilizers have been often used that include soil application, foliar spray, seed priming, root-dip treatment of seedling and fertigation *etc* (Shang *et al*., 2019) [55].

Seed priming is a pre-sowing procedure that alters the physiological makeup of the seed to germinate rapidly (Bruce *et al*., 2007) [56]. Priming is the process of pre-treating seeds before planting that may involve methods such as pre-soaking and coating (Nile *et al*., 2022) [57]. It also enhances crop activity by enhancing the resistance/tolerance against a variety of abiotic and biotic stresses (Arnott *et al*., 2021) [58]. Therefore, it is anticipated that the seed priming with nano-fertilizers may provide initial growth advantage to the crop plants, thereby leading to a better growth and yield. In the present study, the impact of seed priming by Nano-Urea and Nano-Zinc on the growth, quality and yield of radish was studied and it was observed that the nano-fertiliser treatments considerably enhanced radish growth, yield and quality when compared to the control and the conventional fertilizers treatments. The outcomes of the current findings are covered in the parts that follow and are supported by the results of other research studies.

Growth attributes

Some nano-fertilizers like Nano-Zinc has been reported to increase the germination percentage and reduce time of germination. It was found that the treatment of nano-zinc oxide (ZnO) leads to the enhancement of germination percentage in soybean under drought stress (Sedghi *et al*., 2013) [59]. Further, it was also found that the nano zinc oxide at 1000 ppm concentration enhanced seed germination and seedling vigour in peanut, leading to better seedling establishment resulting in higher growth (Prasad *et al*., 2012) [60]. However, there was no clear-cut report of enhancing germination percentage upon Nano-Urea treatment. Whereas, seed priming of maize with urea resulted in the improved germination (Anosheh *et al*., 2011) [61]. In the present work, the seed priming with Nano-Urea treatment T_9 (NPK *i.e*., 100% recommended dose + Nano-Urea *i.e*., 100%), which was significantly at par with treatment T_3 (Nano-Urea *i.e*., 100%) and T_{11} (NPK *i.e*., 100% recommended dose + Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%) was effective in terms of minimum days to 50% germination.

An increased nitrogen supply to the plant, which also promotes cell division and the formation of new tissues, may result in a rise in plant height (Gendy *et al*., 2013) [62]. In the present work, the plant height was found maximum in the treatment T_6 (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%). Application of nitrogen is generally associated with the increase in cell growth (Bahmaniar and Mashaee, 2010) [63]. The nano-fertilizers are more effective in efficiently releasing the nutrients (Midde *et al*., 2021) [64]. Even with a decreased application rate, mixing nano fertiliser with traditional fertilisers increase plant height (Benzon *et al*., 2015) [65]. It was found that the application of nano fertilizers *i.e*., Nano-N and Nano-Zinc significantly improved the plant height and dry matter in potato (Neogi *et al*., 2022) [66]. Another investigation was conducted on the impact of nano ZnO particles on the root and shoot development of mungbean (*Vigna radiata*) and chickpea (*Cicer arietinum*) seedlings. The nano-fertilizer concentrations up to 20 ppm were helpful in enhancing plant height (Mahajan *et al*., 2011) [67].

The maximum number of leaves per plant can rise when there is an adequate nitrogen supply to the plants (Cechin and Fatima, 2004) [68]. The direct role of nano-hydroxyapatite (containing phosphate) fertilizer in boosting cell division and growth, particularly in the leaf cells, which was positively reflected in expanding the leaf area of the plant, may be the reason for the increase in the number of leaves in plants (Abd *et al*., 2020) [69]. In the present study, the maximum number of leaves per plant was observed in the treatment T_6 (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%). A study in tomato the number of leaves were enhanced by the foliar application of Nano-Urea (Mondal *et al.*, 2011) [70]. A similar increase in number of leaves per plant was observed in pea by the combined application of 0.1% Nano-Zinc + 0.2% Nano-Urea (Sathyan, 2022) [71].

The leaf length, leaf width and leaf area of plant is an important parameter that influences the plant's ability of growth and development, which is important for proper root production (Yin *et al*., 2003) [72]. The amount of nitrogen in the leaf also affects leaf area of the plant (Grindlay, 1997) [73]. In the present study, the leaf length and leaf area were found maximum in the treatment T_9 (NPK *i.e*., 100% recommended dose + Nano-Urea *i.e*., 100%) whereas, the maximum leaf width was found in the treatment T_6 (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%). The results of present investigation indicated that there was an enhancing effect of Nano-Urea and Nano-Zinc on vegetative growth *i.e*., leaf width and leaf length. Similar observation of the increase in leaf length and leaf area were recorded in wheat upon the combined application of 0.1% Nano-Zinc + 0.2% Nano-Urea (Sheoran *et al*., 2021) [74]. In an experiment was conducted to investigate the impact of Nano-Carbon (25, 75 and 125 mg pot^{-1}) on the growth of tobacco plants, it was observed that Nano-Urea treatment boosted plant height by 6.33, 10.56 and 10.00% while increasing leaf area by 6.64, 19.51 and 21.58%, respectively (Liang *et al*., 2013) [75].

Yield attributes

The root length of plant is most important in radish production, as it directly determines the marketable yield and economic value of the crop. In the present study, the root length of plant was observed maximum in the treatment T_9 (NPK *i.e*., 100% recommended dose + Nano-Urea *i.e*., 100%). In another study, the increase in root length and yield of radish with the application of Nano-Urea and Nano-Zinc was observed (Liu *et al.*, 2009) [76].

The root diameter of plant is also an important factor in radish production. Root diameter of radish increases initially with an increase in each level of nitrogen application (Jilani *et al*., 2010) [77]. In the present study, the root diameter was observed maximum in the treatment T_6 (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%). The diameter of root was significantly influenced among the different treatments. In another experiment on sugar beet, root diameter was improved with an application of nano-fertilizer *i.e*., Nano-N (Dewdar *et al*., 2018) [78].

The root fresh weight and total yield of plant is most important parameter in radish production, as it directly determines the marketable yield and economic value of the crop. In the present study, the weight of root and total yield were observed maximum in the treatment T_6 (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%). In an experiment on cucumber, the maximum yield (149.17 t ha^{-1}) was observed with the application of Nano-Urea (Ekinci *et al*., 2014) [79]. In another experiment on soybean plants cultivated in soils containing ZnO nanoparticles displayed a significantly higher pod and seed-biomass, when compared to plants grown in control soil (Priester *et al*., 2012) [80]. In another experiment Nano-zinc oxide was applied on rice, as a result increase in grain was observed on the application of ZnO NPs over control. Grain yield was also improved by 8.84% over control (Singh *et al*., 2019) [81]. The increased photosynthetic activity will lead to larger plant organs, which will result in the increased dry weight of the plant (Novoa *et al*., 1981) [82]. In the present study, the dry weight of plant was observed maximum in the treatment T_6 (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%). In a study, an increase in dry weight of potato tuber was observed with the application of nano-nitrogen (Banjare *et al*., 2014) [83].

Quality attributes

An increase in TSS after N application can be contributed to the important roles of N in chloroplast structure, CO_2 assimilation and activations of enzymes involved in photosynthesis, which leads to an increase in carbohydrate accumulation also consequently increase in TSS (Kumar *et al*., 2014) [11]. In the present study, the TSS was observed maximum in the treatment T_6 (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%). Similar results were also observed in shoots of lettuce plants with the combined application Nano-Urea and Nano-Zinc at the concentration of 1000 mg/L (Roosta *et al*., 2017) [84]. In another study, the TSS content was increased with the application of Nano-Urea in guava (Arora and Singh, 1970) [85]. Ascorbic acid (vitamin C) is an important antioxidant present in radish. An adequate supply of nitrogen is essential for the growth and development of any crop, as it is an essential constituent of various metabolically active compounds (Lawlor, 2002) [86]. In the present study, ascorbic acid was observed maximum in the treatment T_6 (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%). The increased accumulation of nitrogen and other micro and macro nutrients led to an increase in vitamin C content. In an experiment, a considerable increase in nutritional content and ascorbic acid was observed with the application of Nano-N and Nano-Zinc in sorghum (Rani *et al*., 2019) [87].

Amino acids are one of the essential building blocks of proteins, which play a vital role in growth and maintenance of plants (Ryan, 2000) [88]. In addition, proteins also have a wide range of functions such as enzymatic activities, nutrient's transportation and other physiological roles (Robbin *et al.*, 1987) [89]. The enhanced production of proteins thereby resulting into higher growth is aided by higher level of nitrogen input (Lawlor *et al*., 1989) [90]. Nitrogen is essential for growth of plants and is an important constituent of all proteins and hence of the protoplasm (Arora and Singh, 1970) [85]. The higher level of nitrogen supply increases the extra protein produced and helps the plant to grow larger and hence to have a larger surface for photosynthesis (Lawlor *et al.*, 1989) [90]. In the present study, the highest protein content was observed in the treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e*., 100%). In a study, similar results were recorded with the combined application of nano-nitrogen (foliar application) and NPK in pearl millet (Sharma *et al.*, 2022) [91].

Plant carotenoids play diverse functions in plant growth and development (Cazzonelli and Pogson, 2010) [92]. In plants, carotenoids exist as both primary and specialized metabolites and exert distinct functions as one or the other (Sun and Li, 2020) [93]. In the present study, the highest carotenoid content was observed in the treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 100%). In a similar study on red radish, with the application of Nano-Urea, the increase in carotenoid content was recorded (Mahmoud *et al.*, 2019) [94]. In another study, the combined application of Nano-Urea and NPK resulted into the increase in carotenoid content in another root vegetable *i.e.*, carrot (Siddiqui *et al.*, 2019) [95]. Further, the carotenoids were observed maximum after the application of ZnO NPs through seed priming as well as coating treatments in maize (Tondey *et al.*, 2021) [96].

The synthesis of chlorophyll in plants depends heavily on zinc, whereas its deficit might cause the quantity of chlorophyll to decrease. The photosynthetic process, leaf colour and general plant growth are all significantly influenced by the chlorophyll content (Lichtenthaler and Rinderle, 1988) [97]. In the present study, chlorophyll content was observed maximum in the treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 100%). In lettuce, the amount of chlorophyll increased by raising the concentration of nano fertilizer *i.e*., Nano-N (Abdel Salam *et al*., 2018) [98]. Further, in cowpea the use Nano-Urea and Nano-Zinc treatments were linked to the enhanced chlorophyll synthesis (Salim *et al*., 2023) [99]. This incensement of chlorophyll due to the role of nano particle improved the leaves photosynthesis and decreased the rate of respiration.

Flavonoids are natural antioxidant that present in plants (Ghasemzadeh, 2011) [100]. In the present study, flavonoid content was observed maximum in the treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e*., 100%). In another study on radish, the flavonoid content increased with the application of nano-nitrogen (Mahmoud *et al*., 2019) [94]. A similar increase of the flavonoid content was recorded in potato with the application of nano-nitrogen (Jin *et al*., 2014) [101].

Phenolic compounds have antioxidant properties and other associated health benefits (Pal *et al*., 2013) [102]. Radish is also a good source of phenolic compounds, which are present in both its skin and the flesh. There have been some indications that seed soaking/priming can boost phenolic content and antioxidant activity in crops (Islam and Becerra, 2012) [103]. In the present study, phenolic content was observed maximum in the treatment T_9 (NPK *i.e*., 100% recommended dose + Nano-Urea *i.e*., 100%). Similar observation was recorded in rice, where the total phenolic content increased with the combined application of Nano-Urea and NPK (Benzon *et al*., 2015) [104].

Benefit-cost ratio

Application of nanotechnology in agriculture is viewed from the perspective of sustainable agriculture as one of the key strategies to increase crop production and feed the world's rapidly expanding population (Lal, 2008) [105]. Due to their effective delivery technique, nano-fertilizers reduce the fertiliser dosage and increase profit (Singh, 2017) [106]. The rise in the B.C. ratio and other crop economic indicators may be attributable to an increase in yield that brought in higher market pricing. In the present study, the highest B: C ratio was observed in the treatment T_6 (Nano-Urea *i.e.*, 100% + Nano-Zinc *i.e*., 100%). A study was conducted in tomato, with the foliar application of nano N and nano Zn increased benefit-cost ratio (Mishra *et al*., 2020) [107] and in sweet corn, with the application of NPK along with the foliar application of nano zinc also increased benefit-cost ratio (Rajesh *et al*., 2021) [108].

The seed priming effect was found to be significant for emergence percentage and root weight. Seed priming with nano forms of Zn and N proved to be effective in increasing emergence percentage and also seed priming in water increased emergence percentage compared to that of the control. Therefore, it is clear from the present study that from an economic and yield perspective, the application of combined treatment of (Nano-Urea *i.e*., 100% + Nano-Zinc *i.e*., 100%) by seed priming increased crop growth, quality and yield. It is also concluded that use of nano-fertilizers through seed priming minimise the cost of cultivation and also help in enhancing production through a more environmentally sustainable manner. Our group have previously also recorded the improvement in plant growth and yield of potato through pre-soaking of seed tubers in nano-urea and nano-zinc (Chauhan *et al*., 2023) [109]. This further affirms the positive role of nanotechnology in plant science *i.e*., plant growth and nutrition, besides the other roles in environmental clean-up (Bhardwaj *et al*., 2023) [110]. However, certain negative impacts of nanoparticles in the environment (Kaur *et al*., 2021) [111], limit the broad-spread application in agro-ecosystems.

Conclusion and future prospects

The present findings showed that the seed priming with Nano-Urea and Nano-Zinc fertilizers (Nano-Urea *i.e.*, 100% + Nano-Zinc *i.e*., 100%) were effective in improving growth, yield and quality attributes and were also more economical than the conventional fertilizers. Since the nano-fertilizers may increase plant growth to a greater extent than do conventional fertilizers in radish and that to by the minimal treatment (seed priming). Keeping in mind the environmental benefits, economical gains and the slower and sustained release of the nutrients, they can be effectively used in the farmer's fields in a widespread area. However, before their widespread usage in the agricultural fields, the long-term environmental impact assessment and critical evaluation in different varieties of radish in varied environments are required. Nano-fertilizers are taken up directly by plants and they offer a more targeted delivery system for nutrient management in plants. Further, they are required in lower doses than the conventional fertilizers, offer a sustained release of the nutrient to the plants and are not prone to leeching and accumulation in water bodies. However, their dosage and mode of application is to be evaluated on crop-by-crop bases in different combinations, before their widespread use in the agricultural fields. Nano-fertilizers have the potential to meet the nutritional needs of plants, assure farmer's profitability and improve agricultural production and sustainability without reducing crop yields. Since, the application of nano-fertilizers through seed priming is cost-effective because they are required in less quantity. The use of nanotechnology in agriculture will lead to better crop productivity, availability of food grains and a sustainable environment. Before widespread adoption in agricultural practice, more research must be carried out in various local regions and crop varieties to fully understand the long-term effects, economic viability and environmental impact of seed priming by the nano-fertilizers like Nano-Urea and Nano-Zinc in vegetable crops and the combination of treatments, thereof.

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