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Effect of pre-soaking of potato (*Solanum tuberosum* L.) tubers in nano-urea and nano-zinc on its growth, quality and yield

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Abstract

Nano-fertilizers have the potential to enhance crop productivity by increasing nutrient use efficiency. The present investigation was conducted to determine the effect of urea and zinc, when applied in nano form fertilizers through the pre-soaking method on the growth, quality, and yield of potato. The experiment consisted of a variety (Kufri Badshah) and laid in a randomized block design (RBD) with three replications comprising twelve treatments *viz.* T_1 (Control), T_2 (NPK), T_3 (Nano-Urea *i.e.*, 100%), T_4 (Nano-Urea *i.e.*, 50%), T_5 (Nano-Zinc), T_6 (Nano-Urea *i.e.*, 100% + Nano-Zinc), T_7 (Nano-Urea *i.e.*, 50% + Nano-Zinc), T_8 (NPK + Nano-Zinc), T_9 (NPK + Nano-Urea *i.e.*, 100%), T_{10} (NPK +Nano-Urea *i.e.*, 50%), T_{11} (NPK + Nano-Urea *i.e.*, 100% + Nano-Zinc) and T_{12} (NPK + Nano-Urea *i.e.*, 50% + Nano-Zinc). The results showed that the pre-soaking application of Nano-Urea (100%) and Nano-Zinc along with NPK increased the plant height and minimum days to 50% emergence. It was also observed that NPK along with Nano-Urea (100%) and Nano-Zinc increased the number of leaves per plant, further the combination of both Nano-Urea (100%) and Nano-Zinc recorded the highest leaf area. Regarding the tuber yield of potato, the highest tuber yield per hectare, tuber yield per plot, number of tubers per plant, dry weight of tubers and fresh weight of tubers were recorded with the combination of NPK along with Nano-Urea (100%) and Nano-Zinc. Among the quality attributes, starch content, sugar content, reducing sugars, non-reducing sugars, ascorbic acid, and total flavonoid content were recorded highest when NPK was applied with 100% Nano-Urea. The chlorophyll content was recorded maximum when NPK was applied with Nano-Zinc. phenolic content, TSS and flavonoid content were recorded maximum when NPK was applied with 50% Nano-Urea. The result also revealed that pre-soaking treatment of NPK along with Nano-Urea (100%) and Nano-Zinc recorded maximum carotenoid content. The economic analysis depicted the maximum gross income, net income and benefit-cost ratio from the treatment T_{11} (NPK + Nano-Urea *i.e.*, 100% + Nano-Zinc). The present study will help the farmers to utilize the best combination of nano-fertilizers for increasing the yield of potato.

Keywords: Fertilizers, pre-soaking, nano-urea, nano-zinc, benefit-cost ratio, potato

Introduction

The potato (*Solanum tuberosum* L.) is one of the major crops grown both in the sub-tropical as well as temperate regions of the world (Kumar and Chandra, 2018) [59]. It is the fourth-most significant crop in the world after rice, wheat, and maize (Zhang *et al.* 2017) [142]. It belongs to the nightshade family (Solanaceae) having chromosome number (2n=4x=48). It is an annual, herbaceous, and self-pollinated crop that produces edible underground tubers (Kumar and Chandra, 2018 [59]; Shubha *et al.* 2019 [120]; Sharma *et al.* 2021 [115]). Potato is a native of the Andean Mountain region in South America, mainly Bolivia, Colombia, Ecuador and Peru (Larrea and Freire, 2002) [65]. The vegetative and fruiting parts of the potato contain the toxin solanine which) which are not suitable for consumption (Barceloux, 2009) [19]. The optimum yield can be obtained when the temperature is around 18-20 °C (Reddy *et al.* 2018) [103]. Potato is a good source of starch, protein, vitamins C, B, and minerals (Zaheer and Akhtar, 2016) [140]. They are an inexpensive source of energy and provide good-quality protein (Lachman *et al.* 2001) [64]. It is used both as a vegetable and in industries (for manufacturing starch, alcoholic beverages, and other processed products like french-fries, chips, *etc.*) (Valta *et al.* 2015) [132]. Apart from food use, potato products are being used for non-food applications such as bio-degradable packaging, fermentation, vaccines and pharmaceuticals (Shit *et al.* 2014) [119]. Starches have the potential to be used for the treatment of certain medical conditions (*e.g.*, glycogen storage disease and diabetes mellitus) (Tapsell, 2004) [128].

Significant levels of hydrophilic antioxidants, *i.e.*, phenolic compounds and vitamin C, and moderate levels of lipophilic carotenoids and vitamin E have been reported in potatoes (Ezekiel *et al.* 2013) [36]. These phytochemical compounds have received much attention due to their prospective effects on the prevention of various chronic diseases such as cancers cardiovascular and degenerative diseases (Wang *et al.* 1999 [136]; McCullough *et al*. 2012) [80].

India ranks second in terms of potato production after China, with an annual production of potatoes of 53.58 MT under 2.2 Mha and a productivity of 25.07 t/ha, in the year 2021-22 (Kumari, 2023) [63]. The major potato-producing state of India is Uttar Pradesh. India's top ten potato-producing states are Uttar Pradesh, West Bengal, Bihar, Gujarat, Madhya Pradesh, Punjab, Assam, Haryana, Jharkhand, and Chhattisgarh (Nankar, 1990) [89] . In 2021, the annual world production of potatoes was 376,875,686 MT under 47,697,763,36 Mha (Anonymous, 2021) [7]. In Punjab, the area under potato cultivation is 89,993 ha with an annual production of about 30.5 lakh t/ha, (Anonymous, 2023) [8]. The major potato-growing districts of Punjab are Jalandhar, Hoshiarpur, Kapurthala, Ludhiana, Amritsar, Bathinda, and Fatehgarh Sahib (Roul *et al.* 2020) [104].

The growth and yield of vegetable crops mainly depend on the quality and quantity of fertilizers used. As potato is a heavy feeder of fertilizers due to its sparse root structure, it requires high doses of fertilizers to achieve maximum yield (Nurmanov *et al.* 2019) [93]. High doses of application of chemical fertilizers to increase crop productivity is not a suitable option for the long run, as the chemical fertilizers on the one hand increase crop productivity (Yan and Gong, 2010) [138], whereas, on the other hand, disturb the soil mineral balance and decrease soil fertility (Fonte *et al.* 2012) [39]. Loss of mineral nutrients through leaching and runoff to surface and groundwater along with abundant volatilization constitute growing concerns owing to economic losses and environmental pollution (Kumar *et al.* 2021) [62].

In recent years, nanotechnology has extended its relevance in plant science and agriculture (Shang *et al.* 2019) [113]. In order to overcome the limitations of conventional chemical fertilizers, some nano-fertilizers are available, that can reduce the doses of fertilizers and multi-nutrient deficiency in soil by increasing nutrient use efficiency (Singh, 2017 [123]; Qureshi *et al.* 2018 [98]), hence can improve crop productivity by enhancing the rate of seed germination, seedling growth, photosynthetic activity, nitrogen metabolism, carbohydrate and protein synthesis (Elemike *et al.* 2019) [34]. Nano-fertilizers are being prepared by encapsulating plant nutrients into nanomaterials, employing a thin coating of nano nutrients on plant nutrients, and delivering in the form of nano-sized emulsions. The particle size of nano-fertilizers is less than 100 nm (Kumar *et al.* 2021) [60]. Through slow/controlled release methods, they control the nutrients that are available to crops. (Singh and Raliya, 2020) [125]. Nano-fertilizers minimize the bulk requirements with extra benefits of reduction in purchasing and transportation cost with maximizing the profit. Soils show widespread nutrient deficiencies, especially in nitrogen and zinc, which reduces growth and yield (Rashid and Ryan, 2004) [102]. However, the use of nano nitrogen and nano zinc is an alternate source of nitrogen and zinc. Nano-fertilizers can be applied in soil or as foliar application and therefore can be absorbed through the roots or leaves (Hong *et al.* 2021) [44]. Nanoparticles when applied in soil, can enter by the roots and travel through the xylem vessels to the aerial portions. Further, if applied as a foliar spray, they can be absorbed by leaf stomata and are transferred to other plant parts through the phloem (Ebbs *et al.* 2016) [33]. 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) [94]. However, if these nano-fertilizers are used as a pre-soaking (seed priming) technique, they will directly enter the seeds and promote plant growth at the early stages of their establishment. This initial growth advantage may lead to a better improvement in crop production. In this regard, there are some crops in which seed priming is done, and to the best of our knowledge, this is the first report of the pre-soaking treatment of nano-fertilizers in potato. Keeping the above in mind, the present study was conducted to examine the effect of pre-soaking of tubers (*Solanum tuberosum* L.) on the growth, yield and quality parameters of potato.

Materials and Method

A 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), to study the effect pre-soaking of nano-urea and nano-zinc on the growth, yield, and quality of potato (*Solanum tuberosum* L.). Geographically, the research farm is located at 75°56´99´´ East longitude and 31°33´00´´ North latitude, with an average elevation altitude of 230 meters (754.5 feet).

a. **Plant material:** Plant material, *i.e.*, potato *cv.* Kufri Badshah was procured from Bhatti Agritech, Village P.O, Alipur, Mithapur, Dist. Jalandhar, Punjab.

b. **Fertilizers and Nano-fertilizers:** Commercial fertilizers *i.e*., NPK (IFFCO), and Nanofertilizers i.e., nano-urea (IFFCO) and nano-zinc (Zeolife) were procured from the university and the local market of Jalandhar, Punjab, India.

c. **Experiment design:** The experiment was laid out in a randomized block design with three replications comprising twelve treatments represented in table 1, *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%). The soil texture of the experimental field was sandy loam with a pH of 7.3-7.5. Potato variety used was Kufri Badshah. The land was brought to a fine tilth through ploughing and divided into 36 plots. The sprouted tubers were planted at a spacing of 75 cm × 15 cm in a net area of 250 m^2 on 3rd November. The plot size was 3 m × 2 m. The recommended dose of fertilizers was 150 kg N, 100 kg P_2O_5, and 120 kg K_2O_5 per hectare in the form of urea, single super phosphate (SSP) and muriate of potash (MoP). However, 50% recommended dose of nitrogen and 100% recommended dose of phosphorus and potassium were applied treatment-wise during final land preparation. Whereas, the remaining nitrogen was top-dressed 30 days after planting, at the time of earthing up. Intercultural procedures such as weeding and hoeing were carried out, followed by earthing up performed twice: once at the start of tuberization and again at the end of the tuber growth. Regular monitoring was done. The plants were dehaulmed 10 days prior to tuber harvesting. All cultural operations were followed regularly during crop growth and observations were recorded.

Table 1: Treatment details

Treatment no.	Details of the treatment
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%)

d. Pre-soaking treatment: Treatment wise nano-urea and nano-zinc were given through pre-soaking of tubers at the concentrations of 5 g/liters (100%) for Nano-Zinc (of Geolife nano zinc, nanotechnology, micronutrient fertilizers), 60 ml/liters (100%) for Nano-Urea and 30 ml/liters (50%) for Nano-Urea (of IFFCO nano-urea fertilizer).

Collection of experimental data

Growth parameters

Beginning the second week, following planting, morphological observations were taken at different stages. Five plants were randomly selected from each plot and tagged. All observations *viz.* days to 50% emergence, plant height, number of leaves per plant, and leaf area were recorded from these plants (Mehara *et al.* 2018) [81].

Yield parameters

After 90 days of planting, yield measurements were taken from each treatment, excluding rows and plants. On the basis of net plot size, various observations *viz.* fresh tuber weight, dry tuber weight, number of tubers per plant, tuber yield per plot, and tuber yield per hectare were recorded (Mehara *et al.* 2018; Fikre and Mensa, 2021) [81, 37].

Quality parameters

Different quality parameters (*viz.* TSS, ascorbic acid, chlorophyll content, carotenoid content, *etc.*) were measured.

Total soluble solids

Total soluble solids were recorded by using a digital hand refractometer (Erma, Japan Hand Refractometer 0-32°Brix). The TSS of the tubers was determined and presented as an average (Saad *et al.* 2016) [106].

Pigment composition

The chlorophyll content of leaves was determined after sowing at 45 days and 90 days. The observations were taken at 645 nm and 663 nm for chlorophyll content (Arnon, 1949) [10]. The result were expressed in mg/g fresh weight of leaves and was calculated by the formula:

$$\text{Total Chlorophyll (mg/g) tissue} = 20.2(A_{645}) + 8.02(A_{663})$$
$$\text{Chlorophyll a (mg/g) tissue} = 12.7(A_{663}) + 2.69(A_{645})$$
$$\text{Chlorophyll b (mg/g) tissue} = 22.9(A_{645}) - 4.68(A_{663})$$

The values from Arnon's1949 method of chlorophyll a and chlorophyll b were used to calculate the chlorophyll a/b ratio (Porra *et al.* 1989) [97].

The carotenoid content of leaves was determined after sowing at 45 days and 90 days. The observations for carotenoids were taken at 480 nm and 510 nm (Kapoor *et al.* 2014) [52]. The result were expressed in mg/g fresh weight of leaves and were calculated by the formula:

$$\text{Carotenoids (mg/g) tissue} = 7.6(A_{480}) - 1.49(A_{510})$$

Starch and sugar content (mg/g FW)

The presence of starch can be measured by its reaction with iodine (Bates *et al.* 1943) [20]. Starch and iodine form a dark-blue complex with an absorbance maximum at 600 nm. The soluble starch powder was used as standard (Alcazar-Alay and Meireles, 2015) [5].

The reducing sugars in five tubers from each treatment were calculated using the Somogyi-Nelson method (Nelson 1944 [90]; Somogyi 1952 [127]). Glucose was used as a standard and absorbance was recorded at 500 nm.

The total sugars were calculated using the ferricyanide method (Ashwell 1957) [12]. Glucose was used as a standard and absorbance was recorded at 690 nm.

The non-reducing sugars was calculated by using the formula (Basra *et al.* 2005) [20].

$$\text{Non-reducing sugar} = \text{Reducing sugar} - \text{Total sugar}$$

Protein content (μg/g FW)

The protein content was estimated as described by Sharma *et al.* (2011) [114]. The total protein content of leaves was determined by the method of Bradford (1976) [24] 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.

Non-enzymatic antioxidants

Total flavonoid content was determined by using Ardekani's method (Ardekani *et al.* 2011) [9]. Catechin was used as a standard and absorbance was recorded at 510 nm. The results were expressed as mg/g FW of Catechin eq.

Total phenolic content was analyzed by using Singleton's method (Singleton *et al.* 1999) [126]. Gallic acid was used as a standard and absorbance was recorded at 650 nm. Total phenolic content was represented as mg/g FW of Gallic acid eq.

Ascorbic acid was determined using the 2, 6 dichlorophenol-indophenol titration method. The results were expressed as mg/g of sample and were calculated using the formula:

$$\text{Ascorbic acid content (mg/g FW)} = \frac{\text{Titre value} \times \text{dye factor} \times \text{volume made up} \times 100}{\text{Aliquot of extract} \times \text{weight of sample taken}}$$

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 under the following subheadings.

Cost of cultivation (Rs./ha)

Cost of cultivation 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) [141].

Gross returns (Rs./ha)

Gross returns was calculated by multiplying total tuber yield separately under various treatment combinations with their existing market price (Verma *et al.* 2011) [133].

Net returns (Rs./ha)

Net return was calculated by deducting the cost of cultivation from the gross return of the individual treatment combination (Umesh *et al.* 2014) [130].

Net return = Gross return – Cost of cultivation

Benefit-cost ratio (B:C)

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) [85].

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

Results

The observations were recorded on various growth, yield, and quality parameters and were significantly influenced by different treatments.

Growth parameters

The effect of pre-soaking of potato tubers in nano-urea and nano-zinc fertilizers on various growth parameters *viz.* days to 50% emergence, plant height, number of leaves per plant, and leaf area, are presented in table 2. Except for plant emergence, observations for plant height, number of leaves per plant, and leaf area were recorded after 90 days.

Days to 50% emergence

The minimum days to 50% emergence (11.70 days) was observed in the treatment T_9 (table 2), which however, was statistically at par (not significantly different at $p \leq 0.05$) with the treatment T_8 (12.13 days) and T_7 (12.43 days). Whereas, the maximum days to 50% emergence (15.30 days) was observed in the treatment T_1, which was statistically at par with the treatment T_2 (15.10 days) and T_6 (14.80 days).

Plant height (cm)

Significant differences in plant height at 90 DAS was observed among the different treatments (table 2). The maximum plant height (43.13 cm) was observed in treatment T_9, which was statistically at par with the treatment T_{11} (42.67 cm), the treatment T_{12} (42.60 cm), the treatment T_{10} (42.34 cm), and the treatment T_8 (40.60 cm). Whereas, the minimum plant height (30.40 cm) was observed in the treatment T_6. It was statistically at par with the treatment T_7 (32.00 cm), the treatment T_4 (32.00 cm), the treatment T_2 (33.66 cm), and the treatment T_1 (34.40 cm).

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

Treatments	Days to 50% emergence	Plant height (cm)	No. of leaves per plant	Leaf area (cm^2)
T_1	15.30	34.40	39.27	197.56
T_2	15.10	33.66	43.89	215.21
T_3	13.13	32.00	52.18	211.45
T_4	13.10	32.00	49.01	202.72
T_5	14.07	33.27	47.41	205.74
T_6	14.80	30.40	52.04	261.37
T_7	12.43	31.67	52.82	217.61
T_8	12.13	40.60	53.94	209.15
T_9	11.70	43.13	53.01	233.52
T_{10}	13.10	42.34	52.96	228.14
T_{11}	13.20	42.67	58.59	211.59
T_{12}	13.77	42.60	55.6l7	244.00
SE (m) ±	0.262	2.068	0.424	9.493
CD @ 5% ($p \leq 0.05$)	0.775	6.104	1.251	28.021

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

Number of leaves per plant

Significant differences in the number of leaves per plant at 90 DAS was observed among the different treatment. It was observed that the maximum number of leaves (58.59) in the treatment T_{11}, which was, however, significantly highest than all the treatments (Table 2). Whereas, the minimum number of leaves (39.27) was found in the treatment T_1, which was significantly lowest among all the treatments.

Leaf area: Significant differences in leaf area at 90 DAS was observed among the different treatments. The maximum leaf area (261.37 cm^2) was observed in treatment T_6 which was statistically at par with the treatment T_{12} (244.00 cm^2), and the treatment T_9 (233.52 cm^2) (table 2). Whereas, the minimum leaf area (197.56 cm^2), was observed in the treatment T_1 which was however, statistically at par with the treatment T_4 (202.72 cm^2), the treatment T_5 (205.74 cm^2), the treatment T_8 (209.15 cm^2), the treatment T_3 (211.45 cm^2), the treatment T_{11} (211.59 cm^2), the treatment T_2 (215.21 cm^2), and the treatment T_7 (217.61 cm^2).

Yield parameters
The effect of pre-soaking of potato tubers in nano-urea and nano-zinc fertilizers on various yield parameters were recorded after 90 days *viz.* fresh tuber weight, dry tuber weight, number of tubers per plant, tuber yield per plot, and tuber yield per hectare are presented in table 3.

Fresh tuber weight (g)
Maximum fresh tuber weight (983.97 g) was observed in the treatment T_{11}, which was significantly highest among all the treatments (table 3). Whereas, the minimum fresh tuber weight (434.30 g) was observed in T_1, which was statistically at par with T_2 (482.47 g).

Dry tuber weight (g)
Maximum dry tuber weight (44.12 g) was observed in the treatment T_{11}, which was significantly highest among all the treatments (table 3). Minimum dry tuber weight (19.60 g) was observed in the treatment T_1, which was statistically at par with the treatment T_3 (22.80 g), and the treatment T_2 (23.40 g).

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

Treatments	No. of tubers per plant	Fresh weight of tubers (g)	Dry weight of tubers (g)	Tuber yield per plot (kg)	Tuber yield per hectare (t/ha)
T_1	3.57	434.30	19.60	15.65	26.19
T_2	4.94	482.47	23.40	16.87	28.14
T_3	5.07	537.54	22.80	18.81	31.35
T_4	5.04	513.07	33.90	17.65	29.41
T_5	6.04	499.23	27.28	17.47	29.12
T_6	4.87	608.50	27.28	21.29	35.49
T_7	5.50	681.34	32.31	23.84	39.74
T_8	7.40	918.74	39.92	20.55	34.26
T_9	7.47	587.40	27.74	32.15	53.59
T_{10}	6.80	803.90	33.64	28.13	46.89
T_{11}	7.90	983.97	44.12	34.43	57.39
T_{12}	6.77	846.20	32.11	29.61	49.35
SE (m) ±	0.311	19.187	1.402	0.685	1.141
CD @ 5% ($p \leq 0.05$)	0.918	56.636	4.137	2.021	3.368

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

Number of tubers per plant
The maximum number of tubers per plant (7.90), was observed in the treatment T_{11}, which was significantly at par with the treatment T_9 (7.47), and the treatment T_8 (7.40). Whereas, the minimum number of tubers per pant (3.57) was observed in the treatment T_1 which was significantly lower than all the treatments (table 3).

Tuber yield per plot (kg)
Maximum tuber yield per plot (34.43 kg) was observed in the treatment T_{11}, which was statistically at par with the treatment T_9 (32.15 kg). Whereas, the minimum tuber yield per plot (15.65 kg) was observed in the treatment T_1 which was statistically at par with the treatment T_2 (16.87 kg), T_5 (17.47 kg) and T_4 (17.65 kg) (table 3).

Tuber yield per hectare (t/ha)
Maximum tuber yield per hectare (57.39 t/ha) was observed in the treatment T_{11}, which was significantly higher than all the treatments (table 3). Whereas, the minimum tuber yield per hectare (26.19 t/ha) was observed in the treatment T_1 which was statistically at par with the treatment T_2 (28.14 t/ha), T_5 (29.12 t/ha) and T_4 (Nano-Urea *i.e.*, 50%) (29.41 t/ha).

Quality parameters
The effect of pre-soaking of potato tubers in nano-urea and nano-zinc fertilizers on various quality parameters *viz.* TSS, ascorbic acid, carotenoids, total chlorophyll, chlorophyll a, chlorophyll b, starch content, sugar content, proteins, flavonoids and phenolics are presented in table 4, 5 and 6.

TSS (°Brix)
The maximum TSS (4.80°B) was recorded in the treatment T_{10}, which was significantly highest than that of any other treatment (table 4). Whereas, the minimum TSS (2.60 °B) was observed in the treatment T_6 (2.80°B) and the treatment T_{12} (2.87°B).

Table 4: Effect of nano-urea and nano-zinc on some quality attributes (TSS, ascorbic acid, starch, Total sugars, reducing sugars and non-reducing sugars) of potato

Treatments	TSS (°Brix)	Ascorbic acid (mg/g FW)	Starch content (mg/g FW)	Total sugar (mg/g)	Reducing sugars (mg/g)	Non-reducing sugars (mg/g)
T_1	2.60	12.14	51.81	1.93	0.61	1.38
T_2	3.74	14.17	53.41	2.03	0.63	1.42
T_3	3.07	11.70	59.36	2.13	0.70	1.43
T_4	3.17	13.10	61.82	2.34	0.68	1.63
T_5	3.77	14.07	65.86	2.40	0.73	1.66
T_6	2.80	14.80	65.37	2.52	0.84	1.72
T_7	3.80	12.64	67.42	2.42	0.76	1.65
T_8	4.20	15.10	69.25	2.71	0.83	1.90
T_9	3.74	15.30	73.71	3.81	0.95	2.86
T_{10}	4.80	13.14	73.09	2.78	0.81	1.97
T_{11}	4.24	13.20	68.77	3.07	0.86	2.18
T_{12}	2.87	13.77	70.85	2.81	0.83	1.84
SE (m) ±	0.100	0.262	0.844	0.094	0.009	0.126
CD @ 5% ($p \leq 0.05$)	0.296	0.775	2.490	0.279	0.027	0.372

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

Ascorbic acid (mg/g FW)

The maximum ascorbic acid (15.30 mg/g FW) was recorded in the treatment T_9, which was however, statistically at par with the treatment T_8 (15.10 mg/g FW) and the treatment T_6 (14.80 mg/g FW). The minimum ascorbic acid (11.70 mg/g FW) was observed in the treatment T_3, which was statistically at par with the treatment T_1 (12.14 mg/g FW) (table 4).

Starch content (mg/g FW)

The maximum starch content (73.71 mg/g FW) was recorded in the treatment T_9, which was however statistically at par with the treatment T_{10} (73.09 mg/g FW) (table 4). However, the minimum starch content was observed (51.81 mg/g FW) in the treatment T_1 (Control), which was statistically at par with the treatment T_2 (53.41 mg/g FW).

Total sugar (mg/g)

The maximum total sugar (3.81 mg/g) was observed in the treatment T_9 among all the treatments (table 4). However, the minimum total sugar was observed (1.93 mg/g) in T_1, which was statistically at par with the treatment T_2 (2.03 mg/g) and the treatment T_3 (Nano-Urea *i.e.*, 100%) (2.13 mg/g).

Reducing sugar (mg/g)

The maximum reducing sugar (0.95 mg/g) was observed in the treatment T_9 among all the treatments (table 4). However, the minimum reducing sugar was observed (0.61 mg/g) in the treatment T_1, which was statistically at par with the treatment T_2 (0.63 mg/g).

Non-reducing sugar (mg/g)

The maximum reducing sugar (2.86 mg/g) was observed in the treatment T_9 among all the treatment (table 4). However, the minimum reducing sugar was observed (1.38 mg/g) in the treatment T_1, which was statistically at par with the treatment T_2 (1.42 mg/g), the treatment T_3 (1.43 mg/g), the treatment T_4 (1.63 mg/g), the treatment T_5 (1.66 mg/g), the treatment T_7 (1.65 mg/g) and the treatment T_6 (1.72 mg/g).

Protein content (µg/g FW)

Maximum protein content (0.487 µg/g FW) was observed in the treatment T_{10} among all the treatments (table 5). However, the minimum protein content was observed (0.457 µg/g FW) in the treatment T_1 and treatment T_2, which was significantly lower among all the treatments.

Table 5: Effect of nano-urea and nano-zinc on some quality attributes (protein content, phenolics and flavonoid content) of potato

Treatments	Protein content (µg/g FW	Phenolics (mg/g FW of Gallic acid equivalents)		Flavonoids (mg/g FW of Catechin equivalents)	
	90 DAS	45 DAS	90 DAS	45 DAS	90 DAS
T_1	0.457	1.213	1.213	0.307	0.308
T_2	0.457	1.213	1.215	0.307	0.309
T_3	0.460	1.217	1.218	0.309	0.311
T_4	0.460	1.219	1.220	0.315	0.313
T_5	0.470	1.221	1.223	0.319	0.319
T_6	0.475	1.225	1.226	0.321	0.324
T_7	0.477	1.228	1.228	0.324	0.323
T_8	0.479	1.230	1.231	0.326	0.325
T_9	0.482	1.233	1.235	0.339	0.340
T_{10}	0.487	1.240	1.240	0.337	0.339
T_{11}	0.484	1.236	1.238	0.335	0.330
T_{12}	0.481	1.237	1.239	0.336	0.330
SE (m) ±	0.001	0.000	0.000	0.000	0.001
CD @ 5% ($p \leq 0.05$)	0.002	0.001	0.001	0.001	0.003

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

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

Maximum total phenolic content at 45 DAS (1.240 mg Gallic acid eq./g FW) was observed in the treatment T_{10} among all the treatments (table 5). However, the minimum total phenolic content was observed (1.213 mg Gallic acid eq./g FW) in the treatment T_1 and the treatment T_2, which was significantly lower among all the treatments.

Maximum total phenolic content at 90 DAS (1.240 mg Gallic acid eq./g FW) was observed in the treatment T_{10} among all the treatments (table 5). However, the minimum total phenolic content was observed (1.213 mg Gallic acid eq./g FW) in the treatment T_1, which was significantly lower among all the treatments.

Total Flavonoid content (mg/g Catechin eq./g FW)

Maximum total flavonoid content at 45 DAS (0.340 mg/g Catechin eq./g FW) was observed in the treatment T_9 among all the treatments (table 5). However, the minimum total flavonoid content was observed (0.307 mg/g Catechin eq./g FW) in the treatment T_1 and treatment T_2, which was significantly lower among all the treatments.

Maximum total flavonoid content at 90 DAS (0.340 (mg/g Catechin eq./g FW) was observed in the treatment T_9 which was statistically at par with the treatment T_{10} (0.339 mg/g Catechin eq./g FW) (Table 5). However, the minimum total flavonoid content was observed (0.308 mg/g Catechin eq./g FW) in the treatment T_1, which was statistically at par with the treatment T_2 (0.309 mg/g Catechin eq./g FW) and the treatment T_3 (0.311 mg/g Catechin eq./g FW).

Carotenoids (mg/g FW)

Maximum carotenoid content at 45 DAS was observed in the treatment T_{11} (0.40 mg/g FW) among all the treatments (table 6). However, the minimum carotenoid content 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).

Maximum carotenoid content at 90 DAS was observed in the treatment T_{11} (0.52 mg/g FW) among all the treatments (table 6). However, the minimum carotenoid content was observed (0.17 mg/g FW) in the treatment T_2, which was statistically at par with the treatment T_8 (0.18 mg/g FW), the treatment T_4 (Nano-Urea *i.e*., 50%) (0.19 mg/g FW), the treatment T_3 (0.22 mg/g FW), the treatment T_5 (0.22 mg/g FW), T_9 (0.22 mg/g FW), the treatment T_1 (0.24 mg/g FW) and the treatment T_7 (0.24 mg/g FW).

Total Chlorophyll (mg/g FW)

Maximum total chlorophyll content at 45 DAS was observed in the treatment T_8 (0.84 mg/g FW) among all the treatments (table 6). However, the minimum total chlorophyll content was observed (0.05 mg/g FW) in the treatment T_2, which was significantly at par with the treatment T_3 (0.06 mg/g FW).

Maximum total chlorophyll content at 90 DAS was observed in the T_8 resulted in maximum total chlorophyll content (1.48 mg/g FW) among all the treatments (table 6). However, the minimum total chlorophyll content was observed (0.54 mg/g FW) in the treatment T_2, which was significantly lower among all the treatments.

Chlorophyll a (mg/g FW)

Maximum chlorophyll a content at 45 DAS was observed in the treatment T_8 resulted in maximum chlorophyll a content (0.58 mg/g FW) which was statistically at par with the treatment T_4 (0.57 mg/g FW) (table 6). However, the minimum chlorophyll a content was observed (0.03 mg/g FW) in the treatment T_2, which was statistically at par with the treatment T_3 (0.04 mg/g FW).

Maximum chlorophyll a content at 90 DAS was observed in the treatment T_8 resulted in maximum chlorophyll a content (0.81 mg/g FW) among all the treatments (table 6). However, the minimum chlorophyll a content was observed (0.38 mg/g FW) in the treatment T_2, which was significantly lower among all the treatments.

Chlorophyll b (mg/g FW)

Maximum chlorophyll b content at 45 DAS was observed in the treatment T_8 resulted in maximum chlorophyll b content (0.30 mg/g FW), which was statistically at par with the treatment T_4 (0.29 mg/g FW) (table 6). However, the minimum chlorophyll b content was observed (0.02 mg/g FW) in the treatment T_2, which was statistically at par with the treatment T_3 (0.03mg/g FW).

Maximum chlorophyll b content at 90 DAS was observed in the T_8 resulted in maximum chlorophyll b content (0.60 mg/g FW), which was statistically at par with the treatment T_{10} (0.59 mg/g FW) (table 6). However, the minimum chlorophyll b content was observed (0.13 mg/g FW) in the treatment T_2, which was significantly lower among all the treatments.

Chlorophyll a/b ratio

The maximum chlorophyll a/b ratio (2.23) at 45 DAS was observed in the treatment T_8, which was statistically at par with the treatment T_4 (2.08), the treatment T_{11} (2.07) and the treatment T_5 (2.01) (Table 6). However, the minimum chlorophyll a/b ratio (1.15) was observed in the treatment T_2, which was significantly lower among all the treatments.

The maximum chlorophyll a/b ratio (2.73) at 90 DAS was observed in the treatment T_8 among all the treatments (table 6). However, the minimum chlorophyll a/b ratio (1.09) was observed in the treatment T_2, which was statistically at par with the treatment T_3 (1.12).

Table 6: Effect of nano-urea and nano-zinc on quality attributes (carotenoids content, chlorophyll a, chlorophyll b, total chlorophyll and chlorophyll a/b) of potato

Treatments	Carotenoids (mg/g FW)		Chl a (mg/g FW)		Chl b (mg/g FW)		Total Chl (mg/g FW)		Chl a/b	
	45 DAS	90 DAS	45 DAS	90 DAS	45 DAS	90 DAS	45 DAS	90 DAS	45 DAS	90 DAS
T_1	0.11	0.24	0.09	0.67	0.08	0.38	0.18	0.84	1.62	1.75
T_2	0.10	0.17	0.03	0.38	0.02	0.13	0.05	0.54	1.15	1.09
T_3	0.19	0.22	0.04	0.54	0.03	0.26	0.06	0.79	1.40	1.12
T_4	0.32	0.19	0.57	0.58	0.29	0.33	0.81	0.89	2.08	2.06
T_5	0.27	0.22	0.34	0.67	0.18	0.51	0.51	1.17	2.01	1.29
T_6	0.35	0.37	0.53	0.67	0.23	0.45	0.65	1.25	1.89	1.78
T_7	0.27	0.24	0.49	0.61	0.26	0.40	0.73	0.70	1.84	1.54
T_8	0.33	0.18	0.58	0.81	0.30	0.60	0.84	1.48	2.23	2.73
T_9	0.31	0.22	0.10	0.64	0.05	0.43	0.12	1.05	1.65	1.48
T_{10}	0.35	0.30	0.20	0.68	0.10	0.59	0.31	1.25	1.83	1.26

T_{11}	0.40	0.52	0.34	0.58	0.16	0.52	0.50	1.19	2.07	1.73
T_{12}	0.20	0.32	0.19	0.64	0.09	0.40	0.08	1.02	1.91	1.59
SE (m) ±	0.016	0.025	0.004	0.004	0.003	0.006	0.004	0.006	0.089	0.052
CD @ 5% ($p \leq 0.05$)	0.048	0.073	0.013	0.011	0.010	0.017	0.013	0.019	0.262	0.154

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 economics of potato as influenced by the application of nano urea and nano zinc fertilizers are presented in table 7. The gross income (Rs. 229560 ha^{-1}), net income (Rs. 164148 ha^{-1}), and benefit-cost ratio (B:C ratio) (Rs. 2.509448 ha^{-1}) were observed maximum in the treatment T_{11}, followed by the treatment T_9 with B:C ratio (Rs. 2.3115 ha^{-1}) and the treatment T_{12} with B:C ratio (Rs 2.044605 ha^{-1}). Whereas, the minimum gross income (Rs. 102560 ha^{-1}), net income (Rs. 48980 ha^{-1}), and benefit-cost ratio (B:C ratio) (Rs. 0.770368 ha^{-1}) were observed in the treatment T_2, followed by the treatment T_1 with B:C ratio (0.837895).

Table 7: Effect of nano-urea and nano-zinc on the yield economics of potato (Kufri Badshah)

Treatments	Cost of cultivation (Rs/ha)	Gross returns (Rs/ha)	Net returns (Rs/ha)	B:C ratio
T_1	57000	104760	47760	0.837895
T_2	63580	102560	48980	0.770368
T_3	58152	125400	67248	1.156418
T_4	57576	117640	60064	1.043212
T_5	57680	116480	58800	1.019417
T_6	58832	141960	83128	1.412973
T_7	58256	158960	100704	1.728646
T_8	64260	137040	72780	1.132586
T_9	64732	214360	149628	2.3115
T_{10}	64156	187560	123404	1.923499
T_{11}	65412	229560	164148	2.509448
T_{12}	64836	197400	132564	2.044605

Discussion

Nanofertilizer are a type of agricultural input that utilizes nanotechnology to enhance the efficiency and effectiveness of fertilizers. They improve crop growth, yield, and quality parameters with increased nutrient use efficiency, reduce wastage of fertilizers, and cost of cultivation (Singh, 2017) [123]. Nano-fertilizers provide more surface area for different metabolic reactions in the plant, which increases the rate of photosynthesis and produces more dry matter and yield of the crop (Qureshi *et al.* 2018) [98]. Besides this, the controlled release of nutrients contributes to preventing eutrophication and pollution of water resources also (Kumar *et al.* 2020) [61]. As conventional fertilizers offer nutrients in chemical forms that are not often fully accessible to plants (Liu and Lal, 2015) [73]. Therefore, the replacement of conventional fertilizer with nano-fertilizer is beneficial as upon application, it releases nutrients into the soil steadily and in a controlled way, thus preventing water pollution (Manjunatha *et al.* 2016; Kumar *et al.* 2021) [78, 60].

In the present study, the effect of pre-soaking of nano-urea and nano-zinc on the growth, quality and yield of potato were evaluated, further, it was found that the nano-fertilizer treatments significantly improved the growth, yield and quality of potatoes compared with the control treatment. The results of the present findings are discussed in subsequent sections and are supported by the findings of some research studies.

Growth parameters

The emergence of plants from seed tubers generally depends on the physiological stage and sprouts present on the tuber. However, a good and uniform emergence is considered beneficial and is required which ultimately leads to a higher crop yield (Finch-Savage *et al.* 2016) [38]. In the present work, minimum days to 50% emergence were observed in the treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 100%). Slow and continuous release of fertilizers, produced stronger seedlings (Badran and Savin, 2018) [17]. Sahu *et al.* (2016) [107] and Hosseini *et al.* (2017) [45] also observed a similar effect of nitrogen treatments on the plant emergence of potato. Similar results had also been recorded by some other workers in maize (Harris *et al.* 1999) [43] where seed priming was effective. These findings are in line with Pandey *et al.* (2018) [95] in potato.

The plant height may increase due to enhanced vegetative growth with a higher nitrogen supply to the plant which in turn stimulates the assimilation of carbohydrates and proteins that enhances cell division and formulation of more tissues (Ahirwar *et al.* 2021) [3]. In the present work, the plant height was found maximum in the treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 100%). It could be due to the fact that nano-encapsulated nitrogen effectively releases nutrients, regulating plant development and enhancing target activity (Midde *et al.* 2021) [83]. Similar results had also been recorded by some other workers in potato (Dutta, 2022) [32], (Samui *et al.* 2022) [109], (Yuvaraj and Subramanian, 2014) [139] and (Bhargavi *et al.* 2023) [23] in rice, (Sharma *et al.* 2022) [116] in pearl millet, and (Ajithkumar *et al.* 2021) [4] in maize.

The number of leaves per plant is an important characteristic that can impact the plant's overall growth and photosynthetic capacity. A sufficient nitrogen supply can promote leaf growth and increase the maximum number of leaves per plant (Cechin and Fatima, 2004) [25]. In the present study, the maximum number of leaves per plant was observed in the treatment T_{11} (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 100% + Nano Zinc *i.e.*, 100%). The reason for the increase in the number of leaves in plants can be due to the direct role of the nano-hydroxyapatite fertilizer in increasing cell division and expansion (Abd Alqader *et al.* 2020) [2]. Zinc also promotes the uptake of macro-nutrients *viz.* nitrogen, phosphorus, and potassium, from soil which helps in better growth and development (Sati *et al.* 2017) [112]. Similar results had also been recorded by some other workers (Sathyan, 2022) [111] in pea, (Babaeian *et al.* 2011) [16] and (Kaur *et al.* 2018) [53] in potato, (Mondal *et al.* 2011) [86] in tomato, (Pandey *et al.* 2018) [95] in potato.

The leaf area of potato is an important parameter that influences the plant's ability to capture sunlight and carry out photosynthesis, which is crucial for growth and tuber production. Increased leaf area not only depends on genetic factors but also on leaf nitrogen (Grindlay, 1997) [41]. In the present study, the leaf area was found maximum in the treatment T_6 (Nano Urea *i.e.*, 100% + Nano Zinc *i.e.*, 100%). The nano-urea fertilizer is slowly released into the soil and increases leaf area and photosynthetic activity in plants (Kottegoda *et al.* 2011) [54]. The probable reason might be due to the favourable effect of zinc on the proliferation of roots and thereby increasing the uptake of other plant nutrients from the soil, supplying it to the aerial parts of the plant and ultimately enhancing the vegetative growth of plants (Poornima *et al.* 2019) [96]. Similar results had also been recorded by other workers (Mahmoodi *et al.* 2018) [74] in Borage with the treatment of nano urea, in carrot (Elizabath *et al.* 2017) [35] with the treatment of nano zinc oxide and nano iron oxide.

Yield parameters

The fresh weight of tubers is most important in potato production, as it directly determines the marketable yield and economic value of the crop. Larger tubers with higher fresh weight are generally desired, as they contribute to higher-quality products and better marketability (Islam *et al.* 2020) [47]. Dry weight is the result of photosynthetic activity, further, the increased photosynthetic activity will lead to larger plant organs, which will result in the increased dry weight of plants (Novoa *et al.* 1981) [92]. In the present study, the fresh weight of tubers and dry weight of tubers was observed maximum in the treatment T_{11} (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 100% + Nano Zinc *i.e.*, 100%). The adequate amount of nitrogen at tuberization leads to an increase in tuber weight per plant because of the strong sink formation which increases the tuber bulking period ultimately more the weight of the tuber (Pandey *et al.* 2018) [95]. Banjare *et al.* (2014) [18] observed an increase in the fresh and dry weight of tuber per plant with increased nitrogen fertility. Similar observations had also been recorded in maize (Kumar *et al.* 2015) [58], (Kumar and Bohra, 2014) [58], (Manikandan *et al.* 2016) [76], (Dewdar *et al.* 2018) [30] in sugar beet, (Al-Juthery *et al.* 2018) [6] in potato.

The number of tubers per plant is significant as it directly influences the overall yield. The increase in tuber yield might be attributed to an increase in the number of leaves per plant that promote the process of photosynthesis and faster translocation of photosynthates to potato tubers (Singh *et al.* 2018) [122]. Plants supplied with micronutrients along with macronutrients during stolonization, tuberization, and bulking, increased tuber yield and this increase in tuber yield might be due to the positive effect on the mean weight of the tuber as well as increased dry matter percentage (Rahman *et al.* 2018) [99]. In the present study, the maximum number of tubers per plant, tuber yield per plot and tuber yield per hectare was observed in treatment T_{11} (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 100% + Nano Zinc *i.e.*, 100%). Yield contributing traits *viz.* fresh weight of tubers, dry weight of tubers, and number of tubers per plant might have led to the increased tuber yield per plot and tuber yield per hectare (Jatav *et al.* 2017) [49]. This might be due to the fact that nano-nitrogen and nano-zinc increased the average weight of individual tubers, more marketable grade tuber production, thereby increasing the total tuber yield due to increased translocation of starch from source to sink (Neogi and Das, 2022) [91]. Similar findings were reported by (Sharma *et al.* 1988) [117], (Uppal and Singh, 1989) [131], (Das and Chakraborty, 2018) [26], (Manikanta *et al.* 2023) [77] and (Lenka and Das, 2019) [68] in potato, and (Merghany *et al.* 2019) [82] in cucumber. Whereas, in control treatment T_1 the total tuber yield reduced drastically as potato is a heavy feeder crop.

Quality parameters

Starch yield is a characteristic quality of potato tubers in determining nutritional and industrial value (Leonel *et al.* 2017) [70]. Potato tubers are usually characterized by high dry matter content and starch as their main constituent (Wein and Gough, 1999) [137]. N fertilizer treatment could increase crop yield and change the content and component of starch (Duan *et al.* 2020) [31]. In the present study, the maximum starch yield was observed in the treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 100%). This leads to an increase in the speed of growth and increases the quality of protein and starch by activating and synthesizing the process of photosynthesis (Al-Juthery *et al.* 2019) [6]. Similar results had also been recorded in potato (Al- Juthery *et al.* 2019) [6] with the combination of N and K nano-fertilizers.

The sugar content in potato tubers is significant as it directly affects their taste, flavour, and culinary uses. Excessive nitrogen application can lead to increased levels of reducing sugars, such as glucose and fructose, which can cause darkening during cooking and affect the flavour of the potato (Morales *et al.* 2008) [87]. However, controlled application of fertilizers can help to maintain the desired sugar content of potato tubers (Kumar *et al.* 2004) [55]. In the present study, the sugar content including reducing and non-reducing sugars were observed maximum in treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 100%). It has been reported that the effect of N fertilizers on an increase in sugar content may help the absorption of other mineral nutrients, improving fruit quality (Sharma *et al.* 2014) [118]. In a study on potatoes, the maximum sugar content was observed with the application of NPK + nano N and other micronutrients (Manikanta *et al.* 2023) [77]. Similar observations also had been recorded in pomegranate, with the foliar application of nano nitrogen and urea fertilizer (Davarpanah *et al.* 2017) [27], in mango with the application of urea solution at 4% (Sarker and Rahim, 2013) [110].

Phenolic compounds are natural plant chemicals that have been found to have antioxidant properties and other health benefits (Huda-Faujan *et al.* 2009) [46]. Potatoes are a good source of phenolic compounds, including chlorogenic acid, catechins, and flavonoids (Leo *et al.* 2008) [69]. The phenolics are present in both skin and potato flesh, the concentration being higher in the skin (Ezekiel *et al.* 2013) [36]. In the present study, phenolic content was observed maximum in the treatment T_{10} (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 50%). The availability of key macronutrients during the growth of the plant has considerable potential to affect phenolic accumulation. There were reports stating that phenolic content and antioxidant activity can be increased through soaking and germination processes (Islam and Becerra, 2012) [48]. In a study, it was reported that the fresh pulp and skin of potatoes contain 30 to 900 mg/kg and 1000 to 4000 mg/kg, respectively of chlorogenic acid and minor amounts of other phenolic acids between 0 and 30 mg/kg (Lewis *et al.* 1998) [71]. Similar observations were observed in rice, the total phenolic content increased with the application of NPK and nano-fertilizers (NPK) (Benzon *et al.* 2015) [22].

Chlorophyll pigment plays a major role in the process of photosynthesis, leaf colour, and overall plant growth (Lichtenthaler and Rinderle, 1988) [72]. Nitrogen and potassium are considered essential minerals in photosynthesis and the growth of meristematic tissues (Merghany *et al.* 2019) [82]. Zinc plays an important role in chlorophyll synthesis in plants, whereas, deficiency can result in the reduction of chlorophyll content. In the present study, chlorophyll content was observed maximum in the treatment T_8 (NPK *i.e.*, 100% recommended dose + Nano Zinc *i.e.*, 100%). Several studies reported that the utilization of micronutrients increases the performance and quality of potato tubers (Singh and Singh, 2019) [124]. In an experiment, Abbasifar *et al.* (2019) [1] studied that the highest chlorophyll content at 4000 ppm Zn and 2000 ppm Cu nanoparticles were found effective in basil plants. Similar results had also been reported in wheat, where the chlorophyll content increased due to the application of nano Zn and biofertilizer (Babaei *et al.* 2017) [15]. Similar results were found in wheat with the application of nano zinc oxide (Ramesh *et al.* 2014) [101].

The TSS increases due to increased carbohydrate production during the process of photosynthesis (Rahman *et al.* 2021) [99]. An increase in TSS after N application can be contributed to the important roles of N in chloroplast structure, CO_2 assimilation, and activation of enzymes involved in photosynthesis, which leads to an increase in photosynthesis and carbohydrate accumulation also consequently increase in TSS (Kumar *et al.* 2014) [56]. In the present study, the TSS was observed maximum in the treatment T_{10} (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 50%). Similar results were found in mango treated with 5% of urea (Sarker and Rahim, 2013) [110], and in potato with the treatment of nano nitrogen along with NPK (Manikanta *et al.* 2023) [77].

Ascorbic acid, also known as vitamin C, is an important compound found in potato tubers. 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) [66] like amino acids, nucleic acids, pyrimidines, flavines, purines, nucleoproteins, enzymes, alkaloids, *etc.* (Kanuganti *et al.* 2022) [51]. In the present study, ascorbic acid was observed maximum in the treatment T_9 (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 100%). The increased accumulation of nitrogen and other macro and micronutrient led to an increase in vitamin C content. Similar results were found in potato treated with nano nitrogen along with other micronutrients (WA Al- juthery *et al.* 2020) [135], and in guava with the application of NPK, where it was found that only N increased the TSS content (Arora and Singh, 1970) [11].

Proteins are the amino acids that play a major role in plant structure and also in defense (constituent the cell membrane) (Ryan, 2000) [105] further, potatoes are also a good source of amino acids (lysine and tryptophan) (Mu *et al.* 2009) [88]. In the present study, protein content was observed maximum in the treatment T_{10} (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 50%). Nitrogen is essential for the growth of plants as it is a constituent of all proteins and hence of all protoplasm (Arora and Singh, 1970) [11]. The higher level of nitrogen supply increases the extra protein produced and helps the plant to grow larger (Lawlor *et al.* 1989) [67]. Similar results had also been recorded in wheat (Astaneh *et al.* 2021) [13], where nano-chelated nitrogen and urea fertilizers were used. In another study on maize, similar results were recorded with the application of zeolite-based urea (Manikandan and Subramanian, 2016) [76]. In another study on pearl millet, similar results were recorded with the application of nano nitrogen through the foliar application (Sharma *et al.* 2022) [116].

Flavonoids are natural antioxidant present in plants (Ghasemzadeh and Ghasemzadeh, 2011) [40]. Flavonols such as rutin are present in potato (Ezekiel *et al.* 2013) [36]. 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%). Flavonoid biosynthesis often requires various nutrients, such as NPK and other trace elements (Saleem *et al.* 2021) [108]. Similar results have been recorded in dayak onion (medicinal plant), where nitrogen and potassium fertilizers resulted in the highest flavonoid content (Marlin *et al.* 2022) [79]. In a study on potato, flavonoid content increased with the application of nitrogen fertilizers (Jin *et al.* 2014) [50]. In another study on wheat, similar results were recorded with the application of nano-chelated nitrogen and urea fertilizers (Astaneh *et al.* 2018) [13].

Potatoes are a good source of carotenoids, which are lipophilic compounds synthesized in plastids from isoprenoids (Dellapenna and Pogson, 2006) [29]. Lutein, zeaxanthin (results in yellow and orange colour flesh of tuber), violaxanthin and neoxanthin are the major carotenoids present in potatoes along with the β-carotene in trace amounts (Hamouz *et al.* 2016) [42]. In the present study, carotenoid content was observed maximum in the treatment T_{11} (NPK *i.e.*, 100% recommended dose + Nano-Urea *i.e.*, 100% + Nano-Zinc *i.e.*, 100%). In a study on lentil, similar results were obtained with the application of ZnO NPs (Siddiqui *et al.* 2018) [129]. In another study on maize, similar results were observed with the application of ZnO NPs through seed priming and coating treatments (Tondey *et al.* 2021) [129]. In another study, the nano-chelated nitrogen fertilizers along with urea increased the carotenoid content in olive oil (Vishekaii *et al.* 2021) [134].

Benefit-cost ratio

Nano-fertilizers minimize the dosage of fertilizers and maximize profit due to their efficient delivery system (Singh, 2017) [123]. In the present study, the highest B:C ratio was observed in the treatment T_{11} (NPK *i.e.*, 100% recommended dose + Nano Urea *i.e.*, 100% + Nano Zinc *i.e.*, 100%). The increase in B:C ratio and other crop economic parameters might be due to an increase in yield which fetched more prices in the market. Similar results were obtained in potato, with the application of NPK along with the foliar application of both nano nitrogen and zinc (Neogi and Das, 2022) [91], in sweet corn, with the application of NPK along with the foliar application of nano zinc (Rajesh *et al.* 2021) [100], and in tomato, with the application of NPK along with the foliar application of nano N, nano Zn, and other micronutrients

(Mishra *et al.* 2020) [84].

Conclusion and future prospects

From the present investigation, it can be concluded that from yield and economic point of view, the application of 100% recommended dose of NPK along with the pre-soaking application of nano-urea (100%) and nano-zinc (100%) resulted in the increase in growth, quality and productivity of the crop. Our results suggests that the combination of nano-fertilizers along with chemical fertilizers may be utilized for vegetable production in a sustainable agricultural system. It is also concluded that the use of nano-fertilizers through pre-soaking minimizes the cost of cultivation with nutrient use efficiency. As potato is a heavy feeder crop and hence need heavy doses of fertilizers for its growth and yield. It also demands a high level of soil nutrients due to the relatively poorly developed and shallow root systems in relation to yield. Increased use of nano-fertilizers will decrease our dependency on chemical fertilizers, thereby leading to the sustainable and eco-friendly cultivation of potato. Additionally, conducting field trials under specific local conditions is recommended to assess the response of potato crops to these nano-fertilizers and determine their optimal application strategies for maximizing yield.

First and foremost, developing countries like India and several other countries have extensive agriculture practices, which are being mitigated in the rural background. Obtaining the support of farmers (who are the real stakeholders) in such intriguing circumstances and conservative familial associations are challenges that have perhaps eluded most of the scientific distinctions. Therefore, it is important to make grassroots efforts to educate farmers and the farming community about the benefits of fertilizer delivery using nanocarriers.

1. Studies must be focused on the safety, bioavailability, and toxicity aspects of different Nano fertilizers used for different crops.
2. Synthesis and application of nano fertilizers for phosphorus and potassium as like nitrogen to improve nutrient use efficiency of major nutrients.
3. Bio-synthesized or green synthesized nano-biofertilizers and nano fertilizers should be explored to further increase yields in sustainable agriculture.
4. It's important to note that while nano-fertilizers hold great promise, there are also concerns regarding their long-term effects on human health, ecosystem interactions, and their commercial viability. Extensive research, regulatory frameworks, and risk assessments will be necessary to ensure their safe and sustainable implementation in agriculture.

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