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Growth response of cabbage (*Brassica oleracea*) to TiO_2 nanoparticles exposure in Inceptisol of north-western mid-hills of Himachal Pradesh

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ABSTRACT

The experiment was conducted during 2020–21 and 2021–22 at Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh for assessing the effects of TiO_2 (Titanium dioxide) nanoparticles on cabbage (*Brassica oleracea* L. var. *capitata*) growth, yield and economics under Agro-Climatic Zone-II of Himachal Pradesh. A field experiment was laid out in a randomized block dsesign (RBD) with three replications having 13 treatments , comprised of seed and foliar application of TiO_2 nanoparticles (size <25 nm) combined with different nutrient sources. Results revealed that by the application of 100% RDN through integration of chemical fertilizers and vermicompost; the maximum plant height, spread and yield were recorded under seed treatment of TiO_2 nanoparticles @1000 ppm. The findings have also demonstrated that the least number of days needed to attain 50% head maturity, total N content and N uptake was achieved with seed treatment of TiO_2 nanoparticles @1000 ppm. Whereas, total P, K and Fe content; P and K uptake was recorded under foliar spray of TiO_2 nanoparticles @1000 ppm. Among all the treatments, 1000 ppm concentration of TiO_2 nanoparticles concluded with higher yield attributes and maximum benefit-cost ratio (3.76). When it comes to soil characteristics, the integration of chemical fertilizers and vermicompost resulted in improved physico-chemical and microbiological properties which, in general, may be profitable and sustainable for cabbage cultivation in Inceptisol of north-western mid-hills of Himachal Pradesh.

Keywords: Cabbage, Growth, Nanoparticle, Titanium dioxide, Yield

Cabbage (*Brassica oleracea* L. var. *capitata*) often known as cabbage, is a vegetable crop used for both fresh and processed form in various countries. Cabbage is an excellent provider of potassium, calcium, and vitamins B and C (Hasan and Solaiman 2012). After China, India is the world's second-largest producer of cabbage. In India, Uttar Pradesh, Bihar, Orissa, West Bengal, Assam, Maharashtra, Karnataka, Haryana, Rajasthan, Gujarat, Uttarakhand, Himachal Pradesh, and the Nilgiri Hills of Tamil Nadu are the states that cultivate cabbage. In the context of global and national production, cabbage is a vital crop for Himachal Pradesh.

According to Bansal *et al.* (2014), using nanoparticles offers a great deal of potential to improve nutrient utilization efficiency. The unique or radically altered characteristics of nanoparticles produced by modifying individual atoms and molecules aid in triggering the plant system for effective operation, particularly for the absorption of nutrients and water. The use of nanoparticles has huge potential to enhance nutrient use efficiency (Biswal *et al.* 2012). The nanoparticles in crop production have been designed for slow release of active ingredient. TiO_2 nanoparticles have been studied for influence on seed germination and other plant growth parameters. It was recorded that seeds treated with TiO_2 nanoparticles increased germination rates, enhanced root length improved seedling growth of cabbage (Andersen *et al.* 2016). Similar study on the effect of TiO_2 nanoparticles on mustard crop was also conducted by Rathore *et al.* (2019). They recorded high yield attributes, oil content, NPK uptake and B:C ratio under seed treatment with titanium oxide @1000 ppm. Another study by Mahmoodzadeh *et al.* (2013) also recorded beneficial effects of TiO_2 nanoparticles by using concentration 1200 and 1500 ppm in terms of plant growth parameters of canola (*Brassica napus*). The studies of TiO_2 nanoparticles on cabbage is limited, however application of TiO_2 nanoparticles was carried out in various crops belongs to Brassicaceae. Hence, in order to evaluate the substantial impact of TiO_2 nanoparticles on growth and yield parameters of cabbage in Himachal Pradesh, India, the current study was designed.

MATERIALS AND METHODS

Experimental site: The experiment was conducted during 2020–21 and 2021–22 at Dr. Yashwant Singh Parmar

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University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh The average annual rainfall of the area is about 1115 mm and about 75% of it is received during the monsoon period. The average minimum and maximum temperature ranges from 4–36°C. May-June is the hottest and December-January is the coldest months.

Layout and the experimental design: The experiment was laid out in a randomized block design (RBD) replicated thrice. Thirteen treatments were implemented, including seed treatment as well as foliar application of TiO_2 nanoparticles @500, 1000 and 1500 ppm with 100% RDN through chemical fertilizers i.e. Urea, Single Super Phosphate and Muriate of Potash; and 100% RDN through integration of chemical fertilizers and vermicompost in 50:50 ratio on nitrogen equivalence basis [100% RDN (chemical fertilizers) (T_1); 500 ppm TiO_2 as seed treatment + 100% RDN (chemical fertilizers) (T_2); 500 ppm TiO_2 as seed treatment + 100% RDN (integrated) (T_3); 500 ppm TiO_2 as foliar application + 100% RDN (chemical fertilizers) (T_4); 500 ppm TiO_2 as foliar application + 100% RDN (integrated) (T_5); 1000 ppm TiO_2 as seed treatment + 100% RDN (chemical fertilizers) (T_6); 1000 ppm TiO_2 as seed treatment + 100% RDN (integrated) (T_7); 1000 ppm TiO_2 as foliar application + 100% RDN (chemical fertilizers) (T_8); 1000 ppm TiO_2 as foliar application + 100% RDN (integrated) (T_9); 1500 ppm TiO_2 as seed treatment + 100% RDN (chemical fertilizers) (T_{10}); 1500 ppm TiO_2 as seed treatment + 100% RDN (integrated) (T_{11}); 1500 ppm TiO_2 as foliar application + 100% RDN (chemical fertilizers); 1500 ppm TiO_2 as foliar application + 100% RDN (integrated) (T_{13})]. For cabbage, the recommended dose of nutrients (RDN) is 20 t/ha FYM + 125:110:50 kg/ha NPK (Anonymous 2014). TiO_2 also known as anatase, is white in colour, poorly water soluble, and has a 99.7% purity with particles smaller than 25 nm is used in experiment. The initial soil *p*H was 7.2 and electrical conductivity was 0.4 dS/m, respectively. The soil was medium in available N (351.4 kg/ha), high in phosphorus (74.2 kg/ha) and medium in potassium (241.7 kg/ha). All treatments adhered to the recommended practices for managing fertilizer, controlling weeds, providing irrigation, and protecting plants. Plant protection methods were used to manage diseases and insect pests, as recommended by standard protocols.

Observations: All of the plant growth attributes were recorded at maturity of the crop by selecting five random plants from each plot. Digestion of the samples was carried out by method laid down by Piper (1966) for P, K, Zn, Cu, Fe and Mn. The total nitrogen was analyzed by Micro-Kjeldhal's method (AOAC 1980), total phosphorus was estimated by Vanado-molybdate phosphoric yellow colour method (Jackson 1973). Total potassium was estimated in flame photometer (Jackson 1967). The estimation of Zn, Cu, Fe and Mn was carried out on Atomic Absorption Spectrophotometer (Vogel 1978). Nutrient uptake by plant was calculated using the following formula:

$$\text{Nutrient uptake (kg/ha)} = \frac{\text{Nutrient content (\%)} \times \text{Dry matter yield (kg/ha)}}{100}$$

The benefit cost ratio was computed using the given formula:

$$\text{Benefit cost ratio} = \frac{\text{Gross return (₹)}}{\text{Total cost (₹)}}$$

Soil *p*H and EC were measured in a 1:2 soil:water suspension (Jackson 1973). Soil organic carbon was estimated by Walkley and Black method (Walkley and Black 1934). The available nitrogen by alkaline potassium permanganate method (Subbiah and Asija 1956), phosphorus by 0.5 M $NaHCO_3$, *p*H 8.5 method (Olsen *et al.* 1954), available potassium by ammonium acetate method (Merwin and Peech 1951) and exchangeable Ca and Mg (Sarma *et al.* 1987). Available Sulphate sulphur was estimated by using 0.15% $CaCl_2$ extractant and turbidimetric determination (Chesnin and Yien 1950). Soil micronutrients were estimated by using DTPA extractant method (Lindsay and Norvell 1978) by using atomic absorption spectrophotometer. Viable microbial count was determined by spread plate technique (Subba Rao 1999). Microbial biomass-C by soil fumigation extraction method (Vance *et al.* 1987) and Soil enzymes by using standard methods (Casida *et al.* 1964, Hoffman 1965, Tabatabai and Bremner 1969).

Statistical analysis: The data generated from these experiments were appropriately computed, tabulated and analyzed by applying Randomized Block Design (Panse and Sukhatme 2000) and were subjected to statistically analysis using R-Studio and Microsoft Excel 2016. Critical difference at 5% level was used for testing the significant difference among the treatment means.

RESULTS AND DISCUSSION

Plant parameters: Use of nanoparticles through seed treatment and foliar application significantly influenced various plant parameters. TiO_2 nanoparticles @1000 ppm was found to be superior over other concentrations. Seed treatment with 1000 ppm TiO_2 nanoparticles had resulted in higher plant height (28.3 cm), plant spread (59.1 cm) and minimum days taken to 50% head maturity (86.5). Similar trend was found with respect to yield with maximum yield (28.7 t/ha) was recorded under seed treatment of TiO_2 nanoparticles @1000 ppm along with integrated nutrient sources. Whereas, the maximum number of non-wrapper leaves (16.4) and stalk length (5.5 cm) was recorded under treatment comprised of 1000 ppm TiO_2 as foliar application + 100% RDN through chemical fertilizers. However, polar diameter, equatorial diameter and head shape index remained non-significant (Table 1).

This improvement may have been caused by the formation of new pores on the seed coat during penetration, which may have aided in the movement of nutrients inside the seed during germination and accelerated growth rate. Furthermore, it is possible that TiO_2 nanoparticles influences germination process by increasing the plant's intake of oxygen and water, which in turn accelerated its growth parameters. Rathore *et al.* (2019) reported similar results, observing an increase in mustard plant development

Table 1 Effect of nutrient sources and TiO_2 nanoparticles on plant growth, nutrient content and uptake in cabbage

Treatment	Plant height (cm)	No. of non-wrapper leaves	Plant spread (cm)	Stalk length (cm)	Days to 50% head maturity	Polar diameter (cm)	Equatorial diameter (cm)	Head shape index	Yield (t/ha)	Total N (%)	Total P (%)	Total K (%)	Total Fe (ppm)	Total Mn (ppm)	Total Cu (ppm)	Total Zn (ppm)	N uptake (kg/ha)	P uptake (kg/ha)	K uptake (kg/ha)	B:C ratio
T_1	23.2 ± 0.03	14.8 ± 0.76	46.1 ± 0.10	4.9 ± 0.25	111.5 ± 0.31	10.8 ± 0.26	11.6 ± 0.32	0.93 ± 0.01	14.5 ± 0.40	2.23 ± 0.04	0.29 ± 0.01	1.15 ± 0.02	169.8 ± 2.04	113.5 ± 0.33	37.5 ± 4.33	34.2 ± 0.45	62.4 ± 1.88	7.7 ± 0.02	31.0 ± 0.09	2.05
T_2	26.0 ± 0.83	15.0 ± 0.59	55.0 ± 0.11	5.0 ± 0.11	95.4 ± 0.19	10.7 ± 0.10	12.3 ± 0.54	0.88 ± 0.05	26.1 ± 0.09	2.50 ± 0.02	0.34 ± 0.01	1.35 ± 0.02	177.0 ± 1.45	114.1 ± 0.28	37.7 ± 4.40	34.4 ± 0.40	125.4 ± 0.87	16.7 ± 0.47	66.8 ± 1.86	3.67
T_3	27.1 ± 0.97	15.2 ± 1.28	57.3 ± 0.11	5.1 ± 0.25	89.3 ± 0.36	11.3 ± 0.01	13.2 ± 0.38	0.86 ± 0.02	28.0 ± 0.39	2.61 ± 0.02	0.39 ± 0.01	1.57 ± 0.04	198.9 ± 1.70	114.1 ± 0.55	37.7 ± 4.18	34.4 ± 0.30	140.7 ± 3.08	20.7 ± 0.88	82.6 ± 3.54	2.88
T_4	24.7 ± 0.57	13.6 ± 0.28	52.4 ± 0.11	4.5 ± 0.05	100.7 ± 0.47	11.3 ± 0.01	12.9 ± 0.63	0.88 ± 0.04	21.7 ± 0.40	2.35 ± 0.01	0.53 ± 0.01	2.13 ± 0.05	249.2 ± 0.72	114.2 ± 0.14	37.7 ± 4.32	34.4 ± 0.34	98.1 ± 2.03	21.3 ± 1.43	86.5 ± 6.49	2.45
T_5	24.9 ± 0.77	15.6 ± 0.25	52.8 ± 0.11	5.2 ± 0.05	99.2 ± 0.07	11.4 ± 0.04	14.3 ± 0.40	0.80 ± 0.02	22.5 ± 0.24	2.37 ± 0.01	0.60 ± 0.01	2.41 ± 0.02	268.1 ± 1.90	115.3 ± 0.44	38.1 ± 4.28	39.7 ± 5.31	102.5 ± 1.24	25.7 ± 0.69	103.0 ± 2.49	1.96
T_6	26.2 ± 0.03	16.3 ± 0.03	55.3 ± 0.11	5.4 ± 0.01	94.4 ± 0.47	11.1 ± 0.39	13.9 ± 0.97	0.80 ± 0.04	26.8 ± 0.32	2.51 ± 0.00	0.35 ± 0.01	1.40 ± 0.05	187.9 ± 1.85	113.4 ± 0.42	37.5 ± 4.28	38.0 ± 4.72	129.1 ± 1.76	17.5 ± 0.14	71.0 ± 1.19	3.76
T_7	28.3 ± 0.37	16.3 ± 0.88	59.1 ± 0.58	5.4 ± 0.17	86.5 ± 0.29	10.9 ± 0.24	14.2 ± 0.98	0.78 ± 0.08	28.7 ± 0.39	2.72 ± 0.02	0.44 ± 0.01	1.78 ± 0.04	212.0 ± 3.20	112.3 ± 0.29	37.1 ± 4.19	33.9 ± 0.31	149.9 ± 3.40	24.1 ± 0.64	97.3 ± 3.29	2.95
T_8	25.0 ± 0.90	16.4 ± 0.03	48.0 ± 0.10	5.5 ± 0.01	98.4 ± 0.51	11.1 ± 0.23	14.6 ± 1.35	0.78 ± 0.09	23.2 ± 0.55	2.40 ± 0.02	0.57 ± 0.01	2.26 ± 0.02	252.8 ± 1.64	114.0 ± 0.75	37.6 ± 4.13	34.4 ± 0.17	106.9 ± 3.38	24.6 ± 0.91	98.6 ± 3.66	2.19
T_9	25.2 ± 0.07	14.6 ± 0.85	48.3 ± 0.10	4.9 ± 0.16	98.1 ± 0.33	10.9 ± 0.25	15.2 ± 1.20	0.72 ± 0.05	24.6 ± 0.18	2.48 ± 0.01	0.62 ± 0.00	2.50 ± 0.05	271.2 ± 6.29	114.2 ± 0.46	37.7 ± 4.32	34.4 ± 0.45	117.3 ± 1.02	29.1 ± 0.37	116.9 ± 3.38	1.86
T_{10}	25.6 ± 0.50	15.2 ± 0.36	49.1 ± 0.11	5.1 ± 0.07	96.8 ± 0.25	11.6 ± 0.14	15.1 ± 0.99	0.77 ± 0.06	25.2 ± 0.28	2.49 ± 0.02	0.34 ± 0.01	1.34 ± 0.02	173.2 ± 3.08	112.5 ± 0.36	37.2 ± 4.19	33.9 ± 0.27	120.6 ± 2.22	16.1 ± 0.64	64.4 ± 2.56	3.54
T_{11}	26.6 ± 0.47	15.9 ± 0.45	51.0 ± 0.10	5.3 ± 0.09	91.2 ± 0.07	11.1 ± 0.60	15.1 ± 0.98	0.74 ± 0.05	27.3 ± 0.44	2.60 ± 0.01	0.36 ± 0.01	1.43 ± 0.03	192.8 ± 0.98	113.1 ± 0.62	37.4 ± 4.48	34.9 ± 5.30	136.5 ± 2.56	18.7 ± 0.75	74.9 ± 3.01	2.80
T_{12}	24.1 ± 0.93	15.1 ± 0.68	49.2 ± 0.12	5.0 ± 0.13	105.8 ± 0.66	11.4 ± 0.13	13.5 ± 1.22	0.86 ± 0.08	19.2 ± 0.28	2.30 ± 0.03	0.48 ± 0.01	1.93 ± 0.03	231.8 ± 1.78	112.1 ± 0.26	37.1 ± 4.26	33.8 ± 0.42	85.1 ± 2.21	17.7 ± 0.06	70.9 ± 0.23	1.56
T_{13}	24.4 ± 0.23	14.9 ± 1.08	46.7 ± 0.10	5.0 ± 0.21	101.4 ± 0.30	11.3 ± 0.52	14.2 ± 0.82	0.80 ± 0.06	20.6 ± 0.49	2.31 ± 0.00	0.58 ± 0.00	2.32 ± 0.13	266.3 ± 1.98	113.6 ± 1.61	41.6 ± 1.23	36.2 ± 1.35	91.1 ± 2.05	22.7 ± 0.51	90.4 ± 2.88	1.38
Mean	25.46	15.31	51.56	5.10	97.60	11.14	13.86	0.82	23.72	2.45	0.45	1.81	219.32	113.56	37.85	35.12	112.73	20.21	81.09	
LSD ($p \leq 0.05$)	0.57	1.17	0.49	0.39	0.98	NS	NS	NS	0.83	0.05	0.02	0.13	7.22	1.76	NS	NS	4.82	1.84	8.24	
SEM ±	0.19	0.40	0.17	0.13	0.33	0.27	0.81	0.05	0.28	0.02	0.01	0.05	2.46	0.60	0.99	2.53	1.64	0.63	2.81	

Treatment details are given under Materials and Methods.

characteristics upon administration of TiO_2 nanoparticles @1000 ppm concentration by seed treatment.

The higher total nitrogen and nitrogen uptake was also noticed under 1000 ppm TiO_2 nanoparticles as seed treatment (Table 1). However, higher phosphorus and potassium content and their uptake were recorded in foliar application of TiO_2 nanoparticles @1000 ppm with integration of nutrient sources. The maximum total Fe and Mn (271.2 and 115.3 ppm) content was noticed under treatment T_9 and T_5, respectively. But total Cu and Zn content remained statistically non-significant. According to Giraldo *et al.* (2014), nanoparticles have unique physico-chemical properties and the potential to boost the plant metabolism. They also reported ability of nanoparticles to enter into plants cells and leaves which accelerate growth and development. Similarly, application of TiO_2 nanoparticles significantly increased nutritional content (N, P and K content) in mustard, coriander and wheat as recorded by Rathore *et al.* (2019), Hu *et al.* (2020) and Mustafa *et al.* (2021).

The benefit-cost ratio increased noticeably (3.76), when TiO_2 nanoparticles @1000 ppm was applied as seed treatment (T_6). Benefit-cost ratios were less than 2.5 for foliar application treatments and more than 2.5 for seed treatments (Table 1). According to Govorov and Carmeli (2007), metal nanoparticles can increase the chemical energy generation efficiency in WUE and photosynthetic systems.

Soil parameters: The impact of different concentrations of TiO_2 nanoparticles with integration of nutrient sources were evident on soil parameters. Soil *p*H, EC, exchangeable Ca and Mg remained non-significant. But significantly higher organic carbon (0.57%) was recorded under the treatment T_{13}. The maximum NPK (391.3, 89.3 and 250.3 kg/ha) was recorded under T_{12}, T_{10} and T_1, respectively. The highest available sulphate sulphur (59.75 kg/ha) was also recorded under T_{12} (Table 2).

Similar findings were also reported by Singh (2019), who, recorded the maximum nitrogen, phosphorus and potassium content by following the recommended package of practices. Applying the right and appropriate quantity of fertilizers on recommendation basis, provide the soil with an appropriate supply of readily available nutrients, is the reason for the greater macro nutrient under treatment comprised of 100% RDN through chemical fertilizers. The findings are in consistent with those of Singh and Varu (2013) who also noted a rise in macronutrient availability after fertilizer application.

Among the micronutrients, the maximum DTPA extractable Fe (7.28 ppm) was noted under T_{13}, however the maximum DTPA extractable Mn, Cu and Zn (2.68, 2.48 and 2.40 ppm) were recorded under treatment T_{11}. The improvement of soil characteristics, which improved micronutrient availability to the plant and ultimately increased plant growth, accounts for the rise in soil characteristics under treatments with integrated nutrient sources. The addition of nutrients via chemical fertilizers and vermicompost improves the physical state of soil and resulted in nutrient richness and rapid mineralization which enhance soil fertility. The increment in microbial activity due to addition of vermicompost in integration with chemical fertilizers led to nutrient acquisition which further increased micronutrient availability by producing siderophores and protons, both of which are responsible for increased bioavailability of nutrients in soil. Similar studies were also carried out by Parven *et al.* (2020), concluded an enhanced micronutrient content in soil due to integrated nutrient management through chemical fertilizers and bulky manures. The improvement in micronutrient content by the application of integrated nutrients has also been studied by Elayaraja *et al.* (2024) in brinjal. They reported increase in DTPA extractable cations in soil by the application of different nutrient sources.

The breakdown of organic matter, nutrient cycling, fertilization and development of soil structure is facilitated by activity of soil microorganisms. In terms of soil microbiological properties, the maximum bacterial count (159.65 cfu/g soil) was recorded in treatment T_3 comprising integrated nutrient sources with 500 ppm TiO_2 nanoparticles as seed treatment. The maximum value of dehydrogenase (3.97 mg TPF/h/g soil) and microbial biomass (64.05 µg/g soil) was recorded in treatment T_7 whereas, significant higher value of urease (0.29 mg NH_4^+/g soil) enzyme activity was recorded in treatment T_{11} and significantly higher phosphatase (29.00 µmole PNP/h/g soil) in soil was noted under treatment T_3. However, the data on actinomycetes and fungal count was recorded non-significant as given in Table 2. These results were in line with the results of Nayak *et al.* (2007) who concluded that the activity of soil enzymes is enhanced by the continuous application of organic amendments in various forms in soil. Involved in oxidative phosphorylation, soil enzymes are a key indicator of microbial activity in the soil. Also, the addition of high-quality organic matter served to increase the biological qualities of the soil. The results concluded by Toor *et al.* (2024) also revealed that vermicompost improved the microbial characteristics of the soil, which is advantageous for plant development and disease prevention. According to the study, vermicompost is a useful organic amendment that may be used in agricultural areas to improve soil microbial qualities and plant development.

TiO_2 nanoparticles can be easily processed downstream, are safe for the environment, and are inexpensive to produce. By promoting plant metabolic processes, they might therefore function as a nano nutrient fertilizer to increase agricultural productivity. The use of 1000 ppm of TiO_2 nanoparticles as seed treatment led to a notable enhancement in growth, yield qualities and cost-effectiveness. Additionally, TiO_2 nanoparticles as seed treatment performed better than foliar application in terms of benefit-cost ratio. Because in foliar application, large quantity of nano material is required to spray as compare to seed treatments in term of per hectare basis. The use of nanoparticles in cabbage also resulted in a greater B:C ratio and an overall profit. Utilizing nanoparticles in agricultural production may enable more precise application of technological inputs. It may also

Table 2 Effect of nutrient sources and TiO_2 nanoparticles on soil nutrient status and microbiological parameters in cabbage

Treatment	*p*H	EC (dS/m)	Organic carbon (%)	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)	Exchangeable Ca (cmol p+/kg)	Exchangeable Mg (cmol p+/kg)	Available sulphate sulphur (kg/ha)	DTPA extractable Fe (ppm)	DTPA extractable Mn (ppm)	DTPA extractable Cu (ppm)	DTPA extractable Zn (ppm)	Bacterial count ($\times 10^5$ cfu/g soil)	Actinomycetes count ($\times 10^3$ cfu/g soil)	Fungal count ($\times 10^2$ cfu/g soil)	Microbial Biomass-C (µg/g soil)	Dehydrogenase (mg TPF/h/g soil)	Urease (mg NH_4^+/g soil)	Phosphatase (µmol PNP/h/g soil)
T_1	7.23 ± 0.11	0.40 ± 0.05	0.43 ± 0.01	365.5 ± 3.39	83.1 ± 0.71	250.3 ± 1.33	2.48 ± 0.02	2.21 ± 0.04	41.80 ± 0.57	4.47 ± 0.14	1.13 ± 0.01	1.22 ± 0.00	1.20 ± 0.01	108.11 ± 1.78	3.21 ± 0.11	2.28 ± 0.03	30.30 ± 0.15	2.58 ± 0.04	0.16 ± 0.00	16.33 ± 0.17
T_2	7.17 ± 0.11	0.41 ± 0.08	0.43 ± 0.01	326.0 ± 1.46	87.8 ± 0.58	240.5 ± 2.09	2.95 ± 0.04	2.30 ± 0.02	51.75 ± 0.52	4.35 ± 0.06	1.14 ± 0.00	1.21 ± 0.01	1.20 ± 0.00	117.05 ± 1.21	3.23 ± 0.20	2.50 ± 0.08	34.98 ± 1.28	2.78 ± 0.02	0.17 ± 0.01	17.00 ± 0.76
T_3	7.20 ± 0.11	0.41 ± 0.08	0.55 ± 0.03	302.5 ± 5.40	81.5 ± 1.56	226.6 ± 6.78	3.17 ± 0.11	2.24 ± 0.05	56.85 ± 0.45	7.16 ± 0.01	2.67 ± 0.02	2.08 ± 0.03	2.04 ± 0.03	159.65 ± 2.59	3.45 ± 0.15	3.88 ± 0.59	62.18 ± 1.38	3.58 ± 0.04	0.23 ± 0.01	29.00 ± 0.00
T_4	7.09 ± 0.04	0.44 ± 0.06	0.42 ± 0.01	364.3 ± 5.11	80.6 ± 2.21	233.3 ± 11.06	2.74 ± 0.09	2.27 ± 0.07	41.33 ± 0.88	4.49 ± 0.05	1.14 ± 0.01	1.23 ± 0.00	1.22 ± 0.17	116.01 ± 1.51	3.91 ± 0.17	3.43 ± 0.02	34.08 ± 0.91	2.74 ± 0.06	0.17 ± 0.01	18.17 ± 0.33
T_5	7.21 ± 0.04	0.43 ± 0.02	0.53 ± 0.00	355.3 ± 2.15	73.9 ± 1.00	217.8 ± 3.68	3.03 ± 0.10	2.34 ± 0.09	44.00 ± 0.58	7.14 ± 0.02	2.64 ± 0.02	2.21 ± 0.01	2.20 ± 0.00	149.12 ± 1.44	3.50 ± 0.38	4.40 ± 1.03	60.45 ± 1.02	3.67 ± 0.03	0.23 ± 0.01	25.00 ± 0.29
T_6	7.22 ± 0.04	0.42 ± 0.08	0.43 ± 0.01	318.6 ± 2.96	86.5 ± 0.12	226.1 ± 2.31	3.16 ± 0.18	2.37 ± 0.02	52.40 ± 0.78	4.67 ± 0.05	1.14 ± 0.01	1.35 ± 0.01	1.34 ± 0.01	114.35 ± 0.68	3.87 ± 0.31	3.31 ± 0.16	33.40 ± 0.20	2.45 ± 0.03	0.16 ± 0.01	17.83 ± 0.33
T_7	7.31 ± 0.14	0.45 ± 0.05	0.54 ± 0.01	286.2 ± 5.65	76.4 ± 0.90	230.5 ± 5.76	2.89 ± 0.03	2.37 ± 0.08	38.11 ± 0.39	7.09 ± 0.05	2.49 ± 0.04	2.33 ± 0.01	2.31 ± 0.01	151.68 ± 2.21	3.92 ± 0.14	4.58 ± 0.69	64.05 ± 0.61	3.97 ± 0.01	0.26 ± 0.01	25.33 ± 0.44
T_8	7.37 ± 0.21	0.41 ± 0.12	0.42 ± 0.00	351.5 ± 5.66	76.3 ± 1.42	227.0 ± 6.73	3.00 ± 0.17	2.40 ± 0.09	46.85 ± 0.46	5.21 ± 0.02	1.16 ± 0.01	1.39 ± 0.02	1.40 ± 0.01	115.02 ± 0.68	3.72 ± 0.14	3.33 ± 0.14	31.50 ± 0.61	2.60 ± 0.06	0.18 ± 0.01	18.67 ± 0.44
T_9	7.07 ± 0.09	0.38 ± 0.09	0.52 ± 0.01	333.1 ± 1.66	69.2 ± 0.54	206.1 ± 4.93	2.87 ± 0.27	2.41 ± 0.04	49.00 ± 0.58	7.16 ± 0.03	2.67 ± 0.01	2.42 ± 0.01	2.40 ± 0.01	142.45 ± 0.93	3.75 ± 0.28	4.40 ± 1.09	59.77 ± 1.13	3.66 ± 0.07	0.26 ± 0.01	22.50 ± 0.29
T_{10}	7.15 ± 0.15	0.47 ± 0.07	0.44 ± 0.01	338.5 ± 4.32	89.3 ± 0.85	243.1 ± 3.92	2.69 ± 0.16	2.31 ± 0.08	47.84 ± 0.44	4.48 ± 0.16	1.18 ± 0.02	1.51 ± 0.02	1.50 ± 0.03	115.21 ± 1.63	3.70 ± 0.34	3.18 ± 0.61	31.33 ± 0.63	3.19 ± 0.16	0.18 ± 0.02	19.17 ± 0.60
T_{11}	7.10 ± 0.20	0.38 ± 0.06	0.55 ± 0.01	312.4 ± 4.44	85.1 ± 1.04	225.5 ± 4.89	2.74 ± 0.16	2.29 ± 0.03	56.10 ± 0.38	7.20 ± 0.01	2.68 ± 0.02	2.48 ± 0.07	2.40 ± 0.06	141.04 ± 1.04	3.83 ± 0.32	4.50 ± 0.71	59.23 ± 0.62	3.18 ± 0.08	0.29 ± 0.00	25.50 ± 0.00
T_{12}	7.11 ± 0.04	0.35 ± 0.08	0.40 ± 0.02	391.3 ± 3.31	87.2 ± 0.21	232.1 ± 0.95	2.64 ± 0.11	2.24 ± 0.01	59.75 ± 0.52	4.75 ± 0.09	1.17 ± 0.02	1.56 ± 0.01	1.56 ± 0.01	119.57 ± 0.66	3.72 ± 0.37	3.38 ± 1.02	31.17 ± 0.33	3.24 ± 0.10	0.16 ± 0.01	18.50 ± 0.50
T_{13}	7.26 ± 0.18	0.47 ± 0.07	0.57 ± 0.01	379.7 ± 3.63	80.4 ± 0.77	228.0 ± 4.05	3.02 ± 0.32	2.30 ± 0.07	39.76 ± 0.53	7.28 ± 0.01	2.46 ± 0.01	2.28 ± 0.03	2.30 ± 0.03	135.97 ± 2.86	3.95 ± 0.35	4.10 ± 1.04	62.87 ± 1.18	3.24 ± 0.13	0.25 ± 0.01	22.17 ± 1.67
Mean	7.19	0.42	0.48	340.37	81.34	229.77	2.87	2.31	48.12	5.80	1.82	1.79	1.79	129.63	3.67	3.64	45.79	3.14	0.21	21.17
LSD ($p \leq 0.05$)	NS	NS	0.03	9.47	2.84	12.92	NS	NS	1.18	0.22	0.04	0.08	0.15	4.25	NS	NS	1.88	0.23	0.01	1.62
SEM ±	0.12	0.07	0.01	3.22	0.97	4.40	0.16	0.06	0.40	0.07	0.02	0.03	0.05	1.45	0.23	0.55	0.64	0.08	0.00	0.55

Treatment details are given under Materials and Methods.

effectively address the significant issue of low production and inefficient use of resources at the same time. However, standardizing the present study's findings in various agro-ecological scenarios is needed.

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