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USE OF NANO FERTILIZERS TO REDUCE CHEMICAL FERTILIZER LOAD FOR OKRA PRODUCTION

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ABSTRACT

Efficacy of nano urea, titanium dioxide and zinc oxide nanoparticles on growth, fruiting and yield of okra plant (cv. Kashi Lalima) was evaluated in the present study. The cop was grown on high pH (8.2) soil at subtropical agro-climatic condition of Lucknow during *Zaid* season of 2022-23 and 2023-24 at Horticulture Research Farm, Department of Horticulture, Babasaheb Bhimrao Ambedkar University, Lucknow, Uttar Pradesh, India. The experiment was laid out in Randomized Block Design (RBD) with 17 treatments viz. Control (no fertilizer), recommended dose of fertilizer (RDF 100%, 75%, 50% and 25%), Nano urea (2 ml/l, 4 ml/l and 6 ml/l), TiO_2NPs (10, 15 and 20 ppm), ZnO NPs (50, 75 and 100 ppm) with 3 replications having 51 plots (1.8 m × 1.2 m). ZnO and TiO_2 nanoparticles (NPs) were prepared through green synthesis technology using aqueous extract of *Ipomoea carnea* (morning glory) leaves and Nano urea which was procured from IFFCO. Detailed characterisation i.e. size, morphology, composition and stability of selected NPs was carried out using UV-visible spectroscopy, FTIR, HRTEM, EDX, BET, X-ray diffraction, XPS and particle size distribution studies at department of Chemistry and University Scientific Instrumentation Centre (USIC) of the University. Recorded observations indicated that foliar application of 75% RDF + 2 ml/l Nano urea + 50 ppm ZnO NPs performed best in terms of growth parameters *i.e*. higher plant height- 128.84 cm, maximum number of leaves- 32.25/plant, basal stem diameter- 2.70 cm and number of primary branches/plant) at 120 DAS. It also caused earliness in flowering for 39.38 days as compare to control (49.88 DAS). This treatment also exhibited higher flowering (22.8) and yield (159.81 q/ha) thus, the study concluded that application of 75 % RDF + 2 ml/l Nano urea + 50 ppm ZnO NPs may be beneficial for getting better crop growth and fruit yield of okra.

Key words : Nano-fertilizer, Okra, Growth, Flowering.

Introduction

To ensure sustainable food and agricultural production, advanced applications of nanotechnology are critical (Fraceto *et al*., 2016; Wang *et al*., 2018; Neme *et al*., 2021). Climate change and land degradation have a global impact on crop cultivation sustainability (Webb *et al*., 2017; Jiang *et al*., 2021). Nanotechnology plays an increasingly important role in most areas of human activity including crop production. Engineered nanoparticles (ENPs) have catalytic, photovoltaic, energetic, and sensory applications in diverse industries (Williams *et al*., 2020; Ismael *et al*., 2020; Esfe *et al*., 2020; Vinitha *et al*., 2021; Selvakumar *et al*., 2021). Nanotechnology has gained significant attention in the field of agriculture due to its potential for improving crop productivity. Researchers have extensively studied the ability of nanoparticles to absolve in plants body due to their nano size (Agrawal *et al*., 2022; Faizan *et al*., 2020). The studies on beneficial effects showed that, at optimum concentrations, NPs might improve enzyme activities, photosynthesis, nitrogen absorption and growth parameters of early seedlings (Gao *et al*., 2006; Yang *et al*., 2006). Nano fertilizers (NFs), which are modified versions of conventional fertilizers that are extracted from various plant parts by chemical, physical, mechanical, or biological means, are utilised to enhance soil fertility, crop productivity, and the quality of agricultural products (Qureshi *et al*., 2018). Furthermore, using plants is a more convenient method than using commercial products because it avoids the time-consuming process of nurturing cell cultures and is better suited for the large-scale synthesis of nanoparticles (Ahmad *et al*., 2020) with minimal environmental impact. Nanoparticles are nanomaterials with unique physicochemical properties such as increased reactivity, standard surface structure, and a high ratio of surface to volume (Noohpisheh *et al*., 2021; Badawy *et al*., 2021). Because of these properties, NPs can be utilised as nanofertilizers in a better way (Jiang *et al*., 2021; Noohpisheh *et al*., 2021; Awan *et al*., 2021) and to minimise nutrient deficiency (Étienne *et al*., 2018). Thus, controlled and targeted mineral nutrients supplied to plants (Salama *et al*., 2019) leads to improved crop expansion and growth (Wang *et al*., 2018; Rajput *et al*., 2021; Srivastava *et al*., 2021). According to the Indian Farmers Fertilizer Co-operative Limited, India (IFFCO), nanofertilizers are needed in very small amounts *viz*., 500 ml of Nano-urea may substitute 45 kg of commercial urea, while just 10g of nano-zinc is enough for a hectare of the land. This may helps to reduce the need for chemical fertilizers by 50% to 70% (Lakshman *et al*., 2022). Nano urea is energy saving and resource friendly and it reduces excess application of bulk urea and associated volatilization as well as leaching and run off losses (Anonymous, 2022; Kumar *et al*., 2023). Nano - urea enhances crop efficiency, yield and quality parameters by increasing nutrient use efficiency, reducing nutrients waste and lowering cultivation costs (Prem Baboo, 2021). Similarly, TiO_2 nanoparticles enhanced germination and photosynthesis (Khan *et al*., 2019). TiO_2 NPs have a wide range of applications in diverse fields of human activity, including agriculture. Similar to ZnO NPs, surface properties of TiO_2 NPs are often modified to help with their stability or to increase their positive effects and decrease their toxicity (Macwan *et al*., 2011; Silva *et al*., 2013). TiO_2 NPs have been applied to protect seeds, enhance plant growth and germination, control crop diseases (Servin *et al*., 2015), degrade pesticides and detect their residues (Aragay *et al*., 2012). In addition, these NPs have been reported to increase root and shoot growth, seed or produce yield, and improve plant health. Environmental stresses, such as drought in wheat (Mustafa *et al*., 2021) and high Cd levels in maize (Lian *et al*., 2020), were also alleviated significantly with the use of TiO_2 NPs. The studies showed the need to explore further the effects and interaction of NPs under more realistic conditions as the underlying trend from laboratory experiments involved the application of higher doses of the nanoparticles which were toxic to the plants. In contrast, at appropriate lower concentrations, many NPs were found to positively affect the plants' growth, health, and quality (Du *et al*., 2015: Prasad *et al*., 2012). For example, TiO_2 NPs applied on barley during stem elongation and a second time during the four-leaf stage at concentrations of 0.01 to 0.03% increased grain yield and the weight of 1000 grains (Moaveni *et al*., 2011). Likewise, peanut plants also responded positively to low concentrations of ZnO NPs and higher concentrations of 2000 mg Zn L^{-1} revealed inhibitory effects (Prasad *et al*., 2012). Mostly, both ZnO and TiO_2 NPs are only toxic at high concentrations, *i.e.* concentrations higher than 2000 mg.L^{-1} (Prasad *et al*., 2012). Both ZnO and TiO_2 NPs were found to alleviate stresses caused by drought and heavy metals such as Cd. Three different concentration ranges of TiO_2 NPs were used to improve plants' growth and yield parameters and health (Korosi *et al*., 2019 and Kolencik *et al*., 2020) the application of TiO_2 NPs at a lower concentration range of 25 to 300 mg.L^{-1} was found to have promising positive effects on plant height, straw and grain yields, dry biomass, the weight of 1000 grains, and chlorophyll contents (Moaveni *et al*., 2011; Irshad *et al*., 2021; Kattak *et al*., 2021). TiO_2 NPs synthesised by the green method with plant extracts exhibited a significantly better effect when compared with TiO_2 NPs synthesised via the sol-gel method (Irshad *et al*., 2021). It was proposed that this effect can be caused by the presence of the plant extract traces on the TiO_2 NPs surface or their slightly smaller size (6 to 8 nm for green synthesised TiO_2 NPs compared with 10 to 13 nm for chemically synthesised ones) (Irshad *et al*., 2021). Moreover, these were also found to increase the plant height, a number of branches, fruit yield, increase in amino acids, total sugars, total phenols, total indoles, and pigments in coriander (Khater *et al*., 2015). ZnO NPs have been revealed as the smartest delivery method for meeting plant zinc demands, replacing traditional zinc fertiliser and increasing Zn availability (Rajput *et al*., 2021; Awan *et al*., 2021). ZnO nanoparticles improved yield in lentil (*Lens culinaris* Medik.) crops (Alwan *et al*., 2022; Kolencik *et al*., 2022), improved growth, photosynthesis and maturation of corn, onion, tomato, olive, capsicum, cucumber, wheat and zucchini. However, plant responses to ZnO NPs application vary depending on genotype, plant stage and nanoparticle concentration (Salama *et al*., 2019). The use of chemically synthesised ZnO NPs has been criticised when compared to biosynthesised counters (Rai *et al*., 2018; Jamkhande *et al*., 2019). Nevertheless, the use of biologically generated ZnO NPs as nanofertilizers to enhance zinc content and improve the physiological and morphological characteristics and antioxidant properties of leafy vegetables during the initial vegetative stages is limited (Iziy *et al*., 2019; Salama *et al*., 2019; Regni *et al*., 2022). In addition, ZnO NPs are reported to have an ability to decrease the effect of environmental stresses on plants, such as drought (Dimkpa *et al*., 2020), temperature (Hassan *et al*., 2018), metals, metalloids (Rizwana *et al.*, 2019: Rizwana *et al.*, 2019), and salt (Torabian *et al.*, 2016). When applied at suitable concentrations, ZnO NPs increase seed germination (Garcia-Lopez *et al*., 2018), growth (Singh *et al.*, 2019), the activity of antioxidants and protein production (Salama *et al*., 2019), chlorophyll content (Pullagurala *et al*., 2018), photosynthesis (Faizan *et al*., 2018), production of oils and seeds (Kolencik *et al*., 2020: Kolencik *et al*., 2019), and uptake of essential elements (Peralta-vedia *et al*., 2014). Thus, there is a need to evaluate the effect of nano urea, TiO_2 and ZnO NPs on growth, yield and quality of okra specially when grown on slightly saline soil having pH 8.2 under sub-tropical climate.

Materials and Methods

The field experiment was carried out at Horticulture Research Farm, Department of Horticulture, Babasaheb Bhimrao Amdedkar University, Lucknow (U.P.)-226025 (26^0 84′ North latitude and 80^0 94′ East longitudes, 123 m above mean sea level (MSL) during February to May 2022. Experimental site had 21.1 -41.8^{0}C temperature in summer, relative humidity of 30-67.9% and 750 mm annual rainfall, while, soil of the site is quite alkaline with 8.2 pH. The experiment was comprised of 17 treatments having foliar application of Nano urea (2ml/l, 4ml/l and 6ml/l), TiO_2 NPs (10, 15, 20 ppm) and ZnO NPs (50, 75, 100 ppm) with soil application of different percentage of RDF (75%, 50%, 25%). The treatments were replicated thrice randomly following Randomized Block Design (RBD) having 51 plots (1.8 m × 1.2m). The field operations were done to maintain healthy plant and standard agronomical practices like sowing, weeding, hoeing, earthing up, irrigation and plant protection measures were adapted. The seeds of selected cultivar Kashi Lalima were collected from Indian Institute of Vegetable Research (IIVR, Varanasi). Kashi Lalima is a reddish-purple coloured okra hybrid variety released by IIVR, Varanasi and shows resistance against yellow vein mosaic virus (YVMV), okra leaf curl virus (OLCV). It is a short duration crop having high yield, high anthocyanin and phenolic content, suitable for both summer and kharif season cultivation, popular in agro-climatic condition of Uttar Pradesh and Bihar state of India having subtropical dry to humid climate. The seeds were sown on 1st February at 45cm × 30 cm spacing, germination started 4-7 days after sowing (DAS). Okra is a nutrient loving plant requiring N, P, K – 120 kg, 80 kg, 50 kg, respectively. Nano urea are collected from IFFCO Bhawan, Lucknow. It expressed desirable particle size about 20-50nm and more surface area (10,000 times over 1 mm urea prill) and number of particles (55,000 nitrogen particles over 1 mm urea prill). Hence, Nano urea increase its availability to crop by more than 80% resulting in higher nutrient use efficiency (Kumar *et al.*, 2023). TiO_2 and ZnO NPs were green synthesized with *Ipomoea carnea* sub sp. fistulosa (morning glory) leaves with the help of aqueous solution of $TiCl_4$ (0.1M) and zinc nitrate hexahydrate (0.1M). The formation and quality of compounds were investigated by X-ray diffraction technique. The powder X-ray diffraction pattern of TiO_2 and ZnO NPs were recorded on Pananalytical's X'Pert Pro X-ray diffractometer. UV–visible absorption spectrum of TiO_2 NPs synthesized by reduc- tion of aqueous solution of $TiCl_4$ by equeous extract of Ipomoea carnea (morning glory) leaves exhibits a strong UV–visible absorption band at 277 nm. which is blue shifted corresponds to the excitonic peak of TiO_2 NPs due to quantum size effect (Hitkari *et al*., 2018). The quantum confinement also observed in case of ZnO NPs which exhibited absorption peak at 275 nm. The UV–visible absorption study results revealed formation of small size ZnO and TiO_2 NPs the direct band gap energy of TiO_2 and ZnO NPs has been calcu- lated using the Tauc relation. The band gap energy of TiO_2 and ZnO NPs are found to be 3.5 and 3.4 eV, respectively. Phase, crystal structure and purity of as-synthesized TiO_2 and ZnO NPs were determined by powder XRD study. The TiO_2 NPs formed after reduction of $TiCl_4$ by plant extraction aqueous medium. All the diffraction peaks are well assigned well to anatase phase with a reference pattern (JCPDS 21–1272) of TiO_2. It is noteworthy that only anatase TiO_2 detected and no rutile phase can be found in this sample, which is attributed to the contribution of the low concentration of oxygen vacancies due to the high concentration of gaseous oxygen during particle growth, hindering the transformation from anatase to rutile phase (Rulison *et al*., 1996). Moreover, observance of very sharp and broad XRD peaks indicate formation of small size crystalline TiO_2 NPs. The average crystallite size (D) has been determined from the Debye-Scherrer formula: $D = 0.9\ \lambda / \beta \cos \beta$. Where, D is the crystallites size (in nm), λ the wavelength (in nm), β is the full width at half maxima (FWHM) and θ is the Bragg's diffraction angle. All the diffraction peaks in the XRD Pattern in ZnO are readily indexed to hexagonal wurtzite ZnO (JCPDS card 80-0075, a = 0.3253 nm, c = 0.5209 nm) with space group p63mc. From the XRD pattern it is evident that as- synthesized material obtained by reduction zinc nitrate hexahydrate using plant extract is phase pure ZnO. Furthermore, it is obvious from the diffraction pattern that the XRD peaks are intense and broadened, indicating formation of good crystalline and small size ZnO NPs are formed. The average crystallites size of TiO_2 and ZnO particles were estimated to be 7 and 52nm respectively. The particle size distribution of TiO_2 and ZnO NPs has been studied on Zeta sizer. Particle shape, sizes and composition of materials were examined on JEOL-2100 transmission electron microscope (TEM with EDX; model no. TECNAI 200G2 FEI). The particle distribution range TiO_2 NPs 7-10NM, ZnO NPs 42-79nm, maximum population fall at 58.89nm and 8.69nm respectively. The synthesis and characterization were done at the Department of Chemistry, Babasaheb Bhimrao Ambedkar University, Lucknow. TiO_2 and ZnO NPs were applied to the crop as per treatment combination at 30 and 60 days after seed sowing (DAS). Crop vegetative growth, fruit yield and quality observations were recorded as per the standard methods (Ranganna., 1986). Total sugars and reducing sugar were determined by titration method using Fehling's solution A and B and methylene blue as an indicator (Miller, 1959). TSS was recorded by digital refractometer (model HI 96801, 0 to 85% Brix (Hanna Intruments). The observed values of various treatments were statistically analyzed at OPSTAT (Sheoran *et al.*, 1998) and mean value were compared at 5% level of significance (Sahu and Das, 2014).

Results and Discussion

Plant height

The data showed that there was a significant difference among the treatments on plant height at various stage of growth during both the years. At 30 DAS plant height was found maximum in T_2, Recommended dose of fertilizer (RDF) (16.77cm and 17.06cm) followed by T_{13} Treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO), (16.28 cm and 16.60cm). while minimum was recorded in T_1(control) (13.37 cm and 13.67 cm) during first and second year, respectively. Similar pattern was also observed in case of pooled data at 30 DAS T_2 (16.91cm) followed by T_{13}(16.44 cm), while minimum was recorded in T_1 (13.52 cm). But at 60, 90 and 120 DAS, T_{13} treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO) had highest plant height (54.80 and 54.21 cm), (90.70 and 93.06 cm) and (128.84 and 130.63 cm) followed by T_{12} treatment (75% RDF + 2ml/l Nano Urea+ 10 ppm TiO_2), (47.49 and 48.77 cm), (89.12 and 93.33 cm) and (122.89 and 124.70 cm) during 1st year and 2nd year trial, respectively. Plant height lowest was recorded in T_1 (control), (31.55 and 32.66 cm), (62.31 and 65.22 cm) and (84.20 and 86.02 cm) during first and second year, respectively. Pooled value also showed the similar trend recording higher plant height of (54.21cm), (93.06cm) and (129.74cm) at 60, 90 and 120 DAS respectively by the treatment T_{13} (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO). ZnNPs improve the availability of zinc, a crucial micronutrient, leading to enhanced nutrient absorption and utilization in plants (Guardiola-Márquez *et al.*, 2023). Treatments with ZnNPs have been linked to increased chlorophyll content, which boosts photosynthesis and overall plant vigor. a study reported a 52% increase in chlorophyll levels in treated plants (Olkhovskaya *et al.*, 2024). The use of nano Fertiliser can significantly improve the growth and heights of okra plants by Subramanian *et al.* (2015), delivering essential nutrients far more efficiently and precisely (Solanki *et al.*, 2015a; Alabdallah and Al-Zahrani, 2020). These nano-fertilizers enhance nutrient uptake, utilisation and overall plant health, resulting in better vegetative development and plant height. Similar results also reported by Satti *et al.* (2021), Semida *et al.* (2021), Pejam *et al.* (2021).

Number of leaves per plant

Data indicated that there was significant change due to treatments on number of leaves at the all stages of growth, during both the years. The data revealed that at 30, 60, 90 and 120 DAS, In early stage of growth at 30DAS the maximum Number of leaves/plant found in T_2 Recommended dose of fertilizer (RDF) (6.62 and 6.50) followed by T_{13} Treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO) (6.04 and 6.01), while lowest number of leaves/plant recorded in T_1 (4.30 and 4.37) during 1st year and 2nd year, respectively. Similar trends also seen in case of pooled data at 30 DAS T_2 (6.56) followed by T_{13} (6.03), while minimum was recorded in T_1(control) (4.34). But at 60, 90 and 120 DAS, T_{13} Treatment (75% RDF + 2ml/l Nano Urea + 50 ppm ZnO), had highest Number of leaves/plant (15.58 and 16.00), (24.33 and 25.66) and (32.25 and 33.75) followed by T_{12} Treatment (75% RDF + 2ml/l Nano Urea+ 10 ppm TiO_2),(14.75 and 14.92), (22.25 and 23.25) and (29.83 and 31.33) during 1 year and 2 nd year trial, respectively. Minimum Number of leaves/plants was recorded in T_1(control) (9.33 and 10.08), (13.58 and 14.75) and (17.75 and 19.25) during first and second year, respectively. Pooled value also showed similar trend was also reporting higher number of leaves at 60, 90 and 120 DAS, (15.79), (25.00) and (33.00), respectively by treatment T_{13} (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO). application of Zn NPs has

Table 1 : Effect of nano fertilizers in plant height(cm) of okra.

Treatments	30 DAS			60DAS			90DAS			120DAS		
	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled
T_1	13.37	13.67	13.52	31.55	32.67	32.11	62.31	65.22	63.76	84.20	86.02	85.11
T_2	16.77	17.06	16.91	46.25	47.40	46.82	87.32	88.93	88.13	120.26	122.13	121.20
T_3	15.80	16.30	16.05	45.73	46.90	46.32	84.88	86.45	85.66	119.07	121.00	120.04
T_4	13.66	13.98	13.82	38.89	40.17	39.53	73.09	74.68	73.89	101.76	103.52	102.64
T_5	13.53	13.84	13.69	38.75	39.84	39.29	72.81	74.35	73.58	100.65	102.58	101.62
T_6	14.97	15.30	15.13	42.97	44.08	43.53	78.59	80.17	79.38	112.59	114.38	113.49
T_7	14.56	14.80	14.68	41.73	42.85	42.29	76.30	77.87	77.08	108.42	110.52	109.47
T_8	14.30	14.60	14.45	41.08	42.20	41.64	75.59	77.48	76.54	106.75	108.85	107.80
T_9	15.27	15.60	15.43	43.22	44.42	43.82	79.69	81.47	80.58	113.41	115.25	114.33
T_{10}	14.81	15.12	14.97	42.43	43.52	42.98	78.13	79.78	78.96	111.75	113.55	112.65
T_{11}	14.40	14.73	14.57	41.43	42.52	41.98	75.99	77.64	76.82	107.32	109.12	108.22
T_{12}	15.99	16.32	16.15	47.49	48.77	48.13	89.12	93.33	91.23	122.89	124.70	123.80
T_{13}	16.28	16.60	16.44	53.61	54.80	54.21	95.42	90.70	93.06	128.84	130.63	129.74
T_{14}	15.40	15.68	15.54	43.41	44.70	44.06	82.55	84.10	83.33	115.85	117.58	116.72
T_{15}	15.67	16.07	15.87	44.39	45.49	44.94	84.29	85.85	85.07	118.28	120.35	119.31
T_{16}	15.48	15.78	15.63	43.83	44.95	44.39	83.28	84.95	84.11	117.07	118.82	117.94
T_{17}	15.57	15.88	15.73	44.00	45.21	44.61	83.44	85.05	84.25	118.00	119.80	118.90
CD (P=0.05)	0.06	0.03	0.04	0.056	0.23	0.15	0.10	0.09	0.10	0.06	0.09	0.08
SEm ±	0.02	0.01	0.01	0.019	0.08	0.05	0.03	0.03	0.04	0.02	0.03	0.03

Table 2 : Effect of nano fertilizers in basal stem diameter(cm) of okra.

Treatments	30 DAS			60DAS			90DAS			120DAS		
	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled
T_1	0.10	0.14	0.12	0.49	0.56	0.53	0.86	1.01	0.93	1.28	1.32	1.30
T_2	0.35	0.39	0.37	1.20	1.21	1.20	1.94	2.07	2.01	2.52	2.56	2.54
T_3	0.28	0.31	0.30	1.11	1.11	1.11	1.83	2.00	1.92	2.42	2.45	2.44
T_4	0.12	0.17	0.15	0.55	0.62	0.58	1.04	1.10	1.07	1.61	1.65	1.63
T_5	0.11	0.16	0.14	0.52	0.60	0.56	0.97	1.05	1.01	1.57	1.60	1.58
T_6	0.17	0.23	0.20	0.69	0.75	0.72	1.34	1.54	1.44	1.86	1.92	1.89
T_7	0.15	0.20	0.18	0.63	0.70	0.67	1.21	1.32	1.27	1.76	1.80	1.78
T_8	0.13	0.18	0.16	0.57	0.65	0.61	1.10	1.15	1.13	1.66	1.70	1.68
T_9	0.18	0.24	0.21	0.72	0.78	0.75	1.40	1.60	1.50	1.92	1.96	1.94
T_{10}	0.16	0.22	0.19	0.66	0.72	0.69	1.27	1.42	1.34	1.81	1.86	1.84
T_{11}	0.14	0.19	0.17	0.60	0.67	0.63	1.16	1.23	1.20	1.70	1.75	1.73
T_{12}	0.30	0.33	0.31	1.20	1.32	1.26	2.02	2.21	2.12	2.66	2.77	2.71
T_{13}	0.32	0.36	0.34	1.35	1.47	1.41	2.30	2.40	2.35	2.94	2.98	2.96
T_{14}	0.20	0.25	0.22	0.76	0.84	0.80	1.47	1.65	1.56	1.98	2.00	1.99
T_{15}	0.26	0.29	0.28	1.00	1.03	1.02	1.75	1.90	1.83	2.30	2.35	2.33
T_{16}	0.22	0.26	0.24	0.83	0.87	0.85	1.56	1.72	1.64	2.10	2.16	2.13
T_{17}	0.24	0.27	0.25	0.92	0.93	0.92	1.65	1.80	1.72	2.20	2.25	2.23
CD (P=0.05)	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.04	0.04	0.04	0.03	0.04
SEm ±	0.005	0.005	0.01	0.008	0.006	0.01	0.012	0.01	0.01	0.015	0.011	0.01

been shown to increase the levels of growth-promoting hormones, such as auxins, which are vital for leaf expansion and bud formation (Olkhovskaya *et al.*, 2024). In pepper plants, seed treatment with Zn NPs resulted in a significant increase in the number of leaves and buds, indicating hormonal stimulation (Olkhovskaya *et al.*, 2024). Zn NPs facilitate the absorption of zinc ions through stomata, allowing for efficient translocation to mesophyll cells, which is crucial for leaf development (Zhu *et al*., 2020).

Number of branches per plant

The number of branches/plant was counted at 60, 90 and 120 DAS. The data (Table 4) indicated that there were significant change in treatments on number of branches/plant at the stages of growth, during both the years. The data revealed that at 60, 90 and 120 DAS, T_{13} Treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO), had highest number of branches /plant (2.08 and 2.13), (3.01 and 3.12) and (3.58 and 3.92) followed by T_{12} Treatment (75% RDF + 2ml/l Nano Urea+ 10 ppm TiO_2), (1.83 and 1.90), (2.65 and 2.86) and (3.30 and 3.50), while Minimum Number of leaves/plant was recorded in T_1(control), (0.42 and 0.43), (0.80 and 0.84) and (1.48 and 1.50) during first and second year, respectively. Similar trend was also reported in case of pooled data. The maximum number of branches per plant seen in T_{13}(75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO) at 60, 90 and 120 DAS, (2.11), (3.06) and (3.75), respectively. ZnO NPs enhance chlorophyll synthesis and photosynthetic efficiency, which are crucial for plant growth. They facilitate better nutrient absorption, leading to improved branches ,biomass as well as yield of the crop (Hassan *et al*., 2024; Michael, 2024). Okra can produce a significant increase in branches by applying foliar nano-particles that includes NPK, Fe, Zn and Ti (Raliya *et al*., 2018; Lekhshmi *et al*., 2022). These fertilizers improve photosynthesis (Tighe-Neira *et al*., 2020; Ogunkunle *et al*., 2020) enhance nutrient uptake (Sompornpailin and Chayaprasert, 2020), preserve hormonal balance (Satti *et al*., 2021; Semida *et al*., 2021; Pejam *et al*., 2021) and increase stress tolerance (Sheteiwy *et al*., 2021). This result is confirmation in findings of Mogazy and Hanafy (2022).

Stem diameter

It is evident that there was significant difference among Treatment on stem diameter during both the years. The data presented in the Table 2, clearly indicate that initially at 30 DAS the maximum stem diameter found in T_2, Recommended dose of fertilizer (RDF) (0.35cm and 0.39cm) followed by T_{13} Treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO), (0.32 cm and 0.36cm) while minimum was recorded in T_1(control) (0.10 cm and 0.14 cm) during first and second year, respectively. Similar patterns also observed in pooled data at 30 DAS T_2(0.37cm) followed by T_{13} (0.34 cm), while minimum was recorded in T_1(control) (0.12 cm). But at 60, 90 and 120 DAS, T_{13} Treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO), had highest stem diameter (1.35 and 1.47 cm), (2.30 and 2.40 cm) and (2.94 and 2.98 cm) followed by T_{12} Treatment (75% RDF + 2ml/l Nano Urea+ 10 ppm TiO_2), (1.20 and 1.32 cm), (2.02 and 2.21cm) and (2.66 and 2.77 cm), while lowest was recorded in T_1(control) (0.49 and 0.56 cm), (0.86 and 1.01 cm) and (1.28 and 1.32 cm) during first and second year, respectively. Pooled value also showed the similar trend recording higher stem diameter of (1.41cm), (2.35cm) and (2.96 cm) at 60, 90 and 120 DAS respectively by treatment T_{13} (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO). ZnO NPs influence plant hormone signaling pathways, particularly auxins and cytokinins, which are vital for stem elongation and overall growth. ZnO NPs have been shown to upregulate genes associated with hormone biosynthesis, leading to enhanced growth responses (Wang *et al*., 2024). The presence of ZnO NPs can also modulate stomatal behavior, improving gas exchange and photosynthesis, which further supports stem growth (Zhu *et al*., 2020). The use of nano-fertilizers like nitrogen, phosphorus, potassium, iron, and zinc can positively affect the stem diameter of okra by improving nutrient availability and uptake (Sharma and Gupta, 2019). This results in enhanced plant growth and structural development. These results are close conformity with earlier reports of Ahmed and Khan (2022).

Number of days to first flowering

An inquisition of data in Table clearly indicate that among the Treatments, early flowering (39.50 and 39.25 days) was recorded in T_{13} Treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO), followed by T_{12} (75% RDF + 2ml/l Nano Urea+ 10 ppm TiO_2) (40.42 and 40.17 days) and late flowering (50.00 and 49.75 days) was noted in T_1 (contro),during first and second year, respectively. pooled value also showed the similar trend early flowering occurring in T_{13}(75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO), (39.38days) and late flowering seen in T_1(control) (49.88 Days). ZnONPs facilitate better absorption of essential nutrients, which is crucial during the early growth stages. Improved nutrient availability supports the development of reproductive structures, contributing to early flowering (Donia and Carbone, 2023). The time until okra flowers can be greatly shortened by applying foliar nano-fertilizers containing nitrogen, phosphorus, potassium, iron, zinc and Titanium (Prasad *et al*., 2012b; Tarafdar *et al*., 2014). These nutrients are essential for a number of physiological functions (Adhikari *et al*., 2016) and their effective delivery through nanofertilizers promotes photosynthesis (Tighe-Neira *et al*., 2020) and metabolic activity (Ogunkunle *et al*., 2020), increases

Table 3 : Effect of nano fertilizers in number of leaf in okra.

Treatments	30 DAS			60DAS			90DAS			120DAS		
	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled
T_1	4.30	4.37	4.34	9.33	10.08	9.71	13.58	14.75	14.17	17.75	19.25	18.50
T_2	6.62	6.50	6.56	14.17	14.25	14.21	20.92	22.25	21.58	28.00	29.58	28.79
T_3	5.72	5.67	5.70	13.78	13.75	13.76	20.25	21.58	20.92	27.42	28.92	28.17
T_4	4.47	4.75	4.61	10.75	12.22	11.49	16.75	18.08	17.42	22.17	23.67	22.92
T_5	4.45	4.50	4.47	10.47	11.83	11.15	16.42	17.67	17.04	21.67	23.17	22.42
T_6	5.00	5.17	5.08	12.00	13.08	12.54	18.25	19.78	19.01	24.75	26.30	25.53
T_7	4.80	5.08	4.94	11.50	12.75	12.13	17.75	19.25	18.50	24.33	25.89	25.11
T_8	4.61	4.92	4.76	11.06	12.39	11.72	17.08	18.50	17.79	23.42	24.92	24.17
T_9	5.12	5.25	5.19	12.30	13.17	12.74	18.50	20.00	19.25	25.00	26.64	25.82
T_{10}	4.92	5.17	5.04	11.75	12.92	12.33	17.95	19.55	18.75	24.58	26.08	25.33
T_{11}	4.67	5.00	4.83	11.25	12.58	11.92	17.53	18.92	18.22	24.00	25.47	24.74
T_{12}	5.83	5.78	5.81	14.75	14.92	14.83	22.25	23.25	22.75	29.83	31.33	30.58
T_{13}	6.04	6.01	6.03	15.58	16.00	15.79	24.33	25.66	25.00	32.25	33.75	33.00
T_{14}	5.22	5.28	5.25	12.61	13.33	12.97	18.75	20.25	19.50	25.30	26.83	26.07
T_{15}	5.58	5.50	5.54	13.50	14.00	13.75	19.75	21.00	20.38	26.25	28.25	27.25
T_{16}	5.30	5.33	5.32	12.89	13.50	13.19	19.17	20.45	19.81	25.58	27.28	26.43
T_{17}	5.45	5.42	5.43	13.17	13.75	13.46	19.50	20.80	20.15	26.07	27.70	26.88
CD (P=0.05)	0.12	0.14	0.13	0.13	0.14	0.14	0.12	0.17	0.15	0.13	0.15	0.14
SEm ±	0.04	0.05	0.04	0.05	0.05	0.05	0.04	0.06	0.05	0.04	0.05	0.05

Table 4 : Effect of nano fertilizers in number of primary branches of okra.

Treatments	60 DAS			90DAS			120DAS		
	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled
T_1	0.42	0.43	0.43	0.80	0.84	0.82	1.48	1.50	1.49
T_2	1.65	1.78	1.71	2.53	2.55	2.54	3.15	3.21	3.18
T_3	1.52	1.59	1.55	2.44	2.45	2.44	2.95	3.00	2.98
T_4	0.62	0.68	0.65	1.22	1.26	1.24	1.80	1.85	1.82
T_5	0.58	0.61	0.60	1.01	1.05	1.03	1.62	1.66	1.64
T_6	1.17	1.18	1.18	1.88	1.93	1.91	2.33	2.36	2.35
T_7	1.00	1.05	1.02	1.72	1.75	1.74	2.19	2.22	2.21
T_8	0.83	0.87	0.85	1.53	1.55	1.54	2.02	2.13	2.08
T_9	1.25	1.28	1.27	1.94	2.00	1.97	2.42	2.45	2.43
T_{10}	1.09	1.13	1.11	1.79	1.83	1.81	2.26	2.28	2.27
T_{11}	0.90	0.95	0.93	1.64	1.67	1.66	2.12	2.12	2.12
T_{12}	1.83	1.90	1.87	2.65	2.86	2.76	3.30	3.50	3.40
T_{13}	2.08	2.13	2.11	3.01	3.12	3.06	3.58	3.92	3.75
T_{14}	1.30	1.34	1.32	2.03	2.10	2.07	2.50	2.53	2.51
T_{15}	1.45	1.53	1.49	2.30	2.37	2.34	2.80	2.83	2.82
T_{16}	1.35	1.40	1.38	2.12	2.20	2.16	2.58	2.61	2.59
T_{17}	1.40	1.47	1.43	2.22	2.28	2.25	2.69	2.73	2.71
CD (P=0.05)	0.03	0.04	0.04	0.08	0.06	0.07	0.06	0.06	0.06
SEm ±	0.01	0.014	0.01	0.027	0.022	0.02	0.02	0.02	0.020

nutrient uptake (Sompornpailin and Chayaprasert, 2020) and utilisation and guarantees a balanced supply of nutrients (Satti *et al.*, 2021; Semida *et al.*, 2021; Pejam *et al.*, 2021). This results in healthier plants that move from vegetative growth to flowering more quickly. The results are in confirmation with the findings of Sheteiwy

Table 5 : Effect of nano fertilizers in yield and yield attribute traits in okra.

Treatments	First fruit formation			Number of flower/ plant			First flowering (DAS)			Yield (q/ha)		
	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled	1 Year	2 Year	Pooled
T_1	50	49.75	49.88	52.25	51.92	52.08	15.77	16.5	16.1	58.49	63.93	61.21
T_2	41.17	40.92	41.04	42.83	42.5	42.67	21.77	22.42	22.1	140.69	141.48	141.09
T_3	41.58	41.67	41.63	43.42	43.5	43.46	21.1	21.92	21.5	134.69	135.58	135.14
T_4	48.5	48.42	48.46	50.75	50.58	50.67	17.03	17.92	17.5	82.41	83.05	82.73
T_5	49.5	49.25	49.38	51.83	51.5	51.67	16.6	17.42	17	78.41	78.26	78.34
T_6	45.08	45.25	45.17	47.42	46.92	47.17	20.03	20.75	20.4	111.55	112.13	111.84
T_7	46.75	46.75	46.75	48.67	48.5	48.58	19.1	20	19.6	98.76	99.76	99.26
T_8	47.5	47.25	47.38	49.58	49.33	49.46	18.27	19.33	18.8	91.06	91.58	91.32
T_9	44.25	45	44.63	46.08	46.33	46.21	20.27	21.08	20.7	115.09	115.7	115.39
T_{10}	46.17	46.42	46.29	48	47.83	47.92	19.33	18.33	18.8	104.66	105.1	104.88
T_{11}	47.25	47.25	47.25	49.08	48.75	48.92	18.77	20	19.4	93.82	94.17	93.99
T_{12}	40.42	40.17	40.29	42	41.5	41.75	22.33	23.08	22.7	149.32	150.6	149.96
T_{13}	39.5	39.25	39.38	41	40.5	40.75	22.83	23.92	23.4	157.69	161.92	159.81
T_{14}	43.17	43.5	43.33	45.33	44.83	45.08	20.43	21	20.7	118.42	119.09	118.76
T_{15}	42.08	42.42	42.25	44.33	44	44.17	20.77	21.5	21.1	130.79	131.67	131.23
T_{16}	42.75	43.17	42.96	44.92	44.42	44.67	20.53	21.25	20.9	122.84	123.42	123.13
T_{17}	42.5	42.42	42.46	44.42	44.17	44.29	20.6	21.25	20.9	127.17	127.51	127.34
CD (P=0.05)	0.51	0.48	0.5	0.45	0.57	0.51	0.58	0.41	0.5	2.05	1.55	1.8
SEm±	0.17	0.16	0.17	0.15	0.2	0.18	0.2	0.14	0.17	0.707	0.53	0.619

et al. (2021), Mogazy and Hanafy (2022) and Carmona *et al.* (2021).

Number of days to first fruit harvest

The data showed that there were significant differences among treatment. An inquisition of data in Table- clearly indicate that, early fruit harvested (44.50 and 44.36 days) was recorded in T_{13} Treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO), followed by T_{12} (75% RDF + 2ml/l Nano Urea+ 10 ppm TiO_2) (45.75 and 45.72 days) and late fruit harvested (56.67 and 56.69 days) was noted in T_1 (control) during first and second year, respectively. Similar trend was also found in pooled data early fruit harvesting occurring in T_{13} treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO (44.43 days) and late fruit harvesting seen in T_1(control) (56.68 Days). These nanoparticles also influence structural modifications in plants, promoting better water retention and nutrient absorption, which are vital for early fruit development (Anusuya and Rajan, 2024). The time until okra fruit harvesting can be greatly shortened by applying foliar nano-fertilizers containing nitrogen, phosphorus, potassium, iron, zinc and Titanium (Prasad *et al.*, 2012b; Tarafdar *et al.*, 2014; Adhikari *et al.*, 2016). Zinc and titanium nutrients are essential for a number of physiological functions and their effective delivery through nanofertilizers promotes photosynthesis (Tighe-Neira *et al.*, 2020; Ogunkunle *et al.*, 2020) and metabolic activity (Sompornpailin and Chayaprasert, 2020), increases nutrient uptake (Satti *et al.*, 2021; Semida *et al.*, 2021; Pejam *et al.*, 2021) and utilisation and guarantees a balanced supply of nutrients (Sheteiwy *et al.*, 2021). This results in healthier plants that move from vegetative growth to flowering more quickly. The results are in confirmation with the findings of Mogazy and Hanafy (2022) and Carmona *et al.* (2021).

Number of flowers per plant

The findings of the number of flowers per plant of present experiment is showed in Table, which showed significant variation in Treatments on number of flowers per plant. It is clear from the data that T_{13} Treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO), recorded highest number of flowers per plant (22.83 and 22.86) followed by T_{12}Treatment (75% RDF + 2ml/l Nano Urea+ 10 ppm TiO_2) (22.33 and 22.37) and the minimum number of flowers per plant was noted in T_1(control) (15.77 and 15.80) during first and second year, respectively. Same trend was also reported in pooled data at 120 DAS, (22.80). The application of ZnO NPs has been shown to increase the concentration of key enzymes such as guaiacol peroxidase and polyphenol oxidase, which are crucial for flower development (Hafizi and Nasr, 2018). This effect is primarily due to the enhanced nutrient uptake, improved photosynthetic efficiency (Kah *et al*., 2013 and De Rosa *et al*., 2010) and increased stress resistance provided by the nano-sized particles (Subramanian *et al.,* 2015). The efficient absorption and utilization of nutrients lead to better overall plant growth and development, culminating in an increased number of flowers. Similar results were advocated by Raliya *et al.* (2014) and Sharma *et al.* (2018).

Fruit yield

It is clear from the data (Table 5) that T_{13} treatment (75% RDF + 2ml/l Nano Urea+ 50 ppm ZnO), recorded yield (157.69q/ha and 161.92 q/ha) followed by T_{12} Treatment (75% RDF + 2ml/l Nano Urea+ 10 ppm TiO_2) (149.32 q/ha and 150.60 q/ha) and the minimum yield was noted in T_1(control) (58.49 q/ha and 63.93q/ha) during first and second year, respectively. Same trend was also reported in pooled data at 120 DAS, (159.81q/ha). Zn NPs have been found to enhance photosynthetic parameters, leading to increased dry matter accumulation and grain yield in rice. The application of ZnO nanoparticles resulted in higher plant height and grain yield compared to conventional zinc fertilizers (Gobinath *et al*., 2024). In wheat, biosynthesized Zn NPs increased plant height, leaf area, and total dry matter production, contributing to higher grain and straw yields (Nazma *et al*., 2024).

Conclusion

On the basis of results of present investigation, it is clear that use of nano fertilizer is beneficial for okra production which can reduce the chemical fertilizer requirement. Among the treatments under study, it may be concluded that foliar application of 2 ml/l Nano urea + 50 ppm ZnO nanoparticles in two times 30 days and 60 days after seed sowing along with 75% recommended dose of fertilizer (RDF) significantly influenced the vegetative growth parameters of okra along with early flowering and more fruit yield of okra cv. Kashi Lalima grown at subtropical climate.

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