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Efficacy of Nano-fertilizers Applications on Growth Parameters and Flowering Dynamics in Okra (*Abelmoschus esculentus*)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The present study aimed to evaluate the effect of foliar nano-fertilizers on the growth and flowering of okra (*Abelmoschus esculentus*) during the Zaid seasons of 2022-23 and 2023-24 at the Vegetable Research Farm, Chandra Shekhar Azad University of Agriculture and Technology,

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Kanpur. A Factorial Randomized Block Design with 15 treatment combinations and three replications was employed, utilizing five major nutrients and three levels of micronutrients. The combination of 75% recommended soil applied NPK with foliar nano NPK (4 ml/L) and nano Zn and Fe (1g/4L) showed maximum improvements in growth parameters, including plant height (120.35cm), number of leaves/plant (55.38), number of nodes/plant (15.30), number of branches/plant (4.61), stem diameter (2.77cm) and minimum inter-nodal length (7.67cm) and flowering traits such as earlier first flowering (39.88 days), days to 50% flowering (44.36days) and increased flower production (22.60 flowers/plant).

Keywords: Nano-fertilizer; okra; foliar-application; growth and flowering.

1. INTRODUCTION

Okra (*Abelmoschus esculents*) is one of the most important rainy and summer season vegetable crop, belongs to family Malvaceae. Several workers have reported various numbers of chromosome ranging from 2n = 72 to 2n = 132, but 2n = 130 is the most common one in okra. It is known by many local names in different parts of the world. It is also known as lady's finger in England, guino - gombo in Spanish, gumbo in the United States of America, guibeiro in Portuguese and bhindi species in India. It is valued for its tender pods. Nutritionally, 100 g of edible portion of okra provide calories 35.0 mg, calcium 66.0 mg, moisture 89.6 g, iron 0.35 mg, carbohydrates 6.4 g, potassium 103.0 mg, protein 1.9 g, magnesium 53.0 mg, fat 0.2 g, copper 0.19 mg, fiber 1.2 g, riboflavin 0.01 mg, minerals 0.7g, thiamine 0.07 mg, phosphorus 56.0 mg, nicotinic acid 0.06 mg, sodium 6.9 mg, vitamin C 13.10 mg, sulphur 30.0 mg and oxalic acid 8.0 mg [1]. Dried seeds contain 13-22% edible oil and 20-24% protein and used for refined edible oil. Dry fruit skin and fibers are used in manufacture of paper, card board and fibers [2]. India is the largest producer of okra with 6.87 million tones that is account for 61.19 % of okra production in world followed by Nigeria 1.91 million tonnes [3]. In India, the annual production of okra is 6465 MT on an area of 530 thousand hectare with the productivity of 12.2 MT/hectare [4]. Okra requires adequate nutrients for better growth and flowering and most of Indian soils are deficient in major and micro nutrients. Indiscriminate use of conventional fertilizers by farmers for increasing crop productivity causes several problems like – water contamination, environmental pollution, soil degradation and food toxicity that caused health hazards for human beings and animals also. Nanotechnology is a better alternative for plant nutrition management because it does not degrade the health of soil, environment and food quality as well as maintains sustainability. The term "Nanotechnology" was first defined in 1974 by Norio Taniguchi of the Tokyo Science University [5]. Nanotechnology is the science and technology of tiny things, the materials that are less than 100 nm in size (1 Nanometer = 10^{-9} m = 1 billionth of a meter) [6]. The change in properties is due to the reduced molecular size and also because of changed interactions between molecules. Properties and possibilities of nanotechnology, which have more interest in agricultural revolution, are high reactivity, enhanced bioavailability and bioactivity, adherent effects and surface effects of nanoparticles [7]. Nanotechnology provides different nano devices and nano material which has a unique role in agriculture such as nano biosensors to detect moisture content and nutrient status of the soil and also applicable to site specific water and nutrient management, nano-fertilizers for efficient nutrient management, nano-herbicides for selective weed control in crop field, nano-nutrient particles to increase seed vigour, nano-pesticides for efficient pest management. Nano fertilizers increase the soil fertility, yield and quality of the crop, they are non-toxic and less harmful to humans and environment, they reduce the cost and increase profit. Nano fertilizers are required in very less amount since 500 ml nano-urea would able to replace 45 kg of urea and only 10 gm of nano-zinc would be sufficient for a hectare of land and thus help in reduction in the requirement of chemical fertilizers by 50% - 70% and raise crop production started by the Indian Farmers Fertilizer Co-operative Limited (IFFCO) [8].

2. MATERIALS AND METHODS

The experiment was conducted over two consecutive Zaid seasons, 2022-23 and 2023-24 at Vegetable Research Farm, Department of Vegetable Science, Chandra Shekhar Azad University of Agriculture & Technology, Kalyanpur, Kanpur, U.P. (208024) India. Geographically Kanpur is situated in the

Gangetic plains of alluvium soil of central U.P. It lies in altitude and longitude ranges between 25.28˚ to 28.50˚ north and 79.31˚ to 84.34˚ east at elevation of 125.90 m above mean sea level. The okra variety Pusa Bhindi-5 was used for carrying out of the experiment and seeds sowing were done at a spacing of 45cm row to row and 30cm plant to plant on 20th February during 2022-23 and 2023-24, respectively. The experiment followed a Factorial Randomized Block Design (FRBD) with 15 treatment combinations and three replications. Recommended package of practices were followed for the crop. Ten plants were selected randomly from each plot and tagged. The observations were recorded on growth characters *viz.,* plant height (cm), number of leaves, number of nodes, inter-nodal length (cm), number of branches, stem diameter (cm) and on flowering characters *viz.,* number of days to first flowering, days to 50% flowering, number of flowers/plant. The experiment comprised 5 major nutrients and 3 levels of micro nutrients which are given below in Table 1.

Table 1. Five major nutrients and three levels of micro nutrients

Sr.no.	Major nutrients	Notation	Micro nutrients	Notation
1.	Control (zero major nutrient application)	M_0	Control (zero micro nutrient application)	N_0
2.	Soil application of 100% Recommended NPK (100:60:50 kg/ha.)	M_1	Soil application of Zn and Fe @20kg/ha.	N_1
3.	Foliar application of Nano NPK @4ml/liter of water (Two spray)	M_2	Foliar application of Nano Zn and Nano Fe (Two spray @1g/4 liter of water)	N_2
4.	Soil application of 75% Recommended NPK + Foliar application of Nano NPK @4ml/liter of water (Two spray)	M_3		
5.	Soil application of 50% Recommended NPK + Foliar application of Nano NPK @4ml/liter of water (Two spray)	M_4		

Table 2. There are 15 treatment combinations as given below

Treatments	Notation	Treatment details
T_1	M_0N_0	Control (no nutrients application)
T_2	M_1N_0	[Soil application of 100% Recommended N,P,K (100:60:60 kg/ha.)] + (Control)
T_3	M_2N_0	[Foliar application of Nano N,P,K @4ml/liter of water (Two spray)] + (Control)
T_4	M_3N_0	[Soil application of 75% Recommended N,P,K + Foliar application of Nano N,P,K @4ml/liter of water (Two spray)] + (Control)
T_5	M_4N_0	[Soil application of 50% Recommended N,P,K + Foliar application of Nano N,P,K @4ml/liter of water (Two spray)] + (Control)
T_6	M_0N_1	Control (no nutrients application) + (Soil application of Zn and Fe @20kg/ha.)
T_7	M_1N_1	[Soil application of 100% Recommended N,P,K (100:60:60 kg/ha.)] + (Soil application of Zn and Fe @20kg/ha.)
T_8	M_2N_1	[Foliar application of Nano N,P,K @4ml/liter of water (Two spray)] + (Soil application of Zn and Fe @20kg/ha.)
T_9	M_3N_1	[Soil application of 75% Recommended N,P,K + Foliar application of Nano N,P,K @4ml/liter of water (Two spray)] + (Soil application of Zn and Fe @20kg/ha.)

Treatments	Notation	Treatment details
T_{10}	M_4N_1	[Soil application of 50% Recommended N,P,K + Foliar application of Nano N,P,K @4ml/liter of water (Two spray)] + (Soil application of Zn and Fe @20kg/ha.)
T_{11}	M_0N_2	[Control (no nutrients application)] + [Foliar application of Nano Zn and Nano Fe (Two spray @1g/4 liter of water)]
T_{12}	M_1N_2	[Soil application of 100% Recommended N,P,K (100:60:60 kg/ha.)] + [Foliar application of Nano Zn and Nano Fe (Two spray @1g/4 liter of water)]
T_{13}	M_2N_2	[Foliar application of Nano N,P,K @4ml/liter of water (Two spray)] + [Foliar application of Nano Zn and Nano Fe (Two spray @1g/4 liter of water)]
T_{14}	M_3N_2	[Soil application of 75% Recommended N,P,K + Foliar application of Nano N,P,K @4ml/liter of water (Two spray)] + [Foliar application of Nano Zn and Nano Fe (Two spray @1g/4 liter of water)]
T_{15}	M_4N_2	[Soil application of 50% Recommended N,P,K + Foliar application of Nano N,P,K @4ml/liter of water (Two spray)] + [Foliar application of Nano Zn and Nano Fe (Two spray @1g/4 liter of water)]

2.1 Statistical Analysis

The data were analyzed using Factorial Randomized Block Design (FRBD) as advised by [9].

2.2 Source of Fertilizers

2.2.1 Nano fertiliers

Nano NPK: Tropical Agro: Tag Nano NPK is an innovative, first of its kind product that combines gluconated fertilizers and Indian Council of Agricultural Research (ICAR) '4G' Nano nutrient technologies. Tag Nano NPK is a unique proteino-lacto-gluconate formulation, formulated with organic and chelated micro-nutrients, vitamins, probiotics, seaweed extracts, humic acid besides Nitrogen, Phosphorus and Potash.

Nano Zn and Fe: Geolife Agritech India Pvt. Ltd. : Nano Zn and Fe is a powder formulation which is chelated with 12% EDTA & Aminos.

2.2.2 Conventional fertilizers

Source of NPK: Urea (46% N), Di-ammonium Phosphate (18% N & 46% P_2O_5) and Muriate of Potash (60% K_2O), respectively.

2.2.3 Application of nano-fertilizers

Nano-fertilizers (NPK) were applied as foliar application @4ml/liter of water and (Fe and Zn) @1g/4 liter of water two times once at 25 days after seed sowing and second at 20 days after first spray.

3. RESULTS AND DISCUSSION

3.1 Growth Characters

3.1.1 Plant height (cm)

The plant height was recorded at 30, 60 and 90 days after sowing. The data showed that there were significant difference among major nutrients and micro-nutrients on plant height during both the years. The data presented in the Table 3, clearly indicate that at 30, 60 and 90 DAS, major nutrients M_3, had highest plant height (21.39 and 22.53 cm), (85.86 and 87.60 cm) and (112.84 and 114.89 cm) followed by M_1, (19.33 and 20.43 cm), (82.54 and 84.14 cm) and (108.01 and 109.90 cm), while lowest was recorded in M_0, (12.74 and 13.52 cm), (67.93 and 68.81 cm) and (84.94 and 86.37 cm) during first and second year, respectively. Similar trend was also reported in pooled data at 30, 60 and 90 DAS, (21.39cm), (86.73cm) and (114.89cm), respectively. In the case of micro-nutrients, there were also significant variations in observations, At all stages 30, 60 and 90 DAS, maximum plant height was recorded in N_2, (18.39 and 19.42 cm), (79.57 and 80.86 cm) and (101.64 and 103.34 cm) followed by (17.47 and 18.49 cm), (77.74 and 79.09 cm) and (98.98 and 100.83 cm) while minimum was recorded in N_0, (15.44 and 16.36 cm), (74.84 and 75.94 cm) and (93.64 and 95.33 cm) during first and second year, respectively. Similar trend was also found in pooled data at 30, 60 and 90 DAS, (18.91cm), (80.22cm) and (102.49cm), respectively. The combined effect of major and micro-nutrients also revealed that there were significant variations on plant height at all stages of plant growth. Among the interactions, at the all stages 30, 60 and 90 DAS, the maximum plant height was recorded under the treatment combination M_3N_2, (23.94 and 25.12 cm), (89.55 and 91.34 cm) and (119.25 and 121.45 cm) followed by M_3N_1, (21.78 and 22.92 cm), (86.25 and 88.62 cm) and (114.50 and 116.38 cm) while minimum was recorded in treatment combination M_0N_0, (10.22 and 10.65 cm), (64.22 and 65.12 cm) and (81.25 and 82.10 cm) during first and second year, respectively. Same trend was also reported in pooled data at 30, 60 and 90 DAS, (24.53cm), (90.45cm) and (120.35cm), respectively. The application of nano-fertilizers can significantly enhance the growth and height of okra plants by providing essential nutrients in a more efficient and targeted manner. These nano-fertilizers improve nutrient uptake, utilization and overall plant health, leading to increased vegetative growth and plant height. Similar results also reported by [10] and [11].

3.1.2 Number of leaves per plant

The number of leaves/plant were counted at 30, 60 and 90 DAS. The data in Table 3 indicate significant changes in major nutrients and micro-nutrients on number of leaves at the all stages of growth, during both the years. The data revealed that at 30, 60 and 90 DAS, major nutrients M_3, recorded highest number of leaves/plant (13.79 and 14.86), (43.13 and 44.23) and (52.14) followed by M_1, (12.57 and 13.67), (40.83 and 41.82) and (49.60 and 50.61) whereas the lowest was found in M_0, (9.47 and 10.22), (31.88 and 32.68) and (40.35 and 41.23) during first and second year, respectively. Similar trend was also found in pooled data at 30, 60 and 90 DAS, (14.33), (43.68) and (52.66), respectively. In the case of micro-nutrients, it was recorded that the micro-nutrient N_2 produce maximum number of leaves/plant (12.22 and 13.28), (38.85 and 39.84) and (48.04 and 49.05) followed by N_1, (11.67 and 12.65), (37.84 and 38.85) and (47.11 and 48.07) whereas the lowest was found in N_0 (10.74 and 11.64), (35.37 and 36.28) and (44.32 and 45.21) during first and second year, respectively. Same trend was also found in pooled data at 30, 60 and 90 DAS, (12.75), (39.35) and (48.55), respectively. The combination effect of major and micro-nutrients also found significant effect on number of leaves/plant at all stages of plant growth. Among interactions, the maximum number of leaves/plant (15.45 and 16.55), (45.72 and 46.85) and (54.82 and 55.94) were recorded in treatment combination M_3N_2, followed by M_3N_1, (13.78 and 14.82), (43.58 and 44.61) and (52.78 and 53.82) whereas the lowest was found in treatment combination M_0N_0 (8.42 and 8.78), (28.75 and 29.24) and (36.25 and 37.02) at all stages during first and second year, respectively. Similar trend was also found in pooled data at 30, 60 and 90 DAS, (16.00), (46.29) and (55.38), respectively. The application of nano-fertilizers in okra can lead to improved nutrient uptake, better photosynthetic efficiency, enhanced stress resistance and hormonal regulation, all contributing to an increase in the number of leaves. These findings were closely related with the result of [12,13] and [14].

3.1.3 Number of nodes per plant

The number of nodes/plant were counted at 90 DAS. The data regarding to number of nodes/plant of okra is presented in Table 3. After perusal of the data, it is clear that maximum number of nodes/plant (13.09 and 13.22) was noted in major nutrients M_3 followed by M_1, (11.13 and 11.26) and minimum in M_0 (5.86 and 5.96) during first and second year, respectively. Same trend was also reported in pooled data at 90 DAS, (13.26). The effect of micro-nutrients on number of nodes/plant was also found significant and maximum number of nodes/plant was recorded in N_2, (10.20 and 10.33) followed by N_1, (9.38 and 9.51) and minimum was found in N_0, (8.09 and 8.20) during first and second year, respectively. Similar trend was also reported in pooled data at 90 DAS, (10.27). The combined effect of major and micro-nutrients on number of leaves/plant was also found significant and maximum number of nodes /plant was found in treatment combination M_3N_2, (15.24 and 15.35) followed by M_3N_1, (13.58 and 13.72) and minimum number of nodes /plant was found in M_0N_0 (5.10 and 5.18) during first and second year, respectively. Same trend was also reported in pooled data at 90 DAS, (15.30). Foliar application of nano-fertilizers (N, P, K, Fe, and Zn) can significantly increase the number of nodes in okra by enhancing nutrient availability, uptake, and utilization. This leads to improved plant growth, vigor and overall development. The use of nano-fertilizers offers a more efficient and targeted delivery of nutrients, promoting better growth responses compared to conventional fertilizers. Similar findings were also noticed by [15,16,17] and [18].

Table 3. Effect of Foliar Application of Nano-fertilizers on Plant height (cm), Number of Leaves per plant, Number of Nodes per plant and Inter-nodal Length (cm)

Treatments	Plant Height (cm)									Number of Leaves per plant									Number of Nodes per plant			Inter-nodal Length (cm)		
	At 30 DAS			At 60 DAS			At 90 DAS			At 30 DAS			At 60 DAS			At 90 DAS			At 90 DAS			At 90 DAS		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
Effect of Major Nutrients																								
M_0	12.74	13.52	12.74	67.93	68.81	68.37	84.94	86.37	85.66	9.47	10.22	9.85	31.88	32.68	32.28	40.35	41.23	40.79	5.86	5.96	5.91	14.25	14.45	14.35
M_1	19.33	20.43	19.33	82.54	84.14	83.34	108.01	109.90	108.96	12.57	13.67	13.12	40.83	41.82	41.33	49.60	50.61	50.11	11.13	11.26	11.20	9.66	9.74	9.70
M_2	15.29	16.23	15.29	73.06	73.93	73.50	89.58	91.32	90.45	10.62	11.58	11.10	34.59	35.57	35.08	44.30	45.22	44.76	7.33	7.45	7.39	12.09	12.17	12.13
M_3	21.39	22.53	21.39	85.86	87.60	86.73	112.84	114.89	113.87	13.79	14.86	14.33	43.13	44.23	43.68	52.14	53.17	52.66	13.09	13.22	13.16	8.61	8.71	8.66
M_4	16.74	17.73	16.74	77.51	78.66	78.09	95.05	96.68	95.87	11.27	12.28	11.78	36.33	37.32	36.83	46.06	46.98	46.52	8.71	8.84	8.78	10.64	10.80	10.72
SE(m) ±	0.31	0.32	0.21	1.37	1.39	1.06	1.74	1.76	1.32	0.21	0.22	0.14	0.66	0.68	0.46	0.82	0.84	0.61	0.17	0.17	0.09	0.20	0.20	0.13
CD at 5%	0.89	0.94	0.65	3.98	4.05	3.02	5.06	5.13	4.57	0.60	0.65	0.48	1.93	1.98	1.43	2.40	2.44	1.96	0.50	0.50	0.31	0.58	0.58	0.42
Effect of Micro Nutrients																								
N_0	15.44	16.36	15.90	74.84	75.94	75.39	93.64	95.33	94.49	10.74	11.64	11.19	35.37	36.28	35.83	44.32	45.21	44.77	8.09	8.20	8.15	11.85	12.00	11.93
N_1	17.47	18.49	17.98	77.74	79.09	78.42	98.98	100.83	99.91	11.67	12.65	12.16	37.84	38.85	38.35	47.11	48.07	47.59	9.38	9.51	9.45	10.93	11.05	10.99
N_2	18.39	19.42	18.91	79.57	80.86	80.22	101.64	103.34	102.49	12.22	13.28	12.75	38.85	39.84	39.35	48.04	49.05	48.55	10.20	10.33	10.27	10.36	10.47	10.42
SE(m) ±	0.24	0.25	0.16	1.06	1.08	0.94	1.35	1.37	1.09	0.16	0.17	0.07	0.51	0.53	0.31	0.64	0.65	0.48	0.13	0.13	0.07	0.15	0.16	0.08
CD at 5%	0.69	0.73	0.55	3.09	3.14	2.76	3.92	3.97	3.37	0.46	0.50	0.25	1.50	1.53	1.04	1.86	1.89	1.54	0.38	0.39	0.27	0.45	0.45	0.32
Interaction (Major ×Micro Nutrients)																								
M_0N_0	10.22	10.65	10.44	64.22	65.12	64.67	81.25	82.10	81.68	8.42	8.78	8.60	28.75	29.24	29.00	36.25	37.02	36.64	5.10	5.18	5.14	15.34	15.70	15.52
M_0N_1	13.88	14.82	14.35	68.92	69.86	69.39	86.32	87.96	87.14	9.85	10.75	10.30	33.12	34.16	33.64	42.15	43.08	42.62	6.12	6.22	6.17	13.98	14.02	14.00
M_0N_2	14.12	15.10	14.61	70.65	71.44	71.05	87.25	89.06	88.16	10.14	11.12	10.63	33.76	34.64	34.20	42.65	43.58	43.12	6.36	6.47	6.42	13.42	13.62	13.52
M_1N_0	17.57	18.68	18.13	80.23	81.76	81.00	101.45	103.35	102.40	11.72	12.84	12.28	38.22	39.30	38.76	47.45	48.38	47.92	9.72	9.85	9.79	10.22	10.38	10.30
M_1N_1	19.68	20.76	20.22	83.14	84.55	83.85	110.25	112.12	111.19	12.76	13.82	13.29	41.72	42.68	42.20	50.24	51.20	50.72	11.22	11.34	11.28	9.78	9.83	9.81
M_1N_2	20.75	21.84	21.30	84.26	86.12	85.19	112.34	114.22	113.28	13.22	14.35	13.79	42.54	43.48	43.01	51.12	52.26	51.69	12.46	12.58	12.52	8.97	9.02	9.00
M_2N_0	14.76	15.65	15.21	71.66	72.54	72.10	88.55	90.26	89.41	10.42	11.34	10.88	34.12	35.08	34.60	43.74	44.64	44.19	6.92	7.02	6.97	12.74	12.74	12.74
M_2N_1	15.22	16.30	15.76	72.80	73.68	73.24	89.42	91.35	90.39	10.61	11.55	11.08	34.54	35.48	35.01	44.26	45.18	44.72	7.23	7.36	7.30	12.11	12.32	12.22
M_2N_2	15.89	16.74	16.32	74.72	75.56	75.14	90.78	92.35	91.57	10.82	11.86	11.34	35.10	36.16	35.63	44.90	45.85	45.38	7.84	7.96	7.90	11.43	11.46	11.45
M_3N_0	18.45	19.56	19.01	81.78	82.85	82.32	104.78	106.86	105.82	12.15	13.22	12.69	40.10	41.22	40.66	48.82	49.76	49.29	10.45	10.58	10.52	9.96	10.04	10.00
M_3N_1	21.78	22.92	22.35	86.25	88.62	87.44	114.50	116.38	115.44	13.78	14.82	14.30	43.58	44.61	44.10	52.78	53.82	53.30	13.58	13.72	13.65	8.24	8.36	8.30
M_3N_2	23.94	25.12	24.53	89.55	91.34	90.45	119.25	121.45	120.35	15.45	16.55	16.00	45.72	46.85	46.29	54.82	55.94	55.38	15.24	15.35	15.30	7.62	7.72	7.67
M_4N_0	16.21	17.24	16.73	76.30	77.44	76.87	92.15	94.08	93.12	11.00	12.02	11.51	35.64	36.56	36.10	45.34	46.26	45.80	8.24	8.36	8.30	10.97	11.12	11.05
M_4N_1	16.78	17.66	17.22	77.56	78.72	78.14	94.40	96.35	95.38	11.34	12.30	11.82	36.24	37.32	36.78	46.12	47.06	46.59	8.76	8.89	8.83	10.56	10.73	10.65
M_4N_2	17.23	18.28	17.76	78.66	79.82	79.24	98.60	99.60	99.10	11.48	12.52	12.00	37.10	38.08	37.59	46.72	47.62	47.17	9.12	9.26	9.19	10.38	10.54	10.46
SE(m) ±	0.53	0.56	0.39	2.37	2.41	1.96	3.01	3.05	2.37	0.36	0.39	0.26	1.15	1.18	1.02	1.42	1.45	1.26	0.29	0.30	0.19	0.34	0.35	0.21
CD at 5%	1.546	1.635	1.59	N/A	N/A	N/A	N/A	N/A	N/A	1.04	1.13	0.85	N/A	N/A	N/A	N/A	N/A	N/A	0.86	0.86	0.64	N/A	N/A	N/A

3.1.4 Inter-nodal Length (cm)

The inter-nodal length was measured at 90 DAS. The data regarding to inter-nodal length of okra has showed in Table 3. After perusal of the data, it is clear from the table that lowest inter-nodal length was noted in major nutrient M_3 (8.61 and 8.71 cm) followed by M_1, (9.66 and 9.74 cm) while maximum inter-nodal length was found in M_0 (14.25 and 14.45 cm) during first and second year, respectively. Similar trend was also found in pooled data at 90 DAS, (8.66cm). The effect of micro-nutrients on inter-nodal length was also found significant and minimum inter-nodal length was found in N_2, (10.36 and 10.47 cm) followed by N_1, (10.93 and 11.05 cm) while maximum inter-nodal length was found in N_0 (11.85 and 12.00 cm) during first and second year, respectively. Same trend was also reported in pooled data at 90 DAS, (10.42 cm). The combined effect of major and micro-nutrients on inter-nodal length was also found significant and minimum inter-nodal length was reported in treatment combination M_3N_2, (7.62 and 7.72 cm) followed by M_3N_1, (8.24 and 8.36 cm) and maximum inter-nodal length was found in M_0N_0 (15.34 and 15.70 cm) during first and second year, respectively. Similar trend was also found in pooled data at 90 DAS, (7.67cm). This might be due to improving nutrient availability and enhancing various physiological processes, the foliar application of nano-fertilizers can significantly contribute to the increased inter-nodal length of okra. This result corroborated the finding of [19,20,21,22] and [23].

3.1.5 Number of branches per plant

We counted the number of branches per plant at 60 and 90 DAS. The data recorded in Table 4 indicates that there were a significant effect in major nutrients and micro-nutrients on number of branches/plant at the all stages of growth, during both the years. At 60 and 90 DAS, treatment M_3 recorded the highest number of branches per plant (2.47 and 2.70 at 60 DAS; 4.36 and 4.49 at 90 DAS), followed by M_1, with 2.33 and 2.46 branches at 60 DAS, and 4.18 and 4.30 at 90 DAS. The lowest number of branches was observed in M_0 (1.45 and 1.53 at 60 DAS; 2.97 and 3.06 at 90 DAS) during both years. Pooled data at 60 and 90 DAS similarly showed significant differences, with treatment M_3 leading with 2.59 branches at 60 DAS and 4.43 branches at 90 DAS. For the micro-nutrients, treatment N_2 produced the maximum number of branches (2.15 and 2.29 at 60 DAS; 3.97 and 4.08 at 90 DAS), followed by N_1, while the lowest branch number was observed in N_0. The combined effect of major and micro-nutrients was also significant. The highest number of branches (2.62 and 2.92 at 60 DAS; 4.54 and 4.68 at 90 DAS) was recorded in the M_3N_2 combination, while the minimum number of branches was found in the M_0N_0 treatment. These findings align with previous research [24,25,26] and [27], which demonstrated that foliar application of nano-fertilizers containing NPK, Fe, and Zn significantly enhances nutrient uptake, photosynthesis, hormonal balance, and stress tolerance, ultimately increasing the number of branches in okra.

3.1.6 Stem diameter (cm)

The stem diameter was measured at 90 DAS. The data regarding to stem diameter presented in Table 4. It is evident from the data that maximum stem diameter (2.39 and 2.42 cm) was noted in major nutrient M_3 followed by M_1, (2.34 and 2.37 cm) while the minimum stem diameter (1.84 and 1.87 cm) was reported in M_0, during first and second year, respectively. Same trend was also reported in pooled data at 90 DAS, (2.41cm). The effect of micro-nutrients on stem diameter was also found significant and maximum stem diameter was found in N_2, (2.20 and 2.24 cm) followed by N_1, (2.15 and 2.19 cm) while minimum stem diameter was found in N_0 (2.08 and 2.12 cm) during first and second year, respectively. Similar trend was also reported in pooled data at 90 DAS, (2.22cm). The combined effect of major and micro-nutrients on stem diameter was also found to be significant and highest stem diameter was found in treatment combination M_3N_2, (2.45 and 2.49 cm) followed by M_3N_1, (2.41 and 2.44 cm) and lowest stem diameter was found in M_0N_0 (1.77 and 1.80 cm) during first and second year, respectively. Same trend was also reported in pooled data at 90 DAS, (2.77cm). The use of nano-fertilizers for nitrogen, phosphorus, potassium, iron, and zinc can positively affect the stem diameter of okra by improving nutrient availability and uptake. This results in enhanced plant growth and structural development. These results are close conformity with earlier reports of [28,29,30,31] and [32].

3.2 Flowering Characters

3.2.1 Number of days to first flowering

An inquisition of data in Table 4, clearly indicate that among the major nutrients, minimum number of days to first flowering (41.08 and 40.35 days) was recorded in major nutrient M_3, followed by

M_1, (41.87 and 41.28 days) and maximum number of days to first flowering (47.15 and 46.39 days) was noted in M_0, during first and second year, respectively. Similar trend was also found in pooled data at 90 DAS, (40.72 days). The minimum number of days to first flowering (43.12 and 42.41 days) was noted in micro-nutrients N_2, followed by N_1, (43.54 and 42.83 days) while the maximum number of days to first flowering (44.77 and 44.10 days) was observed in N_0 during first and second year, respectively. Same trend was also reported in pooled data at 90 DAS, (42.77 days). The combined effect of major and micro-nutrients showed influence on number of days to first flowering. Among the treatments M_3N_2, recorded lowest number of days to first flowering (40.30 and 39.45 days) followed by M_3N_1, (40.85 and 40.05 days) and maximum number of days to first flowering (49.24 and 48.48 days) was noted in M_0N_0, during first and second year, respectively. Similar trend was also reported in pooled data at 90 DAS, (39.88 days). The foliar application of nano-fertilizers containing nitrogen, phosphorus, potassium, iron and zinc can significantly reduce the number of days to first flowering in okra. These nutrients play vital roles in various physiological processes and their efficient delivery through nano-fertilizers enhances nutrient uptake and utilization, improves photosynthesis and metabolic activities and ensures a balanced nutrient supply. This results in healthier plants that transition from vegetative growth to flowering more quickly. The results are in confirmation with the findings of [33,34] and [35].

3.2.2 Days to 50% flowering

As the data revealed from the Table 4. It is clear that major nutrient M_3, had minimum days to 50% flowering (45.40 and 44.61 days) followed by M_1, (46.02 and 45.39 days) while the maximum days to 50% flowering (51.87 and 51.19 days) was found in M_0, during first and second year, respectively. Similar trend was also found in pooled data at 90 DAS, (45.01 days). Among the micro-nutrients, minimum days to 50% flowering (47.75 and 46.97 days) was noted in N_2, followed by N_1, (48.15 and 47.39 days) while maximum days to 50% flowering (49.02 and 48.26 days) was noted in N_0, during first and second year, respectively. Same trend was also reported in pooled data at 90 DAS, (47.36 days). Among the treatment combination, M_3N_2, recorded lowest days to 50% flowering (44.76 and 43.95 days) followed by M_3N_1, (44.88 and 44.12 days) and highest days to 50% flowering was reported in M_0N_0, (52.68 and 52.24 days) during first and second year, respectively. Similar trend was also reported in pooled data at 90 DAS, (44.36 days). This effect is due to the enhanced nutrient uptake and efficiency, improved photosynthesis and optimized hormonal balance provided by the nano-fertilizers. Each nutrient contributes uniquely to accelerating the flowering process: nitrogen for vegetative growth, phosphorus for energy transfer and root development, potassium for physiological regulation, iron for chlorophyll synthesis and photosynthesis and zinc for enzyme activation and protein synthesis. These combined effects result in faster development and earlier flowering in okra. These results are in aggregate with those obtained by [36,37,38,39] and [40].

3.2.3 Number of flowers per plant

The findings of the number of flowers per plant of present experiment is showed in Table 4, which showed significant variation in major and micro-nutrients on number of flowers per plant. It is clear from the data that major nutrients M_3, recorded highest number of flowers per plant (21.71 and 22.15) followed by M_1, (20.86 and 21.48) and the lowest number of flowers per plant was noted in M_0, (16.45 and 16.63) during first and second year, respectively. Same trend was also reported in pooled data at 90 DAS, (21.93). Among the micro-nutrients, maximum number of flowers per plant (19.64 and 20.02) was found in N_2, followed by N_1 (19.15 and 19.68) whereas minimum number of flowers per plant (18.38 and 18.78) was noted in N_0, during first and second year, respectively. Similar trend was also found in pooled data at 90 DAS, (19.83). The combination effect of major and micro-nutrients also revealed statistically significant influence on number of flowers per plant. Among the treatment combination, M_3N_2, recorded highest number of flowers per plant (22.34 and 22.86) followed by M_3N_1, (22.11 and 22.54) and minimum was noted in M_0N_0, (16.00 and 16.10) during first and second year, respectively. Same trend was also reported in pooled data at 90 DAS, (22.60). This effect is primarily due to the enhanced nutrient uptake, improved photosynthetic efficiency and increased stress resistance provided by the nano-sized particles. 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 [41,42,43] and [44].

Table 4. Effect of Foliar Application of Nano-fertilizers on number of branches per plant, Stem Diameter, Number of days to first flowering, Number of flowers per plant and Days to 50% flowering

Treatments	Number of Branches per plant						Stem Diameter (cm)			Number of days to first flowering			Number of flowers per plant			Days to 50% flowering		
	At 60 DAS			At 90 DAS			At 90 DAS											
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
Effect of Major Nutrients																		
M_0	1.45	1.53	1.49	2.97	3.06	3.02	1.84	1.87	1.86	47.15	46.39	46.77	16.45	16.63	16.54	51.87	51.19	51.53
M_1	2.33	2.46	2.40	4.18	4.30	4.24	2.34	2.37	2.36	41.87	41.28	41.58	20.86	21.48	21.17	46.02	45.39	45.71
M_2	1.83	1.90	1.87	3.55	3.66	3.61	1.99	2.05	2.02	45.27	44.52	44.90	17.42	17.86	17.64	49.61	48.79	49.20
M_3	2.47	2.70	2.59	4.36	4.49	4.43	2.39	2.42	2.41	41.08	40.35	40.72	21.71	22.15	21.93	45.40	44.61	45.01
M_4	2.03	2.11	2.07	3.85	3.94	3.90	2.16	2.20	2.18	43.66	43.03	43.35	18.83	19.35	19.09	48.64	47.71	48.18
SE(m) ±	0.04	0.04	0.03	0.07	0.07	0.04	0.04	0.04	0.02	0.77	0.76	0.61	0.34	0.35	0.25	0.85	0.84	0.69
CD at 5%	0.11	0.11	0.10	0.20	0.20	0.15	0.11	0.11	0.08	2.25	2.21	1.95	0.98	1.01	0.84	2.48	2.44	2.08
Effect of Micro Nutrients																		
N_0	1.85	1.94	1.90	3.53	3.63	3.58	2.08	2.12	2.10	44.77	44.10	44.44	18.38	18.78	18.58	49.02	48.26	48.64
N_1	2.06	2.19	2.13	3.86	3.97	3.92	2.15	2.19	2.17	43.54	42.83	43.19	19.15	19.68	19.42	48.15	47.39	47.77
N_2	2.15	2.29	2.22	3.97	4.08	4.03	2.20	2.24	2.22	43.12	42.41	42.77	19.64	20.02	19.83	47.75	46.97	47.36
SE(m) ±	0.03	0.03	0.02	0.05	0.05	0.03	0.03	0.03	0.02	0.60	0.59	0.48	0.26	0.27	0.19	0.66	0.65	0.51
CD at 5%	0.08	0.09	0.07	0.15	0.16	0.11	0.09	0.09	0.07	N/A	N/A	N/A	0.76	0.78	0.62	N/A	N/A	N/A
Interaction (Major ×Micro Nutrients)																		
M_0N_0	1.05	1.15	1.10	2.26	2.35	2.31	1.77	1.80	1.79	49.24	48.48	48.86	16.00	16.10	16.05	52.68	52.24	52.46
M_0N_1	1.60	1.68	1.64	3.27	3.36	3.32	1.84	1.88	1.86	46.32	45.56	45.94	16.57	16.77	16.67	51.70	50.85	51.28
M_0N_2	1.69	1.76	1.73	3.37	3.47	3.42	1.90	1.94	1.92	45.89	45.13	45.51	16.78	17.02	16.90	51.23	50.48	50.86
M_1N_0	2.19	2.30	2.25	4.02	4.12	4.07	2.28	2.32	2.30	42.74	42.11	42.43	19.88	20.67	20.28	46.95	46.11	46.53
M_1N_1	2.36	2.47	2.42	4.22	4.34	4.28	2.36	2.38	2.37	41.56	40.96	41.26	20.95	21.76	21.36	45.78	45.34	45.56
M_1N_2	2.45	2.61	2.53	4.31	4.43	4.37	2.38	2.41	2.40	41.32	40.76	41.04	21.76	22.02	21.89	45.33	44.72	45.03
M_2N_0	1.76	1.82	1.79	3.46	3.56	3.51	1.94	1.99	1.97	45.64	44.88	45.26	17.01	17.28	17.15	49.94	49.06	49.50
M_2N_1	1.82	1.90	1.86	3.52	3.65	3.59	1.98	2.05	2.02	45.31	44.55	44.93	17.27	17.96	17.62	49.67	48.86	49.27
M_2N_2	1.90	1.97	1.94	3.67	3.77	3.72	2.06	2.10	2.08	44.87	44.12	44.50	17.98	18.34	18.16	49.21	48.44	48.83
M_3N_0	2.28	2.38	2.33	4.13	4.23	4.18	2.32	2.35	2.34	42.10	41.56	41.83	20.67	21.04	20.86	46.56	45.76	46.16
M_3N_1	2.51	2.78	2.65	4.42	4.55	4.49	2.41	2.44	2.43	40.85	40.05	40.45	22.11	22.54	22.33	44.88	44.12	44.50
M_3N_2	2.62	2.92	2.77	4.54	4.68	4.61	2.45	2.49	2.47	40.30	39.45	39.88	22.34	22.86	22.60	44.76	43.95	44.36
M_4N_0	1.98	2.04	2.01	3.78	3.86	3.82	2.11	2.15	2.13	44.11	43.46	43.79	18.32	18.83	18.58	48.98	48.12	48.55
M_4N_1	2.02	2.10	2.06	3.85	3.94	3.90	2.16	2.20	2.18	43.67	43.04	43.36	18.83	19.35	19.09	48.70	47.76	48.23
M_4N_2	2.10	2.19	2.15	3.93	4.03	3.98	2.21	2.26	2.24	43.21	42.58	42.90	19.32	19.88	19.60	48.24	47.25	47.75
SE(m) ±	0.06	0.07	0.04	0.12	0.12	0.09	0.07	0.07	0.04	1.34	1.32	1.19	0.58	0.60	0.45	1.48	1.45	1.29
CD at 5%	0.18	0.19	0.14	0.34	0.35	0.30	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

4. CONCLUSION

On the basis of results of present investigation, it may be concluded that the combination of soil application of 75% recommended NPK + foliar application of nano NPK @ 4ml/liter of water coupled with foliar application of nano Zn and nano Fe @ 1g/4 liter of water were recorded maximum on growth characters *viz.,* plant height (cm), number of leaves/plant, number of nodes/plant, inter-nodal length (cm), number of branches/plant, stem diameter (cm) and on flowering characters *viz.,* number of days to first flowering, days to 50% flowering, number of flowers/plant.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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