**Effect of Botanical based Nano Formulations on the Morphological Growth and Yield of Okra (*Abelmoschus esculentus* L.)**

**ABSTRACT:**

Agriculture has to face major challenges related to the provision of a sufficient quantity of healthy food for a constantly increasing world population considering decreasing arable areas and approaching the limits of genetic potential of crops, the only solution to achieve this is the enhancement of crop yield and its protection. Okra requires high quantities of both macro and micro nutrients for economic production. Nitrogen, phosphorus and potash nutrients are important and play a key role in the production of both quantity and quality level in okra. The present study aimed to determines the effect of botanical based nano formulations on the morphological growth and yield of okra (*Abelmoschus esculentus* L.). An experiment was conducted at the Main Vegetable Research Station, Anand Agricultural University, Anand with a view to study the effect of botanical-based nano-formulations on the morpho-physiological growth of okra (*abelmoschus esculentus* L.) during the summer and *kharif,* 2024. The experiment was arranged in randomized block design (RBD) with three replication having thirteen treatments (**T1:** Control, **T2:** RDF, **T3:** 50% RDN + 10% GNF, **T4:** 50% RDN + 15% GNF, **T5:** 50% RDN + 20% GNF, **T6:** 50% RDN + 10% MNF, **T7:** 50% RDN + 15% MNF, **T8:** 50% RDN + 10% GNF + 10% MNF, **T9:** 50% RDN + 10% GNF + 15% MNF, **T10:** 50% RDN + 15% GNF + 10% MNF, **T11:** 50% RDN + 15% GNF + 15% MNF, **T12:** 50% RDN + 20% GNF + 10% MNF and **T13:** 50% RDN + 20% GNF + 15% MNF. The results revealed that the treatments included 50% Recommended Dose of Nitrogen supplemented with varying levels of GNF and MNF. The growth parameters, such as plant height, number of branches and dry matter accumulation were significantly influenced by treatments. The highest values across 60, 90 days after sowing (DAS) and harvest were consistently observed under treatment T8 (50% RDN + 10% GNF + 10% MNF), while the lowest were recorded in the control treatment (T1). Though crop growth rate (CGR) was not significantly affected during early stages (30–60 and 60–90 DAS), a marked improvement was recorded during the 90 DAS to harvest phase in pooled analysis, indicating cumulative effects of the nano formulations. Where, GNF: Gliricidia Nano formulation and MNF: Moringa Nano formulation. Foliar spraying of nano formulations significantly increased the number of fruits per plant, fruit length, and fruit weight in okra. The enhanced yield may be attributed to improved biomass dry matter (BMD), along with better morpho-physiological and biochemical traits.

**Keywords:** Morphological parameters, yield Parameter, Botanical based extract, RDF, RDN, GNF, MNF

**Introduction**

Agro-nanotechnology-the use of nanotechnology to agriculture-has been the subject of a number of research programs in recent years, and it has had a significant impact on global trade. Because of the high adsorption capacity, surface area, and controlled release of nutrients to specific areas that this technique produces, the nano-nutrient fertilizers can be considered as intelligent nutrient delivery systems (Ghuge et al., 2024).Okra (*Abelmoschus esculentus*), commonly known as lady’s finger, bhindi or gumbo, is a seed-propagated crop well-suited to warm climates. It is highly sensitive to frost, low temperatures (below 15°C), waterlogging and drought. Okra is predominantly cultivated in tropical and subtropical regions and also in the warmer zones of temperate regions. The crop flourishes in hot and humid conditions, with optimal growth and fruiting observed at average temperatures around 25°C and relative humidity ranging from 65–85%. Seed germination in okra is most efficient at temperatures between 30–35°C. When temperatures fall below 25°C, germination slows down considerably, while temperatures above 42°C negatively impact plant and fruit development, causing desiccation, drying and premature dropping of flower buds. Okra plays an important role in the diet by supplying carbohydrate, protein, fat, minerals and vitamins that are usually deficient in the staple food. It is basically low in calories and dry matter constituents which when consumed in a meal with basic starchy food makes the food more palatable (Lekshmi et al., 2022).

In India, major okra-producing states are Gujarat, Maharashtra, Andhra Pradesh, Uttar Pradesh, Tamil Nadu, Karnataka, Haryana and Punjab, where it is grown during both the *kharif* and summer seasons. In Gujarat, key okra-growing districts include Surat, Tapi, Navsari, Banaskantha, Vadodara, Kheda, Bharuch, Anand and Mahesana. Nationwide, okra is cultivated over an area of 5.50 lakh hectares, yielding an annual production of 68.73 lakh tonnes with an average productivity of 12.50 tonnes per hectare (Anon., 2023). In Gujarat, the crop occupies 0.91 lakh hectares, producing 10.98 lakh tonnes, with a productivity of 12.04 tonnes per hectare (Anon., 2023).

Okra requires high quantities of both macro and micro nutrients for economic production. Nitrogen, phosphorus and potash nutrients are important and play a key role in the production of both quantity and quality level in okra. These nutrients are specific in function and must be supplied to the plant at the right time and in the right quantity. Indiscriminate use of inorganic fertilizers has resulted in decreased nutrient uptake, poor quality of vegetables and deterioration of soil fertility (Agrawal, 2003).

Currently, agriculture has to face major challenges related to the provision of a sufficient quantity of healthy food for a constantly increasing world population Taking into account decreasing arable areas and approaching the limits of the genetic potential of crops, the only solution to achieve this is the enhancement of crop yield and its protection. It is important to produce high-quality nutritious food, which could help in the protection against hunger and malnutrition (Povero *et al.,* 2016; Zulfiqar *et al.,* 2020; Kumar and Aloke, 2020; Colla *et al.,* 2017; Rouphael and Colla, 2018).

Nowadays, farmers and researchers put close attention to biostimulants to improve agricultural sustainability, however, other natural products should be considered, studied and assessed and the present review intends to highlight the importance of plant extracts to improve agricultural sustainability and in particular, crops quality and quantity. Primary and secondary plant metabolites affect important biological activities, influencing plant physiological responses and plant phenotype. Several previous studies reported the effects of plant extracts on hormones and polyphenols (Lucini *et al.,* 2018), organic acids and sugars contents (Abou Chehade *et al.,* 2018).

*Moringa oleifera* leaf extract as an organic bio-stimulant for the growth of various plants. Effect of the natural growth stimulant *moringa oleifera* leaf extract and its important role in triggering growth and boosting the economic yield of crops. High performance in the yield of plants by using bio-stimulant showed healthier results in various plants like capsicum, brinjal and etc. The effect of *moringa oleifera* was studied and the enhancement of plant height, early bloom, chlorophyll content, number of vegetables per plant, seedling germination and nutrient content of shoot tissues. Application of natural plant growth enhancers in the form of diluted *moringa oleifera* leaf extracts containing effective micronutrients has been reported and found to be very effective in the growth of various crops (Karthiga *et al.*, 2022).

*Gliricidia sepium* is a leguminous tree and is used in many tropical and sub-tropical countries as live fencing. The foliage of *gliricidia sepium* is used for green manuring and to produce other kinds of organic manure due to its higher nutritional composition (Ganesan, 1994). It is a perennial, medium-sized (2-15 m high) legume tree. It is mostly deciduous during the dry season but is reported to remain evergreen in humid areas. It is one of the major tropical forage trees due to its protein-rich forage and high nutritive value. It is also possible to make silage from chopped forage, which may be mixed with grasses or maize. Additives, such as molasses, sugarcane or formic acid (0.85%), should be added to provide fermentable carbohydrates (Wiersum and Nitis, 1992).

Nanotechnology is the most dynamic subject of material science study and the production of nanoparticles (NPs) is rapidly increasing around the world. NPs display completely new or improved properties as a result of specific qualities, such as size (1–100 nm), shape and structure (Nejatzadeh, 2021; Taran *et al.,* 2017). Inorganic and organic NPs are the two types of NPs that can be synthesized. Inorganic nanoparticles include metallic nanoparticles (like Au, Ag, Cu, Al), magnetic nanoparticles (like Co, Fe, Ni) and semi-conductor nanoparticles (like ZnO, ZnS, CdS), while organic nanoparticles include carbon nanoparticles (like quantum dots, carbon nanotubes) (Taran *et al.,* 2017). Several innovations and products integrating engineered nanoparticles (NPs) into agricultural practices, such as nanopesticides, nanofertilizers and nanosensors, have been established over the last decade with the aim of improving the quality and sustainability of agronomic systems that need less production and generate less waste than traditional products and approaches (Servin *et al.,* 2015; Liu and Lal, 2015).

**Materials and Methods**

An experiment was carried out at Main Vegetable Research Station (MVRS), Anand Agricultural University, Anand (Gujarat) during summer and *kharif* seasons of the year 2024. The experiment was arranged in randomized block design (RBD) with three replication having thirteen treatments (T1: Control (without any application), T2: RDF (application of Recommended Dose of Fertilizer) and the rest with 50% Recommended Dose of Nitrogen (RDN) supplemented with varying levels of Gliricidia Nano formulation (GNF) and Moringa Nano formulation (MNF), T3: 50% RDN + 10% GNF, T4: 50% RDN + 15% GNF, T5: 50% RDN + 20% GNF, T6: 50% RDN + 10% MNF, T7: 50% RDN + 15% MNF, T8: 50% RDN + 10% GNF + 10% MNF, T9: 50% RDN + 10% GNF + 15% MNF, T10: 50% RDN + 15% GNF + 10% MNF, T11: 50% RDN + 15% GNF + 15% MNF, T12: 50% RDN + 20% GNF + 10% MNF and T13: 50% RDN + 20% GNF + 15% MNF). Application of recommended dose of fertilizer (RDF) (T2) @ 100:50:50 kg/ha nitrogen, phosphorus and potash were given through chemical fertilisers urea, DAP and murate of potash. Half dose of nitrogen and full dose of phosphorus and potash were given at the time of sowing and the remaining half nitrogen was given at 30 DAS. Application of RDF treatment T3 to T13 only half dose of nitrogen was given through urea at the time of sowing. The nano formulations were sprayed on foliage in aqueous form using fresh solution at each spray. Spraying was done with knapsack sprayer and leaves were wetted thoroughly with fine mist. Foliar spray was applied at 30 DAS and 60 DAS, respectively.

**Results and Discussion**

**Effect of Nano Formulation on Plant Height (cm)**

Data shown in Table 1 indicated that the effect of nano formulation treatment did not exert a significant effect on plant height at 30 DAS during both seasons and in pooled analysis. While, the significantly lower plant height at 60 DAS (68.96, 93.81 and 81.38 cm), 90 DAS (122.23, 149.40 and 135.81 cm) and at harvest (151.89, 192.82 and 172.36 cm) were recorded with control (T1) during both the seasons and in pooled analysis, respectively. While, higher plant height at 60 DAS (85.87, 111.56 and 98.72 cm), 90 DAS (140.94 and 162.25 cm) and harvest (178.10, 222.37 and 200.24 cm) were recorded with 50% RDN + 10% GNF + 10% MNF (T8) during both the seasons, 2024 and pooled results, respectively. This significant increase in plant height under T8 treatment may be attributed to the synergistic effect of the nano formulations, which likely enhanced nutrient availability, uptake efficiency, and hormonal stimulation during the active growth phase.

**Effect of Nano Formulation on Number of Branches per Plant**

At 30 DAS the effect of nano-formulation treatments on the number of branches per plant was found to be non-significant during both the summer and *kharif* seasons of 2024, as well as in the pooled analysis (Table 2). The number of branches per plant at 60 DAS (1.87, 2.44 and 2.16), 90 DAS (2.62, 3.40, 3.01) and at harvest (3.49, 4.65 and 4.07) significantly highest summer, *kharif* and pooled basis respectively. Contrarily, the minimum number of branches per plantat 60 DAS (1.41, 1.94 and 1.68), 90 DAS and harvest (2.81, 3.75 and 3.28) was observed under control (T1) during both seasons and pooled analysis.

**Effect of Nano Formulation on Dry Weight of Leaf (g)**

The data presented in Table 3 indicated that different nano formulation treatments did not show their significant influence on dry weight of leaf at 30 DAS during both the season (summer and *kharif,* 2024) as well as on pooled analysis. While, the significant influence on dry weight of leaf at 60 DAS (10.65, 15.87 and 13.26 g), 90 DAS (17.23, 28.54 and 22.89 g) and at harvest (14.98, 23.20 and 19.09 g) it was revealed that the maximum dry weight of leaf was recorded in treatment T8 of 50% RDN + 10% GNF + 10% MNF in summer, *kharif* and pooled basis respectively. This enhanced biomass accumulation under T8 may be attributed to improved nutrient availability, efficient uptake, and better assimilation facilitated by the nano-sized formulations. These nano-formulations likely promoted enhanced photosynthetic activity and cellular metabolism, leading to greater dry matter partitioning in leaves. In contrast, the minimum dry weight of leaf at 60 DAS (8.56, 13.49 and 11.03 g), 90 DAS (14.60, 22.12 and 18.86 g) and at harvest (11.56, 17.84 and 14.70 g) were observed under control (T1) during both the seasons and pooled analysis.

**Effect of Nano Formulation on Dry Weight of Stem (g)**

As presented in Table 4 the data revealed that the application of different nano formulation treatments did not result in a statistically significant difference in stem dry weight at 30 DAS during both the summer and *kharif* seasons of 2024 as well as in the pooled analysis. The higher dry weight of stem was recorded in treatment T8 of 50% RDN + 10% GNF + 10% MNF reported 60 DAS (9.12, 15.39 and 12.26 g), 90 DAS (13.45, 21.81 and 17.63 g) and at harvest (17.74, 24.89 and 21.32 g) during both the season as well as in pooled analysis, respectively. Contrarily, the minimum dry weight of stem at 60 DAS (7.76, 12.46 and 10.11 g), 90 DAS (11.05, 17.17 and 14.11 g) and at harvest (15.05, 20.80 and 17.93 g) was observed under control (T1) during both the seasons and pooled analysis.

**Effect of Nano Formulation on Total Dry Weight (g)**

As presented in Table 5 the data revealed that the application of different nano formulation treatments did not result in a statistically significant difference in total dry weight at 30 DAS during both the summer and *kharif* seasons of 2024 as well as in the pooled analysis. The higher total dry weight was recorded in treatment T8 of 50% RDN + 10% GNF + 10% MNF reported 60 DAS (21.23, 34.33 and 27.78 g), 90 DAS (34.98, 50.64 and 42.81 g) and at harvest (37.10, 54.39 and 45.75 g) during both the season as well as in pooled analysis, respectively. Contrarily, the minimum dry weight of stem at 60 DAS (17.46, 27.17 and 22.32 g), 90 DAS (28.20, 41.16 and 34.68 g) and at harvest (30.68, 44.40 and 37.54 g) was observed under control (T1) during both the seasons and pooled analysis.

**Yield Parameter**

**Fruit length (cm) and fruit weight (g)**

The data presented in table 6 regarding fruit length and fruit weight influenced by nano formulation treatments was found significant in both seasons and in pooled analysis. The maximum fruit length (12.51, 13.37 and 12.94 cm) and fruit weight (14.20, 14.82 and 14.51 g) was observed with treatment T8 (50% RDN + 10% GNF + 10% MNF) in both seasons and in pooled data, respectively. While, minimum fruit length (9.75, 10.96 and 10.36 cm) and fruit weight (11.56, 12.30 and 11.93 g) were registered in T1 (Control) in both season and in pooled data, respectively.

This increase in fruit length under T8 may be attributed to the synergistic effects of nano nutrients and Moringa Leaf Extract (MLE) which are rich in growth-promoting substances such as cytokinins, auxins and gibberellins, along with micronutrients like zinc and iron. These compounds enhance cell division and elongation, improve nutrient uptake, and promote photosynthetic efficiency, which together contribute to better pod development. The nano-scale delivery of nutrients likely enhanced their absorption and translocation within the plant, leading to improved physiological performance and ultimately, longer fruits.

**Fruit girth (mm)**

The data presented in Table 6 indicated that different nano formulation treatments did not show their significant influence on fruit girth during both the season (summer and *kharif,* 2024) as well as on pooled analysis.

**Fruit per plant and fruit yield per plant (g)**

The data presented in Table 6 showed that the effect of different nano-formulations on fruit per plant and fruit yield per plant was found to be significant during both seasons and in pooled results. The highest fruit per plant (14.57, 24.85 and 19.71) and fruit yield per plant (185.56, 325.51 and 255.54 g) were observed with treatment T8 of (50% RDN + 10% GNF + 10% MNF) in both seasons and in pooled data, respectively. which, was found statistically at par with treatments T6 (19.24) in pooled analysis, respectively. While, minimum fruit weight (11.29, 20.21 and 15.75 g) and fruit yield per plant (140.50, 253.42 and 196.96 g) was registered in T1 (Control) in both seasons and in pooled data, respectively.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Plant height (cm)** | | | | | | | | | | | | | |
| **Treatment** | | **30 DAS** | | | **60 DAS** | | | **90 DAS** | | | **At Harvest** | | |
|  | | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** |
| **T1** | | 36.27 | 43.28 | 39.77 | 68.96 | 93.81 | 81.38 | 122.23 | 149.40 | 135.81 | 151.89 | 192.82 | 172.36 |
| **T2** | | 37.08 | 44.96 | 41.02 | 71.87 | 94.53 | 83.20 | 123.08 | 151.71 | 137.40 | 156.22 | 196.93 | 176.58 |
| **T3** | | 38.75 | 42.52 | 40.64 | 80.78 | 104.15 | 92.46 | 132.51 | 158.42 | 145.47 | 167.01 | 201.21 | 184.11 |
| **T4** | | 37.86 | 43.25 | 40.56 | 83.11 | 109.35 | 96.23 | 136.22 | 180.59 | 158.41 | 165.34 | 220.37 | 192.86 |
| **T5** | | 40.28 | 44.35 | 42.32 | 81.58 | 107.13 | 94.35 | 131.09 | 162.62 | 146.86 | 173.68 | 197.83 | 185.76 |
| **T6** | | 39.19 | 44.77 | 41.98 | 76.81 | 96.31 | 86.56 | 126.11 | 183.56 | 154.84 | 160.11 | 218.09 | 189.10 |
| **T7** | | 40.03 | 44.56 | 42.30 | 75.53 | 98.27 | 86.90 | 128.79 | 154.12 | 141.45 | 158.33 | 199.97 | 179.15 |
| **T8** | | 41.08 | 45.57 | 43.33 | 85.87 | 111.56 | 98.72 | 140.94 | 182.96 | 161.95 | 178.10 | 222.37 | 200.24 |
| **T9** | | 38.13 | 47.28 | 42.71 | 78.08 | 103.60 | 90.84 | 129.00 | 150.81 | 139.90 | 163.34 | 217.85 | 190.60 |
| **T10** | | 40.70 | 48.25 | 44.48 | 81.03 | 107.54 | 94.29 | 136.35 | 155.66 | 146.00 | 177.39 | 194.70 | 186.04 |
| **T11** | | 37.93 | 43.52 | 40.72 | 81.27 | 104.97 | 93.12 | 139.80 | 169.77 | 154.79 | 176.91 | 214.65 | 195.78 |
| **T12** | | 39.60 | 42.65 | 41.13 | 84.62 | 110.56 | 97.59 | 135.78 | 156.41 | 146.10 | 174.91 | 205.36 | 190.14 |
| **T13** | | 37.32 | 44.31 | 40.82 | 79.84 | 100.31 | 90.07 | 131.77 | 177.77 | 154.77 | 173.55 | 214.56 | 194.06 |
| **S.Em. (±)** | **S** | ̶ | ̶ | 0.46 | ̶ | ̶ | 1.03 | ̶ | ̶ | 1.68 | ̶ | ̶ | 1.85 |
| **T** | 1.50 | 1.50 | 1.16 | 3.28 | 4.11 | 2.63 | 4.01 | 7.56 | 4.28 | 5.99 | 7.27 | 4.71 |
| **S × T** | ̶ | ̶ | 1.64 | ̶ | ̶ | 3.72 | ̶ | ̶ | 6.05 | ̶ | ̶ | 6.67 |
| **C.D. (0.05)** | **S** | ̶ | ̶ | 1.30 | ̶ | ̶ | 2.93 | ̶ | ̶ | 4.77 | ̶ | ̶ | 5.26 |
| **T** | NS | NS | NS | 9.59 | 11.98 | 7.47 | 11.70 | 22.06 | 12.17 | 17.50 | 21.23 | 13.40 |
| **S × T** | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS |
| **C.V. (%)** | | 6.70 | 6.90 | 6.83 | 7.18 | 6.89 | 7.06 | 5.27 | 7.98 | 7.08 | 6.20 | 6.07 | 6.16 |

**Table 1. Effect of nano formulation on plant height in okra during summer and *kharif,* 2024 as well as in pooled analysis**

**Table 2. Effect of nano formulation on number of branches per plant in okra during summer and *kharif,* 2024 as well as in pooled analysis**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Number of branches per plant** | | | | | | | | | | | | | |
| **Treatment** | | **30 DAS** | | | **60 DAS** | | | **90 DAS** | | | **At Harvest** | | |
|  | | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** |
| **T1** | | 1.08 | 1.51 | 1.29 | 1.41 | 1.94 | 1.68 | 2.07 | 2.73 | 2.40 | 2.81 | 3.75 | 3.28 |
| **T2** | | 1.07 | 1.56 | 1.32 | 1.55 | 1.97 | 1.76 | 2.29 | 2.85 | 2.57 | 2.91 | 3.89 | 3.40 |
| **T3** | | 1.11 | 1.67 | 1.39 | 1.46 | 2.12 | 1.79 | 2.51 | 3.31 | 2.91 | 3.08 | 4.05 | 3.57 |
| **T4** | | 1.09 | 1.61 | 1.35 | 1.52 | 2.20 | 1.86 | 2.58 | 3.35 | 2.96 | 3.18 | 4.30 | 3.74 |
| **T5** | | 1.10 | 1.64 | 1.37 | 1.72 | 2.29 | 2.00 | 2.36 | 2.87 | 2.62 | 3.32 | 4.55 | 3.94 |
| **T6** | | 1.07 | 1.59 | 1.33 | 1.50 | 2.00 | 1.75 | 2.47 | 3.08 | 2.78 | 3.01 | 3.90 | 3.46 |
| **T7** | | 1.13 | 1.65 | 1.39 | 1.54 | 2.24 | 1.89 | 2.32 | 2.72 | 2.52 | 2.97 | 3.81 | 3.39 |
| **T8** | | 1.09 | 1.88 | 1.49 | 1.87 | 2.44 | 2.16 | 2.62 | 3.40 | 3.01 | 3.49 | 4.65 | 4.07 |
| **T9** | | 1.12 | 1.72 | 1.42 | 1.56 | 2.41 | 1.99 | 2.25 | 2.91 | 2.58 | 3.27 | 4.22 | 3.74 |
| **T10** | | 1.08 | 1.79 | 1.43 | 1.67 | 2.33 | 2.00 | 2.41 | 3.30 | 2.85 | 3.38 | 4.35 | 3.87 |
| **T11** | | 1.07 | 1.59 | 1.33 | 1.80 | 2.09 | 1.94 | 2.46 | 2.84 | 2.65 | 3.41 | 4.39 | 3.90 |
| **T12** | | 1.11 | 1.70 | 1.40 | 1.63 | 2.36 | 1.99 | 2.57 | 3.31 | 2.94 | 3.21 | 4.13 | 3.67 |
| **T13** | | 1.06 | 1.77 | 1.42 | 1.62 | 2.30 | 1.96 | 2.38 | 2.80 | 2.59 | 3.33 | 4.49 | 3.91 |
| **S.Em. (±)** | **S** | ̶ | ̶ | 0.02 | ̶ | ̶ | 0.03 | ̶ | ̶ | 0.04 | ̶ | ̶ | 0.04 |
| **T** | 0.04 | 0.07 | 0.04 | 0.08 | 0.11 | 0.07 | 0.10 | 0.15 | 0.09 | 0.13 | 0.18 | 0.11 |
| **S × T** | ̶ | ̶ | 0.06 | ̶ | ̶ | 0.10 | ̶ | ̶ | 0.13 | ̶ | ̶ | 0.16 |
| **C.D. (0.05)** | **S** | ̶ | ̶ | 0.04 | ̶ | ̶ | 0.08 | ̶ | ̶ | 0.10 | ̶ | ̶ | 0.12 |
| **T** | NS | NS | NS | 0.24 | 0.31 | 0.19 | 0.29 | 0.44 | 0.26 | 0.37 | 0.54 | 0.32 |
| **S × T** | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS |
| **C.V. (%)** | | 6.25 | 7.31 | 7.16 | 8.92 | 8.37 | 8.67 | 7.09 | 8.58 | 8.09 | 6.85 | 7.60 | 7.40 |

**Table 3. Effect of nano formulation on leaf dry weight in okra during summer and *kharif,* 2024 as well as in pooled analysis**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Leaf dry weight (g)** | | | | | | | | | | | | | |
| **Treatment** | | **30 DAS** | | | **60 DAS** | | | **90 DAS** | | | **At Harvest** | | |
|  | | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** |
| **T1** | | 3.27 | 5.28 | 4.28 | 8.56 | 13.49 | 11.03 | 14.60 | 22.12 | 18.36 | 11.56 | 17.84 | 14.70 |
| **T2** | | 3.32 | 5.35 | 4.33 | 8.72 | 13.50 | 11.11 | 14.81 | 23.28 | 19.05 | 12.78 | 18.21 | 15.50 |
| **T3** | | 3.36 | 5.87 | 4.62 | 9.17 | 13.91 | 11.54 | 15.24 | 23.54 | 19.39 | 13.36 | 19.95 | 16.66 |
| **T4** | | 3.61 | 5.23 | 4.42 | 10.54 | 15.36 | 12.95 | 17.20 | 27.40 | 22.30 | 14.87 | 22.86 | 18.86 |
| **T5** | | 3.32 | 5.76 | 4.54 | 9.01 | 13.80 | 11.41 | 14.84 | 23.50 | 19.17 | 12.85 | 19.75 | 16.30 |
| **T6** | | 3.40 | 5.35 | 4.38 | 9.38 | 14.00 | 11.69 | 15.48 | 23.61 | 19.54 | 13.48 | 20.18 | 16.83 |
| **T7** | | 3.46 | 5.45 | 4.46 | 9.52 | 14.91 | 12.22 | 15.95 | 23.82 | 19.89 | 13.81 | 21.91 | 17.86 |
| **T8** | | 3.63 | 5.33 | 4.48 | 10.65 | 15.87 | 13.26 | 17.23 | 28.54 | 22.89 | 14.98 | 23.20 | 19.09 |
| **T9** | | 3.41 | 5.85 | 4.63 | 9.39 | 14.25 | 11.82 | 15.64 | 23.62 | 19.63 | 13.65 | 20.93 | 17.29 |
| **T10** | | 3.54 | 5.71 | 4.63 | 10.12 | 15.27 | 12.70 | 16.65 | 25.20 | 20.93 | 14.55 | 22.10 | 18.33 |
| **T11** | | 3.48 | 5.75 | 4.62 | 9.63 | 15.00 | 12.32 | 16.34 | 24.05 | 20.20 | 13.99 | 22.00 | 18.00 |
| **T12** | | 3.59 | 5.34 | 4.47 | 10.39 | 15.34 | 12.87 | 16.91 | 26.66 | 21.78 | 14.65 | 22.35 | 18.50 |
| **T13** | | 3.53 | 5.87 | 4.70 | 9.65 | 15.24 | 12.44 | 16.49 | 24.45 | 20.47 | 14.15 | 22.09 | 18.12 |
| **S.Em. (±)** | **S** | ̶ | ̶ | 0.05 | ̶ | ̶ | 0.12 | ̶ | ̶ | 0.24 | ̶ | ̶ | 0.23 |
| **T** | 0.13 | 0.23 | 0.13 | 0.39 | 0.48 | 0.31 | 0.61 | 1.06 | 0.61 | 0.61 | 0.99 | 0.58 |
| **S × T** | ̶ | ̶ | 0.18 | ̶ | ̶ | 0.44 | ̶ | ̶ | 0.87 | ̶ | ̶ | 0.82 |
| **C.D. (0.05)** | **S** | ̶ | ̶ | 0.14 | ̶ | ̶ | 0.34 | ̶ | ̶ | 0.68 | ̶ | ̶ | 0.65 |
| **T** | NS | NS | NS | 1.13 | 1.40 | 0.88 | 1.79 | 3.10 | 1.75 | 1.78 | 2.90 | 1.66 |
| **S × T** | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS |
| **C.V. (%)** | | 6.33 | 7.06 | 7.04 | 6.97 | 5.68 | 6.23 | 6.67 | 7.49 | 7.42 | 7.70 | 8.17 | 8.21 |

**Table 4. Effect of nano formulation on stem dry weight in okra during summer and *kharif,* 2024 as well as in pooled analysis**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Stem dry weight (g)** | | | | | | | | | | | | | |
| **Treatment** | | **30 DAS** | | | **60 DAS** | | | **90 DAS** | | | **At Harvest** | | |
|  | | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** |
| **T1** | | 4.04 | 8.61 | 6.33 | 7.76 | 12.46 | 10.11 | 11.05 | 17.17 | 14.11 | 15.05 | 20.80 | 17.93 |
| **T2** | | 4.14 | 8.72 | 6.43 | 7.82 | 13.72 | 10.77 | 11.12 | 18.04 | 14.58 | 15.25 | 20.96 | 18.11 |
| **T3** | | 4.21 | 8.64 | 6.43 | 7.92 | 13.82 | 10.87 | 12.29 | 18.56 | 15.42 | 16.41 | 23.28 | 19.85 |
| **T4** | | 4.71 | 8.79 | 6.75 | 9.00 | 15.10 | 12.05 | 13.35 | 20.50 | 16.93 | 17.59 | 24.25 | 20.92 |
| **T5** | | 4.16 | 8.17 | 6.17 | 7.86 | 13.80 | 10.83 | 11.36 | 18.39 | 14.88 | 15.48 | 21.45 | 18.47 |
| **T6** | | 4.28 | 8.32 | 6.30 | 8.02 | 13.83 | 10.92 | 12.35 | 18.84 | 15.59 | 16.56 | 23.58 | 20.07 |
| **T7** | | 4.52 | 8.28 | 6.40 | 8.26 | 14.35 | 11.30 | 12.51 | 18.98 | 15.75 | 16.65 | 23.71 | 20.18 |
| **T8** | | 4.73 | 8.90 | 6.82 | 9.12 | 15.39 | 12.26 | 13.45 | 21.81 | 17.63 | 17.74 | 24.89 | 21.32 |
| **T9** | | 4.40 | 8.15 | 6.28 | 8.12 | 14.16 | 11.14 | 12.40 | 18.96 | 15.68 | 16.59 | 23.61 | 20.10 |
| **T10** | | 4.63 | 8.32 | 6.48 | 8.73 | 14.92 | 11.83 | 13.00 | 19.55 | 16.28 | 17.23 | 24.05 | 20.64 |
| **T11** | | 4.54 | 8.68 | 6.61 | 8.41 | 14.58 | 11.49 | 12.71 | 19.01 | 15.86 | 16.83 | 23.87 | 20.35 |
| **T12** | | 4.69 | 8.58 | 6.63 | 8.85 | 14.95 | 11.90 | 13.21 | 20.10 | 16.65 | 17.37 | 23.88 | 20.63 |
| **T13** | | 4.60 | 8.34 | 6.47 | 8.63 | 14.78 | 11.70 | 12.86 | 19.31 | 16.09 | 17.01 | 24.20 | 20.61 |
| **S.Em. (±)** | **S** | ̶ | ̶ | 0.06 | ̶ | ̶ | 0.12 | ̶ | ̶ | 0.17 | ̶ | ̶ | 0.20 |
| **T** | 0.17 | 0.24 | 0.15 | 0.29 | 0.53 | 0.30 | 0.47 | 0.76 | 0.45 | 0.55 | 0.83 | 0.50 |
| **S × T** | ̶ | ̶ | 0.21 | ̶ | ̶ | 0.42 | ̶ | ̶ | 0.63 | ̶ | ̶ | 0.70 |
| **C.D. (0.05)** | **S** | ̶ | ̶ | 0.16 | ̶ | ̶ | 0.33 | ̶ | ̶ | 0.50 | ̶ | ̶ | 0.55 |
| **T** | NS | NS | NS | 0.84 | 1.53 | 0.85 | 1.37 | 2.21 | 1.27 | 1.61 | 2.42 | 1.41 |
| **S × T** | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS |
| **C.V. (%)** | | 6.66 | 4.81 | 5.51 | 5.94 | 6.36 | 6.47 | 6.51 | 6.86 | 6.91 | 5.76 | 6.16 | 6.11 |

**Table 5. Effect of nano formulation on total dry weight in okra during summer and *kharif,* 2024 as well as in pooled analysis**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Total dry weight (g)** | | | | | | | | | | | | | |
| **Treatment** | | **30 DAS** | | | **60 DAS** | | | **90 DAS** | | | **At Harvest** | | |
|  | | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** |
| **T1** | | 7.76 | 14.26 | 11.01 | 17.46 | 27.17 | 22.32 | 28.20 | 41.16 | 34.68 | 30.68 | 44.40 | 37.54 |
| **T2** | | 8.20 | 14.56 | 11.38 | 17.78 | 28.76 | 23.27 | 29.11 | 42.93 | 36.02 | 31.59 | 45.45 | 38.52 |
| **T3** | | 8.32 | 15.37 | 11.85 | 18.64 | 29.03 | 23.84 | 31.39 | 44.52 | 37.96 | 33.67 | 50.12 | 41.89 |
| **T4** | | 8.78 | 14.60 | 11.69 | 20.55 | 32.64 | 26.59 | 34.06 | 48.69 | 41.37 | 36.92 | 52.45 | 44.69 |
| **T5** | | 8.22 | 14.88 | 11.55 | 18.14 | 28.94 | 23.54 | 29.51 | 44.76 | 37.14 | 31.95 | 48.19 | 40.07 |
| **T6** | | 8.34 | 14.39 | 11.36 | 18.97 | 29.34 | 24.15 | 31.60 | 44.92 | 38.26 | 34.39 | 50.97 | 42.68 |
| **T7** | | 8.40 | 14.44 | 11.42 | 19.23 | 30.56 | 24.89 | 31.82 | 45.41 | 38.62 | 34.70 | 51.56 | 43.13 |
| **T8** | | 9.05 | 15.52 | 12.29 | 21.23 | 34.33 | 27.78 | 34.98 | 50.64 | 42.81 | 37.10 | 54.39 | 45.75 |
| **T9** | | 8.36 | 14.89 | 11.63 | 19.19 | 29.53 | 24.36 | 31.61 | 45.81 | 38.71 | 34.62 | 51.33 | 42.98 |
| **T10** | | 8.66 | 14.96 | 11.81 | 19.68 | 31.64 | 25.66 | 33.20 | 46.98 | 40.09 | 36.16 | 52.17 | 44.16 |
| **T11** | | 8.55 | 15.33 | 11.94 | 19.40 | 30.94 | 25.17 | 32.51 | 46.11 | 39.31 | 35.11 | 51.64 | 43.38 |
| **T12** | | 8.71 | 14.41 | 11.56 | 19.96 | 32.47 | 26.22 | 33.80 | 47.67 | 40.73 | 36.01 | 52.15 | 44.08 |
| **T13** | | 8.65 | 15.11 | 11.88 | 19.42 | 31.51 | 25.47 | 33.18 | 47.21 | 40.20 | 35.37 | 51.77 | 43.57 |
| **S.Em. (±)** | **S** | ̶ | ̶ | 0.16 | ̶ | ̶ | 0.30 | ̶ | ̶ | 0.36 | ̶ | ̶ | 0.39 |
| **T** | 0.31 | 0.74 | 0.40 | 0.70 | 1.33 | 0.75 | 1.17 | 1.41 | 0.91 | 1.16 | 1.64 | 1.00 |
| **S × T** | ̶ | ̶ | 0.57 | ̶ | ̶ | 1.06 | ̶ | ̶ | 1.29 | ̶ | ̶ | 1.42 |
| **C.D. (0.05)** | **S** | ̶ | ̶ | 0.45 | ̶ | ̶ | 0.84 | ̶ | ̶ | 1.02 | ̶ | ̶ | 1.12 |
| **T** | NS | NS | NS | 2.05 | 3.89 | 2.14 | 3.41 | 4.11 | 2.60 | 3.39 | 4.78 | 2.86 |
| **S × T** | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS |
| **C.V. (%)** | | 6.42 | 8.64 | 8.45 | 6.33 | 7.56 | 7.42 | 6.34 | 5.31 | 5.76 | 5.84 | 5.62 | 5.79 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Treatment** | | **Fruit length (cm)** | | | **Fruit girth (mm)** | | | **Fruit weight (g)** | | | **No. of fruit per plant** | | | **Yield per plant (g)** | | |
| **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** | **Summer** | ***kharif*** | **Pooled** |
| **T1** | | 9.75 | 10.96 | 10.36 | 46.49 | 49.53 | 48.01 | 11.56 | 12.30 | 11.93 | 11.29 | 20.21 | 15.75 | 140.50 | 253.42 | 196.96 |
| **T2** | | 10.03 | 11.19 | 10.61 | 47.66 | 50.40 | 49.03 | 11.99 | 12.46 | 12.23 | 12.40 | 20.46 | 16.43 | 148.51 | 260.60 | 204.56 |
| **T3** | | 11.11 | 13.25 | 12.18 | 50.01 | 53.17 | 51.59 | 12.30 | 14.19 | 13.25 | 12.29 | 23.39 | 17.84 | 151.77 | 312.39 | 232.08 |
| **T4** | | 11.91 | 11.46 | 11.69 | 52.51 | 53.26 | 52.89 | 12.46 | 14.45 | 13.46 | 12.14 | 22.16 | 17.15 | 155.73 | 310.34 | 233.04 |
| **T5** | | 11.27 | 12.65 | 11.96 | 53.65 | 51.30 | 52.47 | 12.65 | 12.65 | 12.65 | 12.43 | 21.15 | 16.79 | 165.65 | 268.86 | 217.26 |
| **T6** | | 11.34 | 12.56 | 11.95 | 48.18 | 56.27 | 52.22 | 14.00 | 14.00 | 14.00 | 13.71 | 24.76 | 19.24 | 167.95 | 319.71 | 243.83 |
| **T7** | | 11.83 | 12.71 | 12.27 | 48.52 | 55.27 | 51.89 | 14.12 | 13.89 | 14.00 | 13.57 | 21.81 | 17.69 | 183.49 | 303.25 | 243.37 |
| **T8** | | 12.51 | 13.37 | 12.94 | 53.73 | 56.70 | 55.22 | 14.20 | 14.82 | 14.51 | 14.57 | 24.85 | 19.71 | 185.56 | 325.51 | 255.54 |
| **T9** | | 11.74 | 12.87 | 12.30 | 49.27 | 53.23 | 51.25 | 12.57 | 13.15 | 12.86 | 14.10 | 21.02 | 17.56 | 177.30 | 275.98 | 226.64 |
| **T10** | | 11.26 | 11.31 | 11.29 | 50.60 | 51.87 | 51.24 | 13.40 | 13.78 | 13.59 | 13.43 | 21.56 | 17.50 | 179.01 | 297.59 | 238.30 |
| **T11** | | 10.09 | 11.99 | 11.04 | 51.23 | 53.20 | 52.22 | 13.75 | 13.50 | 13.62 | 13.14 | 22.71 | 17.93 | 171.72 | 300.97 | 236.35 |
| **T12** | | 11.60 | 13.17 | 12.39 | 51.55 | 54.33 | 52.94 | 13.50 | 14.60 | 14.05 | 13.57 | 21.70 | 17.63 | 180.54 | 307.22 | 243.88 |
| **T13** | | 11.76 | 13.02 | 12.39 | 50.09 | 54.57 | 52.33 | 13.98 | 13.74 | 13.86 | 13.71 | 21.36 | 17.53 | 175.82 | 293.45 | 234.64 |
| **S.Em. (±)** | **S** | ̶ | ̶ | 0.14 | ̶ | ̶ | 0.80 | ̶ | ̶ | 0.16 | ̶ | ̶ | 0.22 | ̶ | ̶ | 3.56 |
| **T** | 0.55 | 0.49 | 0.37 | 1.94 | 2.47 | 2.03 | 0.59 | 0.55 | 0.40 | 0.54 | 0.99 | 0.56 | 9.57 | 15.43 | 9.08 |
| **S × T** | ̶ | ̶ | 0.52 | ̶ | ̶ | 2.87 | ̶ | ̶ | 0.57 | ̶ | ̶ | 0.80 | ̶ | ̶ | 12.84 |
| **C.D. (0.05)** | **S** | ̶ | ̶ | 0.41 | ̶ | ̶ | 2.26 | ̶ | ̶ | 0.45 | ̶ | ̶ | 0.63 | ̶ | ̶ | 10.13 |
| **T** | 1.60 | 1.43 | 1.05 | NS | NS | NS | 1.72 | 1.60 | 1.14 | 1.56 | 2.89 | 1.60 | 27.92 | 45.05 | 25.82 |
| **S × T** | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS | ̶ | ̶ | NS |
| **C.V. (%)** | | 8.45 | 6.89 | 7.64 | 6.68 | 8.12 | 6.39 | 7.76 | 6.95 | 7.35 | 7.08 | 7.77 | 7.84 | 9.86 | 9.08 | 9.62 |

**Table 6. Effect of nano formulation on fruit length, fruit girth, fruit weight, no. of fruit per plant and yield per plant in okra during summer and *kharif,* 2024 as well as in pooled analysis**

**Interaction (S × T)**

The interaction effect of season and treatment (S × T) were found to be non-significant with respect to the plant height, number of branches per plant, leaf dry weight, stem dry weight and total dry weight at 30, 60, 90 DAS, at harvest under pooled analysis.

**Conclusion**

Field trials during both summer and *kharif* seasons confirmed that T8 (50% RDN + 10% GNF + 10% MNF) consistently recorded significantly higher plant height, number of branches, leaf and stem dry weights, and total biomass across all stages (60 DAS, 90 DAS, and harvest). It also led to the synergistic benefit of combining reduced chemical nitrogen dose (RDN) with dual botanical nano inputs.

In the present study, foliar spraying of nanoformulations significantly increased the number of fruits per plant, fruit length, and fruit weight in okra. The enhanced yield may be attributed to improved biomass dry matter (BMD), along with better morpho-physiological and biochemical traits.

Overall, the application of nanoformulations resulted in substantial improvements in vegetative growth, physiological efficiency, and ultimately, yield. Among the tested treatments, the combination of 50% RDN + 10% GNF + 10% MNF (T8) consistently outperformed others by significantly enhancing most growth parameters and yield attributes of okra.

**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 the writing or editing of this manuscript.

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