**The efficacy of Nano fertilizer on yield and physico-chemical quality of okra fruit**

**ABSTRACT**

The study assessed the effects of nano urea, Tio2, and ZnO nanoparticles on fruit yield and morphological as well as biochemical qualities of okra fruit (cv. Kashi Lalima) grown under subtropical climate of lucknow, Uttar Pradesh, India during the Zaid seasons of 2022–2023 and 2023–2024 which had high soil pH (8.2) . There were 17 treatments consisting of recommended dose of fertilizer (RDF 100%, 75%, 50%, and 25%) along with application of Nano urea (2 ml/l, 4 ml/l, and 6 ml/l), TiO2 NPs (10, 15, and 20 ppm), and ZnO NPs (50, 75, and 100 ppm) and control (no fertilizer) having 3 replications following randomized block design with 51 plots (1.8 m × 1.2 m).  (morning glory) leaf liquid extract was used to create TiO2 and ZnO nanoparticles in an eco-friendly manner and Nano urea was obtained from IFFCO. Synthesized nanoparticles were characterized by UV-visible spectroscopy, FTIR, HRTEM, EDX, BET, X-ray diffraction, and XPS at the Department of Chemistry and the University Scientific Instrumentation Centre (USIC). Recorded observations indicated that foliar application of 75 % RDF + 2 ml/l Nano urea + 50 ppm ZnO NPs produced the highest yield (159.81q/ha). These treatments also showed better fruit quality in term of fruit length (13.19 cm), fruit width (1.72cm), average fruit weight (10.61g), moisture content (82.87%), total soluble solids (6.61°Brix), It also increased the dry weight (17.13%) of fruit as compare to control (11.43%). However, the biochemical attributes of okra fruits, including total sugars (4.15%), vitamin C content (18.21mg/100g), were examined and found to be superior with the application of 75 % RDF + 2 ml/l Nano urea + 10 ppm TiO2.

**Keywords-** Nano-fertilizer, okra, fruit length, dry weight and yield.

1. **INTRODUCTION**

Fertilizers are critical for modern agricultural practices as they provide essential nutrients that support plant growth and improve crop yields. Chemical fertilizers currently contribute to about 50–55% of crop yield increases in developing countries **(Adhikari & Ramana, 2019).** In fact, 40% to 60% of global food production relies on the use of fertilizers **(Tisdale et al., 1993).** However, traditional chemical fertilizers, when applied to the soil, face several limitations, such as nutrient fixation, leaching, and environmental degradation. Many nutrients supplied through chemical fertilizers are either not available for plant uptake due to soil reactions or are lost to the environment through leaching, especially under heavy rainfall or irrigation **(Alshaal and El-Ramady, 2017)**. In an effort to improve crop production, farmers were compelled to apply more N fertilizers due to the high loss of nitrogen and its low use efficiency (**Rathnayaka et al., 2018).** This increased farming costs and the resulting environmental consequences **(Chhowalla, 2017 and Marchiol, 2019).** These limitations increase the amount of fertilizers needed, which not only raises the cost of production but also contributes to environmental pollution.In recent years, nanotechnology has emerged as a promising solution to these challenges. Nanotechnology is an interdisciplinary field that spans various industries, including medicine, electronics, pharmaceuticals, and agriculture. It involves the manipulation of materials at the nanoscale, typically between 1 and100 nanometres, to create particles that exhibit unique optical, physical, and chemical properties due to their large surface area and small size (**Alshaal and El-Ramady, 2017**).In agriculture, nano-fertilizers represent a new generation of fertilizers that deliver nutrients in a controlled and efficient manner. Nano-fertilizers contain essential nutrients in nano-scale particles, which enhance the availability and uptake of nutrients by plants. The small size of these nanoparticles allows them to penetrate plant tissues more effectively, ensuring that nutrients reach the right place at the right time **(Eichert et al., 2008; Perez-de-Luque, 2017**). Additionally, nano-fertilizers reduce nutrient loss due to leaching and volatilization, making them an environmentally friendly alternative to conventional chemical fertilizers(**Abou-El-nour, 2002**).NFs are designed to supply essential macro- and micronutrients to crops in a controlled, targeted manner **(Shang et al., 2019).** Their development is part of the emerging "Nano-Bio Revolution," aiming to provide an environmentally friendly alternative to synthetic fertilizers, which are often detrimental to ecosystems**(Chugh et al., 2021).** Their nanoscale dimensions (<100 nm), NFs can easily penetrate plant systems when applied as foliar sprays or through soil application **(Seleiman et al., 2021**). The small particle size also increases their surface area and enhances nutrient retention compared to traditional fertilizers, leading to improved efficiency and reduced environmental impact **(Hussain et al.,2022).** Moreover, NFs release nutrients gradually, catering to the specific needs of crops over time without causing harm **(Siddiqi & Husen, 2017).** In contrast, conventional fertilizers suffer from low nutrient uptake efficiency, with substantial losses through leaching, volatilization, and emissions, which contribute to environmental degradation **(Dimkpa et al., 2015a, b).**Recent advancements in nanomaterials for agriculture, such as nanopesticides,nano-formulations, and nano-fertilizers, have revolutionized how fertilisers are applied to crops. Nanoparticles (NPs), including Titanium Dioxide(TiO₂) and Zinc Oxide (ZnO), have been shown to enhance nutrient uptake, support plant growth, and improve crop yields **(Pestovsky and Martinez-Antonio,2017; Panpatte et al., 2016).** Additionally, these nanoparticles have been found tomitigate the harmful effects of environmental stressors, such as heavy metal accumulation, by aiding in nutrient absorption and improving plant tolerance to adverse conditions **(Ogunkunle et al., 2020; Irshad et al., 2021)**Nanotechnology offers numerous advantages in agriculture, particularly inimproving nutrient management in crops like okra. Nanoparticles such as TiO₂and ZnO have been shown to enhance plant metabolism, improve photosynthetic efficiency, and increase nutrient utilization, all of which contribute to higher crop yields and improved quality **(Chaudhary and Singh, 2020; Raliya et al., 2013).**TiO₂ nanoparticles, in particular, have been found to increase the activity of enzymes involved in plant growth and stress tolerance, leading to greater biomass production and improved yield quality **(Lei et al., 2007).** The use of Nano Urea is another promising approach in okra cultivation. Urea is one of the most widely used nitrogen fertilizers, but its efficiency is often limited by leaching and volatilisation. Nano Urea offers an advantage by releasing nitrogen slowly and in a controlled manner, ensuring that the nutrient is available to the plant over a longer period. This reduces nutrient losses and increases nitrogen use efficiency, ultimately leading to better plant growth and yield **(Josko and Oleszczuk, 2013).** NFs offer several advantages, such as reducing chemical loads in the soil, improving nutrient use efficiency (NUE), minimizing the adverse effects of conventional fertilizers, and decreasing the frequency of fertiliser application **(El-Ghamry et al., 2018).** NFs hold significant potential for promoting sustainable agriculture, particularly in developing countries **(Liu &Lal, 2014)**. However, concerns remain regarding the potential phytotoxicity and environmental risks associated with the overuse of NFs **(Ruttkay-Nedecky et al.,2017).** Additionally, challenges such as cost-effectiveness, toxicity management, recyclability, biodegradability, and recovery after use need to be addressed to ensure the responsible production and application of NFs **(Guerra et al., 2018).** The primary aim of this study is to evaluate the effects of Nano Urea, Titanium Dioxide (TiO₂), and Zinc Oxide (ZnO) nanoparticles on the growth, yield, and quality of okra (*Abelmoschus esculentus*). This research was conducted to determine whether these nano-fertilizers can serve as a viable alternative to traditional chemical fertilizers in okra cultivation.

1. **MATERIALS AND METHODS**

The field experiment took place in Horticulture Research Farm, Department of Horticulture, Babasaheb Bhimrao Ambedkar University Lucknow (U.P)-226025 (26◦ 84ʹ North latitude and 80◦ 94ʹ East longitudes, 123 m above mean sea level) from February to May 2022. The location of the experiment had a typical summer temperature of 21.1 -41.8◦C, relative humidity of 30-67.9%, and an annual rainfall of 750 mm. The soil was alkaline with a pH of 8.2. The experiment consisted of 17 treatments with foliar use of Nano urea (2ml/l, 4ml/l, and 6ml/l), TiO2 NPs (10,15,20 ppm) and ZnO NPs (50,75,100 ppm) and soil application of varying percentages of RDF (75%, 50%, 25%).The treatments were repeated three times randomly using Randomized Block Design (RBD) with 51 plots (1.8 m x 1.2m). The field activities were carried out to maintain healthy plants, and normal agronomical methods such as sowing, weeding, hoeing, earthing up, watering, and plant protection measures were implemented. The seeds of the chosen cultivar Kashi Lalima were obtained from the Indian Institute of Vegetable Research (IIVR, Varanasi). Kashi Lalima is a reddish -purple okra hybrid cultivar released by IIVR, Varanasi, that is resistant to yellow vein mosaic virus (YVMV) and 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 the agro-climatic condition of Uttar Pradesh and Bihar state of India, having a subtropical dry to humid climate. The seeds were sown on 1st February at 45cm x 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 is collected from IFFCO Bhawan, Lucknow. It showed an acceptable particle size of 20-50nm, as well as increased surface area (10,000 times over 1 mm urea prill) and particle count (55,000 nitrogen particles over 1 mm urea prill). Consequently, Nano urea increases its availability to crops by more than 80%, resulting in greater fertilizer usage efficiency. **(Kumar et al., 2023).**TiO2 and ZnO NPs were green produced using *Ipomoea carnea* subsp. fistulosa (morning glory) leaves in an aqueous solution of TiCl4 (0.1M) and zinc nitrate hexahydrate (0.1M). The formation and quality of compounds were examined using X-ray diffraction techniques. The particle X-ray absorption pattern of TiO2 and ZnO NPs was obtained using a Pan analytical X'Pert Pro X-ray diffractometer. The UV-visible consumption spectrum of TiO2 NPs produced by reducing an aqueous solution of TiCl4 with an aqueous extract of *Ipomoea carnea* (morning glory) leaves reveals a strong UV-visible absorption band at 277 nm that is blue shifted and matches the excitonic peak of TiO2 NPs due to their quantum size effect.**(Hitkari et al., 2018).** The ZnO NPs, which had an absorbance peak at 275 nm, also showed evidence of quantum confinement. The findings of the UV-visible absorption study showed that ZnO and TiO2 NPs of tiny size were formed. The Tauc relation has been used to calculate the direct band gap energy of ZnO and TiO2 NPs. It is discovered that the band gap energies of ZnO NPs and TiO2 are 3.4 and 3.5 eV, respectively. Powder XRD analysis was used to assess the phase, crystal structure, and purity of the as-synthesised ZnO and TiO2 NPs. Following the reduction of TiCl4 using an aqueous medium for plant extraction, TiO2 NPs were produced. Using the reference pattern (JCPDS 21–1272) of TiO2, all of the diffraction peaks are correctly allocated to the anatase phase. Notably, this sample only shows anatase TiO2 and no rutile phase. This is because the high concentration of gaseous oxygen during particle growth contributes to low oxygen vacancy concentrations, which prevent the transition from anatase to rutile phase **(Rulison et al., 1996).** Furthermore, the creation of small-sized crystalline TiO2 NPs is indicated by the observation of highly broad and sharp XRD peaks. The Debye-Scherrer formula has been used to calculate the average crystallite size (D): D = 0.9 λ/β cos θ where θ is the Bragg's diffraction angle, β is the full width at half maximum (FWHM), λ is the wavelength, and D is the crystallites' size (in nm).It is easy to match hexagonal wurtzite ZnO (JCPDS card 80-0075, a = 0.3253 nm, c = 0.5209 nm) with space group p63mc to all of the diffraction peaks in the ZnO XRD pattern. The as-synthesised material, which was generated by reducing zinc nitrate hexahydrate with plant extract, clearly consists of phase pure ZnO, according to the XRD pattern. Furthermore, the structure of the diffraction pattern demonstrates that the XRD peaks are extended and strong, implying the formation of small and well-crystalline ZnO NPs. TiO2 and ZnO particles had a mean crystallite size of 7 and 52 nm, respectively. The particle size distribution of TiO2 and ZnO NPs was examined using a Zeta sizer. The particle form, size, and composition of materials were studied using a JEOL-2100 transmission electron microscope (TEM with EDX; model number TECNAI 200G2 FEI). The particle distribution range of TiO2 NPs 7- 10 nm and ZnO NPs 42-79nm, with the greatest population falling at 58.89nm and 8.69nm, respectively. The synthesis and characterization were done at the Department of Chemistry, Babasaheb Bhimrao Ambedkar University, Lucknow. TiO2 and ZnO NPs were applied to the crop as per treatment combination at 30 and 60 days after seed sowing(DAS). The physical parameters of okra fruits were measured to assess their quality and characteristics. These parameters included the length of the fruits (cm), selected fruits were measured with the help of scale from the neck node to the tip of the fruit, width of the fruits (cm), The fruit width was measured with vernier callipers, the average weight of the fruits was taken with the help of electronic balance and expressed in grams (g). Additionally, biomass production percentage. The selected fruits were weighed and then they were placed in an oven set at 60°C and dried it for 48 hours. Once dried, the samples were allowed to cool in a desiccator to prevent moisture absorption before being weighed and moisture content of okra fruits was determined by drying the weighed sample of okra fruit at 105°C in hot air oven for 5 hours and the loss of weight was expressed as moisture content **(A.O.A.C., 2019)** were also evaluated to provide a comprehensive understanding of the fruit's physical attributes. The values that were observed of different treatments were statistically assessed using OPSTAT **(Sheoran et al., 1998),** and the results were compared at the 5% level of significance **(Sahu and Das, 2014)**

**3. RESULTS AND DISCUSSION**

**3.1 Yield (Q/ha)**

The treatments exhibited a significant impact on yield per hectare during both years as well as in the pooled analysis. The yield varied from 58.49 to 157.69 q/ha in the first year (2022), from 63.93 to 161.92 q/ha in the second year (2023), and from 61.21 to 159.81 q/ha on average across both years. In 2022, the maximum yield (157.69 q/ha) was observed in treatment T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO₂) with 149.32 q/ha yield. These treatments were significantly higher than all other treatments. The lowest yield was recorded in the control (T1). During 2023, the yield follows a similar trend, with T13 (75% RDF + 2ml/l Nano Urea + 50 ppm ZnO) recording the maximum yield (161.92 q/ha), followed by T12 (75% RDF + 2ml/l Nano Urea + 10 ppm TiO2) at 150.60 q/ha. The lowest yield was again observed in the control (T1) with a 63.93 q/ha yield. The pooled data across both years reconfirmed the superiority of T13 (75% RDF + 2ml/l Nano Urea + 50 ppm ZnO) and T12 (75% RDF + 2ml/l Nano Urea + 10 ppm TiO2) with yields of 159.81 q/ha and 149.96 q/ha, respectively. The control (T1) recorded the lowest pooled yield (61.21Q/ha). Applying ZnO NPs can enhance yield traits because it increases photosynthesis pigments, which in turn increase metabolic processes, compound synthesis, and leaf translocation to other parts of the plant. These qualities of growth appear in the yield and its components (Fletcher et al., 2000; Mina et al., 2023). Zinc is also required for the generation of chlorophyll in leaf cells, as well as the regulation of biosynthesis of starch and root development (Wassel et al., 2007; Abdel-Latef et al., 2016; Tawfik et al., 2017).

**3.2 Fruit length**

Significant variability in fruit length was observed across the treatments during both years of the experiment. In 2022, the fruit length ranged from a minimum of 8.37 cm to a maximum of 13.17 cm, while in 2023, it ranged from 8.45 cm to 13.20 cm. The average fruit length across both years varied from 8.41 cm to 13.19 cm. In 2022, notable differences in fruit length were evident across treatments. The maximum fruit length (13.17 cm) was recorded in fruits harvested from plots treated with T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO NP), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2 NP) with 12.77 cm. The minimum fruit length (8.37 cm) was observed in the control treatment (T1). Similarly, during the 2023, the highest fruit length (13.20 cm) was recorded in fruits from plots treated with T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO NP) followed by fruit length of 12.74 cm under T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2 NP). The minimum fruit length (8.45 cm) was found in the control (T1), followed by T5 (25% RDF + 6 ml/l Nano Urea) and T4 (50% RDF + 4 ml/l Nano Urea) with fruit lengths of 9.55cm and 9.92cm, respectively. Pooled data analysis across both years revealed that T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO NP) resulted in the highest average fruit length (13.19 cm), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2) with fruit length of 12.76 cm. The use of nano-fertilizers, including Zn, resulted in improved flowering dynamics and growth parameters, which indirectly contribute to fruit length **(Goyal et al., 2024).** As per **Zafar et al. (2021),** foliage application of NPs containing zinc at rates of 0.1%, 0.2%, and 0.3% increased fresh and dry weights, which are connected with the improved fruit length. Other crop research suggests that Zn NPs have a favourable impact on fruit growth. An experiment on tomatoes showed that treatment with 100 ppm zinc oxide nanoparticles caused the largest fruits, reaching 4.55 cm in length and 4.33 cm in diameter, indicating that Zn NPs can boost fruit size in some crops ( add reference ). **(Ahmed et al., 2024). Zafar et al. (2021)** explored the effects of ZnNPs synthesized via green and chemical methods on okra plants under saline conditions. The findings revealed that foliar application of Zn NPs led to significant improvements in various growth attributes, such as shoot length, root length, and chlorophyll content. While the study did not provide specific measurements for fruit length and width, the overall enhancement in plant growth suggests a potential positive impact on fruit dimensions. Application of 20 ppm ZnO nanoparticles significantly increased cucumber fruit diameter, along with other parameters like fruit weight and length **(Nisar et al., 2022)**. In strawberries, a foliar application of 200 mg/L ZnO NPs increased the net assimilation rate by 34% and leaf area by 16%, which can indirectly affect fruit size and quality **(Padilla‐Chacon et al., 2024).**

**3.3 Fruit width**

Significant variability in fruit width was observed across the treatments during both growing seasons. In 2022, the fruit width ranged from 1.00 cm to 1.70 cm, while in 2023, it ranged from 1.01 cm to 1.74 cm. The average fruit width across both years varied between 1.01 cm and 1.72 cm. In 2022, notable differences in fruit width were evident across treatments. The maximum fruit width (1.70 cm) was recorded in fruits harvested from plots treated with T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO NP -fruit length of 12.74 cm), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2 NP) with 1.60 cm. The minimum fruit width (1.00 cm) was observed in the control treatment (T1). During the 2023 growing season, the maximum fruit width (1.74 cm) was recorded in fruits from plots treated with T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO NP), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2 NP) with 1.62 cm fruit width. The minimum fruit width (1.01 cm) was found in the control (T1). Pooled data analysis across both years revealed that T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO) resulted in the maximum average fruit width (1.72 cm), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2) with 1.61 cm. The lowest fruit width (1.01 cm) was recorded in the control (T1). Application of 20 ppm ZnO nanoparticles significantly increased cucumber fruit diameter, along with other parameters like fruit weight and length **(Nisar et al., 2022).** A concentration of 30 mg L-1 ZnO nanoparticles resulted in an 18% increase in bell paper fruit size, alongside improvements in weight and number of fruits **(Uresti-Porras et al., 2021**). Foliar application of 0.6% zinc sulfate led to the highest increase in Mandarin fruit diameter, weight, and overall yield compared to other treatments **(Razzaq et al., 2013).**Zn NPs enhance nutrient absorption, which is crucial for fruit development**(Asmat-Campos et al., 2023).**The application of Zn NPs has been shown to upregulate genes associated with growth and stress tolerance, contributing to improved fruit quality **(Pejam et al., 2021).**In strawberries, a foliar application of 200 mg/L ZnO NPs increased the net assimilation rate by 34% and leaf area by 16%, which can indirectly affect fruit size and quality **(Padilla‐Chacon et al., 2024).**

**3.4 Average fruit weight**

There was considerable variability in average fruit weight among the treatments during both growing seasons. In 2022, the average fruit weight ranged from 6.23 g to 10.60 g, while in 2023, it varied from 6.78 g to 10.62 g. The pooled data across both years showed average fruit weights between 6.51 g and 10.61 g. In 2022, significant differences were observed in average fruit weight across the treatments. The maximum average fruit weight (10.60 g) was recorded from the plots treated with T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2), which produced fruit with an average weight of 10.25 g. Conversely, the minimum fruit weight (6.23 g) was recorded in the control treatment (T1), During the year 2023, the maximum average fruit weight (10.62 g) was found in the fruits harvested from plots treated with T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO), followed by T12 (75% RDF + 2 ml/l Nano Urea +10 ppm TiO2) with an average fruit of 10.28g. The control treatment (T1) and showed the minimum average fruit weight of 6.78g.When pooled across both years, T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO) resulted in the maximum average fruit weight (10.61 g), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2) with average fruit weight of 10.27 g. The minimum average fruit weight (6.51 g) was observed in thecontrol treatment (T1). A foliar spray of 200 mg/L ZnO NPs in strawberries enhanced net absorption rate by 34% and leaf area by 16%, potentially impacting fruit size and quality **(Padilla-Chacon et al., 2024).** Zn NPs have been shown to reduce the negative effects of salt stress on okra fruits, resulting in higher fresh and dry weights **(Zafar et al., 2021) (Alabdallah & Al-Zahrani, 2020).** Seed priming with ZnO NPs has shown to enhance germination and early growth, which correlates with increased fruit weight later in the growth cycle **(Ramzan et al., 2024).** Zn NPs contribute to increased chlorophyll content, which is crucial for photosynthesis and overall plant health, thereby indirectly boosting fruit weight **(Kumar et al., 2009; Sharma et al., 2018).**

**3.5 Dry weight percentage**

Significant variability in dry weight (biomass) production was observed across the treatments during both growing seasons. In 2022, biomass production ranged from 11.40% to 17.06%, while in 2023, it ranged from 11.47% to 17.20%. The average biomass production across both years varied from 11.43% to 17.13%. In 2022, notable differences in biomass production were observed across treatments. The maximum biomass production (17.06%) was recorded in fruits harvested from plots treated with T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2) with 16.32% biomass production. The lowest biomass production (11.40%) was observed in the control treatment (T1). During the year 2023, the highest biomass production (17.20%) was recorded in fruits from plots treated with T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2) with 16.37%. The minimum biomass production (11.47%) was found in thecontrol (T1).Pooled data analysis across both years revealed that T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO) resulted in the highest average biomass production (17.13%), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2) with 16.35%. The lowest biomass production (11.43%) was recorded in the control (T1).Foliar application of Zn NPs at concentrations of 0.1%, 0.2%, and 0.3% resulted in increased fresh and dry weights, which are correlated with improved fruit length**(Zafar et al., 2021).** Zn NPs have been shown to reduce the detrimental effects of salt stress on okra fruits, resulting in higher fresh and dry weights (Zafar et al., 2021) (Alabdallah & Al-Zahrani, 2020).Foliar application of ZnO NPs at concentrations of 50 mg/L resulted in a 39.1% increase in fruit dry weight and a 24.9% increase in yield per plant**(Sun et al., 2023).**

**3.6 Moisture percentage**

Significant variation in the average moisture content of fruits was observed across treatments during both the year. In 2022, the moisture content ranged from 82.94% to 88.60%, whereas in 2023, it varied from 82.80% to 88.53%. The pooled data from both years indicated average moisture content values between 82.87% and 88.57%. In 2022, the lowest moisture content (82.94%) was observed in T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO) followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2), with average fruit moisture content of 83.68%. Conversely, the maximum moisture content (88.60%) was recorded in the control treatment (T1). In 2023, the minimum moisture content (82.80%) was recorded in T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO) followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2), with average fruit moisture content of 83.63%. The maximum moisture content (88.53%) was observed in the control treatment (T1).The pooled data analysis revealed that the lowest moisture content (82.87%) was recorded in T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO) followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2), with average fruit moisture content of 83.65%. The highest moisture content (88.57%) was observed in the control treatment (T1).The nanoparticles also enhance chlorophyll content, which is vital for photosynthesis and energy production, further contributing to increased biomass that means decrease moisture content in okra fruit **(Zafar et al., 2021).** The use of ZnO NPs has been demonstrated to increase shoot and root lengths, and also to raise fresh and dry weights, indicating increased overall plant growth; however, increasing fruit dry weight decreases moisture content of okra fruit (**Ramzan et al., 2024**).

**3.7 Total soluble solids**

Significant variability in TSS levels was observed across the treatments during both growing seasons. In 2022, the TSS ranged from 3.83 °Brix to 6.63 °Brix, while in 2023, it ranged from 3.85 °Brix to 6.59 °Brix. The average TSS content across both years varied from 3.84 °Brix to 6.61 °Brix. In 2022, notable differences in TSS content were observed across treatments. The maximum TSS content (6.63 °Brix) was recorded in fruits harvested from plots treated with T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO) followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2) with TSS value of 6.43 °Brix. The lowest TSS content (3.83 °Brix) was observed in the control treatment (T1). During the 2023 growing season, the highest TSS content (6.59 °Brix) was recorded in fruits from plots treated with T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO) followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2), which recorded TSS content of 6.42 °Brix. The minimum TSS content (3.85 °Brix) was found in the control (T1). Pooled data analysis across both years revealed that T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO) resulted in the highest average TSS (6.61 °Brix), followed by T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2) with 6.43 °Brix. The lowest TSS content (3.84 °Brix) was recorded in the control (T1). Zinc oxide (ZnO) nanoparticles, applied in T13, may act as cofactors for enzymes involved in carbohydrate metabolism, promoting sugar synthesis and storage resulting increase in TSS. Supporting to this, **Wolska et al., (2018)** found that nano fertilizers significantly increased TSS levels in sweet peppers, while **Davarpanah et al., (2017)** observed a similar increase in pomegranate fruits under nano nitrogen treatments.

**3.8 Total sugars**

In 2022, total sugar content ranged from 1.33% to 4.13%, while in 2023, it ranged between 1.35% and 4.16%. The average total sugar content across the two years (pooled data) varied from 1.34% to 4.15%. In 2022, the highest total sugar content (4.13%) was recorded in fruits harvested from plants treated with T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2), followed by T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO), which recorded a total sugar content of 3.84%. The lowest total sugar content (1.33%) was observed in the control treatment (T1). During the 2023 growing season, similar trends were observed where maximum total sugar content (4.16%) was recorded in fruits from plots treated with T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2), followed by T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO), which showed a total sugar content of 3.82%. Pooled data analysis across both years further confirmed that T12 (75% RDF + 2 ml/l Nano Urea + 10 ppm TiO2) resulted in the highest average total sugar content (4.15%), followed by T13 (75% RDF + 2 ml/l Nano Urea + 50 ppm ZnO) with 3.82% total sugar. The lowest total sugar content (1.34%) was recorded in the control treatment (T1). **Rezaized et al. (2019)** also found an increase in stevioside content, a crucial sugar component in stevia with application of 400ppm TiO2 nano particles. It was also correlated with the report of **Farahi et al. (2023)** in vitex plant. According to **Sompornpailin and Chayaprasert (2020),** TiO2 nanoparticles enhance photosynthetic activity and chlorophyll content which are essential for sugar synthesis also strengthened the present finding.

**3.9 Vitamin C**

Analysis of variance, as shown in table (2), revealed significant differences in Vitamin c content across the treatments for both 2022 and 2023 growing seasons, as well as in the pooled data. As highlighted by the results, significant variations in vitamin C content were observed with the application of different treatments in both years. In 2022, it ranged from 13.17 mg/100g to 18.24 mg/100g, while in 2023, they ranged from 13.18 mg/100g to 18.17 mg/100g. The average acidity levels over both years ranged from 13.18 mg/100g to 18.21 mg/100g. During the growing season of 2022, the data clearly indicated significant differences in Vitamin C content across the treatments. The highest content of Vitamin C (18.24 mg/100g) was recorded in the fruits harvested from plots treated with T12- 75% RDF + 2ml/l Nano Urea + 10 ppm TiO2, followed by T13- 75% RDF + 2ml/l Nano Urea + 50 ppm nZnO, with Vitamin C content of 17.78 mg/100g. The lowest content of (13.17 mg/100g) was observed in the control (T1). In 2023, the same pattern was observed where maximum Vitamin C content (18.17 mg/100g) was recorded in fruits from plot treated with T12- 75% RDF + 2ml/l Nano Urea + 10 ppm TiO2, followed by T13 (75% RDF + 2ml/l Nano Urea + 50 ppm nZnO) with 17.74 mg/100g. The minimum Vitamin C content (13.18 mg/100g) was observed in the control (T1). When combining data from both years, the highest content (18.21 mg/100g) was recorded in the fruits harvested from plots treated with T12- 75% RDF + 2ml/l Nano Urea + 10 ppm TiO2, followed by T13- 75% RDF + 2ml/l Nano Urea + 50 ppm ZnO, with vitamin C content of 17.76 mg/100g. The lowest content (13.18 mg/100g) was recorded in the control (T1). It was also supported by **Kleiber and Markiewicz (2013)** who reported that Tomato plants cultivated on rockwool and fed a fertilizer solution containing Ti at a rate of 80 g per hectare per year produced fruits with increased amounts of vitamin C and total sugar. A similar result was observed in previous investigations on pepper fruits **(Martinez-Sanchez et al., 1993; Skupien and Oszmianski, 2007**).

1. **CONCLUSION**

The result revealed that application of 75% RDF+2 ml/l Nano urea + 50 ppm ZnO nano particles significantly influenced the fruit yield and fruit morphological characters. Whereas, the fruit quality parameters like sugars, vitamin C were found superior with application of 75% RDF + 2ml/l Nano urea+ 10 ppm TiO2 nanoparticles. Thus, it may be concluded that two-time foliar application of 2ml/l Nano urea, 50 ppm ZnO along with 75% RDF at 30 and 60 days after sowing may be recommended for better yield and morphological quality of okra cv. Kashi Lalima grows under high pH soil (8.2) of the subtropical agro climate condition of Lucknow to get more profit for the farmer.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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**Table 1. Effect of nanofertilizers on fruit yield and fruit morphology of okra fruit.**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Treatments | Yield(q/ha | | | Fruit length (cm) | | | Fruit width (cm) | | | Average weight of fruit (g) | | | Dry matter (%) | | |
| 1st Year | 2nd Year | Pooled | 1st Year | 2nd Year | Pooled | 1st Year | 2nd Year | Pooled | 1st Year | 2nd Year | Pooled | 1st Year | 2nd Year | Pooled |
| T1 | 58.49 | 63.93 | 61.21 | 8.37 | 8.45 | 8.41 | 1.00 | 1.01 | 1.01 | 6.23 | 6.78 | 6.51 | 11.40 | 11.47 | 11.43 |
| T2 | 140.69 | 141.48 | 141.09 | 12.52 | 12.50 | 12.51 | 1.50 | 1.54 | 1.52 | 9.87 | 9.90 | 9.88 | 15.76 | 15.81 | 15.79 |
| T3 | 134.69 | 135.58 | 135.14 | 12.18 | 12.21 | 12.20 | 1.44 | 1.48 | 1.46 | 9.57 | 9.62 | 9.59 | 15.20 | 15.16 | 15.18 |
| T4 | 82.41 | 83.05 | 82.73 | 9.90 | 9.92 | 9.91 | 1.06 | 1.06 | 1.06 | 7.72 | 7.75 | 7.73 | 13.14 | 12.84 | 12.99 |
| T5 | 78.41 | 78.26 | 78.34 | 9.50 | 9.55 | 9.53 | 1.03 | 1.02 | 1.03 | 7.52 | 7.55 | 7.53 | 12.37 | 12.37 | 12.37 |
| T6 | 111.55 | 112.13 | 111.84 | 10.93 | 10.94 | 10.94 | 1.20 | 1.24 | 1.22 | 8.63 | 8.65 | 8.64 | 14.20 | 14.07 | 14.14 |
| T7 | 98.76 | 99.76 | 99.26 | 10.57 | 10.61 | 10.59 | 1.14 | 1.16 | 1.15 | 8.38 | 8.40 | 8.39 | 14.00 | 13.55 | 13.78 |
| T8 | 91.06 | 91.58 | 91.32 | 10.20 | 10.24 | 10.22 | 1.09 | 1.09 | 1.09 | 8.15 | 8.17 | 8.16 | 13.70 | 13.13 | 13.42 |
| T9 | 115.09 | 115.70 | 115.39 | 11.15 | 11.14 | 11.15 | 1.23 | 1.27 | 1.25 | 8.75 | 8.77 | 8.76 | 14.34 | 14.33 | 14.34 |
| T10 | 104.66 | 105.10 | 104.88 | 10.87 | 10.81 | 10.84 | 1.17 | 1.20 | 1.19 | 8.52 | 8.52 | 8.52 | 14.09 | 13.80 | 13.95 |
| T11 | 93.82 | 94.17 | 93.99 | 10.40 | 10.43 | 10.41 | 1.11 | 1.13 | 1.12 | 8.26 | 8.28 | 8.27 | 13.80 | 13.36 | 13.58 |
| T12 | 149.32 | 150.60 | 149.96 | 12.77 | 12.74 | 12.76 | 1.60 | 1.62 | 1.61 | 10.25 | 10.28 | 10.27 | 16.32 | 16.37 | 16.35 |
| T13 | 157.69 | 161.92 | 159.81 | 13.17 | 13.20 | 13.19 | 1.70 | 1.74 | 1.72 | 10.60 | 10.62 | 10.61 | 17.06 | 17.20 | 17.13 |
| T14 | 118.42 | 119.09 | 118.76 | 11.20 | 11.25 | 11.22 | 1.26 | 1.31 | 1.28 | 8.90 | 8.92 | 8.91 | 14.52 | 14.60 | 14.56 |
| T15 | 130.79 | 131.67 | 131.23 | 11.87 | 11.92 | 11.90 | 1.40 | 1.44 | 1.42 | 9.42 | 9.47 | 9.44 | 14.88 | 15.00 | 14.94 |
| T16 | 122.84 | 123.42 | 123.13 | 11.43 | 11.46 | 11.45 | 1.32 | 1.35 | 1.33 | 9.09 | 9.12 | 9.10 | 14.68 | 14.77 | 14.73 |
| T17 | 127.17 | 127.51 | 127.34 | 11.67 | 11.70 | 11.68 | 1.36 | 1.39 | 1.38 | 9.27 | 9.28 | 9.28 | 14.80 | 14.89 | 14.85 |
| CD (P=0.05) | 2.05 | 1.55 | 1.80 | 0.1 | 0.1 | 0.1 | 0.02 | 0.02 | 0.02 | 0.09 | 0.07 | 0.08 | 0.02 | 0.04 | 0.03 |
| SEm± | 0.71 | 0.53 | 0.62 | 0.017 | 0.021 | 0.02 | 0.006 | 0.007 | 0.007 | 0.031 | 0.024 | 0.028 | 0.01 | 0.01 | 0.01 |

**Table 2. Effect of Nanofertilizers on biochemical qualities of okra fruit.**

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Treatments | Moisture percent (%) | | | TSS (O Brix) | | | Total sugars (%) | | | Vitamin C (mg/100g) | | |
| 1st Year | 2nd Year | Pooled | 1st Year | 2nd Year | Pooled | 1st Year | 2nd Year | Pooled | 1st Year | 2nd Year | Pooled |
| T1 | 88.60 | 88.53 | 88.57 | 3.83 | 3.85 | 3.84 | 1.33 | 1.35 | 1.34 | 13.17 | 13.18 | 13.18 |
| T2 | 84.24 | 84.19 | 84.21 | 6.23 | 6.24 | 6.24 | 3.60 | 3.62 | 3.61 | 17.29 | 17.30 | 17.30 |
| T3 | 84.80 | 84.84 | 84.82 | 6.03 | 6.04 | 6.04 | 3.40 | 3.43 | 3.42 | 16.89 | 16.90 | 16.90 |
| T4 | 86.86 | 87.16 | 87.01 | 4.21 | 4.22 | 4.22 | 2.26 | 2.28 | 2.27 | 14.98 | 14.98 | 14.98 |
| T5 | 87.63 | 87.63 | 87.63 | 4.00 | 4.01 | 4.00 | 1.53 | 1.55 | 1.54 | 13.47 | 13.49 | 13.48 |
| T6 | 85.80 | 85.93 | 85.86 | 5.00 | 5.00 | 5.00 | 3.21 | 3.19 | 3.20 | 16.64 | 16.63 | 16.64 |
| T7 | 86.00 | 86.45 | 86.23 | 4.60 | 4.62 | 4.61 | 2.48 | 2.50 | 2.49 | 15.54 | 15.50 | 15.52 |
| T8 | 86.30 | 86.87 | 86.59 | 4.40 | 4.41 | 4.40 | 1.73 | 1.75 | 1.74 | 13.87 | 13.85 | 13.86 |
| T9 | 85.66 | 85.67 | 85.67 | 5.13 | 5.14 | 5.14 | 2.98 | 3.00 | 2.99 | 16.34 | 16.34 | 16.34 |
| T10 | 85.91 | 86.20 | 86.06 | 4.83 | 4.85 | 4.84 | 2.38 | 2.40 | 2.39 | 15.27 | 15.28 | 15.28 |
| T11 | 86.20 | 86.64 | 86.42 | 4.50 | 4.51 | 4.51 | 1.63 | 1.60 | 1.62 | 13.65 | 13.67 | 13.66 |
| T12 | 83.68 | 83.63 | 83.65 | 6.43 | 6.42 | 6.43 | 4.13 | 4.16 | 4.15 | 18.24 | 18.17 | 18.21 |
| T13 | 82.94 | 82.80 | 82.87 | 6.63 | 6.59 | 6.61 | 3.80 | 3.84 | 3.82 | 17.78 | 17.74 | 17.76 |
| T14 | 85.48 | 85.40 | 85.44 | 5.33 | 5.33 | 5.33 | 2.80 | 2.82 | 2.81 | 16.02 | 16.07 | 16.04 |
| T15 | 85.12 | 85.00 | 85.06 | 5.83 | 5.82 | 5.83 | 2.64 | 2.65 | 2.64 | 15.84 | 15.80 | 15.82 |
| T16 | 85.32 | 85.23 | 85.27 | 5.50 | 5.52 | 5.51 | 2.15 | 2.17 | 2.16 | 14.41 | 14.43 | 14.42 |
| T17 | 85.20 | 85.11 | 85.16 | 5.63 | 5.64 | 5.64 | 2.03 | 2.05 | 2.04 | 14.12 | 14.16 | 14.14 |
| CD (P=0.05) | 0.08 | 0.05 | 0.07 | 0.03 | 0.06 | 0.05 | 0.02 | 0.04 | 0.03 | 0.03 | 0.05 | 0.04 |
| SEm± | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 |

Fig 1. Effect of nanofertilizer on yield and yield attributes