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# Foliar Application of Iron Oxide Nanoparticles Enhances Morphophysiological Characteristics and Yield Performance of Capsicum annuum L. in a Controlled Environment

Zulaikha Sarobo[1,*], Noorafizah Dzahir[1], Mohd Azlan Jalal[1], Mohamad Azzuan Rosli[1], Nazrin Abd Aziz[1,2], Raihana Ridzuan[1,2], Usman Magaji[3], Mohd Rafie Johan[4], Durga Devi Suppiah[4], Norlia Ab. Rani[4]

[1] Innovation Centre in Agritechnology for Advanced Bioprocessing (ICA, Universiti Teknologi Malaysia Pagoh, Pagoh 84600, Johor, Malaysia
[2] Department of Biosciences, Faculty of Science, Universiti Teknologi Malaysia, UTM Skudai, Johor, Malaysia
[3] Department of Agronomy, Faculty of Agriculture, Federal University of Kashere Gombe, P.M.B 0182 Gombe, Gombe State, Nigeria
[4] Nanotechnology & Catalysis Research Centre (NANOCAT), University of Malaya, Kuala Lumpur, Malaysia

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**ABSTRACT**

Iron (Fe) is an essential micronutrient that plays a vital role in several plant physiological processes. Nevertheless, iron deficiency remains a significant challenge in chili plants, particularly affecting their fruit production. Therefore this study aimed to characterize the physicochemical of iron oxide nanoparticles (IONPs) and investigate the effects of foliar-applied IONPs on the growth, physiological responses, and yield parameters of *Capsicum annuum*. The physicochemical characteristics of IONPs were analyzed using a High-Resolution Transmission Electron Microscope and scanning electron microscopy with energy dispersive X-ray spectroscopy. Six IONPs concentrations (0, 50, 100, 200, 400, and 800 mg/L) were applied through foliar spray on chili plants during four critical growth stages: vegetative growth, flowering, fruit development, and maturity. The findings revealed the spherical, uniform surface structures with an average size of 12–20 nm and 58.2% of iron composition. On the other hand, the field evaluation demonstrated that foliar application of IONPs at concentrations between 200 mg/L significantly enhanced plant height and photosynthesis activity compared to control treatment. In terms of yield, 400 mg/L IONPs resulted in the highest fruit yield compared to control treatments. This research establishes the effectiveness of IONPs as a growth promoter and yield enhancer in chili cultivation, with optimal concentrations identified for commercial application. Future research should focus on long-term effects and environmental impacts to develop comprehensive application guidelines for sustainable agricultural practices.

## 1. Introduction

Chili is commonly referred to as pepper (*Capsicum spp.*). It is one of the important vegetable crops cultivated globally for dry, fresh, and processing products. It belongs to the family Solanaceae.

[*] *Corresponding author*
*E-mail address: zulaikha-s@utm.my*

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*Capsicum spp.* is an annual or perennial herb or shrub, which originated from South and Central America or also known as Andean region. After that, it was domesticated to Africa and Asia via Europe [1]. This species was also called chili, chile, chili, aji, and paprika in different parts across the world [2]. *Capsicum spp.* consists of 27 species, but the five most cultivated species are *C. annuum, C. frutescens, C. pubescens, C. chinense,* and *C. baccatum* [3-5]. In Malaysia, local chili production meets only 24.9% of domestic demand, primarily due to pest infestations, disease susceptibility, poor seed quality, and climate change impacts. Recent advances in nanotechnology have demonstrated the potential of iron oxide nanoparticles (IONPs) in enhancing crop growth, yield, and disease resistance, presenting a promising solution for improving chili cultivation. Chili fruits have great demand at home as well as outside countries for various culinary preparations such as flavouring or natural red colorants for food and in traditional medicines for various common problems such as high blood pressure, cholesterol, skin problem, joint pain, and used as a stomachic [5]. Domesticated cultivars have various fruit and flower colors. The diversity of chili's colour is due to the presence of pigments such as chlorophyll (green), anthocyanins (violet/purple), α- and β-carotene, zeaxanthin, lutein, and also β-cryptoxanthin (yellow/orange). During ripening, the morphological, physiological, and metabolic changes of chili fruits will also be influenced by genotype, maturity, and growing conditions [3,6]. Micronutrients are important for plant growth, yield and quality attributes [7].

Iron (Fe), a micronutrient, is intricate in numerous physiological functions and has become significantly important in the production of chili plants [8]. Nano-sized micronutrients are smaller and more readily absorbed by the plant through foliar application compared to soil application. Aside from its important roles in synthesis of chlorophyll as well as maintenance of chloroplast structure and its function, iron also directly affects the quality and yield performances of chili. Chili crops required sufficient iron to prevent slower growth and yellowing of leaves and longer maturation time. Iron is generally found abundant in soils; however, it is in the form of ferric ion ($Fe^{3+}$) that does not sufficiently meet the plant needs. Plants primarily absorb iron as the ferrous ion ($Fe^{2+}$), which is readily soluble for uptake by the roots [9]. On the other hand, IONPs offer certain benefits to plants compared to conventional iron fertilizers by which their larger surface area improves nutrient uptake, enhances stress tolerance, and reduces the need for large amounts of iron [10]. The foliar application is particularly advantageous, offering rapid nutrient uptake compared to soil application methods. Studies by researchers demonstrate the viability of innovative approaches to enhance iron uptake and utilization in plants under various stress conditions [9,11]. Iron deficiency can be solved by applying it on leaves in the form of IONPs. Being a very exhaustive crop, chili needs proper nutrient management to express its genetic yield potential.

Moreover, research indicates that an adequate supply of micronutrients—when coupled with major nutrients—can significantly enhance crop yield and quality, vital for meeting the increasing global demand for food [12]. Specifically, the timing of nutrient application can be critical; for example, applying iron and other micronutrients during key physiological stages can result in marked improvements in growth parameters and subsequent yield outcomes. Furthermore, the incorporation of molecular techniques and smart agricultural practices may further refine nutrient management approaches in chili cultivation [13]. Recent studies have shown that micronutrient applications can stimulate physiological and biochemical processes crucial for plant performance. For example, the foliar application of micronutrients has been shown to improve flowering time and branch development, important indicators of yield potential [11]. Furthermore, investigations into the interaction between nanoparticles and micronutrient absorption reveal that nanoparticles can effectively facilitate the movement of these essential elements into plant tissues, maximizing their efficacy [14].

## 2. Methodology
### *2.1 Materials*

The following provides information on chemicals used in this work: NANOCAT™NanoMAG (Product ID: TMO-IOS2B1R1WC), sourced from the Nanotechnology and Catalysis Research Centre (NANOCAT), University of Malaya, Malaysia and used as received without any further purification.

### *2.2 IONPs Characterization using High-Resolution Transmission Electron Microscope (HRTEM)*

The morphology and particle size of IONPs were characterized using high-resolution transmission electron microscopy. Briefly, a small amount of IONPs sample was dispersed in ethanol and sonicated for 30 min to obtain a uniform suspension. A drop of the suspension was then placed onto a copper TEM grid and allowed to dry at room temperature. HRTEM imaging was performed using a JEM-ARM200F ACCELARM Atomic Resolution Analytical Electron Microscope (JEOL Ltd., Japan) operated at an accelerating voltage of 200 kV. Particle size measurements were conducted by averaging the diameters of randomly selected nanoparticles from representative TEM images.

### *2.3 Scanning Electron Microscopy- Energy Dispersive X-ray Spectrometry (SEM-EDX) Analysis*

The microstructure and elemental composition of the IONPs were examined using field-emission scanning electron microscopy (FE-SEM) coupled with energy-dispersive X-ray spectroscopy (EDX). Prior to analysis, the IONP samples were centrifuged at 10,000 rpm for 30 min, and the resulting pellet was redispersed in 10 mL of ethanol. The washing process was repeated three times with sterile distilled water, followed by oven drying of the final pellet. Thin films of dried samples (10 mg/mL) were prepared for surface and compositional analysis. EDX analysis was conducted using a Hitachi SU8020 microscope. Due to the non-conductive nature of IONPs, which may lead to charging effects and image distortion, selected samples were sputter-coated with a platinum layer prior to analysis. Coating was performed using a Quorum Q150RS sputter coater for 1 min, with a sputter current of 30 mA and a tooling factor of 2.60. The coating procedure was applied only to non-conductive samples as required.

### *2.4 Preparation of IONPs Treatment Solutions*

IONPs were used without further purification. Ultrapure deionized water was employed for all solution preparations. Treatment solutions were prepared at concentrations of 0 (control), 50, 100, 200, 400, and 800 mg/L. The required amount of nanoparticles was weighed using an analytical balance and added to 1000 mL of deionized water containing a small amount of Tween 20 as a surfactant. The mixture was then sonicated for 30 minutes to achieve uniform dispersion. All solutions were mixed thoroughly before use. To prevent settling, the dispersions were shaken or stirred prior to each application. Prior to application, the IONPs slurry was stored at recommended conditions (between 20°C to 60°C, protected from sunlight and heat) to maintain stability. The average pH of the IONPs treatment solutions was measured to be between 6.58 and 6.60.

### *2.5 Field Evaluation of Foliar-Applied IONPs*

A field experiment was conducted under a Protected Environment Structure (20 ft × 40 ft) at Kolej Vokasional Pagoh to investigate the effects of IONPs on the growth, yield, and physiological performance of *Capsicum annuum L.* cv. Kulai Sakata 461 (Sakata Seed Corporation, Japan). Seeds were sown in 104-cell germination trays filled with peat moss. After four weeks, uniform seedlings were transplanted into 16 cm × 16 cm white polybags containing 4 kg of coco peat medium and arranged in a fertigation system. The experiment plot was arranged in a Complete Randomized Design (CRD) consisting six treatments and eight plants per treatment laid in four replications, resulting in a total sample size of 192 (n=192). The experimental layout followed a Completely Randomized Design (CRD) with six treatments and four replications, each consisting of eight plants (n = 192). Treatments included: T0 (control, 0 mg/L), T1 (50 mg/L), T2 (100 mg/L), T3 (200 mg/L), T4 (400 mg/L), and T5 (800 mg/L) of IONPs. Plant spacing was maintained at 65 cm between rows and 60 cm within rows. A modified Cooper nutrient solution [15] was applied via fertigation, and electrical conductivity was monitored daily to maintain consistent fertilization. Weekly pest and disease control included Neem oil (B'green), Decis 250 (Bayer), and Vintage 21.7EC (Hextar).

Foliar applications of IONPs were conducted at four key crop development stages: vegetative growth (45–89 days after transplanting (DAT)), flowering (90–140 DAT), fruit development (141–170 DAT), and maturity (171–205 DAT). Solutions were sprayed onto both adaxial and abaxial leaf surfaces to ensure full coverage, with water applied as the control treatment. Sprays were administered in the early morning prior to flowering. Growth and physiological parameters, including plant height (cm), stem diameter (cm), photosynthetic rate (Pn), stomatal conductance (gs), and transpiration rate (E), were recorded at 45, 90, 145, and 201 DAT using a portable photosynthesis system (LI-6400xt, LI-COR, Lincoln, NE, USA) [6]. At harvest, yield parameters—number of fruits per plant, average fruit weight (g), total yield per plant (g), and aerial biomass (fresh and dry weight, g)—were quantified. Data were analyzed using XLSTAT (Addinsoft, Paris, France) and SPSS version 21.0, with statistical procedures including ANOVA, post hoc tests, and Pearson correlation analysis [11].

## 3. Results

The results from the physicochemical characterization of IONPs reveal a spherical shape and a homogeneous surface, with an average size ranging from approximately 12-20 nm, as evidenced by High-Resolution Transmission Electron Microscopy (HR-TEM) as shown in Figure 1. These findings are well-supported by recent studies, which highlight the critical influence of particle size and shape on the properties and various applications of IONPs specifically for foliar booster in plants [16-18].

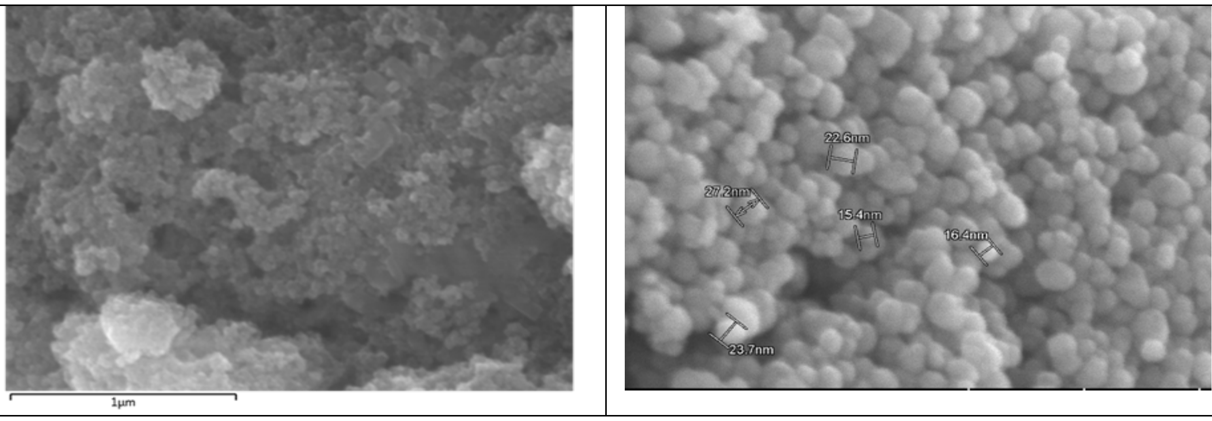


**Fig. 1.** Morphological characterisation of IONPs using High Resolution - Transmission Electron Microscope 200KV equipment (HR-TEM 200KV)

SEM-EDX analysis as shown in Figure 2 confirmed the incorporation of $Fe_2O_3$-NPs into the capsules with Fe as the main element, and other elements, such as Ca, Cl, O, C, and Na were also present. The chemical composition revealed 58.6% iron (Fe) and 33.1% oxygen (O) content, validating that the IONPs sample was devoid of impurities. The presence of elements such as calcium (Ca), chlorine (Cl), carbon (C), and sodium (Na) in the synthesized IONPs, as confirmed by SEM-EDX analysis, likely results from their intentional incorporation during the synthesis process rather than contamination. It also can be due to a combination of CaO (calcium oxide) or NaCl (sodium chloride) as suggested by the IUPAC definition of trace elements as elements present in low concentrations. These trace elements can enhance the properties of the nanoparticles, contributing to improved nutrient delivery and plant health, with calcium playing a vital role in cellular processes and overall physiological function [19]. Consequently, their presence supports the agricultural efficacy of IONPs, making them beneficial for crop growth and resilience.

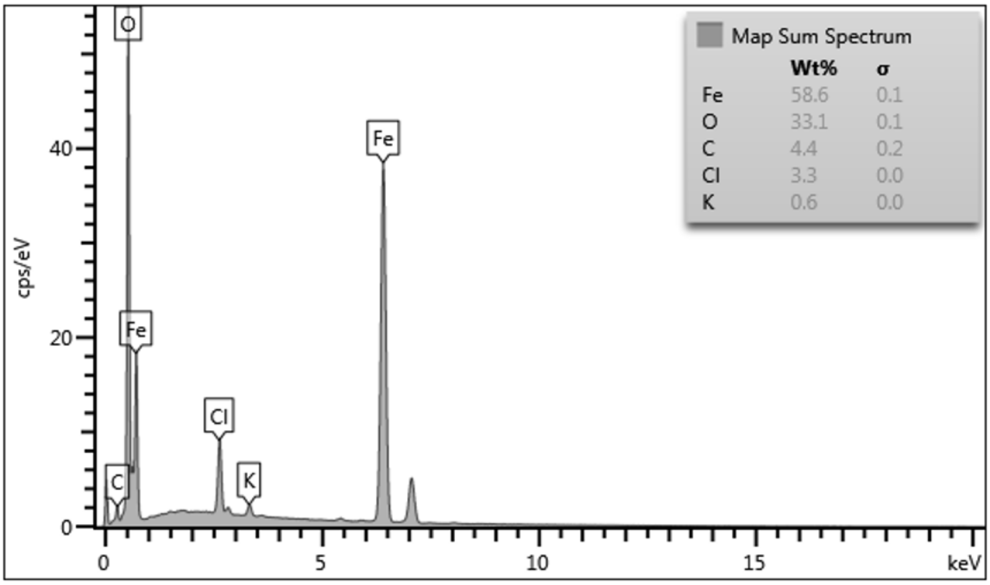


**Fig. 2.** SEM-EDX analysis to determine the elemental composition of individual points or to map out the lateral distribution of elements from the imaged area

The ANOVA based on growth, yield and physiological components in chili treated with different concentrations of IONPs were described in Table 1. Table 1 explains that the significant values were found in plant height (278.19), branches number (630.58), number of fruits per plant (1252.14), yield per plant (59531.54), fruit weight (98.4), fruit length (8.91) and fruit girth (1.59). These results indicate that the treatments had a notable impact on these growth and yield parameters, suggesting that the application of IONPs has a pronounced impact on the growth and productivity of chili plants, consistent with research that highlights the benefits of nanoparticles in agricultural practices. For instance, a research finding noted a similar pattern of impact from IONPs in tomato plants, reinforcing the notion that specific treatments can enhance plant development successfully [20-21]. Conversely, no significant changes were recorded for stem diameter, photosynthesis rate, stomatal conductance, or transpiration rate, indicating that these physiological processes might have remained stable despite the treatments. This outcome aligns with findings from Hạt *et al.*, which showed that while IONPs could enhance root growth effectively, other physiological metrics were less sensitive to varying concentrations [4]. Such data underline the notion presented by Sathyanarayanan *et al.*, [22] suggesting that IONPs can enhance specific growth parameters without adversely affecting the physiological mechanics of plant health—rendering them a promising agricultural supplement.

**Table 1**
ANOVA based on growth, yield and physiological components in chili treated with different concentrations of IONPs

| Source of variation | d.f. | Mean squares | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | PH | SD | BN | DF | NFP | YP | FW | FL | FG | PR | SC | TR |
| Treatments | 5 | 278.19** | 0.03 | 630.58** | 1.80 | 1252.14** | 59531.54** | 98.40** | 8.91** | 1.59** | 39.92 | 0.00 | 0.29 |
| Error | 18 | 8.07 | 0.02 | 2193.65 | 2.28 | 385.68 | 1647.40 | 3.01 | 1.48 | 0.14 | 16.28 | 0.01 | 0.25 |

Notes : **: Significant at P<0.01, PH: plant height (cm), SD: stem diameter (cm), BN: branches number, DF: days to flowering, NFP: number of fruits per plant, YP: yield per plant (g), FW: fruit weight (cm), FL : fruit length (cm), FG: fruit girth (cm), PR: photosynthesis rate (μmolCO2m2⁻ s-1), SC: stomata conductance (mol H2O m-2 s-1), TR: transpiration rate (mmol H2O m-2 s-1)

The application of IONPs has shown significant effects on the growth performance of chili plants, particularly with 200 ppm resulting in the tallest plants measured at 114.50 ± 2.53 cm. However, the introduction of higher concentrations, such as 400 and 800 ppm, correlated with a notable decline in plant height. This trend invites exploration into the underlying mechanisms responsible for this reduction, notably nanoparticle-induced stress, toxicity thresholds, and diminished translocation efficiency. Research indicates that elevated IONP concentrations can lead to oxidative stress, largely due to increased production of reactive oxygen species (ROS) that impair cellular integrity and metabolic processes. Apel and Hirt [23] elucidate how excess ROS can compromise root systems, vital for nutrient uptake, thus inhibiting overall plant growth [24]. This is further supported by Feng *et al.*, who emphasize that while low concentrations of IONPs may enhance plant stress defense response, higher levels can lead to detrimental cellular effects, adversely affecting growth metrics [11].

The concept of toxicity thresholds plays a pivotal role in the application of IONPs. Ahmad *et al.,* [25] demonstrate that while IONPs can provide biofortification benefits, surpassing specific concentrations can initiate harmful effects. Moreover, T. Ahmed *et al.,* [26] highlight that excessive IONP exposure impairs nutrient translocation, precluding optimal growth. This synthesis underscores the necessity for precise management of IONPs applications to harness their benefits while mitigating potential phytotoxic effects on plant growth [27-29].

Additionally, the number of branches which is an important indicator for yield estimations was most pronounced at 400 ppm, with a recorded value of 287 ± 42.02 branches per plant. This observation indicates that higher concentrations of IONPs may enhance the plant's structural growth and potential fruit-bearing capacity. Furthermore, the treatment at 100 ppm also led to the earliest flowering, occurring at 19.75 ± 0.25 days, highlighting this concentration's role in accelerating the reproductive phase and thereby potentially facilitating earlier fruit production. These findings collectively suggest that varying concentrations of IONPs exert distinct influences on different growth parameters in chili plants, with 100 ppm identified as optimal for early flowering, 200 ppm for achieving maximum plant height, and 400 ppm for increased branching (Table 2). This aligns with research, such as that by Ashraf *et al*., [30] which has documented the beneficial effects of IONPs on various plant metrics, including growth and yield enhancements. Asadi-Kavan *et al.,* demonstrated that IONPs can promote germination and growth by, among other mechanisms, enhancing physiological processes and antioxidant systems [31]. However, there is a lack of specific studies directly linking IONPs to enhanced flowering and branching in chili plants. Similarly, while Ndaba *et al.,* focused on iron nanoparticles in a different plant system and highlighted their impact on growth metrics, these findings may not directly extrapolate to chili plants [32].

**Table 2**
Effect of different concentrations of IONPs application on chili plants on growth performances

| Treatment | Plant Height (cm) | Stem Diameter (cm) | Branches Number | Days to Flowering |
|---|---|---|---|---|
| 0 | 93.00 ± 0.91$^{d}$ | 1.50 ± 0.05$^{a}$ | 188.00 ± 9.57$^{b}$ | 21.50 ± 0.50$^{a}$ |
| 50 | 99.00 ± 1.22$^{c}$ | 1.48 ± 0.04$^{a}$ | 209.75 ± 6.18$^{b}$ | 20.75 ± 0.75$^{a}$ |
| 100 | 112.50 ± 1.32$^{a}$ | 1.70 ± 0.14$^{a}$ | 240.00 ± 13.00$^{ab}$ | 19.75 ± 0.25$^{a}$ |
| 200 | 114.50 ± 2.53$^{a}$ | 1.58 ± 0.03$^{a}$ | 241.00 ± 21.20$^{ab}$ | 21.50 ± 1.26$^{a}$ |
| 400 | 99.88 ± 1.09$^{c}$ | 1.68 ± 0.07$^{a}$ | 287.00 ± 42.02$^{a}$ | 21.25 ± 0.75$^{a}$ |
| 800 | 105.50 ± 0.65$^{b}$ | 1.57 ± 0.07$^{a}$ | 285.50 ± 27.87$^{a}$ | 21.25 ± 0.63$^{a}$ |

Data was expressed as mean ± standard error (SE). Different alphabet indicated significantly different at P≤ 0.05 using Post Hoc Duncan Multiple Range Test (DMRT)

The results of the study as shown in Table 3 indicate that the application of different concentrations of IONPs significantly impacted the fruit yield and quality of chili plants. Notably, the highest fruit yield recorded was 1280 g per plant at a concentration of 400 mg/L, suggesting that this level may be optimal for maximizing fruit yield in *Capsicum annuum*. In contrast, significantly lower yields were observed at both the control (0 mg/L) and the highest concentration of 800 mg/L, implying that both insufficient and excessive applications of IONPs may hinder yield enhancement. Similarly, Das *et al*., [33] reported that IONPs application in tomato plants resulted in best yield outputs at moderate concentrations, underscoring the importance of optimizing nanoparticle dosage for desired crop performance [4]. In terms of fruit quality, the maximum fruit girth of 6.45 cm and the highest fruit weight of 30.08 g were also achieved at the 200 mg/L concentration in this study, reinforcing the notion that IONPs treatment can enhance fruit characteristics. These findings suggest that specific concentrations of IONPs are effective in enhancing both quantitative and qualitative traits of the crop. Similar results were reported by Ahmad *et al.,* [34], indicating that IONPs stimulate the expression of genes associated with iron transport and metabolism, thereby improving nutrient absorption. Consistent with this, Adhikari *et al.,* [35] observed significant improvements in fruit quality parameters such as weight and size in tomato and chili plants. These outcomes further support earlier observations of IONPs' positive impact on fruit development and overall quality.

**Table 3**
Effect of different concentrations of IONPs application on chili plants on yield performances

| Treatment | Number of Fruits/Plant | Yield/ Plant | Fruit Weight (cm) | Fruit Length (cm) | Fruit Girth (cm) |
|---|---|---|---|---|---|
| 0 | 63.50 ± 5.69$^{c}$ | 948.75 ± 15.86$^{c}$ | 15.50 ± 0.80$^{d}$ | 14.13 ± 0.31$^{b}$ | 4.75 ± 0.12$^{c}$ |
| 50 | 82.25 ± 3.35$^{bc}$ | 968.75 ± 18.19$^{c}$ | 23.88 ± 0.79$^{c}$ | 17.60 ± 0.47$^{a}$ | 5.38 ± 0.06$^{b}$ |
| 100 | 93.75 ± 7.19$^{abc}$ | 1127.25 ± 36.04$^{b}$ | 26.05 ± 0.71$^{bc}$ | 17.25 ± 0.45$^{a}$ | 5.58 ± 0.17$^{b}$ |
| 200 | 117.25 ± 14.46$^{a}$ | 1137.50 ± 16.39$^{b}$ | 30.08 ± 0.76$^{a}$ | 18.35 ± 0.65$^{a}$ | 6.45 ± 0.25$^{a}$ |
| 400 | 97.00 ± 6.70$^{ab}$ | 1280.00 ± 10.80$^{a}$ | 27.35 ± 0.49$^{b}$ | 17.73 ± 0.46$^{a}$ | 6.18 ± 0.27$^{a}$ |
| 800 | 90.50 ± 15.14$^{abc}$ | 1100.00 ± 14.29$^{b}$ | 24.40 ± 0.67$^{c}$ | 17.35 ± 1.03$^{a}$ | 5.20 ± 0.15$^{bc}$ |

Data was expressed as mean ± standard error (SE). Different alphabet indicated significantly different at P≤ 0.05 using Post Hoc Duncan Multiple Range Test (DMRT)

Photosynthesis rate, stomatal conductance, and transpiration rate showed no significant differences among the treatments, as shown in Table 4. The similar photosynthesis rates at 200 mg/L and 0 mg/L indicate that IONP application had no noticeable effect on this parameter. Photosynthetic activity is primarily influenced by factors such as nitrogen form and ratio, environmental stressors and specific biostimulant applications. As reported by Zhang *et al.,* [36], optimizing the ammonium-to-nitrate ratio can enhance photosynthesis through improvements in chloroplast ultrastructure and enzyme activities. However, there is no evidence in the provided abstracts that IONPs alone affect the photosynthesis rate in capsicum.

**Table 4**
Effect of different concentrations of IONPs application on chili plants on physiological performances

| Treatment | Photosynthesis rate (μmol $CO_2$ m2 s-1) | Stomata conductance (mol H2O m-2 s-1) | Transpiration rate (mmol H2O m-2 s-1) |
|---|---|---|---|
| 0 | 22.01 0 ± 1.64$^{a}$ | 0.22 ± 0.04$^{a}$ | 2.20 ± 0.12$^{a}$ |
| 50 | 15.24 ± 1.81$^{b}$ | 0.14 ± 0.04$^{a}$ | 1.79 ± 0.11$^{a}$ |
| 100 | 20.36 ± 1.27$^{ab}$ | 0.18 ± 0.03$^{a}$ | 1.86 ± 0.26$^{a}$ |
| 200 | 24.44 ± 2.36$^{a}$ | 0.18 ± 0.04$^{a}$ | 1.38 ± 0.26$^{a}$ |
| 400 | 20.94 ± 2.64$^{ab}$ | 0.18 ± 0.04$^{a}$ | 1.62 ± 0.36$^{a}$ |
| 800 | 18.34 ± 2.08$^{ab}$ | 0.17 ± 0.05$^{a}$ | 1.83 ± 0.29$^{a}$ |

Data was expressed as mean ± standard error (SE). Different alphabet indicated significantly different at P≤ 0.05 using Post Hoc Duncan Multiple Range Test (DMRT)

Correlation analysis presented in Table 5 revealed significant correlations among the measured parameters. Plant height exhibited a strong positive correlation with fruit yield and individual fruit weight, indicating that taller plants are more efficient in resource allocation for fruit growth. Similarly, fruit weight and fruit girth showed highly significant correlations with yield, highlighting their significance as yield-determining traits. On the other hand, negative correlations between days to flowering and other measures, including fruit yield and fruit weight, suggest that earlier flowering enhances production. These findings demonstrate the interconnected nature of growth and physiological traits in determining crop performance, aligning with the conclusions of Feng *et al.*, [11] who reported that the translocation of IONPs is influenced by growth conditions and plant species. The dose-dependent impact of IONPs on growth and yield traits was evident. Low concentrations, such as 50 mg/L, showed minimal improvement compared to the control, indicating limited bioavailability of nutrients at these levels. Optimal concentrations, specifically 200 mg/L and 400 mg/L, demonstrated substantial enhancements in both growth and yield traits, likely due to improved nutrient absorption and physiological efficiency. In contrast, higher concentrations, such as 800 mg/L, resulted in diminished yield and fruit quality, potentially due to nanoparticle toxicity or nutrient imbalance at excessive levels. This aligns with the findings of Bilesky-José *et al.*, [37] who noted that the effects of IONPs can be concentration-dependent, influencing plant health and yield outcomes.

The physiological responses observed in this study align with previous research reporting the beneficial effects of nanoparticles on crop performance. Enhanced nutrient uptake and improved photosynthetic activity are key mechanisms through which nanoparticles boost plant growth. However, the observed decline in yield at higher concentrations is consistent with findings that highlight the potential for nanoparticle-induced toxicity beyond optimal thresholds. These results underscore the importance of determining precise application rates to maximize benefits while minimizing adverse effects, as emphasized by Gupta *et al.*, [2] who discussed the significance of nanoparticle properties in agricultural applications.

**Table 5**
Correlation analysis of growth, yield and physiological components in chili treated with different concentrations of IONPs

| Character | PH | SD | BN | DF | NFP | YP | FW | FL | FG | PR | SC | TR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PH | 1.00 | 0.28 | 0.24 | -0.27 | 0.51* | 0.42* | 0.68** | 0.55** | 0.50* | 0.19 | -0.11 | -0.30 |
| SD | | 1.00 | 0.35 | -0.21 | 0.31 | 0.41* | 0.39 | 0.29 | 0.29 | -0.22 | -0.04 | -0.17 |
| BN | | | 1.00 | -0.32 | 0.36 | 0.63** | 0.44* | 0.39 | 0.35 | -0.19 | -0.09 | -0.12 |
| DF | | | | 1.00 | 0.19 | -0.13 | -0.21 | -0.24 | -0.17 | 0.09 | 0.01 | -0.15 |
| NFP | | | | | 1.00 | 0.48* | 0.59** | 0.64** | 0.59** | 0.06 | -0.18 | -0.35 |
| YP | | | | | | 1.00 | 0.73** | 0.47* | 0.64** | 0.22 | 0.05 | -0.21 |
| FW | | | | | | | 1.00 | 0.78** | 0.71** | 0.02 | -0.07 | -0.28 |
| FL | | | | | | | | 1.00 | 0.63** | -0.05 | -0.26 | -0.33 |
| FG | | | | | | | | | 1.00 | 0.20 | -0.10 | -0.32 |
| PR | | | | | | | | | | 1.00 | 0.07 | -0.12 |
| SC | | | | | | | | | | | 1.00 | 0.76** |
| TR | | | | | | | | | | | | 1.00 |

Notes : **: very significant at P≤0.01, *: significant at P≤0.05, PH: plant height (cm), SD: stem diameter (cm), BN: branches number, DF: days to flowering, NFP: number of fruits per plant, YP: yield per plant (g), FW: fruit weight (cm), FL : fruit length (cm), FG: fruit girth (cm), PR: photosynthesis rate (μmol CO2 m2 ⁻s-1), SC: stomata conductance (mol H2O m-2 s-1), TR: transpiration rate (mmol H2O m-2 s-1)

## 4. Conclusions

In summary, results of this study demonstrate the influence of the foliar application of IONPs on development and yield of chili plants. The application of certain concentrations of IONPs appears to facilitate robust growth and yield improvements in chili plants while not compromising their physiological stability, marking an important step in advancing sustainable agricultural practices through nanotechnology interventions. This study provides valuable insights for optimizing the use of IONPs in *Capsicum annuum* cultivation. Foliar application of 200 mg/L to 400 mg/L IONPs is recommended to maximize yield and improve fruit quality. Avoiding higher concentrations, such as 800 mg/L, is essential to prevent potential toxicity and associated yield losses. Additionally, the timing of application, synchronized with critical growth stages, ensures efficient nutrient uptake and utilization, as demonstrated in this study. In summary, understanding the intricate balance of nutrients, particularly regarding IONPs is vital for optimizing the growth and yield of *Capsicum annuum*. Efficient nutrient management strategies, especially through the application of IONPs, are instrumental in navigating the challenges posed by nutrient deficiencies and enhancing the crop's performance across diverse growing conditions.

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