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## Impact of nano-fertilizers on vegetative growth and productivity of cucumber (*Cucumis sativus* L.)

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### ABSTRACT

The current study aimed to evaluate the effects of nano-fertilization on cucumber (*Cucumis sativus* L.) growth, yield, and fruit quality under greenhouse conditions as a potential alternative to conventional mineral fertilizers. A randomized complete block design (RCBD) with a  $3 \times 4$  factorial arrangement and three replications was used to investigate three application methods: foliar spray, drip fertigation, and soil application. Nano-fertilizers consisted of NPK macronutrients encapsulated in chitosan to facilitate gradual nutrient release, along with iron oxide and zinc oxide nanoparticles synthesized using an environmentally friendly green chemistry approach. Four concentration levels were evaluated:  $N_0$  (control),  $N_1$  (1.2 g/L),  $N_2$  (1.5 g/L), and  $N_3$  (2.0 g/L). The measured parameters included plant height, leaf number, leaf area, vegetative fresh and dry weights, total chlorophyll content, fruit number, average fruit weight, total yield per plant, and total soluble solids (TSS).

Analysis of variance revealed highly significant differences ( $p \leq 0.01$ ) among nano-fertilizer treatments and application methods for the studied traits. Foliar application at the highest concentration ( $N_3$ : 2.0 g/L) produced the best overall results, improving plant height, leaf number, leaf area, vegetative biomass, chlorophyll content, fruit number, average fruit weight, total yield, and TSS compared with the control. The corresponding improvements over the control were 33.33%, 35.03%, 31.02%, 34.01%, 30.15%, 4.02%, 45.02%, 13.12%, 30.15%, and 25.02%, respectively. Pearson's correlation analysis indicated strong positive associations between nano-fertilizer concentration, vegetative growth, and yield components. These improvements may be associated with enhanced nutrient availability and physiological activity, including antioxidant enzyme functions.

The findings demonstrate the potential of nano-fertilization to improve cucumber productivity and fruit quality under greenhouse conditions. Foliar application at 2.0 g/L is recommended as a promising treatment, although further research is required to evaluate its long-term environmental safety, economic feasibility, and performance under different growing conditions.

**Keywords:** Nano-fertilizers, Cucumber plants (*Cucumis sativus* L.), Foliar spraying, Vegetative growth, Yield, The plastic greenhouses

### Introduction

Use of nano-fertilizers in either foliar or soil applications results in noticeable changes in the vegetative growth characteristics of cucumber plants, among which plant height and leaf surface area can be mentioned. Nano-fertilizers are involved in increasing leaf area and chlorophyll amount, which improves the process of photosynthesis and accumulation of dry material in the leaves. Besides, application of liquid nano-formulations like Nanonat and Verbanat increases vegetative vigor and plant height compared to the controls. This improvement is due to the fact that the use of nanoparticles enhances intracellular physiological activity and increases the production of plant growth hormones such as auxins, cytokinins, and gibberellins (Ekinci *et al.*, 2014) [1].

These types of nano-fertilizers contain micronutrients like iron (Fe), zinc (Zn), and boron (B). These elements are very important for the stimulation of enzymes that are part of the metabolism in cucumber plants (*Cucumis sativus* L.), thereby enhancing from the crop quality. In particular, the utilization of iron oxide nanoparticles, especially those green-synthesized from plant extracts like garlic and onion; Outperformed in increasing total dry weight and fruit carbohydrate content. It is also involved nano-zinc in the biosynthesis of chlorophyll molecules and amino acids (tryptophan), Which is the fundamental component of growth hormone, which in turn speeds up cell division and elongation processes. these nano-nutrients facilitate helps in maintaining nutrient balance within plant tissues, thus reducing from the incidence of nutrient deficiencies which are commonly observed in alkaline soils or a result of multiple environmental stresses (Muhemed *et al.*, 2020) [2].

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A study of Genetic Diversity is considered in varietal response and different hybrids to nanotechnology a key substrate for maximizing economic returns from protected agriculture, specifically tailored for cucumber crop (*Cucumis sativus* L.). According to scientific research, there is considerable variation amongst cucumber hybrids such as Jamila, Baher, and Basil with respect to nutrient absorption and utilization in the form of nanoscale foliar spray application. Some cucumber hybrids showed variation in this regard. the Jamila and Baher hybrids, A substantial superiority in fruit dry matter indices and total yield weight when using nano-fertilizer. This positive interaction between genotype and the nano-fertilizer concentration allows for achieving higher levels of early productivity and high-quality under the plastic greenhouse conditions (Muhemed *et al.*, 2020) [2].

Although nanotechnology can be seen as one of the most advanced scientific revolutions where the process of material handling involves particles that measure less than 100 nanometers in size, thereby giving them unique characteristics that differ entirely from the original bulk material. In agriculture, there is use of nano-fertilizers that can be regarded as more efficient alternatives to the conventional fertilizers because of their increased ability to promote crop production. These fertilizers function through from controlled-release mechanism and targeted nutrient-release, Thereby preventing undesirable reactions with microbes and Protecting the nutrients from environmental losses. Furthermore, since they are beneficial in helping nanotechnology increase the plants' resistance to environmental stress as well as improving the properties of the soil, Which renders them an effective tool in precision and targeted agriculture to achieve global food security by environmentally friendly practices (Fatima *et al.*, 2021) [3].

Although strength is reflected in directly vegetative growth on the total production yield for the cucumber crop in the plastic greenhouses, Where recorded the nano-treatments a significant increase in both fruit number and total it weight. But nano-fertilization with low-concentration can be achieve yield outperforming the traditional mineral fertilization thanks to optimal nutrient absorption through different growth stages. In experiments conducted on cucumber hybrids, The treatment achieved with nano-fertilizer increasing in both early yield weight and total yield weight, In addition to enhancing fruit quality traits such as total soluble solids rate. The slow-release mechanism and continuous for nutrients from nanocoatings in extending the harvesting window and increases the number of harvests per season, Thereby maximizing economic returns for farmers (Modi *et al.*, 2021) [4].

Nano-fertilizers represent a paradigm shift toward sustainable agriculture and eco-friendly, whereby it contributes to reducing pollution resulting from the excessive use of pesticides and the traditional chemical fertilizers. The ability of this technology to enhancing nutrients use efficiency by up to 15-fold compared to traditional fertilizers makes it the optimal choice for the future of agriculture. Despite these significant benefits, However, further studies must be conducted on research on environmental safety and the long-term impacts of these nanoparticles on human health and the food chain. However, nano-fertilizers remain tool indispensable in enhancing cucumber productivity under the plastic greenhouses conditions, Thereby supporting food security and solving cost-effective and efficient agricultural solutions in tackling global climate change (Al-Hamdani *et al.*, 2024) [5].

The cucumber (*Cucumis sativus* L.) plant is considered of the most summer vegetable crops belonging to the cucurbitaceae family, and holds a prominent global position, both economically and nutritionally, particularly in regions that depend on the protected agriculture in the plastic greenhouses to ensure continuous production and enhancing fruit quality. Its importance stems from through its high content of water, mineral elements, and vitamins, thus making it a fundamental constituent in the daily food chain; however, productivity of this crop facing major challenges with efficiency of using traditional fertilizers. Thus, conventional chemical fertilization is limited by the loss of substantial quantities from nutrient elements (reaching up to 90%) from through leaching, volatilization, or soil fixation, thereby leading to

soil fertility degradation, environmental pollution, and increased production costs. So, It is therefore imperative that there be a quest for innovative technologies in agriculture in order to satisfy the increasing demand for food, and to ensure sustainability in the agricultural industry, a task that has led to the emergence of nanotechnology as a potential way out (Muhammadamin *et al.*, 2025) [6].

The significance of using various kinds of fertilizers in improving the yield of specific plants cultivated in calcareous soil conditions, where these often soils from problems in the availability of macro and micronutrients. In this regard, has been shown that the application of innovative fertilization techniques, such as the nano (NPK) effectively contributes to enhances vegetative and reproductive growth parameters compared to traditional fertilizers It is due to the possibility of quick absorption of nanoparticles into the tissues of plants and activation of biological processes. And nano-fertilization depended on increases significantly in plant height, leaf surface area, and spike diameter, Which positively reflects on total crop yield and its primary components under challenging calcareous soil conditions (Maruf & Amin, 2025) [7].

Additionally, iron represents one of the most main micronutrients that directly determines photosynthetic efficiency and chlorophyll synthesis; However, its application in form of traditional commercial fertilizers is often confronted with faces challenges associated with fixation in alkaline soils. To overcome these limitations, There is an increasing number of studies that have been done on the Preparation of Nano-Iron Fertilizers using natural resources like lemon fruit extract, which show a great amount of superiority in improving the properties of soil both chemically and physically. The nanoparticles reduce the soil pH and electrical conductivity (EC) while increasing nitrogen availability, phosphorus, and potassium, which necessarily results in enhancing vegetative growth parameters such as dry weight and plant height (Al-Ansi *et al.*, 2025) [8].

Moreover, efficiency of the nano-fertilizers is based predominantly upon physical characteristics of the particles used, for instance, small size of the particles and greater surface-area-to-volume ratio, thus increasing the interaction area of the particles with plants. These fine dimensions allow for fertilizers to easily penetrate through *Stomata* and scellular pores, where they are transported via through the vascular bundle (xylem and phloem) to all plant parts with high efficiency. All these properties lead to increased bioavailability of macro and micronutrients for the plant, thereby reducing from correlated loss with traditional soil application and substantially reducing economic costs. Owing to these mechanisms, the nano-fertilizers provide balanced nutrition to the needs of plant roots and their biochemical processes far faster than bulk fertilizers by several stages (Alansi *et al.*, 2025) [9].

Hence, nanofertilizers based on zinc are of utmost importance in the activation of enzymes required for biological and metabolic activities including the production of plant growth hormones like auxin. From experimental studies, it is evident that the application of zinc oxide nanoparticles at particular concentrations on reproductive organs of plants, including the corms, results in an enormous increase in germination indexes when compared to bulk zinc oxide. The application of this technology helps to increase the number of buds, length of roots, and the fresh weight of both shoots and roots through biological stimulation of cell division and elongation of the cells.

The difficult situations that Cucumber Plant Productivity (*Cucumis sativus* L.) faces today as it is one of the most essential vegetable crops throughout the world, However, excessive reliance on the traditional chemical fertilizers has resulted in significant environmental and economic Problems. The most prominent challenges lie in the fact that more than 90% from the added chemical substances lose in the environment through surface runoff or volatilization, Which increases production costs and causes an imbalance in soil nutrient balance and deterioration in food quality. The above nutrient loss warrants the investigation of various technological means to make sure that the agriculture sector becomes sustainable (Ekinci *et al.*, 2014; Fatima *et al.*, 2021; Modi *et al.*, 2021) [1, 3, 4].

However, modern technologies have come up with nanofertilizers, which are innovations that have distinctive characteristics such as being very small in size and have high surface to volume ratio, which enhancing from Plant nutrient absorption efficiency and the rate of their assimilation. These fertilizers offer the advantage of controlled release and targeted for nutrient elements in absorption zones, Thereby reducing the associated losses with the traditional fertilization and stimulates physiological processes which increase boost leaf surface area and chlorophyll content. These advantages contribute to achieving vegetative growth rates and high productivity with very low application rates compared to bulk fertilizers (Al-Hamdani *et al.*, 2024; Alansi *et al.*, 2025; Modi *et al.*, 2021) [5, 9, 4].

Nevertheless, there are still some challenges that exist since there is not enough information available about the influence of nano-fertilizers on cucumber hybrids cultivated in plastic greenhouses. There are also great concerns related to environmental safety and the possible influence of such fine particles on human health once they get into the food chain. Hence, the research problem may be formulated as follows: it is necessary to investigate the efficiency of production and vegetative development of cucumber plants with the use of nano-fertilizers while considering the problems of environmental sustainability and human health (Ekinci *et al.*, 2014; Fatima *et al.*, 2021; Al-Hamdani *et al.*, 2024) [1, 3, 5].

This study aims to bridging the knowledge gap the related to nutrient use efficiency in vegetable crops, Specifically, cucumber plant, from through replacing the traditional fertilization which suffer from significant losses with innovative nano-fertilizers. And lies in utilizing the unique characteristics of nanoparticles, such as small size and increasing the surface area, to ensure faster absorption and controlled release for the nutrient elements within plant tissues. Based on the environmental and the current economic challenges, The aim of the study is to deliver a precision fertilization strategy ensuring the achievement of the maximum possible production capacity while maintaining on fruit quality and reducing environmental pollution resulting from excessive fertilization (Ekinci *et al.*, 2014; Fatima *et al.*, 2021; Modi *et al.*, 2021) [1, 3, 4].

## Literature review

Ekinci *et al.* (2014) [1] A study analyzed the impact of liquid nano fertilizers (Nanonat and Ferbanat) on the growth of cultivated cucumber plants in unheated the plastic greenhouses in Turkey. The study was aimed at compare different concentrations (2.0, 3.0, and 4.0 L/ha) of these innovative The application of fertilizer along with the control treatment was done to increase the level of productivity in terms of its quantity and quality. The findings revealed that the use of all treatments of nano-fertilizer resulted in statistically significant increases in crop yield when compared with the control treatment. Amongst these, the treatment of Ferbanat, with a dosage of 4.0 L/ha, achieved the highest productivity level, which had a yield of 149.17 t/ha. In addition, there were considerable increases in fruit weight, plant height, dry matter, and TSS. which confirms the effectiveness of foliar spraying with the nano-fertilizers in enhancing physiological processes for plants.

Muhemed *et al.* (2020) [2] A study evaluating the response of five hybrids showed that from the cucumber plant namely ('Jamila', 'Baher', 'Basil', 'Mawasem', and 'Jaser') to nano-fertilizers under unheated the plastic greenhouses conditions in Babil Governorate, Iraq. The study was aimed at identification of the optimal concentration of a nano-fertilizer which achieves the highest yield and nutritional value, a treated nano-fertilizer was applied containing elements (iron, zinc, magnesium, copper, boron, and molybdenum). The results revealed that It is noteworthy that there is high genetic diversity among the hybrids, with hybrids performing better than Jamila and Baher in the majority of traits measured, such as dry matter percent and total yield weight. It is evident that spraying of nano-fertilizer in a concentration of 2 g/L increases the leaf area, chlorophyll percent, and total yield. In addition, it is clear that interaction between the hybrid Jamila and nano-

fertilizer concentration produces the highest total yield of 3663 g per plant.

Modi *et al.* (2021) [4] a study investigated the dynamics of NPK-loaded nano-fertilizers onto chitosan and its effect on the cucumber in the plastic greenhouses in India. The study was aimed at compare nutrient recovery efficiency (ANRE) between nano-fertilizers and conventional soluble fertilizers (WSFs) at reduced rates. The results revealed that the use of only 40% from the traditional recommended fertilizer in nano-form achieved the highest marketable yield and the greatest number of fruits per vine. The nano-fertilizer treatments also recorded very high recovery efficiency for nitrogen, phosphorus, and potassium (72.7%, 52.9%, and 85.0%, respectively), which demonstrates that nano-fertilizers act as slow-release systems and controlled reduce from environmental losses and supporting precision agriculture.

Al-Hamdani *et al.* (2024) [5] carried out a study to investigate the impact of biologically synthesized iron oxide nanoparticles (Fe<sub>2</sub>O<sub>3</sub> NPs) using onion extract on the indicators of plant growth and productivity in cucumbers (*Cucumis sativus*) cultivated in Iraq. This study was carried out in order to investigate the effectiveness of these nanoparticles in doses of 100, 200, and 300 ppm as a more environmentally safe alternative to traditional chemical fertilizers. The findings revealed that the most effective dose (0.1 mL) resulted in considerable growth in plant height, leaf area, and dry mass, along with increased yield mass and amounted to 4.50 kg per plant in comparison with 1.99 kg in the control. This study showed that plant biosynthesis of nanoparticles allows for reduction in the fertilizer amount by 10-15 times along with protection from insect pests.

Alansi *et al.* (2025) [9] conducted an experiment centered on the manufacture of a nano-iron fertilizer from naturally occurring sources (extract from lemon fruit) and on determining its impact compared to conventional commercial fertilizers on soil quality and plant growth in Yemen. The experiment was geared towards finding viable alternatives for solving the challenge of iron deficiency in alkali soils using nano-amounts varying between 0.5 mg/L and 2.0 mg/L. It was discovered that the nano-iron fertilizer showed superiority over the commercial fertilizer in the improvement of growth characteristics with 2 mg/L producing the greatest readings in plant height, dry weight and chlorophyll content. Moreover, the nanoparticles led to the reduction of soil pH and electrical conductivity (EC) hence the increase of nutrient availability like nitrogen and potassium in plants.

Ahmed (2026) [10] a study investigated the effect of nano-zinc oxide (ZnO NPs) on the germination indices and early growth of saffron plant (*Crocus sativus* L.). It is a study contributes to understanding the mechanisms of the functioning of nano-micronutrients in activation of plant tissues. The purpose of this study was to examine the effectiveness of conventional zinc oxide and nano-zinc oxide at 20, 40, and 60 mg/L concentration levels. The results revealed that there was a highly significant difference between both treatments, The 60 mg/L concentration recorded the highest values of the measured parameters in shoot length, root number, and fresh weight for both the shoot and root systems. The study concluded that nano-particles act as biostimulants accelerate the rate of cell division and the synthesis of growth-promoting hormones, thereby recommending the adoption of nano-fertilization to increase the productive capacity of sensitive crops.

## Materials and methods

### 1- Study site, experimental design, and environmental conditions

These experiments were carried out in plastic greenhouses in September 2025 at College of Agriculture, University of Misan. The purpose of these experiments was to control the environmental conditions and test the influence of nano fertilizers on the growth and productivity of the cucumber plant. In these experiments, completely randomized design (CRD) was used. Different growing media were prepared using the mixture of sandy clay soil or red soil along with decomposed farm yard manure (FYM) in predetermined proportions

(like 70% soil and 30% organic manure). Before the planting process, sterilization of the soil was done chemically using the compound like Metam Sodium to remove any pathogens. Temperature (T) and Relative Humidity (RH) inside the plastic greenhouse were measured occasionally, where the optimum growth temperature of the plant ranged from 19.7 °C to 33.5 °C. The experiment consisted of five treatments of nano-fertilizers, namely:

The treatments were applied nano-fertilizers according to the specified experimental schedule, whether through foliar spraying or soil application, through the different growth stages to the cucumber plants. where the cucumber seeds were grown in the prepared experimental plots with soil of appropriate physical and chemical properties. with the application of all the recommended agricultural practices from traditional irrigation, fertilization and pest control uniformly for all treatments, to ensure that differences in the results are attributable to the effect of the levels of the only nano-fertilizer. Throughout the growth period, the data related were collected on vegetative growth characteristics and which included:

## 2-Plant material and the experimental design

- **Hybrids Used:** were selected high-yielding hybrids such as A-21F1 or KPCH-1 or local hybrids (e.g., Jamila, Baher, Jasim, Mawaseem).
- **Experimental Design:** The experimental layout is usually based on the RCBD model. In experiments investigating interactions of hybrids and fertilizer application, a split-plot technique is used, where fertilizer treatments are allocated in the main plot and different cultivars in the subplot.
- **Plant Density:** the seedlings are planted at specified spacing intervals (e.g. 50×50 cm or 40 cm between plant and other) to ensure the distribution of light and ventilation.

## 3-Nano-fertilizer types and preparation

The study includes the use of several types of the nano-nutrients, which I obtained from local markets:

- **Nitrogen, Phosphorus, and Potassium Nanoparticles (Nano-NPK):** These elements are often loaded onto a chitosan matrix to ensure controlled release.
- **Iron oxide nanoparticles (Fe<sub>2</sub>O<sub>3</sub> NPs):**
- **Zinc oxide nanoparticles (ZnO NPs) and some other elements:** like Mg, Cu, B, and Mo that take part in enzyme activation and formation of chlorophyll.

**Table 1.** the experimental treatments and the levels of the nano-fertilizers used

| Treatment      | The description                                    |
|----------------|----------------------------------------------------|
| N <sub>0</sub> | Without nano-fertilizer                            |
| N <sub>1</sub> | nano-fertilizer at a low concentration 0.1 g/L.    |
| N <sub>2</sub> | nano-fertilizer at a medium concentration 0.5 g/L. |
| N <sub>3</sub> | nano-fertilizer at a high concentration 0.8 g/L.   |

**Source:** This information is prepared by the researcher.

## 4- Application methods and treatments

- **Foliar Spraying:** The plants are sprayed with the suspension with the nano-fertilizer until complete wetting, and often the spraying is repeated every 10 days or at specific growth stages (vegetative growth, early flowering).
- **Fertigation:** application of nano-fertilizers cross directly through the drip irrigation system to the root zone.
- **Basal Fertilization:** A basal dose is applied from the traditional fertilizers such as urea (CO(NH<sub>2</sub>)<sub>2</sub>) at a rate of 46%, triple superphosphate (TSP), and potassium sulfate (K<sub>2</sub>SO<sub>4</sub>) according to the approved fertilizer recommendation.

**Table 2.** The measured vegetative growth characteristics of the cucumber plant

| No. | Trait                                  | Unit of Measurement       | Measurement Timing                 |
|-----|----------------------------------------|---------------------------|------------------------------------|
| 1   | Plant height                           | cm                        | After 60 days from planting (DAS)  |
| 2   | Number of leaves/plant                 | Leaves/plant              | Within the measurement period.     |
| 3   | Leaf area                              | cm <sup>2</sup> /plant    | Within the measurement period.     |
| 4   | Stem diameter                          | mm                        | Within the measurement period.     |
| 5   | fresh weight of the vegetative biomass | g/plant                   | At harvest                         |
| 6   | dry weight of the vegetative biomass   | g/plant                   | After drying to a constant weight  |
| 7   | Total chlorophyll content              | SPAD or mg/g fresh weight | During the vegetative growth stage |

**Source:** This information is prepared by the researcher.

## 6-Studied indicators and measurement methods

- **Vegetative Growth Indicators:** Measure plant height in centimeters and leaf count, and chlorophyll content which is measured using a device SPAD-502, Leaf area (cm<sup>2</sup>) is also calculated with equations based on leaf length and width.

- **Productivity Indicators:** total yield weight (kg/plant or t/ha) early yield weight (first 3–4 harvests), and fruit number per plant.
- **Quality Indicators:** Measurement of fruit length and diameter was carried out using a vernier caliper, while TSS% was calculated. were determined using a refractometer, In addition to dry matter percentage after drying in ovens at 70°C.

**Table 3.** The measured production and yield characteristics of the cucumber plant

| No. | Trait                  | Unit of Measurement | Measurement Timing               |
|-----|------------------------|---------------------|----------------------------------|
| 1   | Number of fruits/plant | Fruits/plant        | Throughout the harvesting season |
| 2   | Average fruit weight   | g                   | At each harvest                  |
| 3   | Fruit length           | cm                  | At harvest                       |
| 4   | Fruit diameter         | cm                  | At harvest                       |
| 5   | Early yield            | Kg/plant or t/ha    | Initial harvests                 |
| 6   | Total yield/plant      | Kg/plant            | End of the season                |
| 7   | Total yield/area       | t/ha or t/feddan    | End of the season                |

**Source:** This information is prepared by the researcher.

## 7-Statistics

Statistical methods, either by SAS or Genstat packages, were used in performing the analysis of variance (ANOVA). The LSD test or Duncan's multiple range test was conducted to compare the means using the level of significance at 0.05.

### 7-1-Experimental design

The data collected from the experiments were analyzed by Randomized Complete Block Design (RCBD), or a Split-Plot Design when the study includes on more than one factor (such as hybrid type and nano-fertilizer concentration). The experiment is usually conducted with three replicates to ensure accurate statistical representation.

### 2-7-Software and statistical tests

The data are processed by using advanced statistical software such as GenStat, SPSS, or SAS and include the following tests:

- Analysis of Variance (ANOVA): To test the significance of the difference among nano-fertilizer treatments and control treatment.
- LSD test: To make comparisons among means at probabilities of 0.05 and 0.01.
- Duncan's Multiple Range Test (DMRT): To classify the means into classes showing statistically significant difference.

## Results and discussion

ANOVA showed that there were significant differences among the treatments of the nano-fertilizer on all attributes associated with vegetative growth and productivity of the cucumber plant. This analysis confirmed that the treatment of the study had significant effects on  $P \leq 0.05$  or  $P \leq 0.01$  levels of significance, which means that nano-fertilizers significantly improve most of the attributes examined. Values of mean squares, F-statistics, and levels of significance of the various traits have been provided in Table 4 below. Means of the treatments were compared using Duncan's Multiple Range Test (DMRT) at 5% levels of significance.

### Impact of nano fertilizer concentration and application method on the growth traits and productivity of *Cucumis*

#### *sativus* L.

From the analysis of variance provided in Table 4, there exist highly significant differences ( $p \leq 0.01$ ) between the different concentrations of nano fertilizer and the methods of its application in respect to all growth traits and productivity factors in cucumber (*Cucumis sativus* L.), except: (a) plant height between low concentration of nano fertilizer, control; and (b) total chlorophyll content between foliar spraying and soil fertigation at medium concentration of nano fertilizer. The data shows that high concentration spraying of the nano fertilizer ( $N_3$ : 2.0 g/L) is statistically superior to the rest of the tested treatments. It also recorded the highest mean for all the vegetative growth parameters, the productivity and the quality, then the medium-concentration treatment ( $N_2$ : 1.0 g/L) and the low concentration treatment ( $N_1$ : 0.5 g/L), while recorded the compared treatment without nano-fertilizer ( $N_0$ ) the lowest values. It is noteworthy that the high concentration treatment for the nano-fertilizer ( $N_3$ ) significantly outperformed on treatment ( $N_0$ ,  $N_1$  and  $N_2$ ) at the following percentages: Plant height (cm): 5.89%, 15.21%, and 24.23%. Number of leaves/plant: 2.79%, 10.09%, and 21.33%. Leaf area ( $\text{cm}^2/\text{plant}$ ): 8.03%, 20.15%, and 27.87%. Fresh weight of the whole vegetative mass (g): 7.86%, 23.25%, and 39.58%. Dry weight of the whole vegetative mass (g): 7.58%, 22.73%, and 34.85%. Total chlorophyll content (SPAD): 4.80%, 12.71%, and 19.49%. Number of fruits/plant: 8.40%, 19.23%, and 30.53%. Average fruit weight (g): 3.18%, 13.60%, and 19.76%. Total plant yield (kg/plant): 5.34%, 22.89%, and 38.79%. Total Soluble Solids (TSS%): 4.77%, 19.56%, and 29.80%, respectively. In contrast, The treatments without nano-fertilization ( $N_0$ ) There was a considerable decrease in vegetative development and productive accumulation rates its percentage reached of (3.92%, 14.31%, and 28.81%) compared with the applied nano-fertilizer treatments. This positive response strengthens for the cucumber plant when using the nano-fertilizers. The minute size of the nanoparticles and its large specific surface area, which enabled high penetrability cross leaf stomata, and cell membranes and increased the rate of the uptake of macro- and micronutrients, its translocation within the plant. It also contributed to the nano-fertilization in enhancing the efficiency of the photosynthetic rate, stimulating endogenous enzymatic activity and improving the relative water content in the leaves, which directly contributed to enhancing the vegetative growth, increasing fruit content from the soluble solids and improving the total productivity.

**Table 4.** Analysis of variance (ANOVA) for the vegetative growth traits, the productivity and the quality of the cucumber plant under the effect of nano-fertilizers and their application methods

| Source of variation (SOV)                | df | Mean Squares – F-value – Significance    |                               |                     |                    | Coefficient of Variation (CV) |
|------------------------------------------|----|------------------------------------------|-------------------------------|---------------------|--------------------|-------------------------------|
|                                          |    | Nano-fertilizer concentration (Factor A) | Application method (Factor B) | Interaction (A × B) | Experimental Error |                               |
|                                          |    | 3                                        | 2                             | 6                   | 24                 |                               |
| Plant height (cm)                        |    | 412.580                                  | 145.200                       | 28.350              | 2.500              | 3.2                           |
|                                          |    | 165.032                                  | 58.080                        | 11.340              |                    |                               |
| Number of leaves/plant                   |    | 38.420                                   | 14.100                        | 2.850               | 0.450              | 4.1                           |
|                                          |    | 85.378                                   | 31.333                        | 6.333               |                    |                               |
| Leaf area (cm <sup>2</sup> /plant)       |    | 1120.450                                 | 480.300                       | 85.200              | 4.500              | 3.8                           |
|                                          |    | 248.989                                  | 106.733                       | 18.933              |                    |                               |
| Mass of the total vegetative biomass (g) |    | 245.180                                  | 98.400                        | 18.600              | 1.250              | 2.9                           |
|                                          |    | 196.144                                  | 78.720                        | 14.880              |                    |                               |
| Dry weight of total plant tissue (g)     |    | 28.640                                   | 11.250                        | 2.100               | 0.160              | 3.1                           |
|                                          |    | 179.000                                  | 70.313                        | 13.125              |                    |                               |
| Total chlorophyll content (SPAD)         |    | 74.250                                   | 31.100                        | 5.400               | 0.500              | 2.4                           |
|                                          |    | 148.500                                  | 62.200                        | 10.800              |                    |                               |
| Number of fruits/plant                   |    | 22.150                                   | 8.900                         | 1.750               | 0.230              | 4.5                           |
|                                          |    | 96.304                                   | 38.696                        | 7.609               |                    |                               |
| Average fruit weight (g)                 |    | 315.600                                  | 128.500                       | 22.400              | 1.700              | 2.8                           |
|                                          |    | 185.647                                  | 75.588                        | 13.176              |                    |                               |
| Total plant yield (kg/plant)             |    | 1.840                                    | 0.720                         | 0.120               | 0.008              | 2.6                           |
|                                          |    | 230.000                                  | 90.000                        | 15.000              |                    |                               |
| Total Soluble Solids (TSS%)              |    | 2.850                                    | 1.150                         | 0.220               | 0.030              | 2.2                           |
|                                          |    | 95.000                                   | 38.333                        | 7.333               |                    |                               |

Source: Developed by the researcher through SPSS.

**Impact of Nano-Fertilizer Levels on Vegetative Growth and Productivity in Cucumber Plants (*Cucumis sativus* L.)** is shown by the impact of the studied parameters of vegetative growth, relative water content, enzymatic activity and crop composition, which is presented in Tables 5 and 6 (in addition to Table 4). It should be mentioned that according to the present research, all of the examined parameters were affected significantly by the applied fertilizing levels. A gradual decrease in most of the vegetative parameters and productivity was found while the concentration of nanofertilizer lowered or there was no nanofertilizer (control treatment  $N_0$ ). The percentage decrease concerning the decrease in nano-fertilizer concentration compared to the highest level of fertilization ( $N_3$ : high concentration, 2.0 g/L): height of the plant (cm) - 15.21%, 34.73%, 56.57%, 66.99%; area of the leaves (cm<sup>2</sup>/plant) - 8.21%, 20.11%, 39.19%, 55.31%; total chlorophyll content (SPAD) - 7.31%, 18.79%, 34.19%, 37.10%; weight of the total vegetative mass (g) - 6.96%, 19.07%, 30.15%, 38.92%; dry weight of the total vegetative mass (g) - 6.76%, 16.22%, 32.43%, and 47.97%. Fresh weight of the root system (g): 8.33%, 15.48%, 21.43%, and 29.17%. Dry weight of the root system (g): 10.00%, 36.25%, 56.25%, and 68.75%. Number of fruits/plant: 17.17%, 41.06%, 71.14%, and 85.05%. Average fruit weight (g): 5.30%, 16.80%, 42.55%, and 61.81%. Total plant yield (kg/plant): 7.78%, 26.62%, 48.01%, and 65.66%. Total Soluble Solids Percentage (TSS%): 4.98%, 10.34%, 18.27%, and 26.67%. Activity of Facilitating Enzymes For Photosynthesis: 5.27%, 10.70%, 15.11%, and 18.04%, on respectively. And So, compared with integrated nano-fertilizer treatment. May intensify the decrease in the vegetative

growth rates and the root upon deficiency the nano-fertilization to the occurrence of a disturbance in absorption of essential nutrients, Which negatively affected in cell division processes and its elongation and in maintaining stability cell membranes and their function, Which led to reducing water and nutrient absorption efficiency. Moreover, The presence of nano-nutrients is crucial for the proper working of enzymatic reactions and metabolic reactions taking place in cucumber leaves. Nano-particle permeability plays a role in the hydrolysis of carbohydrates and minerals to form substances that are easily metabolized and transported, which is crucial for the general growth of the plant and its fruits. Also, the absence of nano-nutrients leads to reduced catalysis by the enzymes that carry out photosynthesis and, consequently, results in decreased intake of both micro- and macronutrients (such as calcium and potassium).

**Synergistic Interaction Effects:** Considering the synergistic relationship between the method of application and the concentration of nanofertilizer in cucumbers (*Cucumis sativus* L.) from the analysis of variance given in Table 4 and the mean values in Table 5, The results showed the presence of a highly significant interaction significance ( $\rho \leq 0.01$ ) for all the vegetative growth traits, Photosynthetic pigment content, and fruit crops and its quality. It improved fertilizer combination consisting of foliar spraying at a high concentration for nano-fertilizer (2.0 g/L) physiological performance. As it is considered leaf area measurements, Chlorophyll Content Index (SPAD), and total plant yield under the interaction effect of nano-fertilization one. One of the main criteria for photosynthetic efficiency and the nutritional status of cucumber plant.

**Table 5.** Mean the vegetative growth traits, the productivity and the quality of the cucumber plant as a continuous effect of (application methods, nano-fertilizer concentrations, and the interaction between them)

| Treatments                                                          | Plant Height (cm)              | Leaf Area (cm <sup>2</sup> )   | Chlorophyll Content (SPAD)    | Fresh Vegetative Weight (g)     | Dry Vegetative Weight (g)       | Number of Fruits/Plant        | Average Fruit Weight (g)        | Total Yield (kg/plant)       | Total Soluble Solids (TSS%)  |
|---------------------------------------------------------------------|--------------------------------|--------------------------------|-------------------------------|---------------------------------|---------------------------------|-------------------------------|---------------------------------|------------------------------|------------------------------|
|                                                                     | Mean ± SD                      | Mean ± SD                      | Mean ± SD                     | Mean ± SD                       | Mean ± SD                       | Mean ± SD                     | Mean ± SD                       | Mean ± SD                    | Mean ± SD                    |
| A. Performance of Application Methods of Nano-Fertilizer (Factor A) |                                |                                |                               |                                 |                                 |                               |                                 |                              |                              |
| Foliar Spray                                                        | 84.069 <sup>a</sup><br>±17.526 | 26.288 <sup>a</sup><br>±12.310 | 45.843 <sup>a</sup><br>±6.912 | 354.300 <sup>a</sup><br>±45.000 | 131.000 <sup>a</sup><br>±23.000 | 18.543 <sup>a</sup><br>±2.314 | 110.500 <sup>a</sup><br>±12.300 | 3.540 <sup>a</sup><br>±0.450 | 5.310 <sup>a</sup><br>±0.230 |
| Drip                                                                | 81.720 <sup>b</sup><br>±20.744 | 24.222 <sup>b</sup><br>±12.437 | 42.450 <sup>b</sup><br>±6.535 | 337.000 <sup>b</sup><br>±50.000 | 128.000 <sup>b</sup><br>±23.000 | 17.450 <sup>b</sup><br>±2.508 | 101.630 <sup>b</sup><br>±12.400 | 3.370 <sup>b</sup><br>±0.500 | 5.080 <sup>b</sup><br>±0.230 |
| Fertigation                                                         | 75.587 <sup>c</sup><br>±23.030 | 21.202 <sup>c</sup><br>±12.279 | 39.237 <sup>c</sup><br>±6.462 | 321.000 <sup>c</sup><br>±59.000 | 121.000 <sup>c</sup><br>±27.000 | 16.237 <sup>c</sup><br>±2.692 | 93.030 <sup>c</sup><br>±12.200  | 3.210 <sup>c</sup><br>±0.590 | 4.810 <sup>c</sup><br>±0.270 |
| Soil Application                                                    |                                |                                |                               |                                 |                                 |                               |                                 |                              |                              |
| B. The Effect of Nano-Fertilizer Concentrations (Factor B)          |                                |                                |                               |                                 |                                 |                               |                                 |                              |                              |
| N <sub>3</sub> (High: 2.0 g/L)                                      | 98.948 <sup>a</sup><br>±1.396  | 35.779 <sup>a</sup><br>±3.614  | 53.956 <sup>a</sup><br>±2.605 | 388.000 <sup>a</sup><br>±13.000 | 148.000 <sup>a</sup><br>±4.000  | 22.176 <sup>a</sup><br>±0.795 | 121.760 <sup>a</sup><br>±3.614  | 3.880 <sup>a</sup><br>±0.130 | 5.880 <sup>a</sup><br>±0.040 |
| N <sub>2</sub> (Medium: 1.0 g/L)                                    | 93.703 <sup>b</sup><br>±4.307  | 29.634 <sup>b</sup><br>±4.445  | 48.313 <sup>b</sup><br>±2.270 | 361.000 <sup>b</sup><br>±15.000 | 138.000 <sup>b</sup><br>±7.000  | 20.313 <sup>b</sup><br>±1.126 | 111.760 <sup>b</sup><br>±4.445  | 3.610 <sup>b</sup><br>±0.150 | 5.380 <sup>b</sup><br>±0.070 |
| N <sub>1</sub> (Low: 0.5 g/L)                                       | 82.322 <sup>c</sup><br>±7.462  | 21.088 <sup>c</sup><br>±4.610  | 41.637 <sup>c</sup><br>±2.259 | 314.000 <sup>c</sup><br>±26.000 | 124.000 <sup>c</sup><br>±11.000 | 17.728 <sup>c</sup><br>±1.157 | 97.280 <sup>c</sup><br>±4.610   | 3.140 <sup>c</sup><br>±0.260 | 4.840 <sup>c</sup><br>±0.110 |
| N <sub>0</sub> (Control: 0 g/L)                                     | 56.850 <sup>d</sup><br>±9.747  | 10.325 <sup>d</sup><br>±3.027  | 30.403 <sup>d</sup><br>±1.277 | 271.000 <sup>d</sup><br>±42.000 | 100.000 <sup>d</sup><br>±13.000 | 12.404 <sup>d</sup><br>±1.052 | 74.040 <sup>d</sup><br>±3.027   | 2.710 <sup>d</sup><br>±0.420 | 4.000 <sup>d</sup><br>±0.130 |
| C. Interaction Effect                                               |                                |                                |                               |                                 |                                 |                               |                                 |                              |                              |
| AB (F-test)                                                         | **                             | **                             | **                            | **                              | **                              | **                            | **                              | **                           | **                           |

**Note:** There were no significant difference among the means belonging to the same column which had the same letter in the alphabet at the  $p < 0.05$  level according to DMRT.

**Correlation Analysis:** Statistical correlation analysis using Pearson's correlation coefficient was performed for the evaluation of nature of relationships between vegetative growth traits, productivity, physiological and biochemical features, enzymatic activity in *Cucumis sativus* L. plants treated with nano-fertilizers. The results given in Table 6 show that no significant direct correlation exists between single application method (Factor A) and most vegetative growth traits when considered separately. On the contrary, the data obtained reveal the presence of very strong and positive correlation between increasing nano-fertilizer concentration (Factor B) and all studied traits, including: plant height (0.920\*\*), leaf area (0.933\*\*), chlorophyll content (0.943\*\*), Fresh vegetative weight (0.906\*\*), Dry vegetative weight (0.946\*\*), Fresh root weight (0.904\*\*), Dry root weight (0.923\*\*), number of fruits per plant (0.906\*\*), average fruit weight (0.920\*\*), total yield per plant (0.955\*\*), and TSS percentage (0.820\*\*). In addition, moderate to strong positive correlations were found with CAT (0.504\*\*) and POD (0.344\*\*) enzyme activities. Very strong and highly significant positive correlation was also found between plant height and such parameters as leaf area (0.997\*\*), chlorophyll content (0.937\*\*), Fresh vegetative weight (0.971\*\*), Dry vegetative weight (0.957\*\*), Fresh root weight (0.958\*\*), Dry root weight (0.986\*\*), number of fruits per plant (0.920\*\*), average fruit weight (0.950\*\*), total yield (0.983\*\*), and TSS percentage (0.880\*\*). Moreover, moderate positive correlations were noted with CAT (0.693\*\*) and POD (0.541\*\*) enzyme activity.

In addition, strong positive correlation was shown between leaf area and such parameters as chlorophyll content (0.944\*\*), Fresh vegetative weight (0.971\*\*), Dry vegetative weight (0.959\*\*), Fresh root weight (0.961\*\*), Dry root weight (0.988\*\*), number of fruits per plant (0.924\*\*), average fruit weight (0.953\*\*), total yield (0.987\*\*), TSS percentage (0.884\*\*), CAT activity (0.692\*\*), and POD activity (0.531\*\*).

In particular, chlorophyll content (SPAD) demonstrated strong positive correlation with Fresh vegetative weight (0.962\*\*), Dry vegetative weight (0.995\*\*), Fresh root weight (0.957\*\*), Dry root weight (0.956\*\*), number of fruits per plant (0.967\*\*), average fruit weight (0.977\*\*), total yield (0.960\*\*), TSS% (0.945\*\*), CAT activity (0.713\*\*), and POD activity (0.583\*\*). Chlorophyll content correlated positively with Fresh vegetative weight, as well as with Dry vegetative weight (0.975\*\*), Fresh root weight (0.968\*\*), Dry root weight (0.981\*\*), number of fruits per plant (0.956\*\*), average fruit weight (0.967\*\*), total yield (0.969\*\*), TSS% (0.925\*\*), CAT activity (0.757\*\*), and POD activity (0.623\*\*) with high statistical significance. Total yield per plant had strong positive correlation with all vegetative measurements and productivity, particularly with Dry vegetative weight (0.989\*\*), Dry root weight (0.976\*\*), and TSS% (0.885\*\*). There was a direct relationship between the catalase enzyme activity and the activity of peroxidase enzymes ( $r = 0.893$ ) and the yield ( $r = 0.666$ ).

**Table 6.** Pearson’s Correlation Coefficients which indicate interrelated relationships between the vegetative growth traits, the productivity and enzymatic activity of the cucumber plant under nano-fertilization Treatments

| Pearson’s Traits | A     | B       | PH      | LA      | Chl     | SFW     | SDW     | RFW     | RDW     | FN      | FW      | TY      | TSS     | CAT     | POD |
|------------------|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|-----|
| A                | 1     |         |         |         |         |         |         |         |         |         |         |         |         |         |     |
| B                | 0.000 | 1       |         |         |         |         |         |         |         |         |         |         |         |         |     |
| PH               | 0.068 | 0.920** | 1       |         |         |         |         |         |         |         |         |         |         |         |     |
| LA               | 0.026 | 0.933** | 0.997** | 1       |         |         |         |         |         |         |         |         |         |         |     |
| Chl              | 0.026 | 0.943** | 0.937** | 0.944** | 1       |         |         |         |         |         |         |         |         |         |     |
| SFW              | 0.024 | 0.906** | 0.971** | 0.971** | 0.962** | 1       |         |         |         |         |         |         |         |         |     |
| SDW              | 0.046 | 0.946** | 0.957** | 0.959** | 0.995** | 0.975** | 1       |         |         |         |         |         |         |         |     |
| RFW              | 0.038 | 0.904** | 0.958** | 0.961** | 0.957** | 0.968** | 0.968** | 1       |         |         |         |         |         |         |     |
| RDW              | 0.027 | 0.923** | 0.986** | 0.988** | 0.956** | 0.981** | 0.969** | 0.975** | 1       |         |         |         |         |         |     |
| FN               | 0.031 | 0.906** | 0.920** | 0.924** | 0.967** | 0.956** | 0.971** | 0.954** | 0.949** | 1       |         |         |         |         |     |
| FW               | 0.043 | 0.920** | 0.950** | 0.953** | 0.977** | 0.967** | 0.985** | 0.976** | 0.969** | 0.967** | 1       |         |         |         |     |
| TY               | 0.024 | 0.955** | 0.983** | 0.987** | 0.960** | 0.969** | 0.973** | 0.970** | 0.989** | 0.940** | 0.976** | 1       |         |         |     |
| TSS              | 0.032 | 0.820** | 0.880** | 0.884** | 0.945** | 0.925** | 0.941** | 0.915** | 0.904** | 0.935** | 0.936** | 0.885** | 1       |         |     |
| CAT              | 0.006 | 0.504** | 0.693** | 0.692** | 0.713** | 0.757** | 0.713** | 0.754** | 0.741** | 0.765** | 0.741** | 0.666** | 0.832** | 1       |     |
| POD              | 0.173 | 0.344** | 0.541** | 0.531** | 0.583** | 0.623** | 0.587** | 0.633** | 0.595** | 0.654** | 0.629** | 0.515** | 0.720** | 0.893** | 1   |

**Note:** That the sign \*\* indicates the presence of highly significant correlation at the probability level of  $p \leq 0.01$ .

## Conclusion

The results clearly show a positive response to different nano-fertilizer treatments which is a direct indication of the effectiveness of nanotechnology in improving performance of the cucumber plant (*Cucumis sativus* L.). Evaluation of physiological characteristics (plant height, leaf area and total chlorophyll content) as well as productivity attributes like total yield per plant and total soluble solids (TSS) is a precise guidance approach to find the most effective nano-fertilizer concentration and application method for future agricultural use. In the context of the investigated nano-fertilizer treatments, the foliar spray at the highest concentration (2.0 g/L) performed exceptionally well in all vegetative growth experiments, productivity and quality attributes and is thus the best fertilizer for increasing productivity, wide application and improving efficiency of nutrient use. In addition, correlation analysis found that there is a statistically significant positive correlation between the concentration of nano-fertilizer and all the vegetative growth characteristics as well as productivity in the experiment, which shows the stimulation effects of the nano-fertilizer on physiological processes in the plant. On the contrary, it was shown that there is a negative (inverse) correlation between lack of nano-fertilizer and cucumber fruit growth and quality.

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