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Impact of some agricultural treatments on the growth characteristics and yield of broccoli

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SUMMARY: To optimize broccoli growth and productivity, a field experiment was conducted during the 2024 autumn growing season in sandy loam soil at the vegetable research field of the Department of Horticulture and Landscape Design, College of Agriculture and Forestry, University of Mosul, Iraq. The study evaluated the physiological and agronomic impacts of a nano-fertilizer ($N_{20}P_{20}K_{20}$) applied at four concentrations: 0 g·L^{-1} (control), 1 g·L^{-1}, 2 g·L^{-1}, and 3 g·L^{-1}. Two methods of fertilizer application were adopted: soil application and foliar spraying. The Nano-fertilizer was applied at three different stages of plant growth: two weeks after transplanting seedlings, two weeks after the first application, and at the beginning of head emergence. This resulted in a total of eight factorial treatments (2 x 4), which ere applied in a factorial experimental design structured within a randomized complete block design (RCBD) with three replicates.

The statistical analysis of the data was performed using the SAS software, and the results were evaluated at a 5% probability level using Duncan's multiple range test. The findings revealed the following:

The use of Nano-fertilizer markedly enhanced foliar chlorophyll levels and significantly increased leaf count per plant. Additionally, it reduced the number of days required for 20% of the broccoli heads to reach maturity and be ready for harvest, with most concentrations showing significant improvements compared to the control treatment. Moreover, each concentration of Nano-fertilizer demonstrated statistically significant improvements across all evaluated yield metrics compared to untreated plants.

In terms of application methods, soil application of the Nano-fertilizer demonstrated a significant advantage over foliar spraying, particularly in terms of average head weight and total head yield per unit area. Most of the interactions between Nano-fertilizer concentrations and application methods aligned with the individual effects observed for each factor across all traits studied.

These results highlight the potential benefits of Nano-fertilizer in improving broccoli growth and productivity, particularly when applied to the soil.

INTRODUCTION

Broccoli (*Brassica oleracea* var. italica), a member of the Brassicaceae family, is one of the most nutritionally rich cruciferous crops and is widely utilized for medicinal purposes in many countries around the world (Hassan, 2004). Broccoli is a nutrient-dense vegetable, containing essential vitamins (A, B1, B2, B5, B6, B17, E) and minerals such as calcium, manganese, zinc, and iron. It also provides carotene, a bioactive compound that the human body metabolizes into vitamin A (Thapa and Rair, 2012). Its medicinal significance stems from its high antioxidant content. Consuming broccoli—whether cooked or in salads—

has been shown to reduce the risk of cancer by up to 60%. This is attributed to compounds like glucoraphanin, which boosts the immune system's ability to combat cancer by eliminating bacteria linked to an increased risk of stomach cancer. Additionally, indole-3-carbinol, another potent antioxidant compound, fights carcinogens and helps prevent breast and colon cancer while also enhancing liver function (Griffin, 2006).

Broccoli holds significant economic value across all Iraqi governorates due to its relatively high market price, often reaching four to five times that of cabbage or cauliflower. This premium pricing is largely due to limited local production, with approximately 90% of broccoli being imported from neighboring countries. Despite the crop's ease of cultivation and care, its production remains constrained, possibly due to farmers' lack of knowledge about its specific growing requirements (Ibraheem, 2015). Globally, annual production of broccoli and cauliflower stands at approximately 22,833,619 tons, with China leading the way, accounting for 43% of total production. In contrast, Iraq's production amounts to only 31,178 tons, representing just 0.14% of global output (F.A.O., 2020).

Given the global importance of broccoli and its relatively low production levels in Iraq, it is crucial to adopt advanced techniques to enhance growth, yield, and quality. One promising approach is nanotechnology, which involves working with materials at dimensions ranging from 1 to 100 nanometers—roughly equivalent to the length of 10 hydrogen atoms (Iskandarani, 2010). Nanotechnology has made significant inroads into agriculture through the use of Nano-fertilizers, which promote crop growth, reduce agricultural inputs, and improve soil properties, thereby positively impacting crop quality and increasing agricultural productivity (Saleh, 2015). As a multidisciplinary technology, nanotechnology has diverse applications in production, manufacturing, storage, and packaging methods. It has also been instrumental in enhancing plants' ability to absorb nutrients and fertilizers (Hussein and Ibraheem, 2023; Al-Sultan et al., 2023; Umesh and Ashok, 2012).

To evaluate the physiological effects of various fertilizers- organic, conventional, or Nano-fertilizers on the growth, productivity, and quality enhancement of horticultural crops, numerous studies have focused on foliar spray application methods (Potter, 2005; Ibraheem and Mahmoud, 2024; Ahmad et al., 2024). Other researchers have explored soil application methods to assess their impact on the growth and productivity of certain vegetable crops, including broccoli (Helmy, 1992; Ibraheem, 2015; Al-Chalabi et al., 2023). Some studies have compared both foliar spraying and soil application to identify the optimal method for maximizing both quantity and quality of yield (Moalla et al., 2015).

This study aims to enhance the growth and yield of broccoli plants through the application of Nano-fertilizer technology using different application methods. Specifically, it seeks to determine the most effective concentration of Nano-fertilizer for plant response, identify the best method of application, and explore the optimal interaction between Nano-fertilizer concentrations and application methods.

MATERIALS AND METHODS

The experiment was conducted in the vegetable field of the Department of Horticulture and Landscape Design, College of Agriculture and Forestry, University of Mosul, Iraq, during the autumn growing season of 2024. The study focused on evaluating the physiological effects of two factors:

1. **Nano-fertilizer N20P20K20** applied at four concentrations: 0, 1, 2, and 3 $g.L^{-1}$.
2. **Two methods of application** : soil application and foliar spraying.

The foliar spraying of Nano-fertilizer was performed at three stages of plant growth:

- Two weeks after transplanting seedlings,

- Two weeks after the first application,
- At the beginning of head emergence.

The hybrid broccoli cultivar Matsuri (supplied by Tokita Seed Co., Japan) was utilized in this study. The factorial experiment comprised eight treatments, combining four concentrations of nano-fertilizer with two application methods, arranged in a randomized complete block design (RCBD) with three replications. Each experimental unit consisted of four rows (2.45 m in length, spaced 75 cm apart), containing seven plants per row (28 plants per unit), covering a total area of 7.35 m^2.

Seeds were planted on 1 August 2024 in 50-cell plastic trays filled with peat moss as the growth medium. Seedlings were transplanted into the field during morning hours upon reaching the 3–4 true-leaf stage. To minimize transplant shock, peat moss was preserved around root systems, and soil moisture was maintained post-transplantation. Drip irrigation was employed, and standard agronomic protocols for broccoli cultivation were followed to ensure optimal development and marketable curd quality.

Data were analyzed using SAS (2017). Mean comparisons between treatments were performed using Duncan's multiple range test at $p \leq 0.05$ (Al-Rawi & Khalaf Allah, 2000).

Studied Traits:

A. Vegetative Growth Indicators:

1. **Total Chlorophyll Content in Leaves (%) :**
   Leaf chlorophyll levels were quantified using a portable SPAD-502 meter. Ten measurements were taken per leaf, and the mean value was calculated to represent chlorophyll content.

2. **Plant Height ($cm.plant^{-1}$) :**
   Height was measured from the soil surface at the stem base to the apex of the tallest leaf using a rigid metric ruler.

3. **Number of Leaves ($leaf.plant^{-1}$) :**
   The total number of fully expanded leaves per plant was recorded, excluding underdeveloped leaves.

B. Yield Indicators:

1. **Head Formation Speed (Days) :**
   The speed of head formation was assessed by recording the number of curds formed and the date of their appearance every two days until all plants in the experimental unit had formed heads. The calculation was based on the following formula:

Head Formation Speed (Days)=Total Number of HeadsSum (Number of heads formed × Day on whi ch they appeared)

2. **Date of Maturity and Harvest of 20% of Heads (Days):**
   The duration from sowing to harvest readiness was determined by recording the number of days required for 20% of curds in the experimental unit to reach commercial maturity.

3. **Average Head Weight ($g.head^{-1}$) :**
   The average fresh weight of marketable curds was calculated by dividing the total curd yield per experimental unit by the corresponding number of harvested curds.

4. **Total Yield of Heads ($ton.ha^{-1}$) :**
The total yield of heads was calculated in tons per hectare based on the yield obtained from the experimental unit.

5. **Head Circumference (cm) :**
The widest circumference of the primary curd was measured using a flexible measuring tape for ten randomly sampled plants per experimental unit.

This comprehensive approach ensured accurate evaluation of the effects of nano-fertilizer treatments on broccoli growth, yield, and curd quality.

RESULTS AND DISCUSSION

A. Vegetative Growth Indicators

Tables (1, 2, and 3) present the effects of Nano-fertilizer $N_{20}P_{20}K_{20}$ concentrations, application methods, and their interaction on vegetative growth parameters. The data in these tables demonstrate that all concentrations of Nano-fertilizer significantly increased both the percentage of total chlorophyll content in the leaves and the number of leaves per plant compared to the control plants (Tables 1 and 3). While there was a positive increase in plant height with all concentrations of the fertilizer, this increase did not reach statistical significance (Table 2).

Regarding the impact of application methods, the results in the same tables indicate no significant differences between soil application and foliar spraying for any of the vegetative growth traits.

As for the interaction between Nano-fertilizer concentrations and application methods, the results reveal that the combination of 3 g L^{-1} Nano-fertilizer applied to the soil reached the highest values for total chlorophyll content in the leaves (67.700%). This treatment significantly outperformed both the control treatments and the concentration of 1 g L^{-1} when using the same soil application method. Additionally, it surpassed the control treatments and the concentration of 3 g L^{-1} applied via foliar spraying.

For plant height and the number of leaves, the same interaction treatment (3 g L^{-1} applied to the soil) produced the highest significant values for both traits, reaching 78.483 cm per plant and 23.533 leaves per plant, respectively.

This analysis highlights the potential of soil application of Nano-fertilizer at higher concentrations to optimize vegetative growth characteristics in broccoli plants.

A. Vegetative Growth Indicators

The significant increases observed in the percentage of total chlorophyll content in leaves and leaf count, along with the positive (though non-significant) increase in plant height when using Nano-fertilizer compared to the control, underscore the importance of Nano-fertilizer $N_{20}P_{20}K_{20}$ in promoting robust plant growth. This fertilizer enables plants to develop characteristics that enhance their resistance to external environmental conditions. The large surface area of Nano-fertilizers enhances enzymatic activity and accelerates biochemical reactions, leading to increased cell division and nucleic acid synthesis, as well as higher production of peroxidase and catalase enzymes. Furthermore, nanoparticles mitigate the generation of reactive oxygen species (ROS), thereby reducing oxidative stress, delaying senescence, and promoting robust vegetative growth (Monreal et al., 2016).

B. Yield Indicators

The results presented in Table (4) indicate that the shortest time for head emergence was achieved with 3 g L^{-1} of Nano-fertilizer, requiring only 101.783 days. In contrast, the longest time for head emergence, at 104.050 days, was recorded in the control plants. Similarly, the earliest maturity and harvest of 20% of heads occurred in plants treated with 1 g L^{-1} of Nano-fertilizer, taking 134.933 days, while the longest duration for this trait, at 142.217 days, was observed in the control treatment (Table 5).

Regarding head weight, total yield, and head circumference, the highest values were achieved with a concentration of 1 g L^{-1} of Nano-fertilizer. These values reached 558.35 g per head, 21.2705 tons per hectare, and 52.350 cm for head circumference, respectively. These results showed significant differences compared to all other treatments for head weight and yield, while the difference in head circumference was significant only when compared to the control (Tables 6–8).

As for the effect of application methods, soil application significantly outperformed foliar spraying in terms of head weight and yield per unit area (Tables 6 and 7).

From the analysis of two-factor interactions, it is evident that the combination of 3 g L^{-1} Nano-fertilizer applied to the soil resulted in the shortest time for head emergence, at 99.467 days, while the longest time for this trait, at 104.900 days, was observed in the control plants using the same soil application method (Table 4). Furthermore, the interaction of 3 g L^{-1} Nano-fertilizer with soil application reduced the number of days required for the maturity and harvest of 20% of heads to the lowest value, at 131.633 days, making this combination the most effective treatment. Conversely, the longest duration for this trait, at 142.333 days, was recorded when foliar spraying was used on control plants (Table 5).

In terms of head weight, yield per unit area, and head circumference, the best interaction treatment was achieved with the highest concentration of Nano-fertilizer (3 g L^{-1}) combined with soil application. The values for these traits reached 634.27 g per head, 24.1625 tons per hectare, and 57.233 cm for head circumference, respectively. These results demonstrated significant superiority over all other interaction treatments for head weight and yield per unit area (Tables 6 and 7). Additionally, the superiority in head circumference was significant compared to most other interaction treatments (Table 8).

These findings highlight the critical role of Nano-fertilizer concentration and application method in optimizing broccoli yield.

The Nano-fertilizer contains essential nutrients critical for plant growth—nitrogen, phosphorus, and potassium—which play vital roles in the development and overall health of plants. Nitrogen is particularly important for chlorophyll synthesis and directly contributes to the photosynthesis process. It is also a key component of proteins and enzymes, making it indispensable during the vegetative growth stage (Al-Tahir et al., 2014). Phosphorus, on the other hand, promotes cell division and stimulates root and flower development. It is predominantly found in young, actively growing parts of the plant, such as buds and root tips, where metabolic activity and cell division are most intense. Additionally, phosphorus plays a crucial role in transferring and storing energy derived from photosynthesis, which is later utilized for growth and reproduction (Naderi and Shahraki, 2011). Potassium contributes to photosynthesis by activating enzymes and aiding in ATP production. It also enhances disease resistance, regulates root growth, and controls stomatal opening and closing, all of which positively impact yield-related traits.

CONCLUSIONS

From this study, it can be concluded that the application of various concentrations of Nano-fertilizer significantly increased in both height and the leaf count. Furthermore, the results demonstrated that using the soil application method led to significant improvements in head weight and head yield per unit area compared to foliar spraying. Based on these findings, it is recommended to incorporate Nano-fertilizer through soil application in broccoli production systems to optimize growth and productivity.

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Table 1: Effect of N20P20K20 Nano- fertilizer, application methods and interaction on leaf chlorophyll content percentage

Addition methods	Nano fertilizer concentrations N20P20K20 (g L-1)				Average effect of addition method
	0	1	2	3	
Adding to the soil	**46.067** b	**43.367** b	60.533 a	**67.700** a	54.417 a
Foliar spraying	**40.900** b	**64.900** a	**63.400** a	**45.733** b	**53.733** a
Average effect of Nano-fertilizer concentrations	**43.483** c	**54.133** b	**61.967** a	**56.717** b	

"Treatments with the same letter designation did not differ significantly (P > 0.05) according to Duncan's test."

Table 2: Effect of Nano- fertilizer N20P20K20, addition methods and interaction on plant height (cm plant^{-1})

Addition methods	Nano fertilizer concentrations N20P20K20 (g L-1)				Average effect of addition method
	0	1	2	3	
Adding to the soil	**72.567** bc	**77.900** a	**75.900** ab	**78.483** a	**76.213** a
Foliar spraying	**74.333** abc	**74.867** abc	**77.133** ab	**70.467** c	**74.200** a
Average effect of Nano-	**73.450**	**76.383**	**76.517**	**74.475**	

fertilizer concentrations	a	a	a	a	

"Treatments with the same letter designation did not differ significantly (P > 0.05) according to Duncan's test."

Table 3: Effect of Nano- fertilizer N20P20K20, addition methods and interaction on the number of leaves (leaf per plant^{-1})

Addition methods	Nano fertilizer concentrations N20P20K20 (g L^{-1})				Average effect of addition method
	0	1	2	3	
Adding to the soil	**19.7333** d	**22.0667** b	**22.4667** b	**23.5333** a	**21.9500** a
Foliar spraying	**20.6667** cd	**22.5333** b	**21.6333** bc	**21.0333** c	**21.4667** a
Average effect of Nano-fertilizer concentrations	**20.2000** b	**22.3000** a	**22.0500** a	**22.2833** a	

"Treatments with the same letter designation did not differ significantly (P > 0.05) according to Duncan's test."

Table 4: Effect of N20P20K20 Nano-fertilizer, addition methods and interference on head formation rate (day)

Addition methods	Nano fertilizer concentrations N20P20K20 (g L^{-1})				Average effect of addition method
	0	1	2	3	
Adding to the soil	**104.900** a	**102.833** ab	**104.000** ab	**99.467** c	**102.8000** a
Foliar spraying	**103.200** ab	**102.567** abc	**101.033** bc	**104.100** ab	**102.7250** a
Average effect of Nano-fertilizer concentrations	**104.050** a	**102.700** a	**102.517** a	**101.783** a	

"Treatments with the same letter designation did not differ significantly (P > 0.05) according to Duncan's test."

Table 5: Effect of Nano- fertilizer N20P20K20, addition methods and interaction on the number of days of head formation (day)

Addition methods	Nano fertilizer concentrations N20P20K20 (g L^{-1})				Average effect of addition method
	0	1	2	3	
Adding to the soil	142.100 a	134.467 cd	140.800 ab	131.633 d	138.158 a
Foliar spraying	142.333 a	135.400 bcd	135.667 bcd	139.233 abc	137.250 a
Average effect of Nano-fertilizer concentrations	142.217 a	134.933 b	138.233 ab	135.433 b	

"Treatments with the same letter designation did not differ significantly (P > 0.05) according to Duncan's test".

Table 6: Effect of Nano- fertilizer N20P20K20, addition methods and interaction on head weight (g $head^{-1}$)

Addition methods	Nano fertilizer concentrations N20P20K20 (g L^{-1})				Average effect of addition method
	0	1	2	3	
Adding to the soil	373.73 d	548.23 b	466.67 c	634.27 a	505.725 a
Foliar spraying	432.20 c	568.47 b	542.83 b	372.07 d	478.892 b
Average effect of Nano-fertilizer concentrations	402.97 c	558.35 a	504.75 b	503.17 b	

"Treatments with the same letter designation did not differ significantly (P > 0.05) according to Duncan's test."

Table 7: Effect of Nano- fertilizer N20P20K20, addition methods and interaction on head yield (tons ha^{-1})

Addition methods	Nano fertilizer concentrations N20P20K20 (g L^{-1})				Average effect of addition method
	0	1	2	3	
Adding to the soil	14.2375 d	20.8851 b	17.7778 c	24.1625 a	19.2657 a
Foliar spraying	16.4648	21.6559	20.6794	14.1740	18.2435

	c	b	b	d	b
Average effect of Nano-fertilizer concentrations	**15.3511** c	**21.2705** a	**19.2286** b	**19.1683** b	

"Treatments with the same letter designation did not differ significantly (P > 0.05) according to Duncan's test".

Table 8: Effect of Nano- fertilizer N20P20K20, addition methods and interference on head circumference (cm head^{-1})

Addition methods	Nano fertilizer concentrations N20P20K20 (g L^{-1})				Average effect of addition method
	Control	1	2	3	
Adding to the soil	**44.700** d	**51.933** bc	**49.500** cd	**57.233** a	**50.842** a
Foliar spraying	**47.733** cd	**52.767** abc	**54.733** ab	**46.200** d	**50.358** a
Average effect of Nano-fertilizer concentrations	**46.217** b	**52.350** a	**52.117** a	**51.717** a	

"Treatments with the same letter designation did not differ significantly (P > 0.05) according to Duncan's test."