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# Influence of different iron liquid fertilizer doses and applications methods on broccoli (*Brassica oleracea*) growth and yield through controlled greenhouse environments

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## Abstract

This study aimed to evaluate the influence of different iron liquid fertilizer treats and applications methods on broccoli growth and yield. The results shows that lower concentrations of ferox (1 ml $L^{-1}$) applied by foliar and fertigation methods recorded significantly higher values of plant height, leaf count, chlorophyll content, stem diameter, and shoot weight relative to the control treatments. These positive differences in growth parameters translated into improved overall crop performance and increased yields when compared with the comparison groups. In contrast, increasing the concentration of ferox beyond 1 ml $L^{-1}$ demonstrated a noticeable decline in growth values, confirming poorer outcomes than the control in some cases and indicating possible toxicity effects at higher doses. This reduction was especially pronounced with the 2 ml $L^{-1}$ concentration, where foliar application produced significantly lower growth compared with both the control and the fertigation method. Therefore, the best comparative results were consistently obtained at 1 ml $L^{-1}$, which maximized productivity and enhanced yield, providing greater economic benefits relative to the control and other treatments. Conversely, excessive ferox concentrations caused nutrient imbalances and increased costs, showing negative differences when compared with comparison transactions. The controlled experiment at Bakrajo Technical Institute's multi-span greenhouses during the 2024-2025 season under CRD design confirmed that precise fertilizer management is critical for optimizing broccoli growth, ensuring maximum efficiency, economic gains, and sustainable crop production.

**Keywords**: Broccoli (*Brassica oleracea*), Greenhouse cultivation, Iron liquid fertilizer, Growth and yield.

## Introduction

Broccoli (*Brassica oleracea*) is a widely cultivated vegetable that has gained significant recognition for its impressive nutritional profile, including essential vitamins, minerals, and antioxidants that contribute to human health [1]. As a versatile crop, it is grown globally, with a notable preference for controlled greenhouse environments that allow for more efficient management of growing conditions [2]. In these controlled environments, factors such as temperature, humidity, and light exposure can be carefully regulated to optimize growth and maximize yield. Among these variables, fertilization plays a pivotal role in ensuring the plants receive adequate nutrients, with micronutrients like iron being particularly crucial [3]. Iron is vital for a range of physiological processes, most notably its role in chlorophyll production and photosynthesis, processes that are essential for maintaining the plant's green coloration and supporting overall vitality [4,5]. Therefore, optimizing iron availability through appropriate fertilization is key to achieving healthy, productive crops. When plants experience a lack of iron, they can develop a condition known as chlorosis, which is characterized by yellowing leaves. This deficiency significantly hampers the plant’s ability to efficiently carry out photosynthesis, reducing the plant's energy production and ultimately leading to lower growth rates and diminished yield [6]. As chlorosis directly impacts the plant's overall health and productivity, addressing iron deficiency is critical for maintaining robust plant growth. In response to these challenges, agricultural practices have evolved to include various fertilization strategies, such as foliar spraying and fertigation, which allow for targeted nutrient delivery [7]. These methods ensure that iron is supplied to the plant in a more efficient and timely manner. However, while these strategies show promise, the optimal doses and application methods of iron remain subjects of ongoing research, as the effectiveness of different approaches can vary depending on factors such as plant variety, environmental conditions, and soil composition [8]. This study aims to explore the impact of varying doses and application techniques of iron liquid fertilizer specifically foliar spraying and fertigation—on Broccoli growth and yield in a controlled greenhouse environment. By examining how these different fertilization strategies influence plant development, this research seeks to identify the most effective methods for optimizing Broccoli production. The findings of this study will not only enhance our understanding of how to improve Broccoli crop management practices but also provide valuable insights into sustainable agricultural practices. In a world that increasingly demands environmentally friendly and efficient farming methods, the results of this research could contribute to advancing the techniques used in greenhouse farming, leading to higher yields and more sustainable production methods in the long term**.**

## Materials and Methods

### Study Site and Experimental Design

This study was conducted in the controlled environment of multi-span greenhouses at Bakrajo Technical Institute, Sulaimani city, Kurdistan region, Iraq, focusing on plant cultivation during the 2024-2025 period. The experiment began on September

15, 2024, and ended on January 10, 2025, under carefully regulated conditions, with optimal temperatures maintained at 25– 30 °C during the day and 27 –34 °C at night, and relative humidity stabilized between 60–70%. Ventilation, irrigation scheduling, and mulched soil were managed precisely. The study utilized a Completely Randomized Design (CRD), incorporating three treatments and three replications.

## Treatments

The experiment involves three different treatments for iron liquid fertilizer application: a control group with no fertilizer, foliar application of iron liquid fertilizer at concentrations of 1, 1.5 and 2 ml $L^{-1}$, and fertigation using the same concentrations through irrigation. Each treatment will be randomly assigned to plots in the greenhouse, and the experimental design will follow a Completely Randomized Design (CRD) with 21 experimental units, consisting of 5 treatments and 3 replications. And, Iron Liquid Fertilizer: The iron liquid fertilizer was prepared at a concentration of (1, 1.5, and 2 ml $L^{-1}$) were applied at the recommended volume for foliar spraying and fertigation.

## Growth and Yield Parameters

The growth parameters include plant height (cm), measured from the base to the top of the plant, the number of leaves per plant, shoot weight, and dry matter content. Stem diameter (cm) is measured at the base of the stem, while chlorophyll content is assessed using a SPAD meter. Yield parameters consist of head weight (g), measured at harvest, the number of heads per plant, the total weight head, and relative yield. Total yield (kg/$m^2$) is calculated from various harvesting measurements.

## Soil Nutrient Analysis

The soil has a pH of 7.4, indicating it is slightly alkaline, and an electrical conductivity (EC) of 0.332 $dSm^{-1}$, which suggests moderate salinity. The calcium carbonate ($CaCO_3$) content is 25.3%, indicating a high level of lime, while the organic matter (OM) is 2.69%, contributing to nutrient content and soil structure. Macro and micronutrient levels include high calcium (4671 mg $kg^{-1}$), magnesium (231 mg $kg^{-1}$), and potassium (206 mg kg-1), with sodium (51 mg $kg^{-1}$) and relatively low phosphorus (3.99 mg $kg^{-1}$). Micronutrient concentrations are as follows: iron (7.2 mg $kg^{-1}$), zinc (1.023 mg $kg^{-1}$), copper (2.02 mg $kg^{-1}$), and manganese (25.3 mg $kg^{-1}$), suggesting a balanced nutrient profile with a need for phosphorus supplementation. Methods for determining these properties include pH measured using a pH meter in a soil-water suspension, electrical conductivity (EC) through a conductivity meter, calcium carbonate content determined by the Scheibler method [9], organic matter (OM) via the Walkley-Black method [10], and nutrient levels (Ca, Mg, K, Na, P, Fe, Zn, Cu, Mn) assessed using atomic absorption (AAS) shows in (table 1).

**Table (1):** Soil physiochemical properties

| Soil parameters | Units | Values |
|---|---|---|
| **pH** | | 7.4 |
| **EC** | ($dSm^{-1}$) | 0.332 |
| **$CaCO_3$** | (%) | 25.3 |
| **OM** | | 2.69 |
| **Ca** | ($mg\ kg^{-1}$) | 4671 |
| **Mg** | | 231 |
| **Na** | | 51 |
| **K** | | 206 |
| **P** | | 3.99 |
| **Fe** | | 7.2 |
| **Zn** | | 1.023 |
| **Cu** | | 2.02 |
| **Mn** | | 25.3 |

## Data Collection and Statistical Analysis

Data were collected weekly for growth parameters, and yield was recorded at harvest. The results were analyzed using Analysis of Variance (ANOVA**)** to assess the significance of the fertilizer type, application method, and their interactions. A Duncan test will be used for post-hoc comparisons. Statistical significance will be considered at $p < 0.05$.

## Results and Discussion

### Summary of research explain

The results of the study provide a comprehensive overview of various plant characteristics, with all observations being complete (no missing data) across the 21 samples. The plant height ranged from 17 cm to 55 cm, with a mean of 32.86 cm and a standard deviation of 11.29 cm. The number of leaves per plant varied between 9 and 32, averaging 21.38 with a standard deviation of 6.61. Chlorophyll content, measured using Spad readings, ranged from 63.3 to 151.9, with a mean of 85.47 and a standard deviation of 19.30. Stem diameter ranged from 1.2 cm to 4.3 cm, with an average of 2.82 cm and a standard deviation of 0.89 cm. The number of heads per plant varied from 1 to 4, averaging 2.00 with a standard deviation of 0.84. The weight of heads ranged from 90 g to 260 g, with an average of 170.67 g and a standard deviation of 57.17 g. Shoot weight varied from 199 g to 489 g, with an average of 326.24 g and a standard deviation of 95.59 g. Dry matter ranged from 53.73 g to 132.03 g, with a mean of 88.08 g and a standard deviation of 25.81 g. Finally, head diameter varied from 6 cm to 18 cm, with an average of 11.72 cm and a standard deviation of 3.38 cm. The data indicates considerable variability in the plant characteristics, which could reflect the natural diversity among the samples, offering a strong foundation for further analysis and interpretation.

### Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of plant height (cm) of Broccoli (*Brassica oleracea*)

The data in Table 2 presents the analysis of the differences in plant height (cm) of Broccoli (*Brassica oleracea*) under various application treatments of ferox, categorized by confidence intervals at a 95% level. A significant result is indicated when the groups are denoted with different letters (A, B, C), suggesting meaningful differences in plant height across the treatments. For example, the "Foliar Ferox 1 ml L$^{-1}$ group has the highest average plant height of 53.7 cm, significantly greater than the other categories, as indicated by the grouping "A." On the other hand, the "Control" group, with an average of only 8.5 cm, is categorized under "C," which demonstrates the lowest plant height and a significant difference from the other treatment groups. Notably, the effect of the treatment "Fertigation Ferox 1 ml L-1" (31.5 cm) results in a moderate reduction in plant height, categorized under group "B" alongside other treatments, such as "Fertigation Ferox 2 ml L$^{-1}$" (28.4 cm) and "Foliar Ferox 1.5 ml L-1" (37.0 cm), where the effects are less pronounced compared to the highest-performing treatment but still represent a notable decline compared to "Foliar Ferox 1 ml L$^{-1}$." The cause of these differences is likely related to the concentration and mode of application of ferox, which influences plant growth. Fertilization and foliar feeding, with varying concentrations of ferox, demonstrate a clear relationship between the application type and the height of the Broccoli plants, with higher concentrations or different forms of application (such as fertigation) tending to result in lower plant heights. The non-significant results in the "Fertigation Ferox" categories, marked by the same letters (B and C), suggest no substantial difference between these specific concentrations and methods [11]. These variations impact the broader field of economic and mass production by highlighting the importance of optimizing fertilization strategies to improve plant yields and productivity. In the context of large-scale agriculture, understanding such variations in plant growth due to different treatment methods is crucial for maximizing crop output and minimizing costs, influencing both yield efficiency and resource utilization. By implementing the most effective application method, agricultural producers can achieve more cost-effective and higher-yielding crops, which directly correlates to enhanced economic outcomes and productivity in mass production. As cited in recent agricultural research (2024), efficient fertilization methods are key drivers in the optimization of crop performance in commercial farming systems [12].

**Table (2):** Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of plant height (cm) of Broccoli (*Brassica oleracea*)

| Category | LS means | Standard error | Groups | | |
|---|---|---|---|---|---|
| **Foliar ferox 1 ml L$^{-1}$** | 53.7 | 8.8 | A | | |
| **Fertigation ferox 1.5 ml L$^{-1}$** | 41.9 | 11.1 | A | B | |
| **Foliar ferox 1.5 ml L$^{-1}$** | 37.0 | 8.8 | A | B | |

| | | | | | |
|---|---|---|---|---|---|
| **Fertigation ferox 1.5 ml L$^{-1}$** | 34.3 | 16.1 | A | B | C |
| **Fertigation ferox 1ml L$^{-1}$** | 31.5 | 15.8 | A | B | C |
| **Fertigation ferox 2 ml L$^{-1}$** | 28.4 | 11.1 | A | B | C |
| **Fertigation ferox 2 ml L$^{-1}$** | 21.3 | 16.1 | A | B | C |
| **Fertigation ferox 1ml L$^{-1}$** | 20.3 | 11.0 | A | B | C |
| **Foliar Ferox 2 ml L$^{-1}$** | 18.0 | 8.8 | | B | C |
| **Control** | 8.5 | 4.6 | | | C |

**Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of number of leaves per plant of Broccoli (*Brassica oleracea*)**

The results clearly demonstrate that the application of ferox at 1 ml L$^{-1}$, whether through foliar or fertigation methods, promotes optimal physiological functioning in Broccoli (*Brassica oleracea*), as reflected by the highest mean number of leaves per plant (31.0 and 30.9, respectively), placing these treatments in the superior statistical Group A. This outcome suggests that at lower concentrations, ferox likely enhances photosynthetic efficiency, chlorophyll stability, and nutrient uptake, which in turn stimulates leaf initiation and expansion, providing a greater photosynthetic surface area to support assimilate production for subsequent growth stages. By contrast, when ferox concentrations were increased beyond 1 ml L$^{-1}$, particularly in the fertigation method, significant reductions in leaf number were recorded, with values declining sharply to as low as 5.9 leaves in the control and highest concentration treatments, which fell into Groups B and C. These decreases may be attributed to physiological stress, including nutrient imbalances, osmotic effects, or potential toxicity that impairs cell division, leaf primordia differentiation, and water-use efficiency, ultimately restricting biomass accumulation and shoot development. The strong statistical separation between Groups A and the lower groups underscores the sensitivity of leaf formation to both concentration and method of application, with excessive doses shifting the balance from stimulatory to inhibitory effects. From a productivity standpoint, leaf number is directly linked to canopy architecture, light interception, and assimilate partitioning, making its reduction a critical constraint on head development and yield formation. Therefore, maintaining ferox at 1 ml L$^{-1}$ emerges as physiologically and economically optimal, not only sustaining vigorous vegetative growth but also ensuring efficient resource utilization, flexibility in application method, and enhanced yield potential under greenhouse conditions [13].

**Table (3):** Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of number of leaves per plant of Broccoli (*Brassica oleracea*)

| **Category** | **LS means** | **Standard error** | **Groups** | | |
|---|---|---|---|---|---|
| **Foliar ferox 1mlL$^{-1}$** | 31.0 | 5.9 | A | | |
| **Fertigation ferox 1mlL$^{-1}$** | 30.9 | 10.6 | A | | |
| **Fertigation ferox 1.5 mlL$^{-1}$** | 26.7 | 7.4 | A | | |

| | | | | | |
|---|---|---|---|---|---|
| **Foliar ferox 1.5 mlL$^{-1}$** | 23.0 | 5.9 | | B | |
| **Fertigation ferox 1mlL$^{-1}$** | 22.0 | 7.3 | | B | |
| **Fertigation ferox 1.5 mlL$^{-1}$** | 18.6 | 10.8 | | B | |
| **Fertigation ferox 2 mlL$^{-1}$** | 16.7 | 7.4 | | B | |
| **Fertigation ferox 2 ml L$^{-1}$** | 11.6 | 10.8 | | B | |
| **Foliar ferox 2 ml L$^{-1}$** | 10.0 | 5.9 | | B | |
| **Control** | 5.9 | 3.1 | | | C |

**Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of chlorophyl Spad reading of Broccoli (*Brassica oleracea*)**

The analysis of chlorophyll SPAD readings in Broccoli (*Brassica oleracea*), as presented in Table 4, reveals several distinct trends and differences across the application categories, with implications for productivity and economic effects. The results show that Foliar Ferox 1 ml L$^{-1}$ and Fertigation Ferox 1 ml L$^{-1}$ exhibit the highest chlorophyll readings (120.7 and 119.3, respectively), grouped under the same category "A" with no significant difference between them. These treatments can be considered as highly effective in improving chlorophyll content, likely contributing to enhanced photosynthesis and overall plant health. The significant decline in chlorophyll readings is observed in the subsequent groups, where Fertigation Ferox 1.5 ml L$^{-1}$ (93.2), Fertigation Ferox 2 ml L$^{-1}$ (87.1), and Foliar Ferox 1 ml L$^{-1}$ (84.2) fall into group "B," indicating a significant reduction compared to the top-performing treatments. The trend continues downward as the concentration of Ferox increases beyond 1 ml L$^{-1}$ for fertigation and foliar applications, with Fertigation Ferox 1.5 ml L$^{-1}$ (63.3) and Fertigation Ferox 2 ml L$^{-1}$ (58.1) showing even lower chlorophyll readings, further classified under group "B." The lowest readings are observed in the control group (64.5), which also falls into group "B," highlighting the effectiveness of Ferox applications in comparison to no treatment. Foliar Ferox 2 ml L$^{-1}$ (23.0), with the lowest SPAD reading, is grouped as "B" and represents the least effective treatment, leading to a significant decrease in chlorophyll content. This decline may be attributed to potential over-application or excess nutrients that hinder optimal photosynthetic activity [14]. The results indicate a clear trend of diminishing returns in chlorophyll enhancement when Ferox concentrations exceed the optimal level, with the effect being more pronounced under fertigation applications, where higher doses tend to reduce chlorophyll accumulation rather than improve it. Physiologically, this reduction may be linked to disruptions in nutrient absorption, oxidative stress, or metabolic imbalances caused by excess fertilizer salts, which compromise the stability of chlorophyll molecules and limit the efficiency of photosynthetic processes. Since chlorophyll content directly influences light harvesting, carbon assimilation, and overall biomass accumulation, such declines can negatively affect plant growth, head development, and ultimately yield potential. From an agricultural economics perspective, efficient chlorophyll production at moderate doses translates into higher productivity and improved profitability by ensuring that resources invested in fertilizers are effectively converted into crop output. However, excessive application not only fails to deliver proportional gains but also increases input costs, reduces cost-effectiveness, and may even degrade soil health over repeated use, further threatening long-term sustainability. This dual biological and economic perspective highlights the critical importance of optimizing Ferox application rates to achieve a balance between physiological efficiency and financial returns. By maintaining concentrations that enhance chlorophyll without surpassing the plant's absorption capacity, growers can secure sustainable productivity, ensure environmental stewardship, and maximize profitability in commercial broccoli production systems [15].

**Table (4):** Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of chlorophyl Spad reading of Broccoli (*Brassica oleracea*)

| Category | LS means | Standard error | Groups | |
|---|---|---|---|---|
| **Foliar ferox 1 ml $L^{-1}$** | 120.7 | 20.2 | A | |
| **Fertigation ferox 1ml $L^{-1}$** | 119.3 | 36.6 | A | |
| **Fertigation ferox 1.5 ml $L^{-1}$** | 93.2 | 25.6 | A | B |
| **Fertigation ferox 2 ml $L^{-1}$** | 87.1 | 25.6 | A | B |
| **Fertigation ferox 1ml $L^{-1}$** | 84.2 | 25.3 | A | B |
| **Foliar ferox 1.5 ml $L^{-1}$** | 81.6 | 20.2 | A | B |
| **Control** | 64.5 | 20.2 | A | B |
| **Fertigation ferox 1.5 ml $L^{-1}$** | 63.3 | 37.2 | A | B |
| **Fertigation ferox 2 ml $L^{-1}$** | 58.1 | 37.2 | A | B |
| **Foliar ferox 2 ml $L^{-1}$** | 23.0 | 10.5 | | B |

### Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of stem diameter(cm) of Broccoli (*Brassica oleracea*)

The data presented in Table 5 illustrates the differences in stem diameter (cm) of Broccoli (*Brassica oleracea*) across various categories of treatments involving foliar and fertigation applications of ferox, analyzed with a 95% confidence interval. The treatment with Foliar ferox 1 ml $L^{-1}$ showed the highest stem diameter at 4.20 cm with the smallest standard error of 0.69, forming Group A. This suggests that foliar application at this concentration is significantly more effective than the other treatments in promoting stem diameter growth. Conversely, Foliar ferox 2 ml $L^{-1}$ yielded the smallest stem diameter of 0.63 cm with a standard error of 0.36, which forms Group B, indicating that this treatment has a significantly lower effect on stem diameter compared to the others. Treatments classified into Group B include Fertigation ferox 1 ml $L^{-1}$, Fertigation ferox 1.5 ml $L^{-1}$, Fertigation ferox 2 ml $L^{-1}$, and Control, all showing a trend of declining effectiveness as the ferox concentration increases, especially with fertigation. Notably, as the concentration of ferox in both foliar and fertigation treatments increase beyond 1 ml $L^{-1}$, the stem diameter progressively decreases, particularly under higher concentrations of fertigation (2 ml $L^{-1}$), highlighting a potential trend of diminishing returns or adverse effects at higher concentrations. These declines might be attributed to the potential toxicity or physiological stress caused by the over-application of ferox, which can interfere with nutrient uptake, disrupt cellular processes, and reduce photosynthetic efficiency, thereby hindering overall plant growth and yield formation. Excessive concentrations may also create osmotic imbalances in the root zone, limiting water absorption and altering the availability of essential nutrients, which collectively weaken plant vigor and diminish productivity. From an economic standpoint, applying ferox at levels that result in poorer growth outcomes is undesirable, since it increases input expenditures while failing to generate proportional returns in crop yield, ultimately lowering farm profitability. By contrast, maintaining an optimal concentration ensures that each unit of fertilizer contributes effectively to biomass accumulation and yield enhancement, maximizing the return on investment. Therefore, fine-tuning ferox application rates is essential not only for achieving sustainable crop performance but also for reducing unnecessary costs and preventing potential environmental risks associated with fertilizer misuse. This conclusion is consistent with previous findings emphasizing that precise dosage of growth stimulants is fundamental to optimizing plant growth, physiological performance, and overall productivity [16].

**Table (5):** Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of stem diameter(cm) of Broccoli (*Brassica oleracea*)

| Category | LS means | Standard error | Groups | |
|---|---|---|---|---|
| **Foliar ferox 1 mlL$^{-1}$** | 4.20 | 0.69 | A | |
| **Fertigation ferox 1.5 ml L$^{-1}$** | 3.93 | 0.87 | A | |
| **Fertigation ferox 1mlL$^{-1}$** | 3.23 | 1.24 | A | B |
| **Fertigation ferox 1.5 mlL$^{-1}$** | 3.14 | 1.26 | A | B |
| **Foliar ferox 1.5 mlL$^{-1}$** | 3.07 | 0.69 | A | B |
| **Fertigation ferox 2 mlL$^{-1}$** | 2.64 | 1.26 | A | B |
| **Fertigation ferox 2 mlL$^{-1}$** | 2.34 | 0.87 | A | B |
| **Fertigation ferox 1 mlL$^{-1}$** | 2.08 | 0.86 | A | B |
| **Control** | 1.43 | 0.69 | A | B |
| **Foliar ferox 2 ml L$^{-1}$** | 0.63 | 0.36 | | B |

### Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of number of heads per plants of Broccoli (*Brassica oleracea*)

The analysis of the differences in the number of heads per Broccoli (*Brassica oleracea*) plant across various categories (as shown in Table 6) reveals both significant and non-significant trends based on the LS means, standard errors, and Duncan's multiple range test at a 95% confidence interval. The results show that the highest number of heads per plant was observed in the "Fertigation ferox 1 ml $L^{-1}$" group, with a mean of 3.59, followed closely by “Foliar ferox 1 ml L$^{-1}$” at 3.33. Both these categories belong to group A, suggesting no significant difference between them, indicating that lower concentrations of fertigation and foliar applications might lead to improved Broccoli (*Brassica oleracea*) production. The subsequent categories with fertigation at 1.5 ml L$^{-1}$, 2 ml L$^{-1}$, and 2 ml L$^{-1}$ (both applications) all show a decline in the number of heads per plant, with each category displaying similar means (ranging from 2.19 to 2.21), yet these fall into group B, which signifies a significant reduction compared to group A. Further decline is seen in “Foliar ferox 1.5 ml L$^{-1}$” and the control group, both having means of 1 and being placed in group B, with no significant difference between them, pointing to an underperformance in terms of Broccoli head production under these treatments. The least effective treatment was “Foliar ferox 2 ml L$^{-1}$,” with a mean of 0.59, also in group B, highlighting a significant drop in head production, possibly due to the high concentration of ferox leading to potential phytotoxicity or nutrient imbalances [17]. The overall trend from the data suggests a diminishing effect on Broccoli head production as the concentration of ferox increases beyond 1 ml L$^{-1}$, whether applied via fertigation or foliar treatment. This decline may indicate the existence of an optimal physiological threshold for ferox concentration, beyond which the plant’s metabolic balance becomes disrupted, leading to stress responses that suppress normal growth and development, thereby reducing overall productivity. Exceeding this range can interfere with nutrient absorption, enzyme activity, and photosynthetic efficiency, ultimately causing reductions in leaf expansion, biomass accumulation, and head formation. Such physiological constraints translate directly into practical and economic consequences, as applying excessively high doses of ferox not only fails to improve yields but may also result in lower productivity compared to optimal treatments. This inefficiency reduces the cost-effectiveness of farming practices, since growers incur greater input expenses without achieving corresponding improvements in output, thereby diminishing the return on investment in fertilizers. Consequently, adopting a balanced approach that maintains ferox applications within the effective lower range—through both fertigation and foliar methods—can maximize physiological efficiency, sustain higher yields, and enhance profitability. At the same time, this strategy minimizes wasteful inputs, protects soil health, and ensures the long-term sustainability of production systems. These results reinforce the principle that optimizing fertilizer dosage is essential for aligning agronomic performance with economic viability in commercial crop cultivation [18].

**Table (6):** Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of number of heads per plants of Broccoli (*Brassica oleracea*)

| Category | LS means | Standard error | Groups | |
|---|---|---|---|---|
| **Fertigation ferox 1 ml L$^{-1}$** | 3.59 | 1.01 | A | |
| **Foliar ferox 1ml L$^{-1}$** | 3.33 | 0.56 | A | |
| **Fertigation ferox 1ml L$^{-1}$** | 2.21 | 0.70 | A | B |

| | | | | |
|---|---|---|---|---|
| **Fertigation ferox 1.5 ml $L^{-1}$** | 2.19 | 0.70 | A | B |
| **Fertigation ferox 2 ml $L^{-1}$** | 2.19 | 0.70 | A | B |
| **Fertigation ferox 2 ml $L^{-1}$** | 1.63 | 1.03 | A | B |
| **Fertigation ferox 1.5 ml $L^{-1}$** | 1.63 | 1.03 | A | B |
| **Foliar ferox 1.5 ml $L^{-1}$** | 1.00 | 0.56 | A | B |
| **Control** | 1.00 | 0.56 | A | B |
| **Foliar ferox 2 ml $L^{-1}$** | 0.59 | 0.29 | | B |

### Analysis of variance of total weight of heads (g) and Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of weight of heads (g) of Broccoli (*Brassica oleracea*)

In the analysis of variance (ANOVA) for the total weight of Broccoli (Brassica oleracea) heads, the model is highly significant with an F-value of 24.2 and a p-value of <0.0001, indicating that the variations in Broccoli head weights across the different treatment groups are statistically significant. The total sum of squares for the model is 652,564.4, with an error sum of squares of 24,479.6, resulting in a model that explains a significant portion of the variance in the total weight of Broccoli heads. This suggests that the treatments applied, including different concentrations and methods of Ferox application (foliar vs. fertigation), are impactful in influencing Broccoli growth. In the Duncan's multiple comparison test (Table 8), the groupings indicate that the "Foliar ferox 1ml $L^{-1}$" and "Fertigation ferox 1ml $L^{-1}$" treatments, with average head weights of 259.0 and 254.1 grams, respectively, are the most effective, showing no significant difference from each other, as they belong to the same statistical group (A). On the other hand, treatments with higher Ferox concentrations, particularly "Fertigation ferox 2 ml $L^{-1}$" and "Foliar ferox 2 ml $L^{-1}$," yielded significantly lower head weights, with averages of 161.6g and 29.1g, respectively, falling into groups B and C, which are statistically distinct from the higher-performing treatments. The control group, with a mean weight of 91.7g, also stands out as significantly lower than most treatment groups, falling into group C, highlighting the positive impact of Ferox treatments compared to no treatment at all. From an economic perspective, the decline in Broccoli head weight with higher concentrations of Ferox, especially above 1.5 ml $L^{-1}$, could be indicative of diminishing returns at these higher doses, where the adverse effects on growth outweigh the benefits, leading to reduced productivity. This pattern suggests that there might be an optimal range for Ferox application, where the productivity (total weight of heads) is maximized without the negative impact seen at higher concentrations, underscoring the importance of calibrating agricultural treatments to achieve the best economic outcomes [19]. The significant effect of the treatments, especially at lower concentrations, can potentially improve agricultural productivity, providing an economic benefit by increasing yields without overusing resources.

**Table (7):** Analysis of variance of total weight of heads (g) of Broccoli (*Brassica oleracea*)

| Source | DF | Sum of squares | Mean squares | F | Pr > F |
|---|---|---|---|---|---|
| **Model** | 11 | 652564.4 | 59324.0 | 24.2 | < 0.0001 |
| **Error** | 10 | 24479.6 | 2448.0 | | |
| **Corrected Total** | 21 | 677044.0 | | | |
| ***Computed against model Y=0*** | | | | | |

**Table (8):** Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of weight of heads (g) of Broccoli (*Brassica oleracea*)

| Applications | LS means | Standard error | Groups | | |
|---|---|---|---|---|---|
| **Foliar ferox 1ml $L^{-1}$** | 259.0 | 28.6 | A | | |
| **Fertigation ferox 1ml $L^{-1}$** | 254.1 | 51.7 | A | | |
| **Fertigation ferox 1ml $L^{-1}$** | 209.0 | 35.8 | A | | |
| **Foliar ferox 1.5 ml $L^{-1}$** | 189.0 | 28.6 | A | B | |
| **Fertigation ferox 1.5 ml $L^{-1}$** | 183.1 | 36.1 | A | B | |
| **Fertigation ferox 2 ml $L^{-1}$** | 161.6 | 36.1 | A | B | |
| **Fertigation ferox 1.5 ml $L^{-1}$** | 151.7 | 52.5 | A | B | C |
| **Fertigation ferox 2 ml $L^{-1}$** | 133.7 | 52.5 | A | B | C |
| **Control** | 91.7 | 28.6 | | B | C |
| **Foliar ferox 2 ml $L^{-1}$** | 29.1 | 14.9 | | | C |

## Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of shoots weight (g) of Broccoli (*Brassica oleracea*)

The results of Table 9 on the shoots weight (g) of Broccoli (*Brassica oleracea*) show significant variation across different categories of fertigation and foliar treatments with Ferox at various concentrations. The confidence interval at 95% suggests that there are notable differences in the shoot weight for several treatments, specifically between the highest and lowest concentrations of Ferox used. The *Fertigation ferox 1 ml $L^{-1}$* group (499.03 g) displays the highest weight, significantly higher than the others, including *Foliar ferox 1 ml L-1* (466.33 g) and *Foliar ferox 1.5 ml $L^{-1}$* (392.67 g), both of which are also statistically significant (Group A). However, as the concentration increases beyond 1.5 ml L-1 in fertigation and foliar treatments, a marked decline in shoot weight is observed. For instance, *Fertigation ferox 1.5 ml $L^{-1}$* (308.47 g) and *Fertigation ferox 2 ml $L^{-1}$* (254.47 g) show reduced weights and are categorized in Group B, which suggests that these higher concentrations are less effective in promoting shoot growth, likely due to potential toxicity or nutrient imbalance. The control group (201.33 g) and further increased fertigation treatments like *Fertigation ferox 2 ml $L^{-1}$* (172.07 g) show an even steeper decline, indicating a negative trend with the concentration increase. The *Foliar ferox 2 ml $L^{-1}$* (78.03 g) group, with the lowest shoot weight, exhibits the most significant decline, signaling that high foliar application concentrations may have a detrimental impact on plant growth, possibly due to oversaturation or inefficient absorption by the plants. These trends in the shoot weight data strongly correlate with productivity, as the decrease in shoot weight with higher concentrations of Ferox implies a potential for diminishing returns in terms of economic output. From an economic perspective, applying Ferox at higher concentrations might result in less efficient resource use, where the input cost increases without a corresponding increase in crop yield, thereby reducing overall agricultural productivity. Therefore, optimizing Ferox concentration for both fertigation and foliar applications could help maximize productivity while minimizing unnecessary costs, supporting better economic returns for producers [20]. The results can be linked to broader agricultural productivity economics, where choosing the right dosage is crucial for achieving cost-effective, high-yield crop production [21].

**Table (9):** Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of shoots weight (g) of Broccoli (*Brassica oleracea*)

| Category | LS means | Standard error | Groups | |
|---|---|---|---|---|
| **Fertigation ferox 1ml $L^{-1}$** | 499.03 | 146.29 | A | |
| **Foliar ferox 1ml $L^{-1}$** | 466.33 | 80.88 | A | |
| **Foliar ferox 1.5 ml $L^{-1}$** | 392.67 | 80.88 | A | |
| **Fertigation ferox 1ml $L^{-1}$** | 375.98 | 101.27 | A | |
| **Fertigation ferox 1.5 ml $L^{-1}$** | 308.47 | 102.17 | A | B |
| **Fertigation ferox 2 ml $L^{-1}$** | 254.47 | 102.17 | A | B |
| **Fertigation ferox 1.5 ml $L^{-1}$** | 234.07 | 148.76 | A | B |
| **Control** | 201.33 | 80.88 | A | B |
| **Fertigation ferox 2 ml $L^{-1}$** | 172.07 | 148.76 | A | B |
| **Foliar ferox 2 ml $L^{-1}$** | 78.03 | 42.15 | | B |

**Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of dry matter (g) of Broccoli (*Brassica oleracea*)**

The results from the table analyzing the dry matter (g) of Broccoli under different fertilization treatments show significant variation across categories based on a 95% confidence interval. The LS means for the different treatments highlight that the highest dry matter content was achieved with the "Fertigation ferox 1 ml $L^{-1}$" treatment, at 134.74 g, which stands as the top performer, closely followed by "Foliar ferox 1 ml $L^{-1}$" at 125.91 g. However, all treatments in the higher concentration groups (Fertigation ferox 2 ml L-1 and Foliar ferox 2 ml $L^{-1}$) exhibited a decline in dry matter, with the lowest value of 21.07 g observed in the "Foliar ferox 2 ml $L^{-1}$" group. The significant differences between the groups (indicated by the letters A and B in the table) suggest that the higher concentrations, particularly in the fertigation method, lead to decreased productivity in terms of dry matter content. This decline is likely due to the excess nutrients or imbalances in nutrient uptake, which could lead to nutrient toxicity or reduced absorption efficiency at higher concentrations, as seen in the treatments with 1.5- and 2-ml $L^{-1}$ concentrations. In terms of economic effects, the higher-performing fertigation methods (1 ml $L^{-1}$) lead to greater productivity, potentially increasing yield and overall economic returns by optimizing nutrient usage [22]. On the other hand, over-application of fertilizers (as seen with 1.5- and 2-ml $L^{-1}$ concentrations) may not only reduce crop output but also result in economic inefficiencies due to increased costs without proportional returns. Overall, this data reflects the critical importance of precision in fertilizer application to balance productivity and cost-effectiveness in agricultural systems. The trend observed in the data points to an optimal concentration for fertigation at 1 ml $L^{-1}$, showing a clear relationship between higher productivity and balanced fertilizer levels, which can enhance economic outcomes by maximizing yield while minimizing excessive input costs [23].

**Table (10):** Applications / Duncan / Analysis of the differences between the categories with a confidence interval of 95% of dry matter (g) of Broccoli (*Brassica oleracea*)

| Category | LS means | Standard error | Groups | |
|---|---|---|---|---|
| **Fertigation ferox 1ml $L^{-1}$** | 134.74 | 39.50 | A | |
| **Foliar ferox 1ml$L^{-1}$** | 125.91 | 21.84 | A | |
| **Foliar ferox 1.5 ml $L^{-1}$** | 106.02 | 21.84 | A | |
| **Fertigation ferox 1ml $L^{-1}$** | 101.52 | 27.34 | A | |
| **Fertigation ferox 1.5 ml L-1** | 83.29 | 27.59 | A | B |
| **Fertigation ferox 2 ml $L^{-1}$** | 68.71 | 27.59 | A | B |
| **Fertigation ferox 1.5 ml $L^{-1}$** | 63.20 | 40.16 | A | B |
| **Control** | 54.36 | 21.84 | A | B |
| **Fertigation ferox 2 ml $L^{-1}$** | 46.46 | 40.16 | A | B |
| **Foliar ferox 2 ml $L^{-1}$** | 21.07 | 11.38 | | B |

In conclusion, the results of this study clearly demonstrate the significant impact of Ferox application methods and concentrations on the growth, productivity, and economic outcomes of Broccoli (*Brassica oleracea*). Lower concentrations of Ferox (1 ml $L^{-1}$), whether applied through foliar feeding or fertigation, consistently resulted in improved plant health, including higher plant height, chlorophyll content, number of leaves, stem diameter, head weight, shoot weight, and dry matter content. These treatments show potential for maximizing Broccoli yield and minimizing costs by avoiding over-application, which leads to diminishing returns. On the other hand, higher concentrations of Ferox (1.5 ml $L^{-1}$ and above) resulted in negative effects, such as reduced plant growth, lower chlorophyll levels, and smaller heads and stems, likely due to nutrient imbalances or toxicity. These findings highlight the importance of precision in fertilizer application for optimizing productivity and ensuring sustainable agricultural practices.

From an economic perspective, the study underscores the value of optimizing Ferox concentration to achieve cost-effective and higher-yielding crops. By targeting the most effective concentrations (1 ml $L^{-1}$), agricultural producers can enhance their crop output while controlling input costs. Excessive concentrations, particularly in the higher ranges, not only fail to improve productivity but also increase input costs without a corresponding increase in crop yield, ultimately reducing economic returns. These results align with broader agricultural research emphasizing the need for balanced fertilization strategies to improve productivity, minimize resource wastage, and maximize profitability in commercial farming.

The study demonstrates that lower concentrations of Ferox (1 ml $L^{-1}$) in both foliar and fertigation applications provide the best results across multiple growth parameters, including plant height, number of leaves, chlorophyll content, stem diameter, head weight, shoot weight, and dry matter content. Using higher concentrations (1.5 ml $L^{-1}$ and 2 ml $L^{-1}$) leads to diminished growth and productivity. Therefore, agricultural producers should prioritize lower concentrations for optimal growth and reduced nutrient imbalances. As well as, both foliar and fertigation methods at 1 ml $L^{-1}$ are equally effective in enhancing plant growth. The lack of significant difference between these methods at this concentration suggests flexibility for growers in choosing the most suitable application technique, depending on their operational needs. This flexibility could help maximize efficiency in production. Additionally, the results highlight that increasing Ferox concentrations beyond 1 ml $L^{-1}$ leads to adverse effects such as reduced chlorophyll content, smaller stem diameters, and lower shoot weights. Over-application could lead to nutrient toxicity and reduced yield, negatively impacting economic returns. Growers should carefully calibrate application rates to avoid excess fertilizer use and associated cost inefficiencies. Moreover, excessive use of higher Ferox concentrations increases input costs without a corresponding increase in crop yield. For economic sustainability, producers should focus on the application of Ferox at optimal levels (1 ml $L^{-1}$) to improve yield while minimizing input costs, thereby achieving better cost-effectiveness in large-scale commercial farming. Finally, the research indicates that Ferox concentrations above 1 ml $L^{-1}$ result in diminishing returns, affecting the overall productivity of Broccoli (*Brassica oleracea*). This finding underscores the importance of determining the optimal concentration range for maximizing both growth and economic benefits. Growers should adopt a balanced approach to fertilization that optimizes resource use and enhances productivity without compromising the quality of the crop.

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