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Effects of micronutrients and timing of application on the agronomic and yield characteristics of cucumber (*Cucumis sativus*)

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ABSTRACT

Cucumber (*Cucumis sativus* L.) is the most cultivated vegetable worldwide due to its high nutritional value and versatility. As a major economic crop, it plays a critical role in human diets and numerous industries. A key challenge in cucumber production is flower abortion, which, similar to sweet pepper, can be very high, with rates reaching 70–80% of all flowers, substantially impacting yield and fruit quality. This study evaluated the effects of different types of micronutrients and it's timing of application on the agronomic and yield characteristics of cucumber cultivated in South Cotabato, Philippines. Conducted from February to April 2025 under a factorial Randomized Complete Block Design with three replicates, the research measured key parameters including growth, productivity, yield, fruit quality parameters, and a cost-return analysis. Zinc treatments when applied during vegetative stage, resulted in the greatest number of pistillate flowers (25.17) and fruits per plant (11.53), as well as the highest production of graded fruits. Both Boron and Zinc alone minimized flower abscission rates (~53%) and maintained fruit set rates. Boron excelled in increasing total fruit weight (5.32 kg) and marketable fruit weight (3.62 kg). Zinc also enhanced fruit quality through increased TSS (8.82 °Brix). These results demonstrate that micronutrient selection and application timing critically influence cucumber production outcomes. The findings suggest split application strategy integrating Zinc and Boron timed to balance vegetative growth and reproductive success. For future studies, investigations should elucidate the physiological and molecular mechanisms by which micronutrients modulate flower abscission and setting in cucumber.

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INTRODUCTION

Food security continues to be a concern at an alarming rate, especially in low-income countries. High prices of domestic foods, trade conflicts, and climate change are generally the drivers of food insecurity. According to FAO (1996), food security is a situation where safe, healthy, and nutritious food is readily available, accessible, and affordable at all times. However, with these conflicting issues, the stability of the food supply is at risk. The Philippine government acknowledges that the nation's food security is significantly dependent on its agricultural sector (Tiongco and Francisco, 2011); therefore, agricultural development must be implemented to empower local farmers to access market opportunities at local, regional, and national levels.

Cucumber (*Cucumis sativus* L.) is an extensively cultivated vegetable crop, possessing significant nutritional value and diversity in applications. Cucumber is a crucial, commercially significant crop worldwide, essential to both human nutrition and other sectors (Hilli *et al.*, 2010; Samapika Dalai *et al.*, 2015). The diverse applications of the crop underscore its growing importance in agriculture, nutrition, and industrial sectors. The flowering patterns of cucurbits, particularly *Cucumis sativus* L., concerning flower abortion, represent a critical issue that can substantially impact output and fruit quality. Similar to sweet pepper, the abortion rate of cucumber flowers and fruits is elevated, potentially reaching 70-80% of all flowers (Wubs *et al.*, 2009).

Fruit sets have a pronounced cyclical pattern, characterized by intervals of elevated fruit sets alternating with intervals of minimal fruit sets. Consequently, it results in a comparatively volatile market supply and product pricing (Chen *et al.*, 2022). As stated by the PSA (2021), cucumber production in the Philippines was consistently unstable from 2019 to 2021. Due to the adaptability of the cucumber fruit, its production instability leads to an increase in importation from February to March 2024, as reported by Volza's Philippines Import Data (2025).

Micronutrients such as boron (B) and zinc (Zn) have been identified as essential elements that play a crucial role in reproduction. Many things affect flower development and retention. Comprehending the influence of these micronutrients on floral abortion can help optimize cucumber production. Following the Green Revolution, the rise in crop yield per unit area has led to a significant depletion of phytoavailable micronutrients in the soil, alongside a diminished emphasis on micronutrient fertilization. Nonetheless, there is no specific evidence concerning the impact of zinc and boron (Kumar *et al.*, 2019). Micronutrient insufficiency now constrains crop growth in numerous agricultural areas globally (Khoshgoftarmanesh *et al.*, 2010). Thus, the interaction between boron and zinc is noteworthy.

Both micronutrients are associated with regulating physiological processes that influence flower development. These are crucial for optimal reproductive performance in cucumbers. Proper nutrient management is essential in cucumber cultivation due to its significant impact on pollen viability, hormone regulation, and overall plant health. Crop responses to these applications have been recorded for chickpea (*Cicer arietinum* L.) (Ceyhan *et al.*, 2007), Brussels sprout cultivars (*Brassica oleracea* L. Gemmifera) (Turan *et al.*, 2008), and wheat (*Triticum durum* Desf.) (Soylu *et al.*, 2004). Nonetheless, there is still a limited understanding of the requirements for cucumber. The boron requirements in vegetables typically exceed those of other crops (Dursun *et al.*, 2010).

This study aims to assess the impact of boron, zinc, and their combined foliar application on the productivity and quality of cucumbers. Aside from evaluating these micronutrients, this research also aims to assess the optimal timing of their application to minimize or preferably prevent flower abscission in cucumbers resulting from micronutrient deficiencies.

MATERIALS AND METHODS

Experimental design and data analysis

The research was conducted using a factorial Randomized Complete Block Design (RCBD) with eight (8) plots, each replicated three (3) times (Shnain *et al.*, 2014). Each plot comprised 28 crops, spaced 0.50 m apart inside the row and 0.70 m between adjacent furrows. Factors were as follows, with their corresponding treatments: T1 - No Application during Vegetative Stage, T2 - No Application during Reproductive Stage, T3 - 1.25g B/L of Water applied during Vegetative Stage, T4 - 1.25g B/ L of Water applied during Reproductive Stage, T5 - 1.25g Zn/L of Water applied during Vegetative Stage, T6 - 1.25g Zn/L of Water applied during Reproductive Stage, T7 - 1.25 g B + 1.25g Zn/L of Water applied during Vegetative Stage, T8 - 1.25 g B + 1.25g Zn/L of Water applied during Reproductive Stage (Fig. 1).

Fig. 1. Documentation; A) Field lay-outing and staking; B) Pole establishment; C) Micronutrient preparation; D) Micronutrient application; E) Gathering of fruit firmness; F) Gathering of fruit diameter; G) First cycle of cucumber fruit harvesting

Collection of soil sample and analysis

A systematic collection of soil samples from the experimental area was conducted using a spade, employing the zigzag method. A one-kilogram soil sample was meticulously cleaned and ground into a fine powder to remove extraneous materials. The soil sample was subsequently placed on a straw sack to promote air drying over seven (7) days. The soil samples were dispatched for analysis to the Bureau of Soil and Water Management (BSWM) in General Santos City, South Cotabato. The soil analysis focused on determining the NPK content, which served as the foundation for the fertilizer recommendations in the study (DA–BSWM, 2020).

Land preparation

The experimental area was prepared at least one (1) month before seed sowing, allowing weed seeds to germinate (DA-Cagayan Valley, 2018). This was done using different tillage equipment. The experimental area was thoroughly prepared by clearing and removing unwanted vegetation using a shovel and a bolo. The weeds and other vegetation in the area were cut, and other stumps were removed. The area was leveled using a garden rake.

Lay-outing and staking

The experimental area was laid out three (3) days before seed sowing with the use of steel tape and twine. Staking was done using bamboo sticks to maintain proper planting distance during seed sowing (Utobo *et al.*, 2010).

Fertilizer application

The synthetic fertilizer was applied through a basal application at the rate recommended by the soil analysis. On the day of seed sowing, Amophos (16-20-0), Urea (46-0-0), and Muriate of Potash (0-0-60) were used as basal fertilizer with a rate per hill of 2.6 g, 2.4 g, and 10.5 g, respectively. Fertilizers were applied through split application, a month after seed sowing, and from the basal application (DA-Cagayan Valley RFO 2, 2018).

Seed sowing

The cucumber seeds were sown at the rate of two (2) seeds per hill and covered with fine soil (PhilRice, 2010) to facilitate ease of seedling emergence. Watering was also administered right after to provide adequate soil moisture for germination.

Trellising

The trellis was installed in the field soon after emergence. The trellis was primarily constructed using bamboo poles with twines for vines to grow, reaching a height of 2 meters. Cucumber vines were trained on trellises whenever necessary to keep fruits and growing vines off the ground and to prevent disease infestation (DTI, 2012).

Thinning

The thinning was done when the cucumber seedlings obtained at least three (3) leaves. One (1) vigorous seedling of cucumber per hill was maintained (Utobo *et al.*, 2010). This was done to prevent competition for nutrients, sunlight, space, and water.

Preparation of micronutrients

The Boron (B) and Zinc (Zn) were purchased from Arneth Agri-Marts. Pure boron fertilizer was used as the B source, and zinc sulphate hydrate was sourced for the Zn. The B and Zn were diluted with unchlorinated water in a pale prior to sprayer loading to ensure uniform dilution following a 1.25g B and 1.25g Zn per L of water concentration. For the combined treatments, 1.25 g/L water of B and 1.25 g/L water of Zn were diluted with unchlorinated water prior to sprayer loading, as recommended by Shnain *et al.* (2014).

Application of treatments

The B and Zn concentrations were applied to the experimental units through foliar spraying using a single 10L trigger sprayer for each treatment, ensuring a uniform spraying rate. For the treatment application during the vegetative stage of plant development, treatments were applied seven (7) days after thinning, following a 15-day interval. In the first treatment application, a concentration of 2 Liters was utilized per plot.

For the treatment application during the reproductive stage of plant development, treatments were applied at the beginning of flowering (Sabri *et al.*, 2021) with a 15-day interval until fruit setting, as further adopted in the study by Meriño-Gergichevich *et al.* (2021). Treatment concentrations per plot were increased in the succeeding treatment applications to ensure uniform application of the treatments on the plant foliage. There were a total of three (3) treatment applications for the Factor A (Vegetative Stage) and two (2) treatment applications for the Factor B (Reproductive Stage).

Care and management

Watering was performed twice a week during the vegetative stage of the cucumber plants to maintain a 60% soil moisture level (Bahloul, 2021). This was also done whenever necessary to supply sufficient water, which is essential for optimal plant growth. Moreover, off-barring and hilling up were performed at 20 days after emergence to suppress weed growth (DTI, 2012) or were done as often as necessary when unwanted plants and vegetation appeared.

Furthermore, pests and diseases were monitored on a daily basis. Following seed sowing, the Abamectin 1.8EC formulation was applied to the experimental plots to avert seed non-viability due to insect damage. After administering a dosage of 2 tablespoons per 16 liters of water, the same insecticide was utilized to manage leaf miners and aphids noted during the process. The plants were treated with pesticides and fungicides every week until the initial flowering stage (Giban and Salas, 2023).

Harvesting

Harvesting was conducted 38-45 days after emergence and was performed every other day or as needed (DTI, 2012). There were three (3) cycles of harvesting, and fruits were harvested at full maturity or when fruits were dark green in color, already in ideal marketable size, and were already appearing waxy or glossy on the surface.

Data gathered

Growth parameters

Number of days to staminate and pistillate flowering: The number of days to staminate and pistillate flowering was recorded by counting the number of days from seed sowing until 50% of the ten (10) sample plants per plot produced their first open flower (Giban and Salas, 2023; Hamayoun *et al.*, 2018). Results were expressed in day/s.

Number of primary branches per plant: The number of primary branches per plant was counted when the sample plants started to produce their first female flowers. All the primary branches were accounted for in this parameter (Alotaibi *et al.*, 2024). Results were expressed in piece/s.

Production parameters

Number of pistillate flowers: The number of pistillate flowers per plant was properly counted and recorded. The total number of fully opened flowers from sample plants was summed up and then divided by ten to obtain the average number of flowers per plant (Giban and Salas, 2023). Observations and counts of samples were made daily during the first three (3) days after anthesis (Palupi *et al.*, 2010). Results were expressed in piece/s.

Number of fruits: The number of fruits per plant was counted correctly and recorded. The total number of fruits throughout the growing season was summed up and then divided by ten to obtain the average number per plant (Parkash *et al.*, 2021). Results were expressed in piece/s.

Abscission rate: The flower abscission rate was recorded by monitoring the experimental units for three (3) successive days after anthesis. It was calculated by dividing the difference between the number of flowers (nf) and the number of fruits (NF) by the number of flowers (nf) and multiplying by 100. This was computed using the formula of Jean *et al.* (2015).

$$FLAR = \frac{nf - NF}{nf} \times 100$$

Fruit set rate: The fruit set rate was calculated by gathering data on the number of pollinated flowers and the number of fruits set. The number of fruit sets was divided by the number of pollinated flowers multiplied by 100 to obtain the percentage fruit set rate, as shown in the formula below, adopted from Alotaibi *et al.* (2024).

$$Fruit\ Set\ \% = \frac{Total\ Number\ of\ Fruit\ Set}{Total\ Number\ of\ Flowers} \times 100$$

Yield parameters

Grading of fruits: The grading of fruits was recorded by classifying all the harvested fruits from the sample plants into Extra Class, Class I, and Class II according to the standards and tolerances set by the Philippine National Standards (PNS)-BAFPS 62-2008.

Length of fruits: The length of fruits was obtained by randomly selecting a total of 10 sample fruits per experimental plot during the third harvesting (Parkash *et al.*, 2021). This was done by using a measuring tape placed vertically on the fruit body. The average length of fruit was used to analyze this parameter, and the results were expressed in centimeter/s.

Diameter of fruits: The diameter of the fruits was measured using a Vernier caliper (Rashwan *et al.*, 2024). The average diameter of the fruit was utilized to assess this metric, with findings represented in millimeters per second (mm/s).

Weight (kg) of fruits per plant: During each harvest cycle, the weight of fruits per plant was measured and documented. Following the final cycle, the total weights of the fruits were calculated and subsequently divided by ten to determine the average fresh weight of fruits per plant (Alotaibi *et al.*, 2024).

Weight of marketable fruits per plant: The weight of marketable fruits was assessed by weighing all classified marketable fruits from the ten sample plants that fulfilled the criteria outlined by ASEAN Stan 16: 2010. The cumulative weight of all classified marketable fruits from each harvest cycle was documented (Hamayoun *et al.*, 2018). The results were presented in pieces.

Weight of non-marketable fruits per plant: The weight of marketable fruits was evaluated by weighing all classified marketable fruits from the ten sample plants that met the criteria outlined by ASEAN Stan 16: 2010. The total weight of all classified marketable fruits from each harvest cycle was recorded (Hamayoun *et al.*, 2018). The results were presented in pieces.

Yield (ton/ha): The yield (ton/ha) was determined by weighing all harvested fruits from ten (10) sample plants per plot across all harvest cycles. The yield was calculated using the formula outlined below (Amarullah, 2021):

$$Yield\ (ton\ per\ hectare) = \frac{yield\ per\ plot(kg)x\ 10{,}000\ m^2}{(net\ plot\ size)x\ 1000(kg\ per\ ton)}$$

Fruit quality parameters

Ten randomly selected freshly harvested green cucumber fruits at market stage were chosen from each experimental plot to assess fruit quality parameters (Bahloul, 2021). The selected fruits exhibited uniformity in size and color and were free from blemishes and fungal infections. The fruits were washed with tap water and air-dried for 10 minutes before data collection.

Total soluble solids (TSS): The total soluble solids (TSS) were measured using a hand-held refractometer. Following the measurement of peel thickness, the sample fruits were bisected at the middle and manually squeezed to collect their juice (Kahramanoğlu and Usanmaz, 2019). One (1) to two (2) drops of clear juice were applied to the prism for TSS measurement. Results were presented in degree Brix (°Brix).

Fruit firmness: The fruit firmness was measured using a handheld Penetrometer (Bahloul, 2021). Each sample fruit was measured twice for firmness, on opposite sides of the fruit, to record accurate data on firmness. This was done during the third harvest of the study to ensure that all experimental units in each plot had already produced their fruits. Results were expressed in kg/cm^3.

Cost and return analysis: The Return on Investment (ROI) was calculated utilizing a basic economic study. The production cost was determined using the current prices of agricultural inputs and labor in the neighborhood. The gross income was calculated based on the current price of cucumbers per kilogram. The net income equals the gross income less the production costs, and the return on investment is calculated by dividing the net income by the production costs and multiplying by 100 (Lim, 2024).

$$ROI = \frac{Net\ income}{Total\ cost\ of\ production} x\ 100$$

Statistical data analysis

The data collected in this study were analyzed statistically using Analysis of Variance (ANOVA) following the Randomized Complete Block Design (RCBD) factorial experiment (Ortouste *et al.*, n.d.). The Least Significant Difference (LSD) at a 5% significance level is used to determine differences between means (Giban and Salas, 2023).

RESULTS AND DISCUSSION

Number of days to pistillate flowering

As show in Table 1, the use of any micronutrient proves to have an advantage in inducing early flowering of cucumbers, showcasing comparable results in the usage of Boron (B) and Zinc (Zn), and their combination after the analysis of variance, taking up average days to pistillate flowering of 31.83 days, 31.83 days, and 31.50 days, respectively. The Control plants took 35.00 days before producing pistillate flowers.

Between the two timings of micronutrient application, nutrient application during the vegetative stage shows a superior effect on the days to pistillate flowering, showcasing an average of 30.08 days when compared to the 35.00 average days of plants applied during the reproductive stage. This analysis was further supported by a significant interaction between the two factors, indicating that regardless of the type of micronutrient applied, its application during the vegetative stage of the plants yielded superior effects.

Nandal and Solanki (2021) assert that zinc (Zn) is crucial for flowering and seed formation, as it functions as an enzyme cofactor and facilitates the synthesis of hormones, such as auxin. A deficiency in Zn can delay flowering and reduce flower and seed yield. Boron (B), as described by Shireen *et al.* (2018), plays a crucial role in reproductive development by supporting cell wall synthesis, maintaining membrane integrity, and regulating carbohydrate distribution. A lack of B can disrupt pollen tube growth and flower formation, negatively affecting flowering success. Both nutrients are essential for metabolic and cellular processes related to flowering, and a deficiency in either can result in delayed flowering and reduced yields. B is key for pollen viability and germination, while Zn aids in auxin production, which regulates flower and fruit growth.

Table 1. Number of days to pistillate flowering of cucumber as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	35.00[b]	35.00[a]	35.00[b]
A2. Boron	28.33[a]	35.33[a]	31.83[a]
A3. Zinc	28.67[a]	35.00[a]	31.83[a]
A4. Boron + Zinc	28.33[a]	34.67[a]	31.5[a]
Mean	30.08[a]	35.00[b]	

CV = 2.32%; Means that with common letter superscripts are not substantially different at the 5% level, using the LSD test

Table 2. Number of days to staminate flowering of cucumber as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No Application)	33.00[b]	33.00[a]	33.00[b]
A2. Boron	26.33[a]	33.33[a]	29.83[a]
A3. Zinc	26.67[a]	33.00[a]	29.84[a]
A4. Boron + Zinc	27.00[a]	32.67[a]	29.84[a]
Mean	28.25[a]	33.00[a]	

CV = 2.71%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test

Number of days to staminate flowering

As shown in Table 2, the application of micronutrients significantly accelerated the flowering of cucumber plants. Treatments with Boron (B), Zinc (Zn), and their combination resulted in an average of 29.83, 29.84, and 29.84 days, respectively, until the first staminate flower appeared. This was a notable improvement compared to the control group, which took 33.00 days to flower.

The timing of micronutrient application proved to be a critical factor. Plants that received nutrients during their vegetative stage flowered significantly earlier, with an average of 28.25 days. In contrast, plants treated during the reproductive stage took an average of 33.00 days. This finding was further supported by a significant interaction between the type of micronutrient and the timing of its application. This interaction confirmed that regardless of the specific micronutrient used, applying it during the plant's vegetative stage yielded superior results in promoting early flowering.

Research conducted by Sidhu *et al.* (2020) and Akshata *et al.* (2023) indicated that applying exogenous boron and zinc to cucumber plants resulted in accelerated flowering. This was ascribed to augmented nutritional accessibility, heightened metabolic activity, and improved hormonal balance. This conclusion is corroborated by Singh *et al.* (2025), who indicated that the expedited flowering resulted from the functions of these micronutrients in the synthesis of growth hormones.

Number of primary branches per plant

As shown in Table 3, the utilization of micronutrients significantly influenced the growth of primary branches in cucumber plants. The highest number of branches was recorded in plants treated with a combination of Boron (B) and Zinc (Zn), averaging 3.62 branches. This was succeeded by treatments of Boron (B) alone and Zinc (Zn) alone, yielding averages of 3.37 and 3.28 branches, respectively. The control group exhibited the lowest number of branches, averaging 2.90.

Research has shown that boron and zinc are essential micronutrients that affect plant structure by regulating important physiological and biochemical processes, including primary branching. The study demonstrates that the application of these nutrients to the foliage markedly enhances vegetative development. Boron sprayed at a dosage of 0.8% significantly enhanced the quantity of primary and secondary branches, as well as the fresh and dry weight of plants (Mumivand *et al.*, 2021).

Zinc enhances branching via facilitating enzyme activation, auxin production, and glucose metabolism, which are crucial for meristem function and branch development. Zinc foliar applications enhanced the quantity of primary branches and the dry weight of stems in the same study, indicating its function in promoting structural growth. This study's findings indicate that, irrespective of the micronutrients utilized, they individually and synergistically enhance vegetative branching, hence affecting the plant's photosynthetic efficiency and reproductive capability.

Table 3. Number of primary branches per cucumber plant at 40 days after sowing (DAS) as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	2.90	2.90	2.90^{c}
A2. Boron	3.50	3.23	3.37^{ab}
A3. Zinc	3.17	3.40	3.28^{b}
A4. Boron + Zinc	3.85	3.40	3.62^{a}
Mean ^{ns}	3.36 ^{ns}	3.23 ^{ns}	

CV = 6.89 %; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; ns = not significant

Table 4. Number of pistillate flowers per cucumber plant as applied with different types of micronutrients in varying timing of application, April 2025.

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	21.20^{c}	21.20^{ab}	21.20^{c}
A2. Boron	24.27^{b}	23.33^{a}	23.80^{b}
A3. Zinc	31.40^{a}	18.93^{b}	25.17^{a}
A4. Boron + Zinc	21.93^{bc}	21.67^{a}	21.80^{c}
Mean	24.70^{a}	21.29^{b}	

CV = 6.35 %; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test

Number of pistillate flowers

As shown in Table 4, the treatment of either Boron (B) or Zinc (Zn) individually markedly enhanced the quantity of pistillate flowers on cucumber plants. Of the treatments evaluated, Zinc produced the greatest average flower count at 25.17. The Boron treatment subsequently produced an average of 23.80 flowers. The control plants and those treated with the B + Zn combination exhibited the lowest averages, with 21.20 and 21.80 flowers, respectively.

The timing of the application also played a critical role. Plants that received nutrients during their vegetative stage produced a significantly higher average number of flowers at 24.70, compared to an average of 21.29 flowers for plants treated during the reproductive stage. A significant interaction between the type of micronutrient and the timing of application further confirmed this finding. For the highest number of pistillate flowers, Zinc should be applied during the plant's vegetative stage.

Zinc plays a crucial role in pistillate flower development by regulating reproductive processes, including pollen germination, stigma receptivity, and fertilization (Pandey *et al.*, 2013). The foliar application of zinc, especially during the pre-flowering stage, significantly promotes the development of reproductive structures and enhances seed nutritional quality by increasing seed zinc density, glucose levels, and storage proteins. Zinc's role in hormone biosynthesis, enzyme activation, and gene expression is crucial for reproductive processes, hence ensuring optimal pistillate flower function and effective fertilization. Furthermore, other studies have also proven that moderate concentrations of zinc sulfate, ranging from 0.4% to 2.0%, can significantly improve flowering. For instance, Tayade *et al.* (2018) found that a 0.4% concentration applied early in the growth cycle of tuberose reduced the time to flowering and improved floral quality. These findings were also noted in this study, both in the number of flowers and the days to flower initiation.

Number of fruits

Among the treatments tested in Table 5, Zinc (Zn) resulted in the highest average number of fruits at 11.53. This was followed by the Boron (B) treatment and the Boron (B) + Zinc (Zn) treatment, which yielded an average of 10.94 and 9.97 fruits, respectively. The lowest numbers were observed in the control plants, which had an average of 5.80 fruits.

Table 5. Number of fruits per cucumber plant as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	5.80^{c}	5.80^{c}	5.80^{c}
A2. Boron	11.27^{b}	10.60^{a}	10.94^{b}
A3. Zinc	14.33^{a}	8.73^{b}	11.53^{a}
A4. Boron + Zinc	9.87^{b}	10.07^{ab}	9.97^{b}
Mean	10.32^{a}	8.80^{b}	

CV = 6.35 %; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test

As the timing of the application played a critical role, plants that received nutrients during their vegetative stage produced a significantly higher average number of fruits at 10.32, compared to an average of 8.80 fruits for plants treated during the reproductive stage. A significant interaction between the type of micronutrient and the timing of application further confirmed this finding. For the highest number of fruits, Zinc should be applied during the plant's vegetative stage, as also concluded from the results on the number of pistillate flowers.

Zinc is an essential nutrient that enhances fruit quantity in diverse crops by optimizing physiological and metabolic processes necessary for effective fruit growth and development. Research on cucumbers, strawberries, and fruit trees illustrates their efficacy. It was demonstrated that a foliar application of zinc sulfate markedly enhanced the fruit yield per cucumber vine. This was attributed to zinc's role in promoting vegetative growth, preserving flowers, and regulating hormones, which facilitate enzyme activity, photosynthesis, and carbohydrate synthesis essential for fruit development (Sidhu *et al.,* 2020).

Overall, zinc's contribution to higher fruit numbers is a result of its involvement in hormone regulation, specifically auxin synthesis, enzyme activation, enhanced nutrient uptake, and carbohydrate metabolism (Mumivand *et al.*, 2021). Prompt foliar sprays of moderate dosages throughout the first stages are most efficacious for optimizing fruit quantity and yields across various crops.

Abscission rate

Among the treatments tested as shown in Table 6, the sole use of Boron (B) resulted in the lowest rate of pistillate flower abscission, at an average of 53.15%. Zinc (Zn) also significantly reduced the rate, showing a comparable result of 53.97%. The combined B + Zn treatment followed with an average rate of 55.49%. The control plants had the highest rate of flower abscission, at an average of 71.99%.

In line with the study findings, boron is essential for minimizing flower drop by supporting reproductive processes and regulating carbohydrate metabolism. Foliar boron applications have been found to significantly reduce flower abscission in crops such as tomatoes by strengthening floral organs, promoting pollen tube development, and ensuring successful fertilization (Luxmi *et al.*, 2024). When boron is lacking, sugar transport and energy supply to flowers are disrupted, resulting in poor pollen tube growth and increased flower loss. Proper boron nutrition stabilizes cell walls and membranes in floral tissues, maintaining their functionality during critical reproductive phases and thereby diminishing the likelihood of premature flower and fruit abscission.

Table 6. Abscission rate (%) of cucumber as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	71.99	71.99	71.99^{a}
A2. Boron	51.82	54.48	53.15^{c}
A3. Zinc	54.16	53.78	53.97^{bc}
A4. Boron + Zinc	54.72	56.25	55.49^{b}
Means ^{ns}	58.17^{ns}	59.13^{ns}	

CV = 2.28 %; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; ^{ns} = not significant

Fruit set rate

Among the treatments tested, shown in Table 7, the sole use of Boron (B) resulted in the highest fruit set rate, which refers to the direct development of actual cucumber fruit for harvesting, at an average of 47.06%. However, Zinc (Zn) also showed a significant sustained increase in the fruit set rate, yielding a comparable result of 46.03%. The combined B + Zn treatment followed with an average rate of 44.51%. The control plants had the lowest fruit setting rate, averaging 28.01%.

The method of micronutrient application is a key factor contributing to the significant results obtained in this study. Applying zinc as a foliar spray, which was adapted by the study, has a notable impact on fruit production in cucurbit crops, primarily by enhancing flower retention, fruit set, and overall yield. Additional research on the individual and synergistic effects of boron and zinc on fruit setting has revealed their essential contributions to enhancing initial fruit setting and retention, while minimizing fruit abscission in diverse crops. A study on Kinnow mandarins demonstrated that foliar applications of zinc sulfate, boric acid, and potassium sulfate, both individually and in combination, significantly enhanced vegetative growth and fruit characteristics, including improved initial fruit set and retention (Luxmi *et al.*, 2024). B was essential for preserving cell wall integrity, facilitating pollen tube development and nutrient transport, hence enhancing fruit set and mitigating physiological problems such as fruit cracking. However, in this study's findings, the sole use of B obtained the highest fruit set rate, with a comparable result in the sole use of Zn.

Certain research indicates that zinc (Zn) is less efficacious than boron (B) for nut set, attributable to variations in nutrient mobility, interaction effects, and physiological functions during fruit development. Boron is recognized for its vital roles in pollen germination, pollen tube development, and maintaining cell wall integrity, all of which are crucial for successful fertilization and efficient fruit set. Zinc affects enzyme activation, hormone synthesis (including auxins), and overall plant metabolism; however, it exhibits limited mobility within the plant and tends to accumulate primarily in leaves rather than in reproductive tissues, unless it is combined with boron (Meriño-Gergichevich *et al.*, 2021; Vera-Maldonado *et al.*, 2024). The extremely mobile nature of boron in the xylem facilitates direct transfer to reproductive tissues, rendering it essential throughout the crucial phases of nut formation and fruit set.

Table 7. Fruit set rate (%) of cucumber as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	28.01	28.01	28.01^{c}
A2. Boron	48.59	45.52	47.06^{a}
A3. Zinc	45.84	46.22	46.03^{ab}
A4. Boron + Zinc	45.28	43.75	44.51^{b}
Mean ^{ns}	41.93 ^{ns}	40.86 ^{ns}	

CV = 3.54 %; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; ^{ns} = not significant

Grading of fruits – extra class

Among the micronutrient treatments, shown in Table 8, Zinc (Zn) proved to have a superior effect on producing Extra Class graded fruits, with an average of 8.17 fruits per plant. The use of Boron (B) and the combined B + Zn treatment yielded comparable results of 5.59 and 5.75 fruits, respectively. The control plants produced the fewest Extra Class-graded fruits, with an average of 2.00. The investigation revealed a substantial interaction between the type of micronutrient utilized and the timing of its application. During the vegetative phase, Zn most efficiently yielded Extra Class fruits. During the reproductive phase, the simultaneous application of B + Zn and the exclusive application of Zn yielded similar outcomes, with averages of 7.33 and 6.22 Extra Class fruits, respectively.

Zinc exhibits restricted mobility in soil, hence diminishing the efficacy of soil treatments. Foliar zinc application significantly improved plant height, fruit size, number of fruits per plant, and overall fruit output in guava (Arshad and Ali, 2016). A zinc foliar spray at the ideal dose of 0.5% was found to enhance fruit quality metrics, including vitamin C content and total soluble solids. This study demonstrates that zinc biofortification through foliar application can boost citrus productivity and fruit quality, especially when soil zinc levels are below critical limits. Moreover, it was also noted that higher or lower zinc concentrations were less beneficial. Although the effect is dependent on the initial zinc availability in the soil, foliar zinc raises the amount of chlorophyll and vitamin C (Bhantana *et al.*, 2022).

Furthermore, in contrast to boron application, foliar zinc sulfate application in cucumbers led to noticeably higher zinc uptake and related improvements in growth and fruit quality. Zinc administration increased fruit weight and volume. Boron treatment enhanced total soluble solids (TSS) and other quality indicators, although zinc was more effective in mitigating physiological weight loss and prolonging shelf life. Quantitatively, zinc treatments had a greater impact on morphological and physiological characteristics than boron treatments (Singh *et al.*, 2025).

Accordingly, zinc uptake in cucumber fruits under foliar treatment protocols enhances yield and improves quality more than boron. Zinc has an advantage in improving the quality of cucumber fruit due to its role in retaining chlorophyll, extending shelf life, and minimizing fruit drop. Increased fruit size and number, which are important markers of high-quality fruit, are also a result of the noticeable improvements in vegetative development and reproductive parameters (Haleema *et al.*, 2018). These results provide important new insights into nutrient management techniques that prioritize zinc for optimal fruit quality and yield in cucumber farming.

Table 8. Grading of fruits – extra class per cucumber plant as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	2.00[d]	2.00[c]	2.00[c]
A2. Boron	5.67[b]	5.50[b]	5.59[b]
A3. Zinc	10.11[a]	6.22[ab]	8.17[a]
A4. Boron + Zinc	4.17[c]	7.33[a]	5.75[b]
Mean [ns]	5.49 [ns]	5.26 [ns]	

CV = 12.13%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; [ns] = not significant

Grading of fruits – class I

Among the micronutrient treatments, as shown in Table 9, Zinc (Zn) proved to have a superior effect on producing Class I graded fruits, with an average of 3.42 fruits per plant. The use of Boron (B) and the combined B + Zn treatment yielded comparable results of 2.76 and 2.75 fruits, respectively. The control plants produced the fewest Class I graded fruits, with an average of 1.53.

The investigation revealed a substantial interaction between the type of micronutrient used and the timing of its application. During the vegetative stage, the combined use of Zn and B yielded comparable results, with an average of 3.50 fruits per plant. On the other hand, during the reproductive stage, the sole use of B and Zn produced comparable results, with averages of 3.44 and 3.33 Class I fruits, respectively.

As indicated in the preceding table discussion, Zn exhibits a superior effect on the production of quality fruits compared to B. It was determined that the administration of Zn or the simultaneous usage of B and Zn during the vegetative stage of the plants resulted in an increased yield of Class I cucumber fruits. Meriño-Gergichevich *et al.* (2021) assert that optimal timing and dosage of foliar zinc (Zn) application are essential for enhancing the yield of quality fruits. Research indicates that applying zinc to foliage before anthesis is the most efficacious method for enhancing fruit set, development, and overall quality in crops such as citrus and grapes. This timing is optimal since it coincides with elevated levels of photosynthesis and sugar metabolism in the plant, both of which are augmented by zinc through its support of essential enzymes and plant hormone synthesis.

The protocol must be modified according to the particular crop and environmental circumstances. Foliar treatments are essential in soils deficient in zinc, as they offer a rapid and effective method to enhance the zinc content of the fruit, hence boosting its internal and external quality. The combination of zinc with additional micronutrients, such as boron, can produce a synergistic effect, enhancing both nutritional absorption and fruit quality. A good foliar zinc protocol is a data-driven strategy that meticulously balances concentration, timing, formulation, and frequency to achieve the high criteria of quality fruit production (Xie *et al.*, 2020).

Table 9. Grading of fruits – class I per cucumber plant as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	1.53[c]	1.53[c]	1.53[c]
A2. Boron	2.07[b]	3.44[a]	2.76[b]
A3. Zinc	3.50[a]	3.33[a]	3.42[a]
A4. Boron + Zinc	3.50[a]	2.00[b]	2.75[b]
Mean [ns]	2.65 [ns]	2.58 [ns]	

CV = 9.65%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; [ns =] not significant

Table 10. Grading of fruits – class II per cucumber plant as applied with different types of micronutrients in varying timing of application, April 2025

Types Of Micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	1.00[c]	1.00[c]	1.00[c]
A2. Boron	1.93[c]	3.78[a]	2.86[b]
A3. Zinc	6.33[a]	2.33[b]	4.33[a]
A4. Boron + Zinc	3.17[b]	2.50[b]	2.84[b]
Mean	3.11[a]	2.40[b]	

CV = 9.65%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; [ns] = not significant

Grading of fruits – class II

Among the micronutrients tested, as shown in Table 10, Zinc (Zn) resulted in the highest average number of Class II graded fruits at 4.33. This was followed by the Boron (B) treatment and the Boron (B) + Zinc (Zn) treatment, which yielded an average of 2.86 and 2.84 fruits, respectively. The lowest numbers were observed in the control plants, which had an average of 1.00 fruits. In terms of the Class II fruit grading, plants that received nutrients during their vegetative stage produced a significantly higher average number of fruits at 3.11, compared to an average of 2.40 fruits for plants treated during the reproductive stage. A significant interaction between the type of micronutrient and the timing of application further confirmed this finding.

The notable outcomes in the grading of cucumber fruits correspond to the noteworthy findings of the study regarding the quantity of fruits, which consistently exhibited enhanced performance due to Zn. However, Class II fruits were also noted to be improved in their application during the reproductive stage. This highlights the immediate assimilation of boron (B) and its crucial role in improving fruit quality, fruit number, and overall fruit grading by influencing metabolic activities and structural integrity in fruits.

Zn still resulted in superior fruit quality, regardless of the type of micronutrient used to produce quality, marketable fruits. In the research by Gianguzzi *et al.* (2023), foliar application of zinc sulfate at concentrations of 0.2% and 0.4% at various stages post-fruit set significantly enhanced fruit weight, crop load (fruit number), yield efficiency, and skin coloration—elements that directly affect fruit grading. The study noted that foliar zinc was predominantly absorbed through the abaxial (underside) leaf surface, resulting in increased zinc accumulation in leaves, which was correlated with improved fruit quality characteristics, such as cover color index and percentage, measured at successive harvest dates. These findings establish foliar zinc as an effective practice to boost fruit size and quality, essential components of fruit standards (Gianguzzi *et al.*, 2023). The application of zinc on the abaxial leaf surface was also effective in the treatment, regardless of the timing of application.

Table 11. Length (cm) of fruits of cucumber at 50 days after sowing (DAS) as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	19.83	20.07	19.95[b]
A2. Boron	20.72	22.13	21.43[a]
A3. Zinc	21.22	21.27	21.24[a]
A4. Boron + Zinc	20.63	20.91	20.77[ab]
Means [ns]	20.6 [ns]	21.10 [ns]	

CV = 3.82%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; [ns] = not significant

Table 12. Diameter (mm) of fruits of cucumber at 50 days after sowing (DAS) as applied with different types of micronutrients in varying timing of application, April 2025

Type of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	1.84	1.84	1.84[b]
A2. Boron	1.90	1.97	1.93[a]
A3. Zinc	1.93	1.96	1.95[a]
A4. Boron + Zinc	1.94	2.00	1.96[a]
Means [ns]	1.90 [ns]	1.94 [ns]	

CV = 3.27%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; [ns] = not significant

Length (cm) of fruits

Among the treatments evaluated, using only Boron (B) and Zinc (Zn) resulted in the longest cucumber fruits, with an average length of 21.43cm and 21.24cm, respectively. The combined B + Zn treatment resulted in an average length of 20.77cm. The control plants produced the shortest fruit lengths, with an average of 19.95cm, as shown in Table 11.

Zinc and boron foliar applications have consistently been proven in studies to dramatically increase fruit duration in a variety of crops, including brinjal, pineapple, olives, and tomatoes. Zinc, for example, has been recognized as a crucial factor in promoting fruit elongation, often surpassing boron when administered alone (Das *et al.*, 2023; Saadati *et al.*, 2016).

Furthermore, Das *et al.* (2023) also discovered that zinc sulfate alone produced the longest brinjal fruits (20.54 cm), while combining it with boron resulted in a substantial increase in length (19.74 cm) compared to the control (19.25 cm). Similarly, Saadati *et al.* (2016) found that zinc-treated cultivars produced the longest olive fruits (2.08 cm). While zinc appears to be the key factor influencing fruit length by increasing cell division and expansion, boron appears to play a supporting function (Kumari and Deb, 2018; Ali *et al.*, 2015). Its function in facilitating the movement of nutrients (assimilate translocation) and contributing to cellular weight gain supports the overall growth process. The combined application of both nutrients has also been shown to produce a synergistic effect, leading to improved fruit length and quality in crops such as pineapple and tomato (Kumari and Deb, 2018; Ali *et al.*, 2015).

Diameter (mm) of fruits

The application of micronutrients significantly improved the size of cucumber fruits. Treatments with Boron (B), Zinc (Zn), and their combination resulted in an average of 1.93mm, 1.95mm, and 1.96mm, respectively. This represents a significant enhancement relative to the control group, which exhibited an average fruit diameter of 1.84 mm (Table 12).

Multiple studies have revealed that the foliar application of zinc (Zn) and boron (B), both separately and in combination, significantly enhances fruit diameter and other associated quality metrics in various horticultural crops. Dhurve *et al.* (2018) revealed that foliar applications of Zn and B (0.4% each) on pomegranate significantly enhanced fruit diameter at various developmental phases, with combined Zn + B treatment producing the largest diameters and improvements in juice content and sugar concentrations. This synergistic effect reflects Zn's roles in enzymatic activation and protein synthesis, and B's function in cell wall integrity and nutrient transport, collectively enhancing fruit growth and biochemical quality.

Moreover, research on brinjal indicates that the combined application of foliar zinc and boron results in the greatest fruit diameter and weight, reflecting their synergistic effect on cellular growth and assimilate distribution (Das *et al.*, 2022; Ali *et al.*, 2015; Saadati *et al.*, 2016; Dhurve *et al.*, 2018). Collectively, these studies establish that foliar zinc and boron applications are agronomically beneficial in maximizing fruit diameter through enhanced cell division, enzyme activation, and improved nutrient mobilization, essential for meeting high fruit quality and grading standards, which further corroborates the significant results of this study which highlights that regardless of the micronutrient applied, its application alone can significantly increase the girth of cucumbers.

Weight (kg) of fruits per plant

Among the micronutrients tested, Boron (B) resulted in the heaviest weight of fruits at 5.32kg. A comparable result was obtained with zinc (Zn), which had an average weight of 5.06kg. This was followed by the combined use of B + Zn, with an average of 4.19. The lightest weight was observed in the control plants, which had an average of 3.00kg, as shown in Table 13.

Table 13. Weight (kg) of fruits per cucumber plant as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	3.00^{c}	3.00^{c}	3.00^{c}
A2. Boron	4.79^{b}	5.84^{a}	5.32^{a}
A3. Zinc	6.46^{a}	3.66^{bc}	5.06^{ab}
A4. Boron + Zinc	4.19^{b}	4.18^{b}	4.19^{b}
Mean	4.36^{a}	4.17^{b}	

CV = 11.49%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test

In terms of the fruit weight per plant, plants that received nutrients during their vegetative stage produced a significantly heavier weight of fruits at 4.36kg, compared to an average of 4.17kg fruits for plants treated during the reproductive stage. A significant interaction between the type of micronutrient and the timing of application further confirmed this finding.

Numerous studies have reported the beneficial effects of foliar boron (B) application during the vegetative stage on various crops, particularly in relation to increases in fruit weight, which aligns with the key findings of this study. A field experiment by Asad *et al.* (2003) found that foliar boron sprays increased dry mass by over threefold in severely deficient sunflower plants and significantly improved boron content in plant tissues that developed after application, underscoring the efficacy of foliar B in rapidly enhancing boron status and biomass accumulation, which is relevant to fruit and seed weight. A study by Mosa *et al.* (2015) on guava demonstrated a significant increase in fruit weight and quality metrics, highlighting the beneficial effect of boron during the vegetative stage of plant growth.

The augmentation of fruit weight after boron treatment is chiefly ascribed to boron's vital functions in cell wall synthesis, cellular division, expansion, and nutrient translocation within the plant. This structural role facilitates increased cell size, ultimately contributing to larger fruit size and weight. Additionally, boron influences membrane functions and enzymatic activities tied to nutrient uptake and translocation, particularly the transfer of carbohydrates through the phloem to developing fruits. Efficient transport of photosynthates supports fruit growth and biomass accumulation, also enhancing fruit weight (Shireen *et al.*, 2018; Asad *et al.*, 2003).

Moreover, boron involvement in stimulating metabolic and developmental pathways during early fruit growth stages results in improved fruit weight and yield (Lou *et al.*, 2024). In summary, the augmentation of fruit weight post-boron treatment is chiefly ascribed to boron's vital functions in cell wall synthesis, cellular division, expansion, and nutrient translocation within the plant. Boron stabilizes the cell wall structure by cross-linking pectic polysaccharides, such as rhamnogalacturonan-II, thereby maintaining cell wall integrity and elasticity, which supports cell expansion. This structural role facilitates increased cell size, ultimately contributing to larger fruit size and weight. Additionally, boron influences membrane functions and enzymatic activities tied to nutrient uptake and translocation, particularly the transfer of carbohydrates through the phloem to developing fruits. Efficient transport of photosynthates supports fruit growth and biomass accumulation, enhancing fruit weight (Shireen *et al.*, 2018; Asad *et al.*, 2003).

Moreover, boron mobility within the plant varies among species. It depends on the presence of sugar alcohols, which facilitate the phloem translocation of boron to fruits, allowing it to support fruit development processes directly. The significant results of boron observed in this study were applied during the vegetative stage of cucumber plants. Boron plays a crucial role in stimulating metabolic and developmental pathways during the early stages of fruit growth, resulting in increased fruit weight and yield. Excessive boron can induce toxicity, negatively impacting growth and fruit quality, thereby highlighting the necessity for balanced management (Lou *et al.*, 2024).

Weight (kg) of marketable fruits per plant

Among the micronutrient treatments, Boron (B) obtained the heaviest weight of marketable fruits with an average of 3.62kg per plant. The use of Zinc (Zn) and the combined use of B + Zn treatment yielded comparable results in the weight of marketable fruits of 3.19kg and 3.02kg, respectively. The control plants produced the lightest weight, with an average of 2.06kg, as shown in Table 14.

Table 14. Weight (kg) of marketable fruits per cucumber plant as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	2.06^{c}	2.06^{c}	2.06^{c}
A2. Boron	3.36^{b}	3.88^{a}	3.62^{a}
A3. Zinc	4.03^{a}	2.34^{c}	3.19^{b}
A4. Boron + Zinc	2.98^{b}	3.05^{b}	3.02^{b}
Mean ^{ns}	3.11 ^{ns}	2.83 ^{ns}	

CV = 11.42%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; ^{ns} = not significant

The investigation also revealed a substantial difference in the interaction between the type of micronutrient applied and the timing of its application. During the vegetative stage, Zn was the most effective in producing heavier marketable fruits. However, during the reproductive stage, the sole use of B produced heavier fruits, with an average of 3.88kg.

Among the micronutrients tested, the sole application of B significantly affected the weight of marketable fruits of the cucumber plants. However, considering the timing of the treatment application, Zn was found to be most effective in the parameter discussed. Several studies have promoted the frequent foliar application of zinc (Zn) during early developmental stages as highly effective in improving cucumber fruit weight and overall yield. The study by Singh *et al.* (2025) yielded similar results, indicating that foliar spraying of zinc sulfate at 25 and 45 days post-transplantation significantly enhanced cucumber fruit weight compared to lower concentrations and control groups. The study emphasizes that timely, repeated Zn applications optimize cucumber productivity and fruit size, due to improved nutrient absorption and hormonal balance during the early growth stages. This criterion was met by the method adapted by this study, which claims that experimental plants applied during the vegetative stage were applied frequently when compared to the plants applied during their reproductive stage due to an earlier kick start of treatment application, thus further solidifying the same results obtained from previous studies with the same treatments and methods used.

Kazemi (2013) demonstrated that foliar application of Zn significantly enhanced fruit weight, yield, chlorophyll content, and vegetative growth in cucumber plants. The study revealed optimal outcomes from the application of zinc in conjunction with iron, highlighting the importance of providing sufficient micronutrients at critical early developmental stages to support fruit growth and quality. Sidhu *et al.* (2020) discovered that the application of combined foliar sprays of zinc (30 ppm) and boron (20-40 ppm) significantly augmented cucumber fruit weight and yield, due to improved photosynthesis, sugar synthesis, flower retention, and assimilation processes, which are vital during the early reproductive phases.

Weight (kg) of non-marketable fruits per plant

Among the micronutrients used as treatments, Zinc (Zn) yielded the heaviest weight of non-marketable fruits, with an average of 1.74kg per plant. A comparable result was also noted in the sole use of Boron (B) and the combined use of B + Zn treatment, with average weights of 1.70kg and 1.45kg, respectively. The control plants produced the lightest weight of non-marketable fruits, with an average of 0.96kg, as shown in Table 15.

Table 15. Weight (kg) of non-marketable fruits per cucumber plant as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	0.96^{c}	0.96^{b}	0.96^{b}
A2. Boron	1.57^{b}	1.82^{a}	1.70^{ab}
A3. Zinc	2.17^{a}	1.30^{ab}	1.74^{a}
A4. Boron + Zinc	1.52^{b}	1.37^{ab}	1.45^{ab}
Mean ^{ns}	1.56^{ns}	1.36^{ns}	

CV = 21.44%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; ^{ns} = not significant

Furthermore, the analysis reveals a significant interaction between the type of micronutrient applied and the timing of its application. During the vegetative stage, Zn was the most efficient in producing heavier, non-marketable fruits, with an average of 2.17kg. During the reproductive stage, the sole use of B produced heavier fruits, with an average of 1.82kg.

A study by Biswas (2017) reveals that while zinc (Zn) application significantly improves cucumber growth parameters—such as vine length, early flowering, fruit weight, and yield—it may also result in a higher proportion of non-marketable fruits compared to boron (B) application. Zinc enhances vegetative growth and fruit set; however, excessive zinc can cause physiological issues, such as fruit deformities and surface blemishes, which reduce marketable quality. In contrast, boron tends to produce fewer non-marketable fruits by stabilizing cell wall integrity and reducing fruit disorders, thereby improving overall fruit quality, despite slightly lower fruit weight compared to zinc-treated plants. These findings suggest that although zinc enhances fruit size and quantity, its application timing and dosage are crucial to minimize negative impacts on fruit marketability.

In addition, researchers, like Subba *et al.* (2014), attribute the increase in non-marketable fruits following zinc application to zinc-induced physiological stress and toxicity at higher concentrations. Excess zinc can interfere with normal cellular and metabolic activities, resulting in a reduced photosynthetic rate, stomatal conductance, and chlorophyll content. Zinc toxicity may also hinder root and shoot growth by affecting cell division and mitochondrial ultrastructure, reducing overall plant vigor. These physiological disturbances manifest as fruit deformities, blemishes, and reduced shelf life, thereby increasing the proportion of non-marketable fruits compared to boron application, which tends to stabilize cell walls and reduce physiological disorders. Despite zinc stimulating growth at optimal levels, inappropriate doses or timing can trigger these stress responses, leading to quality losses in fruit.

Yield (ton/ha)

Among the micronutrients tested, Boron (B) resulted in the highest yield, with an average of 15.19 tons per hectare. Zinc (Zn) followed with a comparable average of 14.46 tons. The combined B + Zn treatment yielded an average of 12.00 tons, and the control plants had the lowest average weight at 8.57 tons, as shown in Table 16.

Table 16. Yield of cucumber (ton/ha) as applied with different types of micronutrients in varying timing of application,. April 2025

Types of micronutrients	Timing of application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	8.57^{c}	8.57^{c}	8.57^{d}
A2. Boron	13.70^{b}	16.68^{a}	15.19^{a}
A3. Zinc	18.46^{a}	10.46^{bc}	14.46^{ab}
A4. Boron + Zinc	12.07^{b}	11.93^{b}	12.00^{c}
Mean	13.20^{a}	11.91^{b}	

CV = 11.49%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test

Plants that received nutrients during their vegetative stage produced a significantly heavier weight of fruits at 13.20 tons, compared to an average of 11.91 tons for plants treated during the reproductive stage. A significant interaction between the type of micronutrient and the timing of application further confirmed this finding, supporting the notion that certain micronutrients perform best when applied at the right time.

Numerous studies have reported consistent findings about the beneficial impact of foliar boron during the vegetative phase of plant growth. Thanh *et al.* (2021), Giri *et al.* (2024), and Hashem and Al-hadrawi (2025) collectively determined that foliar boron application during the vegetative stage consistently enhances cucumber yield by promoting vegetative growth, flowering, nutrient absorption, and fruit development across various studies and experimental conditions. Thanh (2021) associated the substantial increase in total cucumber yield with boron's dynamic involvement in cell wall production, carbohydrate metabolism, sugar transport, pollen germination, seed set, and fruit development, all of which ultimately enhance various growth and yield metrics of cucumber.

Giri *et al.* (2024) investigated the effects of fertigation and foliar boron on cucumber cv. Himangi, revealing that 120% RDF fertigation combined with 0.2% foliar boron significantly elevated yield to 228 q/ha, expanded leaf area, decreased days to the first female flower, and enhanced the male-to-female flower ratio due to improved photosynthesis and nutrient absorption, thereby enhancing growth and blooming characteristics.

Additionally, boron's role in facilitating the movement of nutrients, creating sugars through photosynthesis, and aiding in reproduction further enhances these effects. Ultimately, the combination of balanced nutrition from fertigation and a boron spray leads to more efficient growth and fruiting, which significantly increases yields.

Finally, Hashem and Al-hadrawi (2025) concurred that foliar treatment of humic acid and boron significantly enhances the vegetative and yield characteristics of cucumber plants. Specifically, foliar boron at a 10 mg/L concentration enhanced vegetative growth and yield components similarly. These treatments improved physiological traits and nutrient uptake, stimulating better growth and fruit production, which in turn boosts the overall development and productivity of cucumber plants.

The application of foliar boron sprays at intervals throughout the vegetative and reproductive phases enhances nutrient uptake efficiency and availability at the leaf surface, promoting prompt absorption in accordance with the plant's requirements. This improves the efficiency of nitrogen, phosphorus, and potassium utilization, which are needed for growth and fruit development. Giri *et al.* (2024) noted that regular foliar boron sprays help maintain nutritional balance during critical growth stages, alleviate stress, promote vine development, and increase the number of viable flowers and fruit set. This results in an increased number of harvests per season and a higher total yield per hectare.

Total soluble solid (TSS)

The variance analysis of the data in Table 17, which presents the Total Soluble Solids (TSS) of cucumber fruits, indicated a significant difference among the treatment means based on the type of micronutrient utilized. Nevertheless, no substantial findings were observed regarding the timing of nutrient application or the interaction between the type of micronutrient and the timing of its application.

Table 17. Total soluble solid (°B) of cucumber at 50 days after sowing (DAS) as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of Application		Mean
	Vegetative stage	Reproductive stage	
A1. Control (No application)	8.76	8.76	8.76^{ab}
A2. Boron	8.85	8.65	8.75^{ab}
A3. Zinc	8.71	8.93	8.82^{a}
A4. Boron + Zinc	8.37	7.43	7.9^{c}
Mean ^{ns}	8.67 ^{ns}	8.44 ^{ns}	

CV = 4.10%; Means with common letter superscripts are not substantially different at the 5% level, using the LSD test; ^{ns} = not significant

Among the treatments tested, the sole use of Zinc (Zn) resulted in the highest TSS, which is often regarded as sweet, at an average of 8.82°B. The combined Boron (B) and plant treatments left untreated, comparably, followed with an average rate of 8.75°B and 8.76°B, respectively. However, it was all noteworthy that the combined use of B + Zn obtained the lowest TSS rating, at an average of 7.9°B.

The timing of micronutrient application did not significantly affect fruit length, nor was there a significant interaction between timing and the type of micronutrient applied to the cucumber plants. This suggests that only the type of micronutrient itself influences the overall TSS in cucumber plants. The phenomenon of using boron or zinc alone increasing total soluble solids (TSS) in cucumber, while their combined use reduces TSS, can be explained by contrasting the physiological and biochemical interactions of these micronutrients in the plant.

Boron, when applied alone, is known to enhance carbohydrate metabolism, sugar transport, and sugar accumulation in fruits, thereby increasing sweetness and TSS content. Boron enhances cell wall formation and membrane integrity, thereby facilitating the better retention and accumulation of soluble solids in cucumber fruits. Further evidence is provided by studies, such as that of Narahari *et al.* (2018), which examined the impact of zinc (Zn) and boron (B) on the performance of fruit crops. The study revealed significant improvements in TSS, ascorbic acid content, and yield metrics when foliar sprays were administered before flowering. These micronutrients play a crucial role in metabolic pathways, influencing fruit set viability and development, which are essential for achieving Extra Class fruit standards. Collectively, these works highlight the agronomic value of carefully timed foliar applications of zinc and boron at or before anthesis in boosting fruit quality attributes, nutrient status, and yield in various horticultural crops (Meriño-Gergichevich *et al.*, 2021; Narahari *et al.*, 2018). A study by Mosa *et al.* (2015) revealed that foliar application of boron, particularly in conjunction with potassium and calcium, markedly enhanced fruit weight and quality metrics.

Similarly, zinc alone contributes to improved chlorophyll retention, photosynthetic efficiency, and enzymatic processes involved in sugar synthesis, which can support higher TSS levels (Singh *et al.*, 2025). Zinc's role in maintaining membrane permeability also helps sustain fruit quality and sugar content during the maturation process. However, when boron and zinc are applied together, antagonistic interactions or nutrient imbalances may occur, which can alter sugar metabolism pathways. A combined application may alter hormonal balances or induce competition for uptake and assimilation, leading to reduced sugar accumulation or redistribution. This can lead to a slight reduction in TSS compared to sole boron or zinc treatments despite improving other quality parameters such as shelf life and chlorophyll content (Akshata *et al.*, 2023).

Thus, while individual applications of boron or zinc can enhance TSS by promoting sugar synthesis and accumulation, their combined use may interfere with these processes through complex physiological crosstalk and nutrient interactions, leading to reduced TSS in cucumber fruits. Understanding these nuanced interactions can help optimize foliar application regimes for balancing yield, fruit quality, and sweetness.

Firmness

The analysis of variance of the data in Table 18, which details the Firmness of the cucumber fruits, revealed no significant results among the treatment means for all factors investigated: the type of micronutrient used, the timing of its application, and the interaction between these two factors.

Table 18. Firmness (kg/cm3) of cucumber at 50 days after sowing (DAS) as applied with different types of micronutrients in varying timing of application, April 2025

Types of micronutrients	Timing of application		$Mean^{ns}$
	Vegetative stage	Reproductive stage	
A1. Control (No application)	8.98	8.98	8.98^{ns}
A2. Boron	9.05	8.67	8.86^{ns}
A3. Zinc	8.42	8.29	8.36^{ns}
A4. Boron + Zinc	9.80	9.87	9.84^{ns}
$Mean^{ns}$	9.06^{ns}	8.95^{ns}	

CV = 12.31%; ^{ns} = not significant

The study reveals no substantial difference in the firmness of cucumber peels across all treatments. This indicates that neither the type of micronutrient used, the timing of its application, nor the interaction between these factors had a measurable effect. Hence, this can serve as a basis for suggesting that the firmness of the cucumber peel is not influenced by the exogenous application of these micronutrients or the timing of their application.

The foliar application of boron and zinc has been shown to affect several quality parameters in cucumber; however, firmness remains unchanged. This is because fruit firmness in cucumbers is predominantly governed by structural components, such as cell wall composition, pectin levels, and calcium content, rather than by micronutrients like boron and zinc alone. Boron primarily facilitates cell wall synthesis and membrane integrity, while zinc supports chlorophyll synthesis and enzymatic functions. While these micronutrients enhance physiological processes that promote growth, yield, and certain quality attributes (such as sweetness and shelf life), their impact on the mechanical characteristics of fruit tissue, which determine firmness, is minimal. Hence, treatments with foliar boron and zinc showed no significant changes in fruit firmness, possibly due to the relatively stable cell wall composition that is less sensitive to these micronutrients alone (Singh *et al.*, 2025).

Furthermore, a study on zucchini, a closely related cucurbit species, showed that foliar application of boron, zinc, and manganese improved quality features, including total soluble solids and fiber content; however, changes in fruit firmness were either modest or inconsistent, suggesting firmness traits are less responsive to micronutrient foliar sprays alone (Pasham Maneela *et al.*, 2024). Furthermore, firmness is commonly linked to calcium-mediated cross-linking of pectins within the cell wall, a process that is not directly affected by foliar applications of boron or zinc. Therefore, while micronutrients like boron and zinc enhance metabolic activities, photosynthesis, and sugar accumulation, they do not markedly affect the firmness of cucumber fruits.

Table 19. Cost and return analysis of cucumber as applied with different types of micronutrients in varying timing of application, April 2025

Treatments	Yield in 334.8 m²	Total production cost	Gross income	Net income	ROI (%)
No Application	286.80	2796.14	8604.04	5807.90	207.71
Boron during vegetative stage	458.57	2829.38	13757.09	10927.71	386.22
Boron during reproductive stage	558.53	2818.30	16755.94	13937.64	494.54
Zinc during vegetative stage	617.95	2829.12	18538.35	15709.24	555.27
Zinc during reproductive stage	350.05	2818.12	10501.56	7683.44	272.64
Boron + Zinc during vegetative stage	400.62	2832.36	12018.68	9186.33	324.34
Boron + Zinc during reproductive stage	399.58	2820.28	11987.43	9167.15	325.04

Cost and return analysis

Table 19 details the yield from the experimental area, total production cost, gross income, net income, and computed Return on Investment (ROI) for each type of micronutrient use and the timing of its application. The cost and return analysis was conducted by comparing the computed Return on Investment (ROI), expressed as a percentage, shown in the table above. The highest ROI was obtained from the application of zinc (Zn) during the vegetative stage of the plant, with an ROI of 555.27%.

This was followed by the application of boron (B) during the reproductive stage (494.54%), B during the vegetative stage (386.22%), a combined application of B + Zn during the reproductive stage (325.04%), B + Zn during the vegetative stage (324.34%), Zn during the reproductive stage (272.64%), and lastly, plants without any treatment application (207.60%). Although the plants without treatment still showed a positive ROI, the highest ROI achieved indicates that the amount invested in cucumber production can be effectively increased by more than fivefold when zinc is applied during the plant's vegetative growth stage (HashMicro, 2025).

CONCLUSION

Using micronutrients substantially impacts the growth, productivity, yield, and quality characteristics of cucumber. Zinc consistently improved essential agronomic traits, including early flowering, increased production of pistillate flowers, higher fruit numbers, and enhanced fruit grading, particularly favoring Extra Class fruits. Despite being less effective in specific growth parameters, boron increased fruit weight and marketability, leading to similar yield performance to Zinc.

The interaction between Boron and Zinc significantly enhanced the quantity of primary branches per plant, indicating a collaborative influence on vegetative growth. Zinc enhanced fruit quality by elevating total soluble solids while maintaining firmness. The results highlight the importance of selecting suitable micronutrients and their optimal application timings to enhance cucumber production.

Applying Zinc and Boron through foliar methods, especially during the vegetative and reproductive phases, can improve both the quantity and quality of yields, ultimately leading to enhanced productivity and economic benefits in cucumber farming.

RECOMMENDATIONS

Therefore, the following recommendations are proposed in accordance with the study's findings and conclusions; 1) To reduce the abscission rate while maintaining or increasing fruit set rates, it is recommended to apply Boron alone during the vegetative stage to minimize flower drop and enhance fruit retention, thereby improving overall fruit set. This targeted nutrient management can reduce losses due to abscission and increase the productive fruit load, optimizing yield efficiency, which is evident in the improved weight of fruits and the increased number of classified marketable cucumbers when applied with B at the earlier stages of cucumber growth; 2) For effective application by farmers, it is recommended to apply Zinc during both the vegetative and reproductive stages through foliar application to enhance early flowering, increase the production of pistillate flowers, and boost the quantity of Extra Class fruits. In parallel, Boron application should be considered to improve fruit weight and marketability. To achieve this, farmers should adopt a separate application strategy timed to match crop growth stages, thereby balancing vegetative growth and reproductive success for improved economic returns; 3) Given the actual market demand for cucumbers among health-conscious individuals who prefer to purchase them in the fresh produce section of supermarkets, focusing on the quality of the fruit (both internal and external attributes) can also be worthwhile. In line with this, the application of Zinc is recommended, as it has yielded improved results in terms of TSS, Fruit Diameter, Fruit Length, Extra-Class Fruits, and Class I fruits. It is also worth noting that this application exhibits a superior effect in the fruit setting; 4) For future research, exploring the mechanistic basis of how Boron and Zinc individually and interactively influence flower abscission and fruit set processes at physiological and molecular levels in cucumber is suggested; 5) Evaluating local environmental factors and soil micronutrient status will help tailor nutrient management recommendations specific to Philippine cucumber production systems; 6) Long-term field trials are warranted to assess the economic and environmental sustainability of micronutrient application strategies.

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