The effect of ventilation systems and drip irrigation levels on water use efficiency and cucumber crop growth and yield

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Abstract

Integrated management of ventilation and irrigation factors is one of the main challenges in greenhouse cucumber production, as poor control of these factors leads to reduced water use efficiency and decreased productivity. This study aimed to evaluate the effect of ventilation systems and drip irrigation levels, as well as their interactions, on some characteristics of the cucumber plant.

The experiment was conducted during the spring season of 2025 in the research field of the College of Agriculture and Forestry at the University of Mosul, inside two plastic greenhouses using a completely randomized block design with a split plot system and two factors: a ventilation system (with and without internal tubular ventilation fans), and two irrigation levels (75% and 100% of field capacity).The results showed the superiority of the ventilation system equipped with tubular fans in improving water use efficiency to obtain the highest productivity with the least water consumption, as the highest number of irrigation hours per season was (14.30 and 10.72 hours season^{-1}) for the ventilated house compared to (14.73 and 11.08 hours season^{-1}) for the house without internal ventilation at field capacity of 100% and 75% respectively, The highest amount of irrigation water was recorded in the season (80.03 and 59.98 m^{3}season^{-1}) compared to (82.46 and 62.03 m^{3} season-1), and the productivity of irrigation water increased to (17.19 and 17.45 L kg yield^{-1}) compared to (20.04 and 18.71 1719.43 L kg yield^{-1}).In terms of vegetative growth and yield characteristics, the 100% irrigation level significantly exceeded the chlorophyll content in the leaves (25.6328 SPAD), the area of a single leaf (251.099 cm^{2} laef^{-1}), the marketable yield per plant (3.49500 kg plant^{-1}), the marketable yield of the fruits (21.8483 kg m^{-2}), and the total marketable yield of the house (4.3688 tons house $^{-1}$) compared to the 75% level. The combined effect of ventilation with internal fans and a 100% irrigation level resulted in the highest yield of 4.9542 tons house^{-1}.

The study concludes the importance of adopting an effective ventilation system with irrigation management at full field capacity to achieve the highest growth, productivity and best water use efficiency in greenhouses.

Keywords: greenhouses, ventilation, Drip irrigation levels, cucumber crop

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Introduction

Greenhouses are one of the most important methods of producing vegetables out of season, as they protect plants from weather fluctuations and harsh weather conditions, and allow control over environmental factors and irrigation. This leads to increased crop productivity, improved quality, and a longer growing season, especially for cucumbers (*Cucumis sativus* L.), This is one of the most important vegetables grown in protected conditions in many countries worldwide. It is a sensitive crop that responds clearly to any change in the agricultural environment, making precise control of ventilation and irrigation crucial for achieving high economic yields. However, the problem arising from high temperatures inside greenhouses is that they lead to heat stress, which reduces the efficiency of the plant's vital processes. Furthermore, excessive irrigation depletes the soil and reduces productivity [1]. Recent statistics indicate a significant expansion in protected agriculture in arid and semi-arid regions with the aim of conserving irrigation water and improving the efficiency of land and water use [2]. However, the success of cucumber production in greenhouses depends largely on the efficiency of local climate management, especially ventilation systems and control of relative humidity and temperature. High temperatures and humidity inside greenhouses lead to a decrease in photosynthetic efficiency, an increase in susceptibility to fungal diseases, and a decrease in fruit quality. Recent studies in hot and sub-hot climates have shown that improving natural ventilation or using effective ventilation and cooling systems can lower the air temperature inside greenhouses by several degrees Celsius, reduce humidity, increase cucumber productivity, and improve fruit quality [3]. At the same time, drip irrigation in greenhouses is one of the most effective irrigation methods in meeting the water needs of cucumber plants while reducing losses due to evaporation and seepage. [4] indicated in their field study that using drip irrigation with appropriate scheduling of irrigation times and depth doubles the efficiency of water use and maintains or increases productivity compared to surface irrigation. Regulated deficit irrigation can be applied without a noticeable decrease in fruit productivity while reducing nutrient loss due to seepage. Recent reviews of energy and water in greenhouse cucumber production indicate that integrating climate management with highly efficient irrigation systems is one of the most important approaches to sustainable greenhouse farming, as it contributes to increasing water use efficiency while maintaining high productivity and outstanding crop quality [2]. Therefore, the research problem lies in the fact that many studies have dealt with each of these factors (the effect of ventilation or irrigation) separately, while the combined interaction of these factors within greenhouses has not been studied sufficiently, especially with regard to their effect on these characteristics as well as on water use efficiency and plant productivity. This highlights the importance of this study, which aims to 1. To determine the best air circulation systems for greenhouse environments and their impact on local climatic parameters and cucumber plant productivity. 2. To determine the optimal drip irrigation levels for the experiment to achieve the highest water use efficiency and yield for cucumber plants under protected growing conditions. 3. To demonstrate the interactions between ventilation and irrigation on yield characteristics and fruit quality in order to determine the optimal treatment or combination in terms of productivity and resource use efficiency. 4. To provide technical recommendations for farmers and future studies on ventilation and irrigation management in greenhouses for cucumber plants to achieve maximum yield and quality with minimal water consumption.

Materials and Methods

The experiment was conducted in the research field of the College of Agriculture and Forestry at the University of Mosul, inside two plastic greenhouses with an area of 450 m^2, length 50 m and width 9 m for each greenhouse, during the spring growing season of 2025. Different samples were taken from the surface layer of the soil at a depth of 0-30 cm for analysis and to estimate some of the physical and chemical properties of the plastic greenhouse soil (Table 1). The average temperature and relative humidity inside and outside the two plastic greenhouses were recorded using sensors that stored the data on an SD flash drive (Table 2). The experiment used the Rover F1 cucumber variety, which was planted on 2/18/2025 in plastic germination trays containing 50 cells using peat moss as the growing medium. After the seedlings reached the stage of three - four true leaves, they were transplanted in the morning in the field on 3/18/2025 manually with great care, keeping the peat moss around the roots during transplanting and maintaining soil moisture. The experiment included studying the effect of two factors: The first factor was the methods of air circulation systems. This factor included two ventilation systems, where the first house included: an air extractor at the front of the plastic house with internal tubular ventilation fans (in the middle of the plastic house), and the second house: an air extractor at the front of the plastic house without internal tubular ventilation fans. The second factor was the levels of drip irrigation. This factor included two levels of drip irrigation (75% and 100%) of the field capacity, Thus, the study included 4 (2×2) treatments carried out in the field using the Split Plot System within the RCBD randomized complete block design [5]. The study illustrated the ventilation methods in the main plots and the irrigation system in the sub-plots. The land for the greenhouse was prepared by plowing with a disc plow and then leveling. The greenhouse was then divided into sections along its length, with each section representing a duplicate for planting using furrow-opening machines. The greenhouse was divided into five equal sections; the three middle sections were used for the study, and then the sections were further divided into raised beds The experimental units are represented by a width of 80 cm for each raised bed, leaving 70 cm between one bed and another, and leaving 100 cm on both sides of the house, with two rows of planting within each raised bed, the distance between one row and another being 70 cm, and the distance between one plant and another being 40 cm, with 5 plants on each side, i.e., 10 plants for the experimental unit and 30 plants for each treatment. The area of the experimental unit was 1.6 m^2. A drip irrigation system was used to water the plants. Drip pipes were laid after the raised beds were constructed, with two pipes per bed. A locally manufactured smart irrigation system, connected to the field's drip irrigation network, was used in this research. The system relies on a set of smart sensors installed in the soil and on the irrigation lines, allowing for precise adjustment of the field capacity of each irrigation line. Agricultural practices were carried out identically for all experimental units, including pruning old leaves, irrigation, fertilization, weeding, preventative control of diseases and insects, and suspending plants by nylon fiber string from the base of the stem upwards. The results were statistically analyzed using the SAS [6] computer model and Duncan's multiple range test to compare means at a probability level of 0.05.

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Table (1): Some chemical and physical properties of greenhouse soil.

Characteristics and unit of measurement	Appreciation
Soil pH level	7.4
Electrical conductivity EC dSiemens/m	0.8
Organic matter %	2.23
Ready-to-use nutrient content mg. kg-1	
Nitrogen parts per million	18
Phosphorus parts per million	12
Potassium parts per million	127
Size distribution of soil fractions	
sand %	19.14
Green %	35.97
clay %	44.89
tissue	clay

* The analysis was carried out at the Central Laboratory / College of Agriculture and Forestry / University of Mosul.

Table (2) Monthly averages inside and outside the greenhouse for temperature and relative humidity during the study period.

Months for 2025	climatic elements					
	Average temperature inside a well-ventilated house (°C)	Average temperature inside the second house without ventilation (°C)	Relative humidity inside the first ventilated house (%)	Relative humidity inside the second house without ventilation (%)	Average outdoor temperature (°C)	Relative humidity outside the house (%)
March	19.03	21.62	71.1	71.21	16.2	57
April	30.18	31.042	56.18	59.22	25.12	50
May	31.7	32.77	45.12	48.01	27.97	35
June	34.27	34.35	27.46	29.02	32.92	20
July	39.44	42.335	21.05	24.44	36.06	18

* Estimated using sensors that store data on SD flash drive.

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The characteristics studied:

1- Number of irrigation hours per season (hseason^{-1}): The number of irrigation hours per season for each treatment was calculated using an automatic timer installed on the drip irrigation lines, which accurately measures the actual number of irrigation hours. The timer records the irrigation duration directly without manual intervention.

2- **Irrigation Water Quantity (m³ season^{-1}):** The irrigation water quantity for the season was calculated based on the dripper discharge and the actual number of irrigation operating hours, as follows:

Irrigation Water Quantity (m³) = Dripper Discharge (L hr $^{-1}$) × Number of Drippers × Actual Operating Hours / 1000

3- Irrigation water productivity (L kg yield^{-1}): The irrigation water productivity for the cucumber crop per season for each treatment was calculated by dividing the total yield of the plant by the total amount of irrigation water added.

4- Chlorophyll content in leaves: The chlorophyll content of the leaves was estimated after the tenth harvest, after the plant had reached its peak, by using the CCM-200 plus device from OPTI-Sciences, The device is digital and high-precision, with an average of five readings per experimental unit, by placing the plant leaf between the jaws of the device and pressing on them with the thumb, and waiting a little while to read the chlorophyll content in it.

5- Percentage of dry matter in leaves: Five leaves were taken from each experimental unit for each replicate and weighed using an electric balance. They were then dried until the weight stabilized and reweighed. The percentage of dry matter in the leaves was then calculated using the following equation:

Percentage of dry matter in leaves (%) = (Weight of dry sample) / (Weight of wet sample) × 100

6- Leaf Area (cm² Leaf $^{-1}$): Five leaves were taken from each treatment, and five discs with an area of 1 cm² were cut from them using a cork punch of known size (1 cm²). The fresh weight of the discs and the fresh weight of the leaves from which the discs were cut were recorded. Knowing the area of the discs, the leaf area per plant was calculated using the following equation: Leaf Area (cm² Leaf $^{-1}$) = Disc Area × Fresh Weight of Leaves / Fresh Weight of Discs. The result was then divided by 5 to obtain the leaf area per leaf.

7- Marketable yield per plant (kg plant^{-1}): The marketable yield per plant was calculated by summing the yields from all harvests during the season after excluding damaged, misshapen, and very small fruits, and calculated as follows:

Marketable yield per plant (kg) = Total yield of plants in the experimental unit ÷ Number of plants in the experimental unit.

8- Marketing yield of fruits (kg m^{-2}): Take the sum of the weights of the marketing yield of the experimental unit and its area, then use the ratio and proportion method to extract the marketing yield per square meter.

9- Total marketing yield of the greenhouse (ton house^{-1}): It was calculated based on the yield per square meter relative to the area of the greenhouse after excluding damaged, deformed and very small fruits.

Results and Discussion

Figure (1) shows the number of irrigation hours during the months of implementation of the experiment from March to July in two plastic greenhouses, one with internal ventilation and the other without internal ventilation, at two levels of irrigation (75% and 100%) of field capacity. The results indicate a clear gradual increase in irrigation hours as the growing season progresses. This is attributed to the gradual increase in temperatures and the increase in solar radiation, which leads to higher rates of evaporation and transpiration in the plastic

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greenhouses. This leads to an increase in the plants' water needs. Also, the increase in vegetative mass leads to an increase in water consumption as a result of the increase in the leaf surface area. This was confirmed by [7] and [8]. In July, a clear difference was observed between the two greenhouses. Irrigation hours reached 6.45 and 8.62 hours in the greenhouse with internal ventilation fans at its field capacity of 75% and 100% respectively, while in the greenhouse without internal ventilation fans, they decreased to 3.12 and 4.15 hours. This decrease in the number of irrigation hours in the greenhouse without internal ventilation fans is attributed to the early end of the growing season for the plants due to heat stress and high temperatures inside it, which led to the deterioration of the plants and the cessation of their growth, and this led to a decrease in their water needs. Overall, the total irrigation hours during the season reached 25.66 and 34.23 hours in the greenhouse with internal ventilation at 75% and 100% field capacity, respectively, while they reached 22.97 and 30.47 hours in the greenhouse without internal ventilation. The results indicate that using an internal ventilation system in the greenhouse led to improved internal environmental conditions and a longer plant growth period compared to the greenhouse without internal ventilation, resulting in a longer period of plant physiological activity In their study, [9] indicated that greenhouse ventilation systems play a crucial role in regulating temperature and humidity, increasing productivity, and improving water use efficiency. The results also show that the number of irrigation hours at 100% of field capacity was higher than at 75% of field capacity in both greenhouses, with and without internal ventilation. Therefore, to maintain soil moisture at 100% field capacity, larger quantities of water must be added to preserve the soil moisture content at this level this leads to an increase in the number of irrigation hours compared to the minimum irrigation level of 75% of field capacity. The availability of a larger quantity of water in the root zone improves the physiological activity of the plant and also increases the rate of transpiration, which is reflected in an increase in the plant's water needs. This is consistent with what [10] stated, which indicated that increasing the soil moisture level to the limits of the full field capacity of 100% increases the plant's water consumption compared to the irrigation level of 75% of field capacity, as a result of the increase in the plant's physiological activity, although lower levels may improve water use efficiency.

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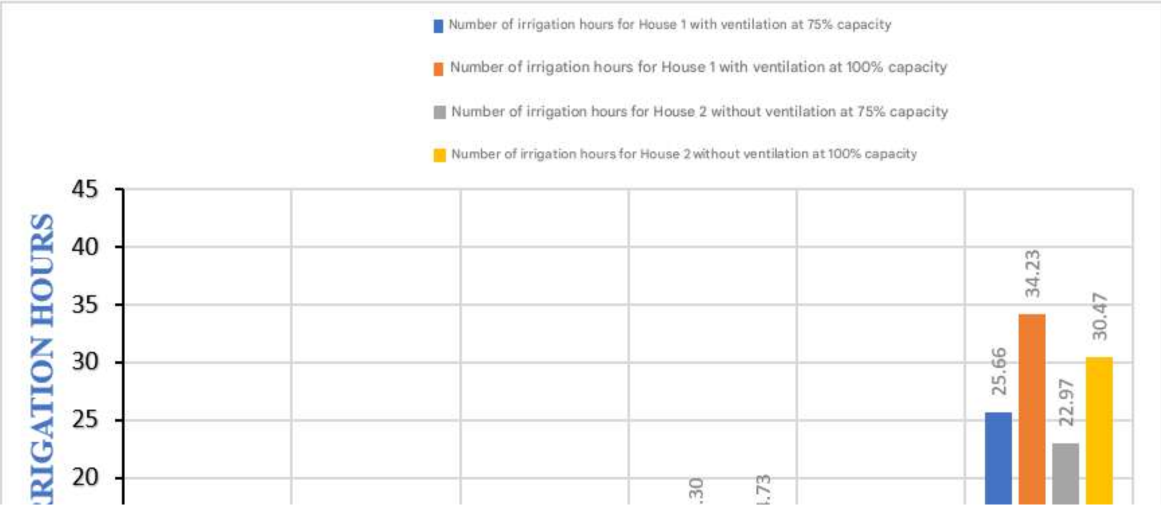

Figure (1) shows the number of hours of irrigation during the growing season for the cucumber crop.

Figure (2) shows the amount of irrigation water used during the months of implementation of the experiment from March to July in two plastic greenhouses, one with internal ventilation and the other without internal ventilation, at two levels of field capacity (75% and 100%). The results show a clear gradual increase in the amounts of irrigation water as the growing season progresses, as it rises from its lowest value in March to its highest value in June. This is explained by climatic changes in terms of the rise in temperature and the increase in solar radiation, as well as the increase in vegetative mass that accompanies the progress of the season. This leads to an increase in evaporation and transpiration rates, and thus an increase in the plants' water needs. This is consistent with [11]. The results showed that the lowest amount of irrigation water during March ranged between 6.48 and 8.63 m³ in the greenhouse with internal ventilation fans at its field capacity of 75% and 100% respectively, while it reached 6.53 and 8.67 m³ in the greenhouse without internal ventilation fans. This is attributed to the decrease in temperatures and the decrease in demand for evaporation from the atmosphere, which leads to a reduction in water consumption by plants and soil. June witnessed the highest irrigation water quantities of the season, ranging between 59.98 and 82.46 m³, as a result of the noticeable rise in temperatures and increased intensity of solar radiation. This led to increased evaporation and transpiration rates, necessitating an increase in the amount of water used inside greenhouses, as confirmed by [12]. In July, a relative decrease in irrigation water quantities was observed, especially in greenhouses without internal ventilation fans, ranging between 17.44 and 23.23 m³ at their field capacity of 75% and 100%, respectively, compared to between 36.10 and 48.22 m³ in greenhouses with internal ventilation fans, This is attributed to the end of the plant life cycle in the greenhouse without internal ventilation fans due to heat stress and high temperatures, which led to the cessation of growth and a decrease in their water needs. In contrast, the plants in the greenhouse with internal ventilation fans continued to grow for a longer period, and this led to continued water consumption. Moreover, increasing irrigation levels, such as 100% of field capacity, leads to an increase in plant water consumption compared to lower levels due to increased physiological activity, as shown by [13]. In general, the total amount of irrigation water during the season was 143.60 and 191.54 m³ in the greenhouse with internal ventilation fans at field capacities of 75% and 100% respectively, compared to 128.53 and 170.51 m³ in the greenhouse without internal ventilation fans. This indicates that ventilation helped improve the environmental conditions inside the greenhouse and prolong the period of physiological activity of the plants, which was reflected in the increase in the amount of water consumed.

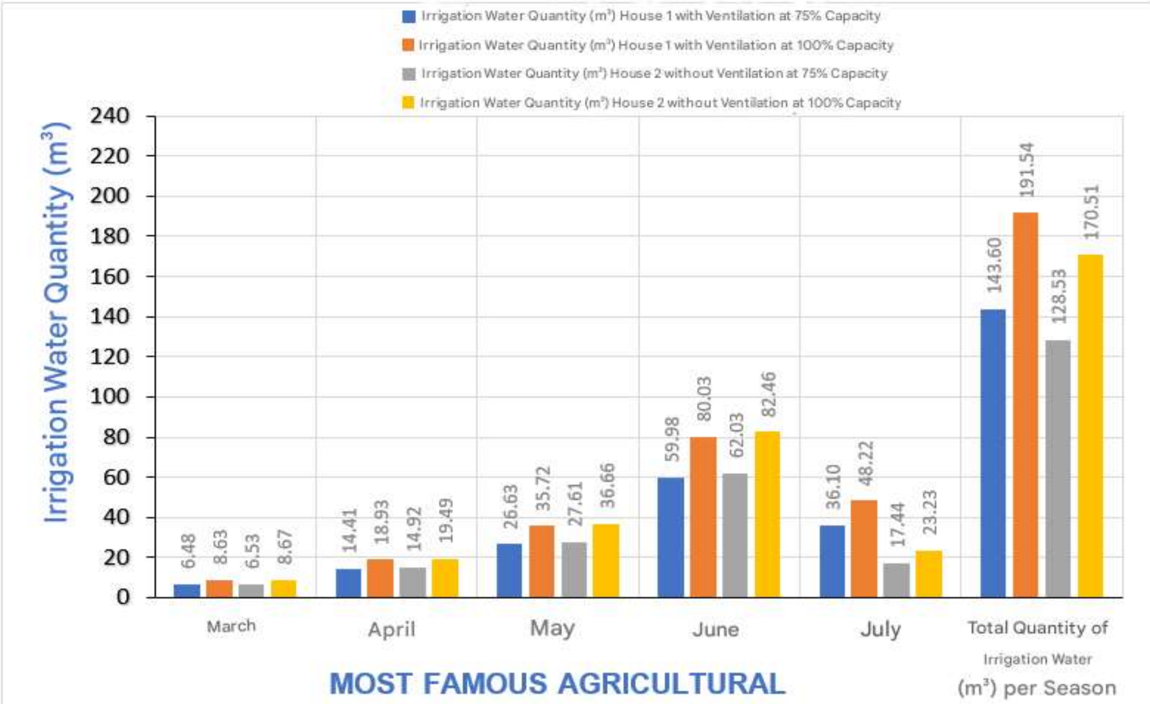

Figure (2) shows the amount of irrigation water (m^3) during the growing season for the cucumber crop.

Figure (3) illustrates the irrigation water productivity during the experimental period from March to July in two greenhouses, one with internal ventilation and the other without, at two levels of field capacity (75% and 100%). The treatment for the first greenhouse, with 100% internal ventilation, recorded the highest water use efficiency, reaching 17.19 L kg⁻ ¹. This significant advantage is attributed to the fact that the presence of ventilation, combined with a full water supply, provided an ideal growing environment that minimized water loss through unproductive transpiration. This aligns with the findings of [14], which confirmed that water use efficiency depends not only on the quantity of water but also on the ability of the ecosystem (whether irrigation depth or aeration) to meet the crop's water requirements without waste. The results show a sharp decrease in irrigation water productivity in the second greenhouse without internal ventilation, especially when irrigated at 100% of field capacity, where the value increased to 20.04 L kg⁻ ¹. This increase (which represents an increase in water consumption per kilogram of yield) is attributed to thermal suffocation and high humidity, which hinders the transpiration process and leads to water waste without a corresponding increase in yield. This is consistent with [15] stated, that controlling the greenhouse environment is the decisive factor in improving water use efficiency, as the absence of ventilation disrupts the physiological balance of the plant. When comparing drip irrigation levels, the greenhouse with internal ventilation responded significantly better to 100% field capacity

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irrigation compared to 75% field capacity irrigation. In the greenhouse without internal ventilation, 75% field capacity irrigation (18.71 L kg^{-1}) was relatively better than 100% field capacity irrigation. This suggests that water conservation under harsh environmental conditions (such as poor ventilation) can reduce plant damage caused by excessive root moisture. This finding supports the study by [16], which indicated the need to adjust irrigation scheduling in greenhouses to match the added quantity and surrounding environmental conditions to ensure consistent and optimal water absorption.

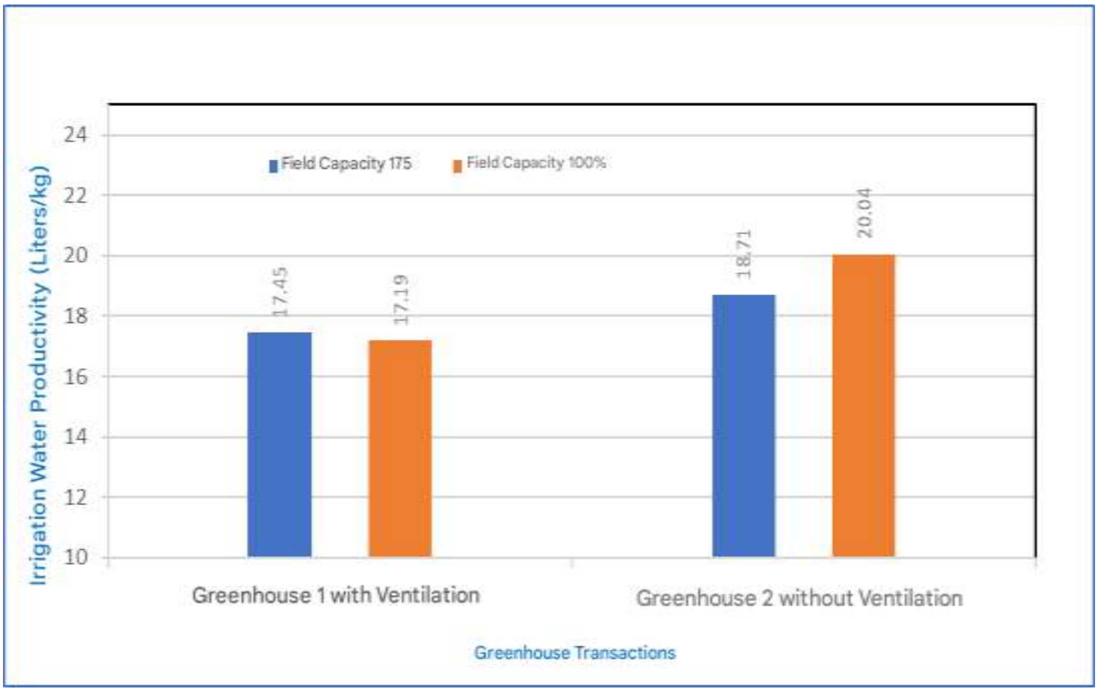

Figure (3) shows the productivity of irrigation water (L kg yield) during the growing season of the cucumber crop.

The results in figure (1.) indicate that the effect of ventilation systems on leaf chlorophyll content was significantly higher when using a ventilation system with an extractor fan at the front of the greenhouse and internal ducted fans (SPAD value 25.4106) than when using a ventilation system with an extractor fan at the front of the greenhouse without internal ducted fans (SPAD value 22.1311). Regarding the effect of drip irrigation levels (75% and 100% of field capacity), the results in the table show a significant difference between the 100% field capacity irrigation level (SPAD value 25.6328) and the 75% field capacity irrigation level (SPAD value 21.9089) in leaf chlorophyll content. In the effect of the dual interaction between ventilation systems and drip irrigation levels, the results show that using a ventilation system with an air extractor at the front of the greenhouse with internal ductual ventilation fans, in conjunction with an irrigation level of 100% of field capacity, gave the best significant value in leaf chlorophyll content of 28.7789 SPAD, which significantly outperformed all treatments of this interaction in this trait, while the lowest value in this trait, 21.7756 SPAD, was recorded in the case of the interaction of a ventilation system with an air extractor at the front of the greenhouse without internal ductual ventilation fans with an irrigation level of 75% of field capacity.

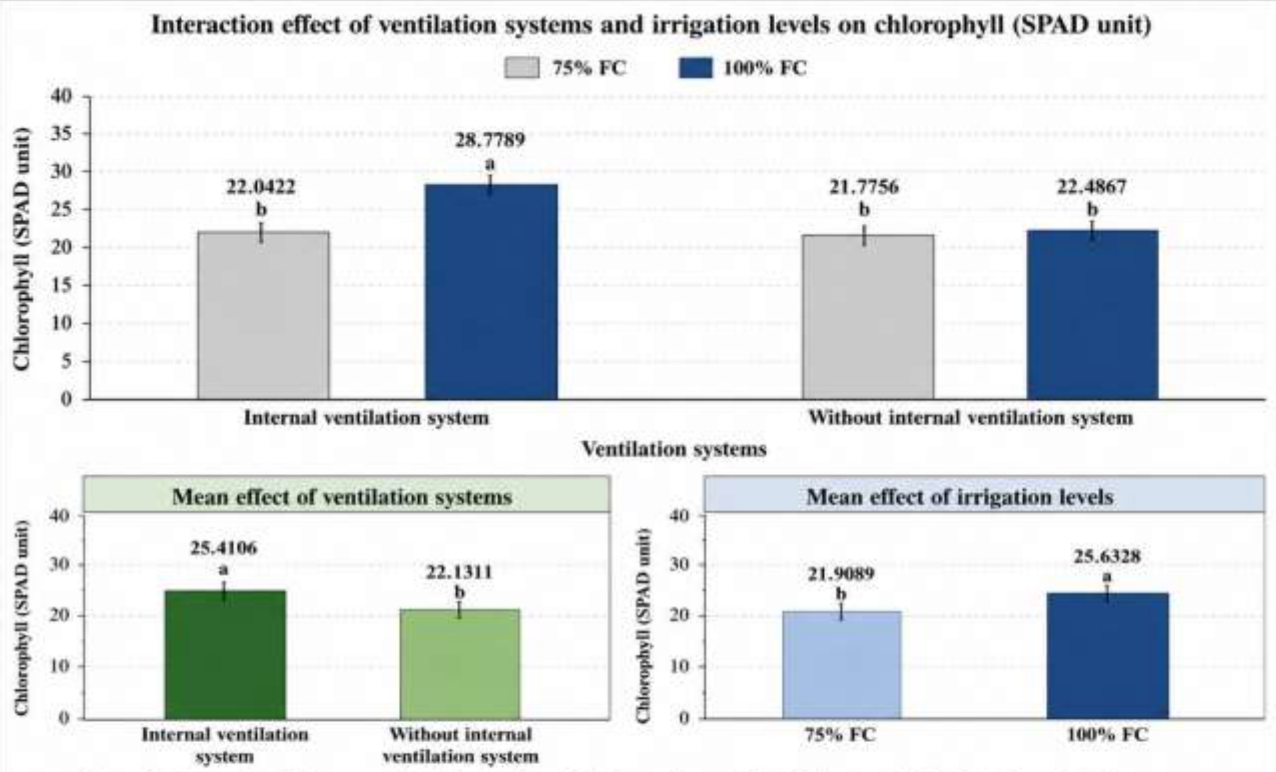

Figure 1. Effect of ventilation systems, irrigation levels, and their interaction on chlorophyll content (SPAD unit) of cucumber plants grown under greenhouse conditions. Means followed by the same letter are not significantly different according to Duncan's multiple range test at $P \leq 0.05$.

The results in figure (2.) indicate no significant differences in dry matter percentage between the greenhouse exhaust system with internal ducted fans and the greenhouse exhaust system without internal ducted fans. Regarding the effect of drip irrigation levels (75% and 100% of field capacity) on leaf dry matter percentage, a significant difference was observed between the 75% field capacity irrigation level (20.9844%) and the 100% field capacity irrigation level (19.8389%). Regarding the effect of the dual interaction between ventilation systems and drip irrigation levels, the data show that the highest value in this characteristic, 21.4778%, was found in the case of using an exhaust ventilation system at the front of the greenhouse with internal tubular ventilation fans and at an irrigation level of 75% of the field capacity. This treatment was only significantly superior to the

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interaction treatment of an exhaust ventilation system at the front of the greenhouse with internal tubular ventilation fans and at an irrigation level of 100% of the field capacity in this characteristic, which gave the lowest value in this characteristic, 19.1033%.

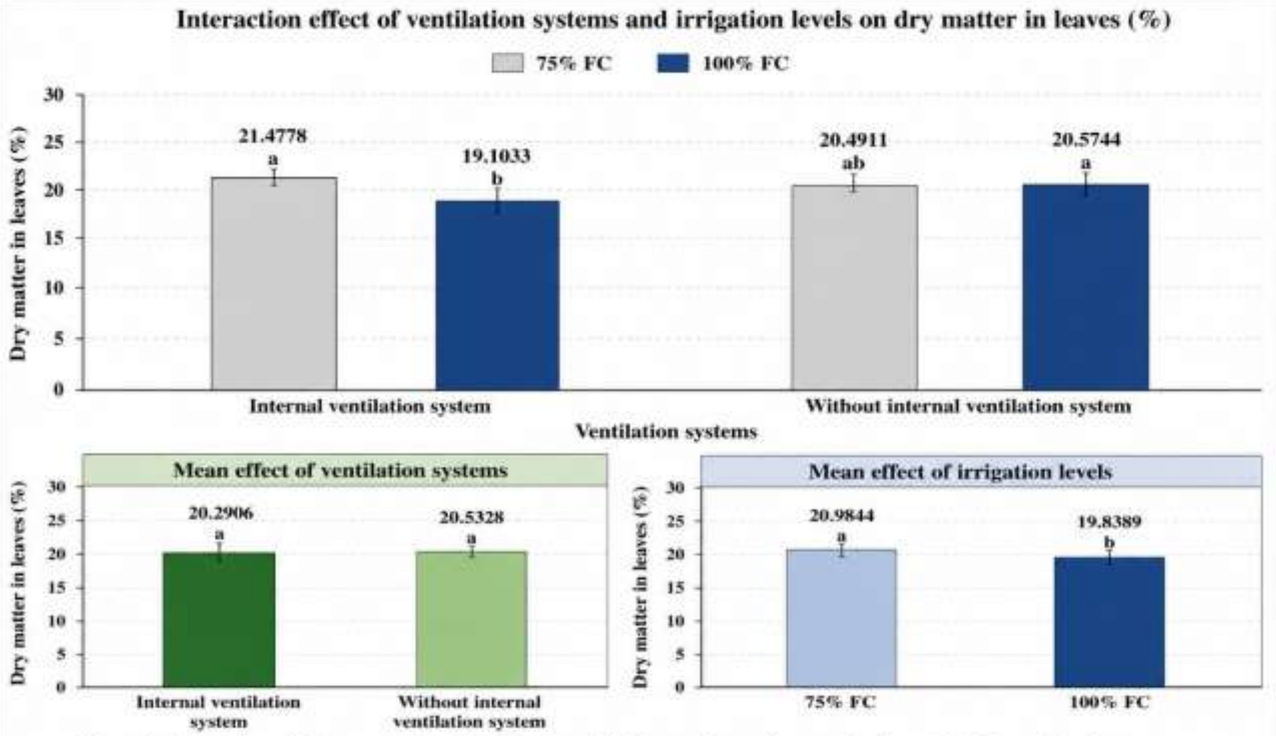

Figure 2. Effect of ventilation systems, irrigation levels, and their interaction on dry matter in leaves (%) of cucumber plants grown under greenhouse conditions. Means followed by the same letter are not significantly different according to Duncan's multiple range test at $P \leq 0.05$.

*Means sharing the same alphabetical letter for each factor and for each interaction do not differ significantly from each other according to Duncan's polynomial test at a probability level of ($P \leq 0.05$).

The results in figure (3.) show that the ventilation system with an extractor fan at the front of the greenhouse and internal ducted fans significantly outperformed the ventilation system with an extractor fan at the front of the greenhouse without internal ducted fans in this characteristic. The area of a single leaf reached 258.506 cm^2 $leaf^{-1}$ in the superior system, while the area of a single leaf in the second system was 218.947 $cm^2 leaf^{-1}$. Regarding the effect of drip irrigation levels, significant differences were also observed between irrigation levels of 75% and 100% of field capacity for the area of a single leaf. The 100% field capacity irrigation level resulted in a value of 251.099 $cm^2 leaf^{-1}$ in this characteristic, compared to 226.353 $cm^2.leaf^{-1}$ at the 75% field capacity irrigation level. The results of the dual interaction between ventilation systems and drip irrigation levels show significant differences in the coefficients of this interaction in terms of single leaf area. The highest significant advantage was recorded when the ventilation system with an extractor at the front of the greenhouse combined with internal ducted fans and an irrigation level of 100% of field capacity, with a single leaf area value of 280.248 $cm^2 leaf^{-1}$, significantly surpassing all other interaction coefficients. The lowest value was recorded when the ventilation system with an extractor at the front of the greenhouse combined with no internal ducted fans and an irrigation level of 75% of field capacity, reaching 215.943 $cm^2 leaf^{-1}$ for this characteristic.

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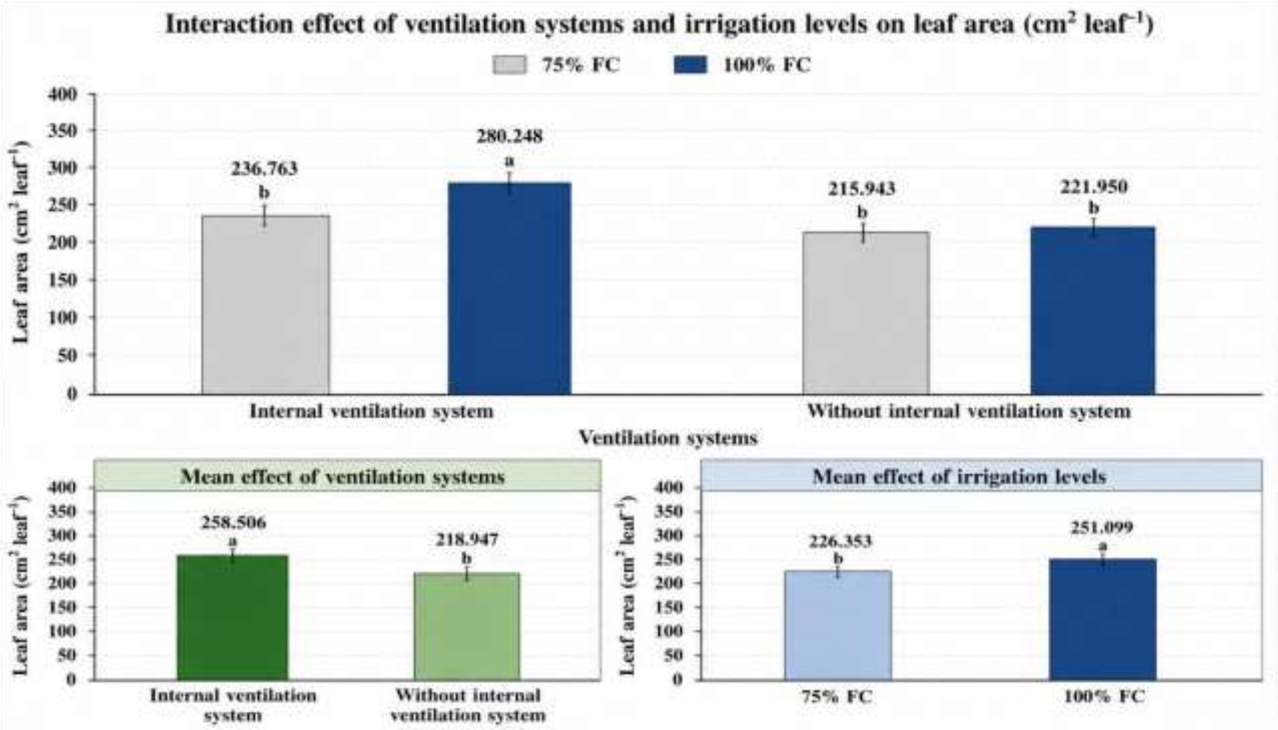

Figure 3. Effect of ventilation systems, irrigation levels, and their interaction on leaf area (cm² leaf⁻¹) of cucumber plants grown under greenhouse conditions. Means followed by the same letter are not significantly different according to Duncan's multiple range test at $P \leq 0.05$.

*Means sharing the same alphabetical letter for each factor and for each interaction do not differ significantly from each other according to Duncan's polynomial test at a probability level of ($P \leq 0.05$).

Based on the results shown in the last three figures when discussing vegetative growth characteristics related to leaf chlorophyll content (SPAD), dry matter percentage, and leaf area, it is clear that plants grown under a ventilation system with internal fans outperformed their counterparts grown without fans in most of the studied characteristics. This superiority was statistically significant in some characteristics and positive in others. The SPAD table results showed a marked advantage for the ventilation system with internal fans, as did the leaf area table, while the leaf dry matter percentage showed a positive advantage. This superiority is attributed to the important role of ventilation in improving the environmental conditions surrounding plants inside greenhouses. Ventilation fans reduce temperatures and increase air movement, which improves the efficiency of photosynthesis and enhances the activity of physiological processes within the plant. This, in turn, positively affects vegetative growth characteristics, including increased chlorophyll and leaf area [17] [18].

Regarding drip irrigation levels (100% and 75% of field capacity), the results showed significant variations in effects. The 100% field capacity irrigation level significantly improved some traits, such as chlorophyll content (SPAD) and leaf area. However, the 100% field capacity irrigation treatment also showed a positive effect on dry matter. This may be because adequate water supply promotes cell turgor and increases cell division and elongation. Conversely, reducing water intake leads to a decrease in some physiological activities [19].

The binary interactions between the studied factors showed significant advantages in many cases. The interaction coefficients of internal fan ventilation + 100% field capacity irrigation achieved the highest values for all studied traits, while the control treatment (no ventilation + 75%) recorded the lowest values. This indicates a synergistic effect

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between the studied environmental and agricultural factors in improving vegetative growth traits.

The results presented in figure (4.) indicate that the ventilation system significantly impacted marketable yield per plant. The ventilation system with an extractor fan at the front of the greenhouse and internal ducted fans significantly outperformed the system with an extractor fan at the front of the greenhouse without internal ducted fans in this regard, with a value of 3.44611 kg plant^{-1}. In contrast, the value of this trait in the ventilation system with an extractor fan but without internal ducted fans was 2.73444 kg plant^{-1}. Regarding the effect of drip irrigation levels on marketable yield per plant (kg plant^{-1}), the irrigation level at 100% of field capacity showed a significant advantage, with a value of 3.49500 kg plant^{-1}, over the irrigation level at 75% of field capacity, with a value of 2.68556 kg plant^{-1}. Based on the results of the dual interaction between ventilation systems and drip irrigation levels, the data shows that the highest marketable yield per plant (3.96333 kg plant^{-1}) was achieved when the ventilation system with an extractor at the front of the greenhouse was combined with internal ducted fans and an irrigation level of 100% of field capacity. This combination significantly outperformed all other treatments in this interaction. Conversely, the lowest marketable yield per plant (2.44222 kg plant^{-1}) was achieved when the ventilation system with an extractor but without internal ducted fans was combined with an irrigation level of 75% of field capacity.

Figure 4. Interaction effect of ventilation systems and irrigation levels on marketing yield (kg plant^{-1}).

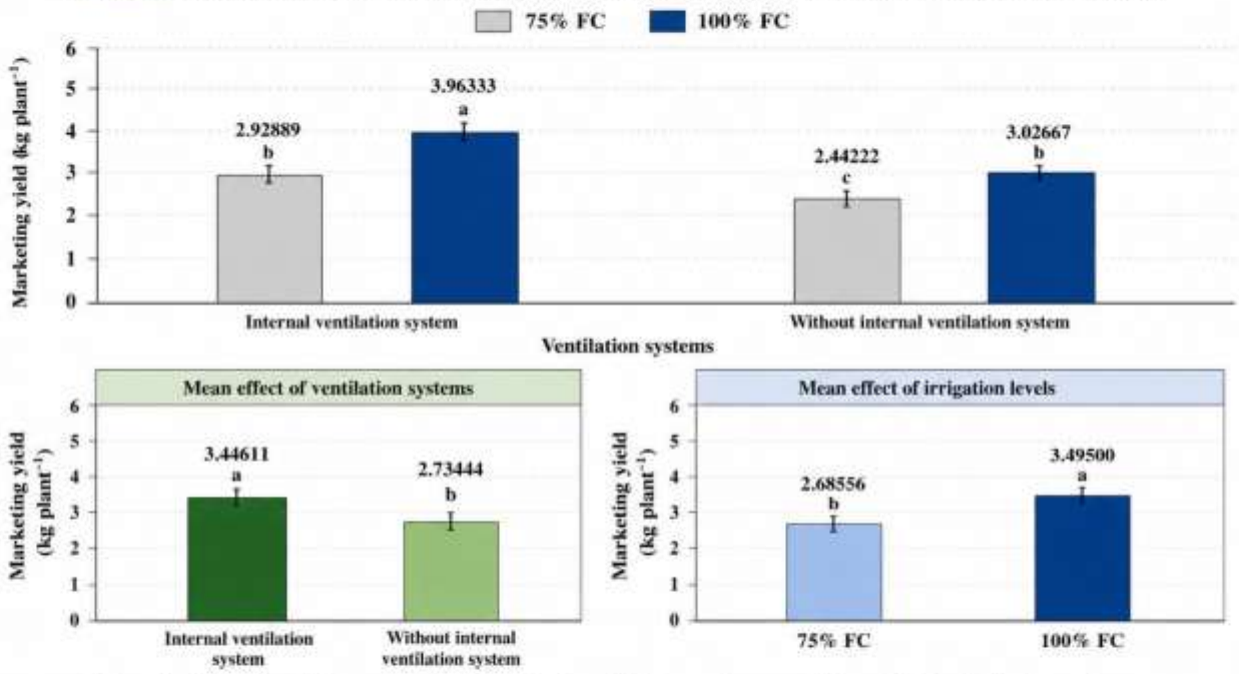

Figure 4. Effect of ventilation systems, irrigation levels, and their interaction on marketing yield (kg plant^{-1}) of cucumber plants grown under greenhouse conditions. Means followed by the same letter are not significantly different according to Duncan's multiple range test at $P \leq 0.05$.

*Means sharing the same alphabetical letter for each factor and for each interaction do not differ significantly from each other according to Duncan's polynomial test at a probability level of ($P \leq 0.05$).

figure (5.) indicates that the effect of ventilation systems on marketable yield was significantly higher when using a ventilation system with an extractor fan at the front of the greenhouse and internal ducted fans, with a value of 21.5322 kg m^{-2}, compared to a

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ventilation system with an extractor fan at the front of the greenhouse without internal ducted fans, which had a value of 17.1000 kg m^{-2} for this trait. Regarding the effect of drip irrigation levels on marketable yield, the 100% field capacity irrigation level was significantly higher, with a value of 21.8483 kg m^{-2}, compared to 16.7839 kg m^{-2} at the 75% field capacity irrigation level. Regarding the effect of the dual interaction between ventilation systems and drip irrigation levels, the results indicate significant differences between the treatments of this interaction in the marketable yield of the fruit. The highest significant value for this trait was recorded when the ventilation system with an extractor at the front of the greenhouse interacted with internal ducted fans at a 100% field capacity irrigation level, reaching 24.7711 kg m^{-2}. The lowest value was 15.2744 kg m^{-2} when the ventilation system with an extractor at the front of the greenhouse interacted with without internal ducted fans at a 75% field capacity irrigation level in the marketable yield of the fruit.

Figure 5. Interaction effect of ventilation systems and irrigation levels on marketing yield (kg m^{-2}).

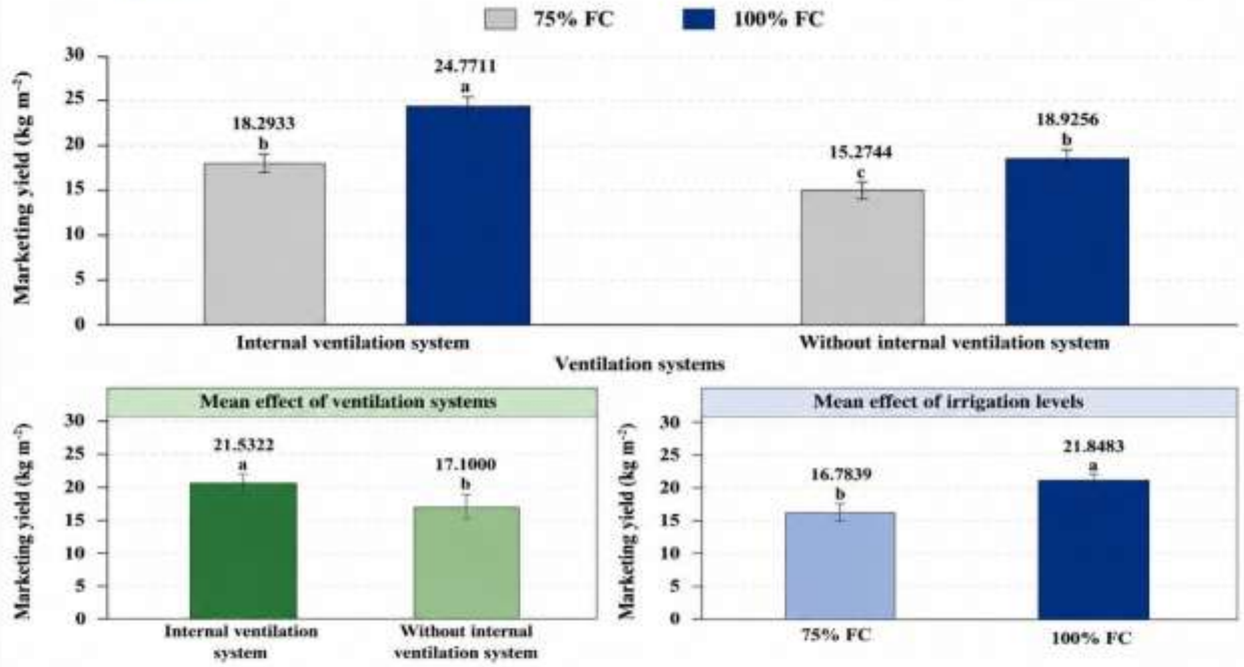

Figure 5. Effect of ventilation systems, irrigation levels, and their interaction on marketing yield (kg m^{-2}) of cucumber plants grown under greenhouse conditions. Means followed by the same letter are not significantly different according to Duncan's multiple range test at $P \leq 0.05$.

*Means sharing the same alphabetical letter for each factor and for each interaction do not differ significantly from each other according to Duncan's polynomial test at a probability level of ($P \leq 0.05$).

figure (6.) indicates that the average effect of ventilation systems on the marketable yield of the greenhouse shows a significant difference between a ventilation system with an extractor fan at the front of the greenhouse and internal ducted fans, and a ventilation system with an extractor fan at the front of the greenhouse without internal ducted fans. The value of the effect reached 4.3077 ton $house^{-2}$ for the superior system compared to the latter, which reached 3.4181 tons. Regarding the effect of drip irrigation levels on this trait, the 100% field capacity irrigation level significantly exceeded the 75% field capacity irrigation level, which reached 3.3569 ton $house^{-2}$. As for the effect of the dual interaction between ventilation systems and drip irrigation levels, the results indicate that in all treatments of this interaction

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there are significant differences in the marketable yield of the greenhouse. The highest significant value for this characteristic was recorded when the ventilation system with an air extractor at the front of the greenhouse was combined with internal ductual ventilation fans and at an irrigation level of 100% of the field capacity, amounting to 4.9542 tons per greenhouse. The lowest value was 3.0528 tons per greenhouse when the ventilation system with an air extractor at the front of the greenhouse was combined with internal ductal ventilation fans and at an irrigation level of 75% of the field capacity in the marketable yield of the greenhouse.

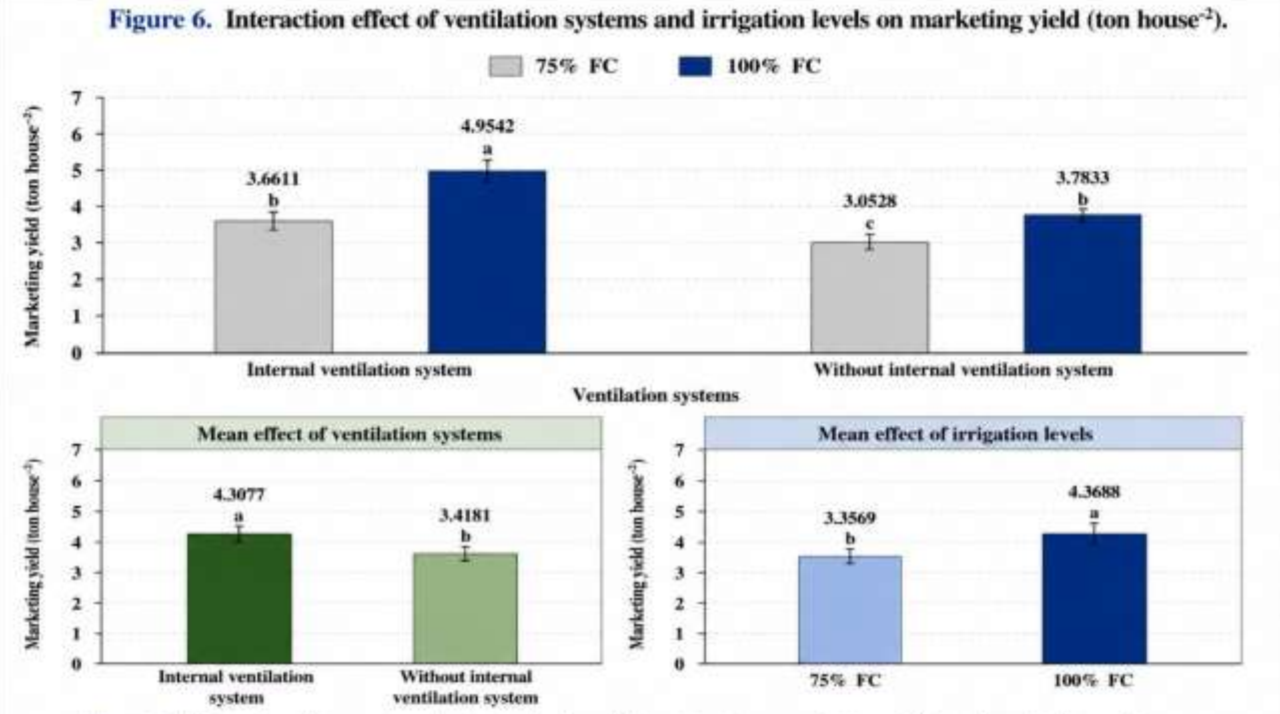

Figure 6. Effect of ventilation systems, irrigation levels, and their interaction on marketing yield (ton house⁻¹) of cucumber plants grown under greenhouse conditions. Means followed by the same letter are not significantly different according to Duncan's multiple range test at $P \leq 0.05$.

*Means sharing the same alphabetical letter for each factor and for each interaction do not differ significantly from each other according to Duncan's polynomial test at a probability level of ($P \leq 0.05$).

The crop analysis results showed that the significant positive increases in vegetative growth characteristics achieved with the use of a ventilation system equipped with internal fans and drip irrigation directly improved various crop traits, including marketable yield per plant, total marketable fruit yield, and the marketable yield of the greenhouse. The results demonstrated the superiority of plants grown in the greenhouse with internal fans in most crop characteristics compared to those grown in the greenhouse without internal fans. This superiority was evident in several characteristics and positive in others. This is attributed to the crucial role of ventilation in improving the environmental conditions within the greenhouse by lowering temperatures, reducing relative humidity, improving air movement, and increasing gas exchange efficiency. This leads to increased photosynthetic efficiency, greater carbohydrate accumulation and translocation to the fruiting organs, and consequently, higher yield indicators. Furthermore, improving the environmental conditions surrounding the vegetative parts leads to increased efficiency in nutrient and water absorption, which is reflected in fruit growth and increased yield. These results are consistent with those [20], who demonstrated that improved ventilation within greenhouses enhances growth and productivity due to improved microclimate. [18] also indicated that regulating air circulation within greenhouses improves the efficiency of plant physiological processes, leading to increased yield.

Regarding the effect of drip irrigation levels, the results showed that irrigating at 100% of field capacity was superior in most yield traits compared to irrigating at 75% of field capacity. This resulted in significant increases in several traits, including the number of fruits and some yield indicators, while other traits, such as fruit weight and length, showed positive results in some treatments. This may be attributed to the fact that providing sufficient water maintains cell turgor and ensures the efficient continuation of physiological processes, particularly photosynthesis and the translocation of its products to the fruits, which in turn leads to increased yield and improved quality. Conversely, low soil moisture reduces the efficiency of vital processes within the plant and decreases the rate of nutrient translocation to the fruits. These results are consistent with those [21], who demonstrated that increased water supply efficiency in greenhouse conditions leads to improved cucumber crop characteristics. Similarly, [22] showed that regular water supply leads to increased water use efficiency and improved productivity.

Based on the yield trait results, it was observed that the bilateral interactions of the studied factors resulted in significant additional increases in several traits compared to the effect of each factor individually. The interaction coefficients between the ventilation system with internal duct fans and irrigation at 100% of field capacity achieved the highest values for most yield traits, while the control parameters recorded the lowest values. This is likely due to the complementary and cumulative effect of various environmental and agricultural factors. Improved ventilation and adequate water supply led to improved vegetative growth efficiency and increased translocation of photosynthetic products to the fruit, which in turn led to increased productivity indicators.

Conclusions

This study concludes that using a ventilation system equipped with an air extractor at the front of the greenhouse, along with internal ducted ventilation fans, significantly improved the growth characteristics and yield of cucumber crops. Furthermore, irrigating at 100% of field capacity yielded the best results compared to other irrigation levels. These findings highlight the importance of integrated ventilation and irrigation management in enhancing the efficiency of the protected environment and increasing crop productivity, which positively impacts overall agricultural production efficiency in greenhouses. The study recommends adopting this system for commercial cucumber production, while emphasizing the need for future studies to evaluate the system's efficiency under different climatic conditions, its impact on energy consumption and water use efficiency, and its applicability to other vegetable crops.

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