



INTEGRATIVE EFFECTS OF SMART IRRIGATION AND VENTILATION SYSTEMS ON YIELD OF CUCUMBER UNDER GREENHOUSE CONDITIONS

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Article history:	Abstract:
Received: 20 th February 2026 Accepted: 11 th March 2026	This study was conducted over two agricultural seasons in Diyala Governorate, Al-Khalis District, Hebheb Subdistrict, Republic of Iraq. Four plastic greenhouses were used, planted with cucumbers, with two designated for a smart irrigation system under both forced and natural ventilation treatments, while the other two were designated for a traditional irrigation system under the same two ventilation treatments. The smart irrigation system relied on soil moisture sensors connected to an automated control system to monitor and regulate irrigation, and its performance was evaluated in comparison to the traditional irrigation system. The experiment was designed according to a split-plot arrangement within a Randomized Complete Block Design (RCBD) with three replications. Ventilation systems (forced and natural) were assigned to the main plots, while irrigation systems (smart and traditional) were assigned to the sub-plots. Means were compared using the Least Significant Difference (LSD) test at a 0.05 significance level. Yield traits showed a notable improvement under the smart irrigation system, with increased fruit weight and number per plant, particularly under forced ventilation, which achieved 45 fruits per plant. Consequently, the early plant yield, total plant yield, and the final production per plastic greenhouse increased compared to traditional irrigation. The highest production was achieved through the combination of smart irrigation and forced ventilation, with averages reaching 0.82 kg, 5.3 kg, and 1082 kg, respectively. This highlights the integrative effect between efficient water management and improved microclimatic conditions inside the protected greenhouse.

Keywords: Smart irrigation, protected agriculture, cucumber crop, forced ventilation.

INTRODUCTION:

By the year 2050, it is estimated that the world population will rise to 9.15 billion people at a rate greater than the current number of 7.79 billion people. This will put pressure on agricultural resources and increase the demand for food. As it is known, food comes from agriculture, and agriculture depends on water. Therefore, there are concerns about water scarcity and all countries should develop strategies for water management and agricultural systems (Aujla *et al.*, 2020). To meet the increasing demand for crops and vegetables, it is necessary to consider and implement sustainable agriculture strategies, such as protected agriculture using modern technology, as this can be compared to traditional irrigation methods and the use of drip irrigation using modern technology, as traditional irrigation methods ensure that fields are flooded with water, which may lead to a large waste of water and contribute to the problem of water scarcity in many areas. On the other hand, drip irrigation is a more efficient way to deliver water directly to plants' roots, reducing water waste and improving crop productivity. Traditional drip irrigation systems can be susceptible to leaks and clogs, reducing efficiency and potential crop loss. To treat these issues, modern technology has been developed to improve the efficiency and effectiveness of drip irrigation systems (Ibragimov *et al.*, 2020).

Reference studies have agreed that in protected agriculture and choosing an appropriate irrigation system is crucial to maximizing crop productivity while conserving vital resources especially water and irrigation systems ensure that crops receive enough water to grow but their effectiveness can vary greatly based on the method used. Several types of irrigation systems have been used in agriculture including surface irrigation, sprinkler irrigation and drip irrigation and

each has its own advantages and disadvantages when applied in protected environments such as greenhouses, tunnels (Kamiński *et al.*, 2019). Drip irrigation systems that use sensors and precise control valves can detect changes in soil moisture levels and adapt to them, ensuring that plants receive the right amount of water at the right time. In addition, the use of advanced materials Advanced in construction drip irrigation systems, such as hydrogel, can help retain moisture in the soil, which reduces irrigation frequency and improves crop productivity (Barragan *et al.*, 2022).

Modern greenhouses are often equipped with automated heating, cooling and ventilation systems which facilitate precise control over environmental conditions, the use of solar panels and geothermal systems for heating, cooling has made these structures more sustainable and reducing reliance on fossil fuels and lowering operational costs, there for other studies have worked with physical barriers and in some cases insect-proof netting is used to prevent pests from entering the greenhouse, this method combined with double door airlocks and reduces insect entry while allowing ventilation and air exchange (Idumah *et al.*, 2020).

The cucumber crop (*Cucumis sativus*) is characterized by its high-water content (up to approximately 95%), in addition to containing a range of vitamins such as vitamin C and some antioxidant compounds, making it an important element in human nutrition. It also plays a significant economic role in supporting farmers' incomes, especially in intensive production systems, where high yields can be achieved under suitable environmental conditions (Shittu *et al.*, 2025).

The current study aims to compare traditional and smart drip irrigation systems and greenhouse ventilation systems and their effect on the growth characteristics cucumber crops.

2. MATERIAL AND METHODS

2.1 Describe the study and location: The experiment was conducted in the Habhab area of Al-Khalis District in Diyala Governorate, Republic of Iraq, where plastic houses were established to conduct a study aimed at improving irrigation strategies in protected agriculture (Gutiérrez *et al.*, 2014). The soil in the region has a silty-sandy composition due to the proximity to the Diyala River and alluvial sediments, which gives it an average ability to retain moisture and the surface layers contain large pores that enhance aeration, but reduce the soil's ability to retain water for long periods, which requires distributing irrigation at close intervals. One of the main challenges of this soil is accumulation of salts in the surface layers due to high evaporation rates and poor natural drainage. Harsh climatic factors interact with soil characteristics to create an environment that requires careful water management (Raheman *et al.*, 2018).

2.2. describe Greenhouses: The greenhouses in this study were designed in a way that combines advanced engineering techniques and modern technology to achieve an ideal agricultural environment that enhances crop growth and improves their productivity and quality (Gupta *et al.*, 2016). The external dimensions of the greenhouse are characterized by a balance between space utilization efficiency and resource distribution effectiveness, as the greenhouse extends to about 30 meters in length and 9 meters in width and the internal space has been carefully divided, so that it is organized into longitudinal agricultural terraces with a central corridor 2 meters wide, which facilitates the movement of workers and provides equal distribution of lighting and ventilation within all sections of the greenhouse, thus ensuring the creation of a suitable environment for plant growth. The structure was covered with a high-performance 200- μ m polyethylene (PE) film, characterized by a light transmittance of 88%, UV-protection of 80%, and infrared (IR) filtration of 77%. This cladding ensures optimal photosynthetically active radiation (PAR) while maintaining thermal stability through effective insulation (Al-Mahdawi and Al-Tikriti, 2023).

To maintain an ideal microclimate, an integrated ventilation and cooling system was utilized. This included a high-capacity industrial blower (3,000 m³/h) positioned at the greenhouse apex, synchronized with strategic ventilation openings to facilitate heat dissipation and humidity regulation, thereby mitigating fungal disease risks (Saber and Hassan, 2024).

Precision management was achieved via an intelligent monitoring system equipped with high-sensitivity sensors for real-time tracking of temperature, relative humidity, and solar radiation. Data were processed through a central automated unit that adjusted ventilation and cooling parameters dynamically. This mechatronic integration optimizes resource efficiency and ensures a stable cultivation environment characterized by minimal fluctuations in ambient conditions (Zhu *et al.*, 2025).

2.3. Drip irrigation systems: Automated Irrigation Control System The experimental site was equipped with a high-precision irrigation controller (Hingo Global, Inc.). The unit is housed in a weather-resistant polymer enclosure (22 × 17.8 × 9.5 cm) and features a dual-power architecture. It utilizes a 220V AC input, regulated by an internal step-down transformer to 24V AC for operational safety and solenoid efficiency. To prevent data loss during power fluctuations, the device incorporates a lithium-based internal backup battery (CR-type), ensuring the retention of temporal settings and programmed schedules. Furthermore, the controller integrates a dedicated interface for auxiliary environmental sensors, specifically tensiometric soil moisture sensors and rain-interruption modules, allowing for real-time irrigation adjustments based on substrate matric potential and ambient precipitation (Al-Hamdani and Roberts, 2024; Smith *et al.*, 2025).

2.4. Plant Material and Cultural Practices: The experiment utilized the cucumber (*Cucumis sativus* L.) hybrid variety 'Ronnie' (Al-Muqadiyah Co., USA), a cultivar selected for its high market value and suitability for protected environments. The fruit characteristics at maturity include a length of 12–15 cm and a mean mass of 80–100 g. Optimal growth was maintained within a temperature range of 15–35°C and a relative humidity of 50–90%.

Sowing commenced on January 13, 2023, using sterilized 209-cell seedling trays filled with a peat moss substrate. To prevent damping-off, a preemptive fungicide treatment was applied. Germination (70% success rate) was completed by January 20, 2023. Seedlings were transplanted into the greenhouse on February 12, 2023, followed by immediate light irrigation to facilitate root establishment (Al-Zubaidi, 2023).

Crop management followed an integrated protocol: Fertilization: Soil applications of balanced NPK were supplemented with bi-weekly foliar fertilization to optimize photosynthetic efficiency. Canopy Management: Pruning was performed regularly to remove lateral shoots and senescent foliage, enhancing vertical growth and airflow. Plant Protection: An Integrated Pest Management (IPM) strategy was employed, utilizing scheduled applications of specific insecticides and fungicides to maintain phytosanitary standards (Kaufman and Miller, 2024; Rodriguez *et al.*, 2025).

2.5. Cultivation Practices: Cucumber seeds (cv. 'Ronnie') were sown on January 10, 2023, in 209-cell seedling trays containing a sterilized peat moss substrate. Initial germination was observed on January 13 (70% germination rate), with full emergence completed by January 20. Seedlings were transplanted into the greenhouse on February 12, 2023, following a standardized plant density protocol of one plant per cell to eliminate resource competition for light and nutrients (Hassan *et al.*, 2023).

Irrigation was managed via a pressure-compensated drip irrigation system, delivering water directly to the rhizospheric zone to maximize water use efficiency (WUE). To further reduce non-productive evaporation and maintain soil moisture stability, a black polyethylene mulch was utilized. Irrigation scheduling was dynamically calibrated based on the crop's developmental stage and evapotranspiration rates. Key monitoring parameters included the vertical moisture penetration depth and the cumulative seasonal water volume, ensuring the matric potential remained within the optimal range for root uptake (Ahmed and Al-Tikriti, 2024).

Harvesting was conducted systematically as fruits reached commercial maturity, characterized by a length of 12–15 cm and a fresh mass of 80–100 g. The early maturation trait of the 'Ronnie' hybrid allowed for an accelerated production cycle, optimizing the economic return per unit area (Miller and Thompson, 2025).

2.6. Studied Traits: Regarding fruiting traits, the average number of fruits per plant, Fruit weight (Kg) and the early fruit yield (Kg) was evaluated at the start of the season to determine early production efficiency and the total fruit yield per greenhouse was also recorded, reflecting overall crop success.

2.7. Statistical Analysis: To determine whether the differences between the smart irrigation system and the traditional system were statistically significant, one-way and two-way ANOVA tests were conducted. These tests assessed the effect of the irrigation strategy on the studied treatments. The means of the different treatments were compared using the least significant difference (LSD) method at a p-value of less than 0.05.

3. RESULTS AND DISCUSSION

3.1 Effect of smart irrigation system, greenhouse type and ventilation system on Number of Fruits (fruit/plant): The number of fruits per plant is a key yield component that reflects flowering success, fruit set efficiency, and the overall balance between vegetative growth and reproductive development. The results in figure (1) indicate that greenhouse type and ventilation system had a highly significant effect on the number of fruits per plant ($P < 0.05$). The clear separation among treatments confirms that environmental control plays a key role in determining crop productivity, which is consistent with previous findings (Montero *et al.*, 2001; Shamshiri *et al.*, 2018).

The highest number of fruits per plant was recorded under T_1 (Smart House + Forced Ventilation) (45), followed by T_2 (Smart House + Natural Ventilation) (43), with no significant difference between them. This suggests that smart greenhouse systems are highly effective in optimizing plant growth conditions through better regulation of temperature, humidity, and light. Similar results were reported by Shamshiri *et al.* (2018), who emphasized that advanced greenhouse technologies improve crop performance and yield stability.

In contrast, T_3 (Conventional House + Forced Ventilation) and T_4 (Conventional House + Natural Ventilation) produced significantly lower fruit numbers, with T_4 recording the lowest values (32). This reflects the limited ability of conventional greenhouses, especially under natural ventilation, to maintain optimal microclimatic conditions. Previous studies have shown that inadequate environmental control leads to reduced fruit set due to heat stress and poor gas exchange (Kittas *et al.*, 2012).

The comparison between ventilation systems indicates that forced ventilation improved fruit number compared with natural ventilation, particularly in conventional houses. This agrees with Kittas *et al.* (2012), who reported that forced ventilation enhances airflow, reduces internal temperature, and improves plant physiological processes. However, the smaller difference between T_1 and T_2 suggests that smart greenhouse systems can partially compensate for less intensive ventilation, as also noted by Montero *et al.* (2001).

Overall, the results demonstrate that greenhouse type has a stronger influence than ventilation system, although the combination of smart house and forced ventilation (T_1) provides optimal conditions for maximizing fruit production. These findings agree with previous research highlighting the importance of integrated environmental control systems in improving greenhouse crop productivity (Shamshiri *et al.*, 2018).

The results of the present study showed that smart irrigation significantly increased the number of fruits per plant compared to the conventional irrigation system. This improvement can be attributed to the precise regulation of water supply, which ensures optimal soil moisture conditions and minimizes plant water stress during critical stages such as flowering and fruit set. Adequate water availability enhances pollination efficiency, reduces flower abortion, and promotes fruit formation, leading to a higher number of fruits per plant.

Moreover, smart irrigation improves nutrient availability and uptake, particularly nitrogen and potassium, which play a vital role in reproductive development and fruit set. Maintaining optimal plant water status also enhances photosynthetic activity and assimilate partitioning towards reproductive organs, thereby increasing fruit number.

These findings are supported by recent studies. For instance, a study on sensor-based irrigation systems reported that optimized smart irrigation increased fruit yield by 47%, with the number of fruits rising from 45 to 56 fruits per plant under improved irrigation management. Similarly, research Ortega-Farias *et al.* (2021) indicated that irrigation levels significantly influence yield components, including the number of fruits per plant, with higher and well-managed irrigation resulting in increased fruit numbers.

Furthermore, recent findings such as Ghazi *et al.* (2025); Martelli *et al.* (2025); Sharma *et al.* (2025) and Dirlik *et al.* (2025) confirmed that irrigation regimes significantly affect both total yield and fruit number, where optimal irrigation conditions led to the highest number of fruits compared to deficit irrigation treatments. These results emphasize the critical role of smart irrigation in enhancing reproductive growth and maximizing crop productivity.

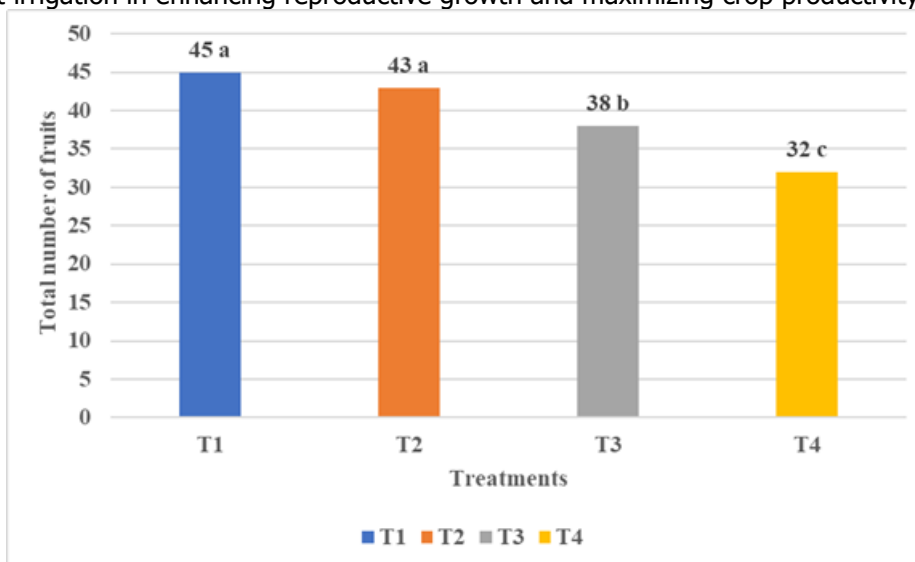


Figure (1): Effect of smart irrigation system, greenhouse type and ventilation system on Number of Fruits (fruit/plant).

T1: Smart House + Forced Ventilation, T2: Smart House + Natural Ventilation, T3: Conventional House + Forced Ventilation, T4: Conventional House + Natural Ventilation.

*Different letters indicate significant differences among treatment means according to LSD Test at the 0.05 level.

3.2. Effect of smart irrigation system, greenhouse type and ventilation system on Yield Components (Early Yield, Yield per Plant, and Total Productivity): Yield traits represent a decisive agronomic indicator that integrates the effects of early yield, yield per plant, and total greenhouse productivity. As shown in the figures (2), (3) and (4), smart irrigation and ventilation systems had a clear impact on early yield, plant yield, and total yield per greenhouse across two growing seasons.

Treatment T₁ recorded the highest values, with an early yield of 0.82 kg·m⁻², a yield per plant of 5.3 kg, and a total yield of 1082 kg per greenhouse, reflecting superior reproductive performance under these conditions. Treatment T₂ produced an early yield of 0.71 kg·m⁻², a yield per plant of 4.76 kg, and a total yield of 981 kg per greenhouse, confirming that smart irrigation combined with forced ventilation outperformed smart irrigation with natural ventilation. In contrast, conventional greenhouses showed lower performance. Treatment T₃ yielded 0.61 kg·m⁻² early yield, 3.82 kg per plant, and a total yield of 787 kg per greenhouse. The lowest performance was observed in treatment T₄, with an early yield of 0.56 kg·m⁻², 3.56 kg per plant, and a total yield of 742 kg per greenhouse. These differences highlight the less favorable production conditions in traditional systems, and the decline in yield serves as an important indicator encouraging farmers to adopt modern technologies such as smart irrigation and forced ventilation.

While ventilation efficiency significantly influences yield by regulating temperature and humidity, irrigation management is equally critical in determining final productivity. Adequate irrigation tailored to plant demand ensures sustained nutrient uptake, maintains leaf turgor, and supports metabolite translocation during fruit filling. In smart greenhouse systems, the integration of environmental control with optimal irrigation scheduling likely improved water use efficiency and reduced stress during key growth stages. Conversely, the lack of synchronization between irrigation and ventilation in conventional systems may have contributed to suboptimal resource utilization and reduced yield accumulation.

Improved climate regulation in greenhouses is widely associated with enhanced biomass accumulation and yield stability through better control of temperature, humidity, and radiation absorption, which collectively support efficient photosynthesis and metabolite distribution (Jones, 2008). The present findings are consistent with this concept and further emphasize the importance of integrating ventilation and irrigation strategies to maximize productivity in protected agriculture systems.

The results of the present study revealed that smart irrigation significantly improved yield per plant, early yield, and total yield compared to the conventional irrigation system. This enhancement can be attributed to the precise regulation of water supply, which ensures optimal soil moisture conditions and minimizes plant exposure to water stress,

particularly during critical growth stages such as flowering and fruit development. Maintaining adequate water availability during these stages promotes better fruit set, reduces flower and fruit drop, and enhances assimilate translocation toward developing fruits.

Smart irrigation also improves nutrient uptake efficiency and physiological processes such as photosynthesis, which directly contribute to increased biomass accumulation and fruit production. Consequently, plants grown under smart irrigation conditions produce higher yields per plant and achieve earlier fruiting, resulting in increased early yield, which is a key economic factor in protected cultivation systems.

These findings are supported by recent studies. For instance, a study of Dal Magro *et al.* (2026) demonstrated that automated irrigation systems significantly enhanced total yield and fruit quality in strawberry plants by maintaining optimal water levels and reducing water stress. Similarly, research on smart irrigation systems indicated that yield improvements of 5–20% can be achieved due to precise water management and reduced stress during critical growth stages.

Furthermore, studies on tomato and horticultural crops showed that water stress significantly reduces total yield and marketable yield, while optimal irrigation conditions lead to the highest productivity and better yield components, including fruit number and weight. In addition, sensor-based irrigation systems were found to significantly influence total yield and biomass accumulation, confirming the importance of precise irrigation scheduling in maximizing crop productivity.

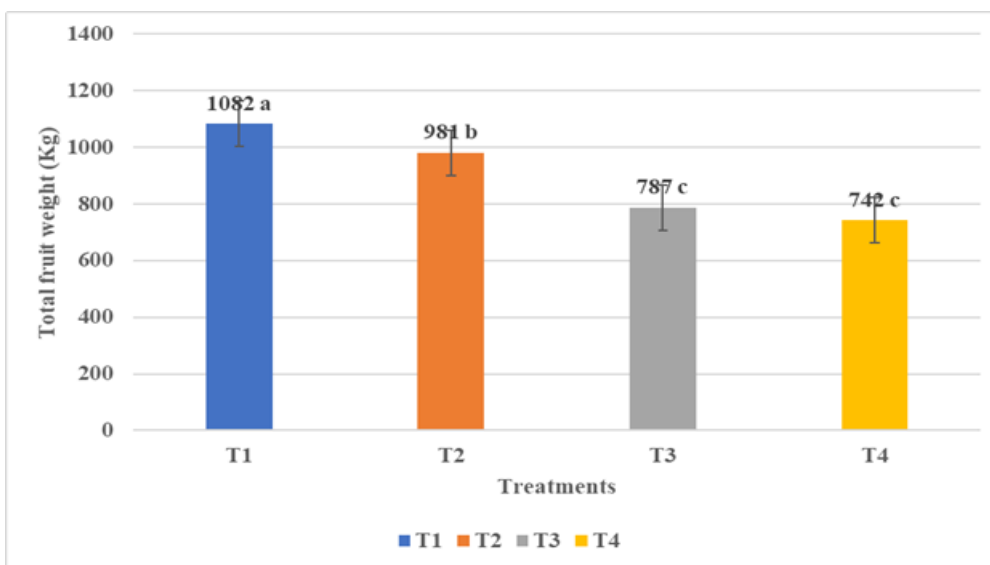


Figure (2): Effect of smart irrigation system, greenhouse type and ventilation system on Total Productivity
 T1: Smart House + Forced Ventilation, T2: Smart House + Natural Ventilation, T3: Conventional House + Forced Ventilation, T4: Conventional House + Natural Ventilation.

*Different letters indicate significant differences among treatment means according to LSD Test at ($P \leq 0.05$).

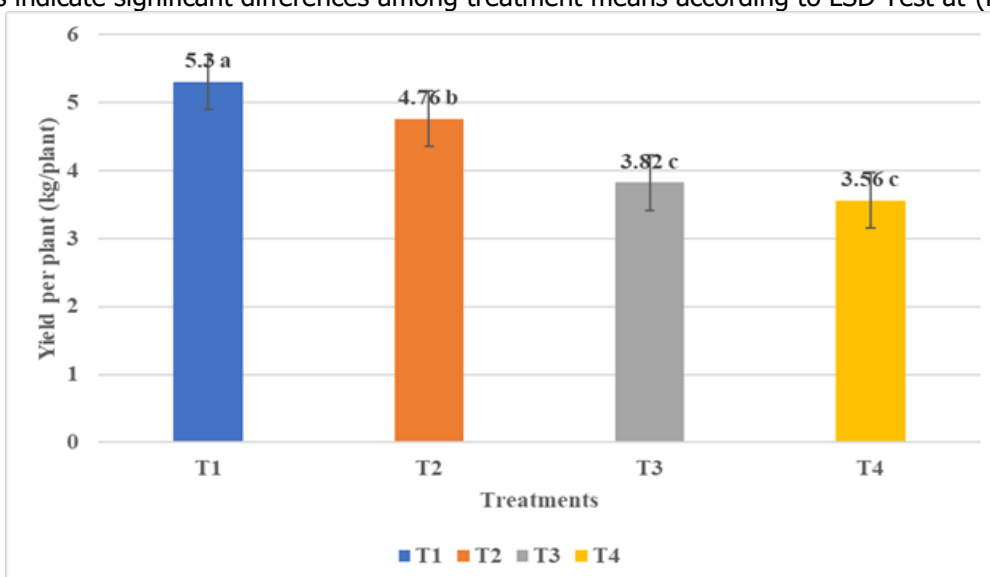


Figure (3): Effect of smart irrigation system, greenhouse type and ventilation system on Yield/ Plant.
 T1: Smart House + Forced Ventilation, T2: Smart House + Natural Ventilation, T3: Conventional House + Forced Ventilation, T4: Conventional House + Natural Ventilation.

*Different letters indicate significant differences among treatment means according to LSD Test at ($P \leq 0.05$).

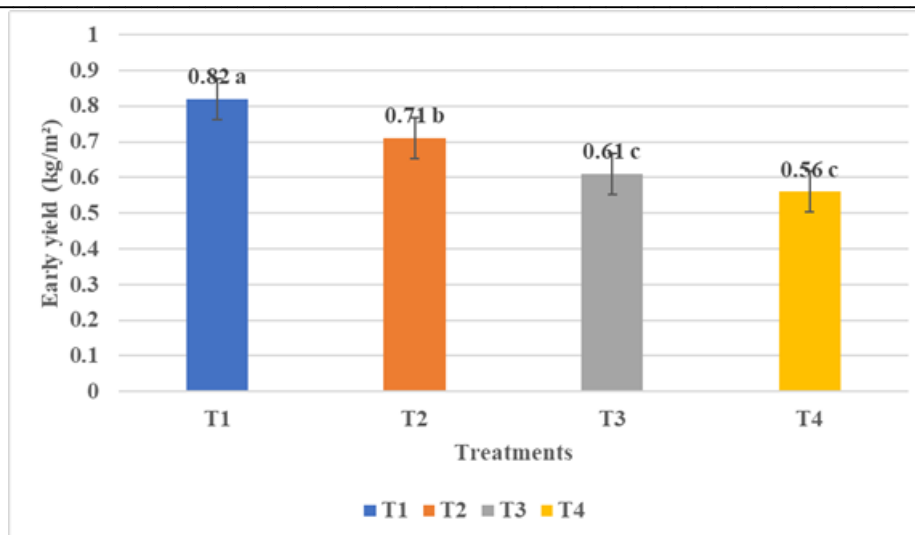


Figure (4): Effect of smart irrigation system, greenhouse type and ventilation system on Early Yield
 T1: Smart House + Forced Ventilation, T2: Smart House + Natural Ventilation, T3: Conventional House + Forced Ventilation, T4: Conventional House + Natural Ventilation.

*Different letters indicate significant differences among treatment means according to LSD Test at ($P \leq 0.05$).

CONCLUSION: This study concludes that the integration of sensor-based smart irrigation and forced ventilation systems represents the optimal strategy for enhancing cucumber productivity in protected environments. The results demonstrate that smart irrigation significantly outperforms traditional methods, not only in water conservation but also in improving key yield components, including fruit weight and number. The synergy between automated moisture control and mechanical ventilation created an ideal microclimate. Therefore, adopting these automated mechatronic systems is highly recommended to ensure agricultural sustainability and maximize resource-use efficiency in arid and semi-arid regions.

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