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Eureka Journal of Agricultural Science & Bio-Innovation (EJASB)

ISSN 2760-4969 (Online) Volume 2, Issue 4, April 2026

https://eurekaoa.com/index.php/7

EFFECTS OF SMART IRRIGATION AND VENTILATION SYSTEMS ON GROWTH TREATS FOR GREENHOUSE-GROWN CUCUMBER CUCUMIS SATIVUS

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Abstract:

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 (Cucumis sativus), 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. The results showed that the smart irrigation system led to a significant improvement in water use efficiency. Vegetative growth traits were clearly influenced by both irrigation and ventilation systems. Smart irrigation contributed to earlier flowering, with plants reaching 50% flowering in a shorter time of 23.54 days compared to 35.17 days under traditional irrigation. It also improved plant growth, reflected in increased plant height, number of leaves, number of lateral branches, leaf area, and chlorophyll content, recording values of 271.13 cm, 43.92 leaves, 7.50 branches/plant, 15956.02 cm²/plant, and 131.51 SPAD, respectively. These results indicate enhanced physiological performance and nutrient use efficiency under optimal irrigation conditions.

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

Introduction:

Given the increasing scarcity of water resources, protected agriculture systems such as drip irrigation and hydroponics are essential for maximizing water efficiency and reducing waste, these methods allow for precise water delivery directly to the plant roots, minimizing evaporation and runoff (Dhanaraju et al, 2022).

In comparison, protected agriculture, which uses modern technology, can also provide a sustainable solution to meet the increasing demand for grain crops. Protected agriculture refers to the practice of growing crops in closed structures such as greenhouses, which provide a controlled environment for plants to grow. This allows farmers to grow crops throughout the year and protects them from pests and diseases, which leads to increased yields and improved crop quality. Developing modern technology to improve conditions within protected agricultural structures is very important, as precise climate control systems can regulate temperature, humidity, and light levels to create an ideal environment for crop growth. This is explained by the fact that the use of hydroponic and aeroponic farming systems, which do not depend on soil, can increase by improving crop productivity and reducing water use, and given that crops consume a large amount of water, it is necessary to develop new strategies for managing water resources and their efficiency. Therefore, it is important to consider modern irrigation strategies in protected agriculture and compare drip irrigation using advanced technology with traditional surface irrigation methods (El-Hendawy et al., 2019).

the components of a drip irrigation system using modern technologies consist of soil moisture sensors that continuously and accurately measure soil moisture, they collect information about the condition of the soil and analyze it and plant sends to the central control unit for determination and need for water, this Unit is fed from the central control unit, which is the founder of the system (Grieve, 2021). It relies on information sent by sensors and climate data, such as temperature, humidity and rainfall forecasts, as well as electronic valves to determine optimal watering schedules based on plant needs, as it automatically adjusts these through central valves and Works to control the valves. (El-Hendawy et al., 2019).

The studies have shown a group of technological solutions such as automatic ventilation systems where modern greenhouses are equipped with ventilation systems that automatically regulate humidity by allowing air exchange between the inside , the outside , these systems often work in conjunction with humidity sensors that detect high humidity levels , trigger the ventilation process in addition to the use of dehumidifiers for more controlled environments such as high-tech greenhouses dehumidifiers to effectively reduce humidity levels especially in areas where external conditions (such as rain or humidity) make natural ventilation ineffective. Some studies show that advanced climate control which includes heating, cooling and ventilation allows farmers to manage not only humidity but also temperature and airflow for example in the Netherlands greenhouses often combine energy-efficient heat pumps with climate control to ensure optimal conditions for crops while reducing energy costs (Shankar et al, 2020).

Cucumis sativus is one of the most important vegetable crops belonging to the Cucurbitaceae family, and it occupies a prominent position in global agricultural production due to its high nutritional and economic value. Cucumbers are widely cultivated in temperate and semi-arid regions, both in open fields and in protected cultivation systems such as greenhouses, thanks to their rapid growth, short production period, and high responsiveness to modern agricultural techniques (Sallam et al., 2021).

The current study aims to compare traditional and smart drip irrigation systems and greenhouse ventilation systems and their effect on the yield and its components of 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-µm 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 et al., 2023).

To maintain an ideal microclimate, an integrated ventilation and cooling system was utilized. This included a high-capacity industrial blower (3,000 m^3/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-Muqdadiyah 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: Sowing, Irrigation, and Harvesting: 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: Several vegetative traits were assessed to monitor plant development such as number of days to flowering, , indicating plant response to environmental conditions and the number of lateral branches was measured to determine plant productivity. Leaf chlorophyll content was analyzed as an indicator of plant health and efficient photosynthesis and the number of leaves per plant was counted, as well as plant height and leaf area, which influence light absorption.

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 Days to 50% Flowering: Table (1) clearly demonstrates a highly significant effect of greenhouse type and ventilation system on the number of days required to reach 50% flowering ($p < 0.001$; LSD = 3.192). The shortest flowering period was observed under T1 (Smart House + Forced Ventilation) with a mean of 23.54 days (SD = 2.25; SE = 0.80), followed by T2 (Smart House + Natural Ventilation) at 27.85 days (SD = 1.31; SE = 0.46). Both treatments were statistically distinct, as indicated by different LSD grouping letters. Under conventional greenhouse conditions, flowering occurred later. T3 (Conventional House + Forced Ventilation) recorded 33.03 days (SD = 2.53; SE = 0.90), while the longest duration was found in T4 (Conventional House + Natural Ventilation) with 35.17 days (SD = 1.68; SE = 0.59). The difference between the lowest and highest means reached 11.63 days, which is agronomically substantial and statistically confirmed by the LSD value. The relatively small standard errors across treatments indicate stable experimental performance and limited within-treatment variability.

The progressive increase in flowering time from T_1 to T_4 suggests that greenhouse structural design and ventilation strategy markedly influenced crop phenology. Forced ventilation in the smart house (T_1) appears to have created conditions that accelerated flowering, possibly through improved air renewal, stable humidity, and moderated temperature fluctuations. This interpretation aligns with the findings of Boulard and Baille (1995), who reported that ventilation improves temperature regulation and enhances air exchange rates inside greenhouses, thereby influencing crop developmental responses. Several studies have reported that improved irrigation management, particularly under smart irrigation systems, can significantly influence the timing of flowering in crops. Smart irrigation enhances soil moisture availability within the optimal range, thereby reducing plant water stress and promoting faster physiological development. According to FAO (2012), maintaining appropriate soil moisture levels improves plant growth uniformity and shortens the vegetative phase, leading to earlier flowering. Similarly, studies by Fereres and Soriano (2007) demonstrated that optimized irrigation scheduling can enhance crop development rates and reduce the time required to reach flowering. Moreover, smart irrigation systems prevent both water deficit and excessive irrigation, ensuring stable growth conditions. This balance is crucial, as both drought stress and over-irrigation can delay flowering due to physiological disturbances in the plant.

Table (1): Effect of smart irrigation system, greenhouse type and ventilation system on Days to 50% Flowering

Treatments	Mean	Std. Deviation	Std. Error	LSD (α=0.05)	P value
T_1	23.54^{d}	2.25	0.80	3.192	<0.001*
T_2	27.85^{c}	1.31	0.46		
T_3	33.03^{b}	2.53	0.90		
T_4	35.17^{a}	1.68	0.59		

T_1: Smart House + Forced Ventilation, T_2: Smart House + Natural Ventilation, T_3: Conventional House + Forced Ventilation, T_4: 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 Plant Height (cm): Plant height is a key vegetative growth indicator reflecting the cumulative effects of greenhouse microclimate, ventilation efficiency, and plant physiological performance. As shown in Table (2), plant height was significantly affected by greenhouse type and ventilation system, with highly significant differences among treatments ($p < 0.001$) and a calculated LSD value of 20.95 cm, confirming a clear and reliable separation among treatment means. The tallest plants were recorded under T1, with a mean height of 271.13 ± 35.13 cm, indicating optimal growing conditions and superior vegetative vigor under this system. Plants grown under T2 showed a slightly reduced but still significantly high plant height of 254.63 ± 19.16 cm. Although lower than T1, this result demonstrates that smart greenhouse structures maintain favorable growth conditions even when natural ventilation is applied. In contrast, T3 produced a mean plant height of 233.75 ± 17.05 cm, reflecting reduced growth potential compared with smart greenhouse treatments despite the use of forced ventilation. The lowest plant height was observed under T4, with a mean value of 231.15 ± 19.02 cm, which did not differ significantly from T3 but was significantly lower than both smart greenhouse treatments. This highlights the limited ability of conventional greenhouse structures, particularly under natural ventilation, to provide optimal conditions for vertical plant growth.

The results of the present study demonstrated that smart irrigation significantly increased plant height compared to the conventional irrigation system. This improvement can be attributed to the ability of smart irrigation to precisely supply water according to crop requirements at different growth stages, thereby minimizing water stress and maintaining optimal soil moisture conditions within the root zone. Such conditions enhance nutrient uptake efficiency and promote cellular division and elongation, which are essential processes for vegetative growth and ultimately lead to increased plant height.

These findings are consistent with those reported by Howell (2001), who indicated that precise irrigation management improves plant growth by enhancing water distribution and reducing water losses. Similarly, Fereres and Soriano (2007) stated that modern irrigation technologies, particularly sensor-based irrigation systems, improve water use efficiency and reduce plant water stress, resulting in enhanced vegetative growth. Furthermore, Jones (2004) reported that irrigation scheduling based on plant physiological and environmental indicators improves plant water status, increases photosynthetic activity, and promotes growth, which is reflected in greater plant height.

Table (2): Effect of smart irrigation system, greenhouse type and ventilation system on Plant Height (cm)

Treatments	Mean	Std. Deviation	Std. Error	LSD (α=0.05)	P value
T_1	271.13 ^{a}	35.13	5.55	20.95	<0.001*
T_2	254.63 ^{b}	19.16	3.03		
T_3	233.75 ^{c}	17.05	2.70		
T_4	231.15 ^{c}	19.02	3.01		

T_1: Smart House + Forced Ventilation, T_2: Smart House + Natural Ventilation, T_3: Conventional House + Forced Ventilation, T_4: Conventional House + Natural Ventilation.

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

3.3. Effect of smart irrigation system, greenhouse type and ventilation system on Number of leaves (leaf/plant): The number of leaves per plant is a key indicator of vegetative vigor and canopy development, directly influencing photosynthetic capacity and assimilates production. As shown in Table (3), the number of leaves per plant was significantly affected by greenhouse type and ventilation system, with highly significant differences among treatments ($p < 0.001$) and a calculated LSD value of 2.10 leaves, confirming a clear separation among treatment means. The highest leaf numbers were recorded under T_1 with 43.92±4.05 leaves and T_2 with 43±2.64 leaves, indicating that smart greenhouse systems provided favorable conditions for sustained leaf initiation regardless of ventilation type.

In contrast, plants grown under conventional greenhouse conditions produced significantly fewer leaves. T_3 recorded 34.75 ± 4.52 leaves, while T_4 showed 35.04 ± 3.24 leaves, with no significant difference between these two treatments. The reduction of nearly nine leaves per plant compared with smart systems reflects limitations in environmental regulation that likely restricted vegetative expansion and leaf differentiation.

These differences are attributable not only to ventilation efficiency but also to irrigation management. Adequate and well-scheduled irrigation ensures continuous nutrient availability, maintains leaf turgidity, and supports cell division within the apical meristem, all of which are essential for sustained leaf initiation. In smart greenhouse systems, improved environmental control enhances water-use efficiency and stabilizes soil moisture levels, preventing both water deficit and excess humidity stress. The interaction between optimized ventilation and precise irrigation scheduling likely created a balanced microclimate that promoted active canopy development and greater leaf production.

These findings agree with those reported by Jones (2004), who indicated that proper irrigation management enhances plant water status and promotes leaf expansion and photosynthetic efficiency. Similarly, Fereres and Soriano (2007) emphasized that advanced irrigation techniques improve vegetative growth traits, including leaf area, by reducing water stress and optimizing water use efficiency. In addition, Howell (2001) highlighted that precise irrigation scheduling contributes to better crop growth through improved water distribution and nutrient uptake, which is reflected in increased leaf development. Recent studies have similarly reported that improved greenhouse climate control enhances leaf development by stabilizing temperature and humidity and optimizing photosynthetic efficiency, leading to increased leaf area and vegetative growth in protected cultivation systems (Zhang et al., 2023).

Table (3): Effect of smart irrigation system, greenhouse type and ventilation system on Number of leaves (leaf/plant)

Treatments	Mean	Std. Deviation	Std. Error	LSD (α=0.05)	P value
T1	43.92 ^{a}	4.05	0.83	2.10	<0.001*
T2	43.00 ^{a}	2.64	0.54		
T3	34.75 ^{b}	4.52	0.92		
T4	35.04 ^{b}	3.24	0.66		

T$_{1:}$ Smart House + Forced Ventilation, T$_{2:}$ Smart House + Natural Ventilation, T$_{3:}$ Conventional House + Forced Ventilation, T$_{4:}$ Conventional House + Natural Ventilation.

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

3.4. Effect of smart irrigation system, greenhouse type and ventilation system on Number of lateral Branches per Plant (branch/plant): The number of lateral branches per plant is an important architectural trait that reflects vegetative vigor, canopy structure, and the potential for increased photosynthetic surface and fruit-bearing sites. As shown in Table (3), the number of lateral branches per plant was significantly influenced by greenhouse type and ventilation system, with highly significant differences among treatments ($p < 0.001$) and a calculated LSD value of 0.66 branches, confirming a clear separation among treatment means. The highest number of lateral branches was recorded under T$_1$, with a mean value of 7.50 ± 1.02 branches, indicating that this system provided optimal conditions for axillary bud initiation and sustained lateral growth. In contrast, conventional greenhouse treatments exhibited a marked reduction in lateral branching. T$_3$ produced 4.83 ± 1.31 branches, while T$_4$ recorded the lowest number at 4.42 ± 1.21 branches, with no significant difference between these two treatments. The difference of more than three branches per plant between T_1 and T_4 is agronomically meaningful and statistically supported by the LSD value (0.66). This reduction under conventional conditions reflects weaker microclimatic regulations, which likely limited assimilate supply and disrupted the hormonal balance required for axillary bud activation and branch elongation.

These findings are consistent with those reported by Jones (2004), who emphasized that proper irrigation scheduling improves plant water status and promotes vegetative growth characteristics, including branching. Similarly, Fereres and Soriano (2007) reported that improved irrigation practices enhance plant growth by minimizing water stress and optimizing physiological processes. In addition, Howell (2001) highlighted that efficient irrigation management contributes to better crop growth and development through improved water and nutrient distribution, which is reflected in increased branching. Recent studies have similarly reported that improved greenhouse microclimate regulation enhances vegetative branching by stabilizing temperature and humidity and optimizing photosynthetic performance in protected cultivation systems (Liu et al., 2022).

Table (4): Effect of smart irrigation system, greenhouse type and ventilation system on Number of lateral Branches per Plant (branch/plant)

Treatments	Mean	Std. Deviation	Std. Error	LSD (α=0.05)	P value
T1	7.50^{a}	1.02	0.21	0.66	<0.001*
T2	6.83^{b}	1.05	0.21		
T3	4.83^{c}	1.31	0.27		
T4	4.42^{c}	1.21	0.25		

$T_{1:}$ Smart House + Forced Ventilation, $T_{2:}$ Smart House + Natural Ventilation, $T_{3:}$ Conventional House + Forced Ventilation, $T_{4:}$ Conventional House + Natural Ventilation.

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

3.5. Effect of smart irrigation system, greenhouse type and ventilation system on Plant Leaf Area (cm²/plant): Mean plant leaf area is a critical indicator of canopy development and photosynthetic potential, directly influencing assimilate production and overall plant growth. As shown in Table (5), mean leaf area was significantly affected by greenhouse type and ventilation system, with highly significant differences among treatments ($p < 0.001$) and a calculated LSD value of 496.15 cm², confirming a clear separation among treatment means. The largest leaf area was recorded under T_1, with a mean value of 15,956.02 ± 1,607.48 cm², indicating optimal microclimatic conditions that promoted leaf expansion and canopy development. Plants grown under T_2 exhibited a slightly lower but still significantly high leaf area of 14,818.20 ± 874.64 cm². Although reduced compared with forced ventilation in the smart house, this result demonstrates that smart greenhouse structures alone effectively support leaf growth even under natural ventilation. In contrast, conventional greenhouse systems showed a marked reduction in leaf area. T_3 recorded 13,673.50 ± 491.22 cm², while T_4 produced the lowest leaf area at 12,969.60 ± 590.21 cm², with no significant difference between these two treatments. The reduction of nearly 3,000 cm² between T_1 and T_4 is substantial and agronomically meaningful. This reduced leaf expansion under conventional greenhouse conditions reflects limitations in environmental regulation, particularly temperature and humidity control, which are essential for sustained leaf growth and cell enlargement.

Importantly, leaf area development is not governed by ventilation alone; irrigation management also plays a decisive role. Adequate and consistent irrigation ensures optimal cell turgor pressure, which is fundamental for leaf expansion and mesophyll development. In smart greenhouse systems, improved environmental control likely enhanced water-use efficiency and stabilized soil moisture levels, preventing transient water stress that could restrict leaf enlargement. The interaction between efficient ventilation and precise irrigation scheduling probably created a favorable balance between evaporative demand and water supply, thereby maximizing leaf expansion and canopy architecture. These findings agree with those reported by Jones (2004), who indicated that proper irrigation scheduling improves plant water status and promotes leaf expansion and photosynthetic activity. Similarly, Fereres and Soriano (2007) reported that advanced irrigation practices reduce water stress and enhance vegetative growth traits, including leaf area. In addition, Howell (2001) highlighted that efficient irrigation management improves water distribution and nutrient uptake, which positively affects plant growth and leaf development. Recent studies have similarly demonstrated that improved greenhouse climate control enhances leaf expansion and canopy structure by optimizing thermal conditions and photosynthetic efficiency (Chen et al., 2022).

Table (5): Effect of smart irrigation system, greenhouse type and ventilation system on Plant Leaf Area (cm²/plant)

Treatments	Mean (cm²)	Std. Deviation	Std. Error	LSD (α = 0.05)	P value
T_1	15956.02 ^{a}	1607.48	568.33	496.15	0.000 S
T_2	14818.20 ^{b}	874.64	309.23		
T_3	13673.50 ^{c}	491.22	173.67		
T_4	12969.60 ^{c}	590.21	208.67		

$T_{1:}$ Smart House + Forced Ventilation, $T_{2:}$ Smart House + Natural Ventilation, $T_{3:}$ Conventional House + Forced Ventilation, $T_{4:}$ Conventional House + Natural Ventilation.

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

3.6 Effect of smart irrigation system, greenhouse type and ventilation system on Leaf Chlorophyll Content: Leaf chlorophyll content is a key physiological indicator of photosynthetic capacity, nitrogen status, and overall plant health. As shown in Table (6), leaf chlorophyll content was significantly influenced by greenhouse type and ventilation system, with highly significant differences among treatments ($p < 0.001$) and a calculated LSD value of 2.20, confirming a clear separation among treatment means. The highest chlorophyll content was recorded under T_1, with a mean value of 131.51 ± 3.01 SPAD units, indicating optimal microclimatic conditions that supported chlorophyll synthesis and pigment stability. In contrast, plants grown under conventional greenhouse systems showed significantly lower chlorophyll content T_3 recorded 112.75 ± 4.13 SPAD units, while T_4 exhibited the lowest chlorophyll content at 106.81 ± 5.31 SPAD units. The reduction of nearly 25 SPAD units between T_1 and T_4 is physiologically meaningful and reflects less efficient control of temperature, humidity, and radiation balance in conventional structures. Such conditions may accelerate chlorophyll degradation, increase photooxidative stress, and reduce photosynthetic efficiency.

Improved irrigation management also enhances nutrient uptake, particularly nitrogen and magnesium, which are essential components of chlorophyll molecules. Consequently, plants grown under smart irrigation conditions exhibit higher chlorophyll content, leading to increased photosynthetic efficiency and improved plant growth. These findings are supported by Farooq et al. (2017), who reported that water stress significantly reduces chlorophyll content due to oxidative damage and impaired chlorophyll synthesis. Similarly, Zhang et al. (2018) found that optimized irrigation strategies improve chlorophyll content and photosynthetic performance by maintaining better plant water relations. Furthermore, Kang et al. (2020) demonstrated that advanced irrigation techniques, including regulated and smart irrigation, significantly enhance chlorophyll concentration and overall physiological performance of crops by reducing water stress and improving nutrient availability. Recent studies have similarly demonstrated that improved greenhouse climate regulation enhances chlorophyll retention and photosynthetic efficiency by stabilizing thermal and radiative conditions within the canopy (Wang et al., 2023).

Table (6): Effect of smart irrigation system, greenhouse type and ventilation system on Leaf Chlorophyll Content

Treatments	Mean	Std. Deviation	Std. Error	LSD (α=0.05)	P value
T1	131.51 ^{a}	3.01	0.87	2.20	<0.001*
T2	128.94 ^{a}	1.58	0.46		
T3	112.75 ^{b}	4.13	1.19		
T4	106.81 ^{c}	5.31	1.53		

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.

Conclusions:

The integration of a sensor-based smart irrigation system significantly accelerates the phenological development of cucumbers, leading to a marked reduction in the time required to reach anthesis compared to traditional methods. The combination of automated moisture regulation and forced ventilation creates a stabilized microclimate that optimizes vegetative vigor. This synergy prevents the degradation of photosynthetic pigments and fosters robust structural growth in hybrid cultivars. Smart irrigation systems demonstrate a superior capacity for maintaining soil matric potential within optimal ranges, thereby improving nutrient uptake and water use efficiency while mitigating the risks associated with over-irrigation or moisture stress. The implementation of precision environmental controls directly correlates with enhanced leaf area expansion and higher chlorophyll density, indicating a more efficient carbon assimilation process throughout the growing seasons.

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