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Research Article

Optimizing cucumber growth: integrating smart irrigation with various fertilization strategies in greenhouse conditions

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Abstract

Two different irrigations (full irrigation (FI) and 50% deficit irrigation (WS)) and fertilizations (G0 (not applied), G1 (only bottom fertilizer applied), G2 (only chemical fertilizer applied), G3 (bottom fertilizer and animal manure combined), and G4 (which is designed to apply the bottom fertilizer and chemical fertilizer combined)) were assessed in this study, which was carried out between autumn 2020–2021 with the aim of optimal water and nutrient use in cucumber cultivation in a greenhouse. These treatments were examined for their impacts on fruit quality (fruit weight, length, volume, and the total number of fruits), yield, leaf area (LA), irrigation water use efficiency (IWUE), physiological aspects (net photosynthesis (Pn), stomatal conductivity (gs), leaf water potential (Ψl), and nutrient content (nitrogen (N) and potassium (K)). The smart irrigation system that sensed soil moisture and strategically utilized water ensured effective application of a fertilization mechanism that improved crop quality. The FI treatment significantly increased the fruit quality parameters LA, Pn, gs, and Ψl compared to other treatments, especially when it was combined with the G3 fertilization scheme. The FI treatment also significantly increased fruit yield by 28.3% compared to WS. Additionally, the smart irrigation system saved 20.6% more water under deficit irrigation (WS) and 9.1% more water under full irrigation (FI) compared to Et-based system. Optimally combined strategic fertilization and smart irrigation significantly changed key metrics in growth and development. The results pointed out that technology-driven systems integrated with real-time irrigation data-informed systems are crucial. This work advances sustainable agricultural practices through the integration of effective water management with optimal fertilization. Its findings have significant implications for water-scarce regions, providing a blueprint to improve agricultural productivity while maintaining critical resources.

Keywords: controlled environment agriculture; nutrient management; precision agriculture; water-saving technologies; yield enhancement

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Introduction

The most crucial elements for greenhouse farmers to meet their needs in agricultural production are irrigation and fertigation. Additionally, although it is still unclear how plants will react to problems like climate

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change and drought (Angelopoulos *et al*., 2020), the inefficient use of water resources and poor fertigation planning are some of the common factors that limit production in many agricultural regions. According to Kacar and Katkat (2006), the cost of fertilizer alone accounts for 10% to 15% of the expense of agricultural products while also increasing production by at least 50%. In addition, a high amount of fertilizer is needed for intensive and rapid production in greenhouse production (Kristensen, 2005). However, it is well recognized that excessive watering and fertigation cause plant diseases, yield and quality reductions, soil aeration, wash out beneficial plant nutrients, antagonistic relationships between nutrients, and pollute water supplies (Celiktopuz *et al*., 2021). To avoid the suffering caused by water stress, it is essential to create new techniques that store water with the least amount of loss in the plant's root zone and with no adverse effects on the plant, the soil, or the environment as a whole. Productivity is currently restricted in many different parts of the world due to ineffective irrigation systems and inefficient water resource use (Angelopoulos *et al*., 2020). The use of technology-based approaches will be required in order to solve all of these issues. The tendency towards technology-based systems is increased by finding the variables' ideal values in plant production with the least amount of error. Crops may indeed be monitored, optimized, and precisely controlled using technology-based systems, enabling farmers to produce the most crops of the highest possible quality (Ko *et al*., 2016; Roopaei *et al*., 2017).

Although many studies have examined the impact of smart irrigation systems and fertigation on crop production, most have focused on single irrigation or fertilization strategies rather than their combined effects under variable water availability conditions. This study differs from previous research by integrating smart irrigation systems with diverse fertilization strategies, including combinations of chemical and organic fertilizers. Additionally, while prior research has primarily highlighted the technical efficiency of smart systems, this study emphasizes their practical implications for cucumber yield, fruit quality, and resource use efficiency under greenhouse conditions. By addressing the synergistic effects of these factors, our research provides a comprehensive framework for optimizing cucumber cultivation in water-scarce regions.

The sensors used in smart agriculture help reduce wasteful water and fertilizer, improve plant fruit and leaf quality, and improve the cost and energy-effectiveness of energy use (Roopaei *et al*., 2017). However, the most crucial inputs are labor expenses, time, irrigation costs, and energy because farmers mostly use manual irrigation. Therefore, smarter use of water (controlling and monitoring flow time based on data analysis) helps improve irrigation efficiency and reduce costs (Roopaei *et al*., 2017). The advancements in these technologies also offer wide functionality at low cost and low energy use. In this context, a mobile application has been created that uses an automatic control system to monitor the soil moisture level in the greenhouse and provide the plants with the appropriate amount of irrigation water at the proper time. A new type of smart irrigation control device that is less expensive than present smart control technologies has also been developed in the current research.

By calculating and providing the precise amount of irrigation water that the cucumber plants require with smart irrigation systems, the current study aims to avoid potential production and quality losses and use water resources efficiently. In this context, yield, physiologically relevant factors (photosynthesis rate, stomatal conductivity, leaf water potential, and leaf area), fruit quality performances (fruit weight, total fruit number, length, diameter, and volume), along with nitrogen (N) and potassium (K) contents in the root, stem, leaf, and fruit parts, were also examined for the cucumber plant under various fertilization programs and irrigation levels.

Materials and Methods

Site description

The research was conducted in the glass greenhouse in the autumn growing season of 2020-2021. The greenhouse, before planting, soil was plowed with a plow, and the drip irrigation system, solenoid valves (Figure 1a), temperature sensors, and soil moisture sensors (Figure 1b) were placed on the field.

a) b)

Figure 1. Solenoid valves (a) and soil moisture sensors (b) used for the designed automatic irrigation system

The seedlings were transplanted to the experimental plots in the greenhouse in mid-October, with a spacing of 0.80 m between rows and 0.50 m between intrarows. The study's plant material was a cucumber type called 'Cemre' that is commercially approved.

Irrigation management

In the experiment, irrigations were applied automatically using soil moisture sensors and the drip irrigation technique with the help of solenoid valves. Soil moisture sensors were positioned at a depth of 25 cm in three replications, which corresponds to around 70% of the cucumber root density. Additionally, an Et-based system was created and compared in order to assess the effectiveness of the designed system (Table 1). Using the FAO-PM equation such as Allen *et al*. (1998) daily reference evapotranspiration (Eto) values were calculated from the automatic climate station (Figure 2) installed in the greenhouse.

Figure 2. Climate station placed on the field for a Et-based irrigation program

The total amounts were compared at the end of research, after the acquired values were multiplied by kc and irrigation water quantities were computed for the Et-based system. The kc data of the cucumber plant was used for irrigation during the development period given in FAO 56 (Allen *et al*., 1998). The developed automatic irrigation system has been found to save 26% more irrigation water for the IR50 (WS) and 10% more for the IR100 (FI) (Table 1).

Table 1. The cumulative amount of irrigation water applied at the end of the trial (ton/da)

Irrigation Levels	Soil moisture-based system	Et-based system
FI	255.7	281.2
WS	127.9	161.1

The drip irrigation system used consists of a fertilizer tank, main pipe, water distribution pipes (Lateral), and drippers. Laterals are black, flexible pipes made of polyethylene with a diameter of 20.00 mm. Irrigation water was conveyed to the beginning of the parcel with a 50 Ø PVC main pipeline. In drip irrigation, one dripper with a flow rate of 2 lt/h was used at 30 cm intervals on the lateral line laid between two rows. All plants received the same amount of irrigation water for three weeks to help the seedlings adjust to the growing environmental conditions, and then different irrigation levels were used. (Şimsek *et al.*, 2005). Full Irrigation (FI) applications were commanded to automatically irrigate each time until the field capacity was reached by the soil moisture sensors with the help of algorithm 1, when 35% of the usable water capacity was drained according to the previously determined field capacity and wilting point of the greenhouse soil. Deficit irrigation at 50% (WS) was commanded to apply half of the full irrigation application at each time.

Smart irrigation system design

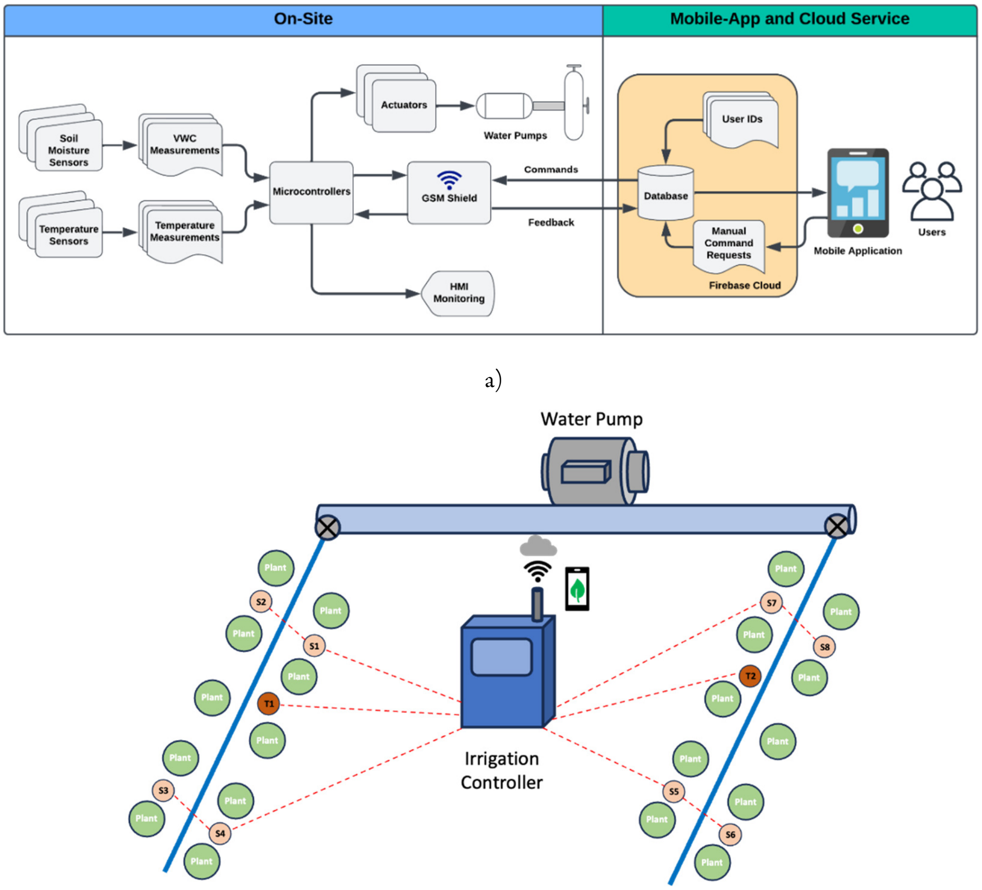
The proposed architecture consists of a microcontroller, soil moisture sensors, a GSM (Global System for Mobile Communication) module, a Liquid Crystal Display (LCD) display, a power supply, and actuators (Figures 3a and 3b). Small-volume soil moisture sensors may not provide an accurate reading in these applications since soil is a naturally heterogeneous system. Therefore, the dielectric constant of the growth condition and the volumetric water content (VWC) were measured using 10 cm long Decagon 10HS soil moisture sensors. The algorithm was established in the study following the calibration of the 10HS soil moisture meter instruments, which are a part of the automatic irrigation system. The resulting calibration equation was y=1.2944x - 1.5182, and its R^2 was 0.9644.

a) b)

Figure 3. Figures related to the controller used in the project

A mobile application has also been developed in the controller, which includes modules that can switch the operating mode between automatic and manual irrigation and allow instant monitoring of the irrigation level. Online cloud services provided assistance for the microcontroller and mobile application's communication. The site architecture is shown in Figure 4b, and the components of smart irrigation are shown in Figure 4a. Furthermore, the VWC value was also computed, in order to determine the soil moisture, using Raw measurement (m) and Equation 1, as shown below:

$$VWC = (1{,}17\ x\ 10^{-9})(m^3) - (3{,}95x10^{-6})(m^2) + (4{,}90x10^{-3})(m) - 1{,}92 \tag{1}$$



a)

b)

Figure 4. Smart irrigation system design overview (a) and site layout (b)

The current automated irrigation system is described in Algorithm 1, which completes irrigation cycles with optimal soil moisture thresholds between 27% and 35%, depending on VWC. The Real-Time Clock (RTC) module was used to retrieve the time and date information for TD. The irrigation bit X from the cloud was used to control the mode change. The mobile application was created to allow users to set M1 and M2 manual irrigation thresholds, yet this feature was never enabled in this project. Our system will alert the users with the A command if the greenhouse temperature falls below 12 °C (shown in Algorithm 1). The smart irrigation system operates by utilizing soil moisture sensors to monitor volumetric water content (VWC) in real-time. The system is designed to trigger irrigation cycles automatically when soil moisture levels fall below a predefined threshold (27%-35% VWC). The microcontroller processes sensor data, communicates with an online cloud service for storage and monitoring, and activates solenoid valves to deliver the precise amount of water required. An integrated real-time clock (RTC) module ensures accurate scheduling, while an optional manual mode allows users to adjust thresholds through a mobile application.

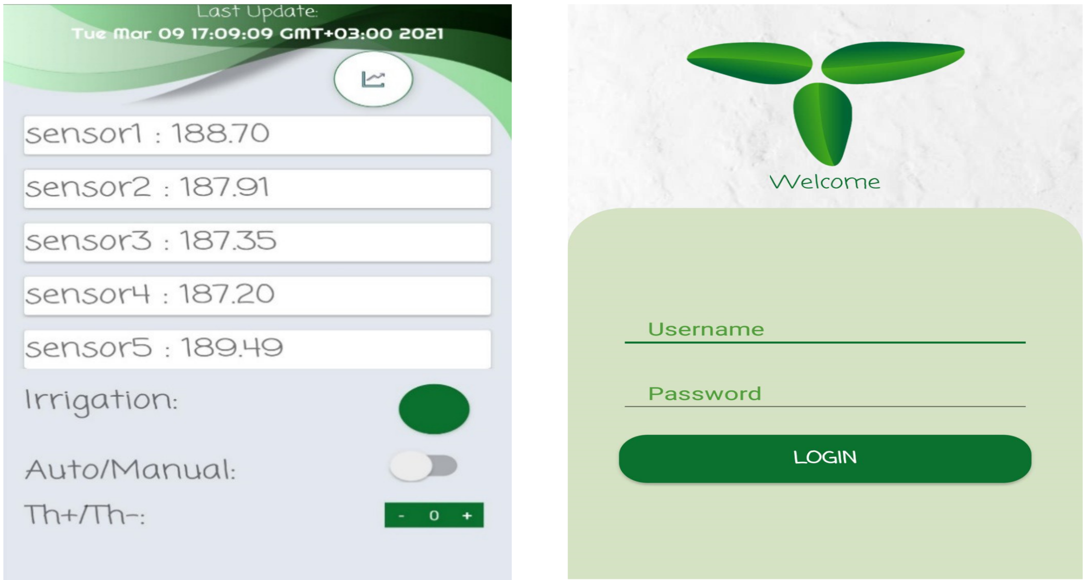
Algorithm 1. Irrigation algorithm

```
Input: Soil moisture measurements            : $S$
       Temperature measurements              : $t$
       Date and time stored using RTC        : $TD$
       Irrigation hours                      : $T_+$
       Allowed Irrigation Dates              : $D$
       Mobile app Irrigation Mode Bit        : $X$
       Mobile App Manual Thresholds          : $M_1, M_2$
       AWC Down-threshold                    : $AWCD$
       AWC Upper-threshold                   : $AWCU$

Output: Solenoid Valve Trigger Signals       : $V$
        Alert Signal                         : $A$

Initialize $S, T_1, T_2\ TD$ and update cloud database for mobile application
for all $TD \in : T_+$ and $D$ do
Start online sampling to cloud database, pull online variable $X$
    if $X = 1$ do
        if $Average(S) < AWCD$ do
            Activate $V$:1
            Until $Average(S) = AWCU$
        else
            Deactivate $V$:0
            end if
        if $Average(S) < AWCD$ ppm do
            Activate $V$: 1
        else
            Deactivate $V$:0
            end if
    update cloud variables
    if $X$:0 do
        if $Average(S) < M_1$ do
            Activate $V$:1
            Until $Average(S) = M_2$
        else
            Deactivate $V$:0
            end if
end for
for all $TD \in : T_+$ or $\notin D$ do
    if $Average(t) < 12°$ do
        Activate $A$: 1
    else    Deactivate $A$: 0
    update cloud variables
end for
repeat
```

T Irrigation mobile software was designed and integrated into the system. The following are the figure (Figure 5) for the mobile application's user interface. Figure 5 illustrates the mobile application interface designed to monitor and control the smart irrigation system. This application enables real-time monitoring of irrigation levels, mode switching between automatic and manual, and threshold adjustments for soil moisture levels. The interface's functionality ensures user-friendly interaction with the system, thereby improving the practical applicability and adoption of the proposed technology.



Last Update:
Tue Mar 09 17:09:09 GMT+03:00 2021

sensor1 : 188.70
sensor2 : 187.91
sensor3 : 187.35
sensor4 : 187.20
sensor5 : 189.49

Irrigation:
Auto/Manual:
Th+/Th-: - 0 +

Figure 5. Images for a designed mobile application interface

Measurements

Yield (ton da^{-1}), Irrigation Water Use Efficiency (IWUE), and Leaf Area (LA) (cm^{2} plant-^{1})

The weights of the fruits harvested from the plot during the growing season were weighed on a scale accurate to 0.1 g, and the yield per plant was calculated by dividing this quantity by the number of plants in the plot. IWUE (kg da^{-1} mm^{-1}) was determined by dividing the total amount of irrigation water used by the ratio of fruit yields (Çakir *et al*., 2017).

A leaf area meter (model 3050A; Li-Cor Lincoln, NE, USA) was used to measure LA at the harvesting time.

Fruit quality parameters

Fruit weight (g)

It was calculated by dividing the total fruit weight received from each harvest by the total fruit count collected during that harvest.

Total number of fruits (g piece^{-1})

The number of fruits harvested for each harvest was counted during the growing season.

Fruit length (mm) and diameter (mm)

Digital calipers were used to measure the fruit length and diameter of ten fruits that were gathered throughout the term of three different time periods.

Fruit volume (ml)

Fruit volumes were determined for 10 of the fruits harvested in three different periods.

Physiological measurements

Net photosynthesis (Pn) (mol CO$_2$ m^{-2} s^{-1}), and stomatal conductivity (gs) (μmol m^{-2} s^{-1})

A leaf CI-340 photosynthesis meter was used to measure net Pnet and gs in three plants from each plot at noon (12:00–13:00) on leaves that are fully exposed to the sun and have just finished developing in order to track the internal water status of the plants under various growing environments.

Leaf water potential (Ψl) (bar)

A pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, CA, USA) was used to determine the midday Ψl at three different periods.

Analysis of plant nutrients (%)

Nutrient element analyses (N, and K) were performed in three repetitions on the root, stem, leaf, and fruit at the end of the harvest period. Many procedures were carried out to determine the changes in the N and K contents of roots, stems, leaves, and fruits of different irrigation and fertilization programs, as mentioned in Celiktopuz *et al.* (2021).

Experimental design

The greenhouse experiment was conducted with three replications at two different irrigation levels and five different fertilization programs according to the experimental design of 25 factorial random plots. Irrigation applications were determined as full irrigation (F1) and 50% limited irrigation (WS). Designs of fertilizer were divided into five categories: not applied any (control) (G0), that fertilizer was only bottom fertilizer (G1), that was applied only chemical fertilizer (G2), that was applied bottom fertilizer and animal manure combined (G3), and designed G4 to apply bottom fertilizer and chemical fertilizer combined. The values of the experiment were analyzed for variance with the program package JMP and test LSD for identifying differences throughout averages. The differences between the averages were compared with the LSD test at the 5% significance level ($P \leq 0.05$).

Results and Discussion

The effects of different irrigation and fertilization techniques on cucumber yield, IWUE, LA, fruit quality parameters, physiological measurements, and analysis of plant nutrients (%) were meticulously evaluated in this extensive greenhouse study. FI and WS were used in the design of the experiment, along with five different fertilization treatments, ranging from control (G0) to combined applications of chemical and bottom fertilizers (G4).

Yield (ton da^{-1}), Irrigation Water Use Efficiency (IWUE), and Leaf Area (LA) (cm^{2} plant^{-1})

The yield data showed a definite benefit of FI over WS (28.3% more), with the G3 treatment, a combination of bottom fertilizer and animal manure, exhibiting the highest yields (Table 2). Clearly, there was effective interaction between irrigations and the incorporation of organic and inorganic fertilizers. Furthermore, G3 had better efficiency than 5.2%, 13.6%, 18.5%, and 27.4% compared to treatments G4, G2, G1, and G0, respectively. Similarly, IWUE considerably increased under WS, especially in treatments involving multiple fertilization techniques, indicating the effectiveness of water use in limited irrigation conditions when combined with thorough nutrient management. G3 treatment, in particular, was found to have higher IWUE compared to other applications, ranging between 5.8% and 26.2%, respectively. Data on LA followed these patterns, with the FI regime showing the most extensive leaf growth (22.3% more than WS), particularly in treatments with combined fertilization (G3), which is clear evidence that optimal availability of water and nutrients will significantly support a healthy amount of leaf development.

Table 2. The effects of different irrigation levels and fertilization treatments on cucumber yield (ton da-1), irrigation water use efficiency (IWUE), and leaf area (LA) (cm^2 plant^{-1})

	Irrigation levels	**G0**	**G1**	**G2**	**G3**	**G4**	**Irr. levels averages**
Yield (ton da^{-1})	FI	2.85 e	3.35 d	3.54 c	4.06 a	3.91 b	3.46 A
	WS	2.16 ı	2.29 h	2.44 g	2.85 e	2.65 f	2.48 B
	Fertilizers averages	2.51 E	2.82 D	2.99 C	3.46 A	3.28 B	
	Lsd $_{\text{fertilizer}}$*= 0.06 Lsd $_{\text{irrigation}}$*= 0.04 Lsd $_{\text{fertilizer × irrigation}}$*= 0.08						
IWUE	Irrigation levels	G0	G1	G2	G3	G4	Irr. levels averages
	FI	11.2 ı	13.1 h	13.9 g	15.9 f	15.3 f	13.9 B
	WS	16.9 e	17.9 d	19.1 c	22.3 a	20.7 b	19.4 A
	Fertilizers averages	14.1 E	15.5 D	16.5 C	19.1 A	18.0 B	
	Lsd $_{\text{fertilizer}}$*= 0.46 Lsd $_{\text{irrigation}}$*=0.29 Lsd $_{\text{fertilizer × irrigation}}$*= 0.65						
Leaf area (cm^2 plant^{-1})	Irrigation levels	G0	G1	G2	G3	G4	Irr. levels averages
	FI	1593 h	1753 g	2083 e	4191 a	3419 b	2570 A
	WS	1097 ı	1149 ı	1897 f	3276 c	2373 d	1996 B
	Fertilizers averages	1345 E	1451 D	1990 C	3734 A	2896 B	
	Lsd$_{\text{fertilizer}}$*= 85 Lsd$_{\text{irrigation}}$*= 54 Lsd$_{\text{fertilizer x irrigation}}$*= 120						

1) Separate letters represent the differences between the averages,
2) N. S.: Not Significant; *P ≤ 0.05

This section contributes to the understanding of optimal irrigation and fertilization techniques for growing cucumbers, with a focus on managing nutrients and water availability in a way that maximizes yield, IWUE, and LA. According to Omotade *et al.* (2019), the knowledge of nutrient expert advice and the intervals at which irrigation should be scheduled according to crop water needs contribute to avoiding the risk of over or under-watering that might reduce productivity and the health of cucumber plants, which is the best method for scheduling the irrigation intervals. Therefore, these results are alike because different irrigation levels in combination with different fertilization treatments significantly influenced our efficiency and yield. The current research results show that, when compared to WS conditions, FI increased the yield by 28.3%. The findings of Rahil *et al.* (2015) are aligned with those of our work, as they observed a yield increase with different irrigation managements for cucumber. The G3 treatment, consisting of the bottom fertilizer together with the animal manure, brings out the efficiency in the integration of organic and inorganic fertilizers as postulated in the theory supported by Yan *et al.* (2019) on the nutrient use efficiency (NUE) of cucumbers. The results of studies highlighting the role of nutrient management in enhancing water use efficiency in limited irrigation scenarios are reflected in the higher IWUE observed under WS conditions, particularly with multiple fertilization techniques (Kirnak; Demirtas, 2006). This is supported by Li *et al.* (2023), who found that a holistic approach to water and fertilizer management, besides improving cucumber productivity efficiency, also increased yield and quality. Thus, such a significant increase of LA under FI, with G3, confirms some statements that were found by Marcelis (1994) concerning the essential nutrient and water supply influence on cucumber leaf development.

Fruit quality parameters

The weight and the number of fruits varied significantly between treatments, according to the results (Table 3). In general, higher fruit weights (7.2%) and numbers (24.7%) were associated with FI. Fruit yield was generally increased by FI, which is in line with research showing that growth parameters are improved by an adequate water supply (Rahil, 2015).

Table 3. The effects of different irrigation levels and fertilization treatments on cucumber Fruit weight (g) and Total number of fruits (g)

	Irrigation levels	**G0**	**G1**	**G2**	**G3**	**G4**	**Irr. levels averages**
Fruit weight (g)	FI	88.3 c	81.7 de	85.8 cd	111.8 a	98.6 b	93.2 A
	WS	75.5 f	80.0 ef	84.1 cde	97.3 b	85.8 b	86.5 B
	Fertilizers averages	81.9 CD	80.8 D	84.9 C	104.5 A	97.2 B	
	Lsd $_{fertilizer}$*= 3.52 Lsd $_{irrigation}$*= 2.22 Lsd $_{fertilizer \times irrigation}$*= 5.30						
Total number of fruits (g piece^{-1})	Irrigation levels	G0	G1	G2	G3	G4	Irr. levels averages
	FI	32.3 c	41.0 a	41.3 a	36.3 b	39.7 a	38.1 A
	WS	28.7 d	28.7 d	29.0 d	29.3 d	27.7 d	28.7 B
	Fertilizers averages	30.5 D	34.8 AB	35.2 A	32.8 C	33.7 BC	
	Lsd$_{fertilizer}$*= 1.18 Lsd$_{irrigation}$*= 0.75 Lsd$_{fertilizer \times irrigation}$*= 1.67						

1) Separate letters represent the differences between the averages
2) N. S.: Not Significant; *P ≤ 0.05

G2 is at the forefront when it comes to the number of fruits, while G3 stands out for producing results in terms of fruit weight. It's worth noting that balanced nutrient management is crucial, as shown by the success of treatments like G2 and G3. G2 helps increase fruit weight, whereas G3 excels at enhancing fruit quantity (Qu *et al.*, 2022; Wang *et al.*, 2023). The differences in fertilization techniques applied in G2 and G3 can explain the variations observed in cucumber fruit weight and quantity. The success of G3 in promoting fruit weight may be attributed to a balanced profile that supports individual fruit development, as suggested by Marcelis's (1994) study on dry matter allocation in cucumbers. On the other hand, G2's high total fruit number can be linked to a fertilization approach that boosts plant productivity and fruit set, as discussed by Omotade *et al.* (2019) when examining yield performance under different irrigation regimes. These findings highlight how water and nutrient availability must interact effectively to maximize cucumber production.

Table 4 displays the fruit length, diameter, and volume values derived from measurements taken 69, 90, and 111 days after planting (dap). Plants under the FI treatments exhibited fruit length, fruit diameter and fruit volume with an average 2.6%, 4.9%, and 24.5% superiority compared to the plants receiving the WS application. The data showed that FI treatments yield cucumbers significantly superior in dimensions than those under WS, and this is in agreement to with Amer *et al.* (2009) explanation that a sufficient supply of water is particularly important for obtaining good sized fruits. This is supported by Dai *et al.* (2011), who studied the interaction between irrigation method and quality of soil and claimed that optimal irrigation regimes could drastically affect cucumber growth.

Table 4. The effects of different irrigation levels and fertilization treatments on cucumber fruit length (mm), fruit diameter (mm), fruit volume (ml)

	Fertilizer applications	**Irrigation levels**	**Dap**			**Fertilizer × Irrigation**	**Fertilizers averages**
			69	**90**	**111**		
Fruit Length (mm)	G0	FI	123.1	130.0	127.4	126.8 cd	124.5 C
		WS	115.7	126.7	124.1	122.2 cde	
	G1	FI	126.7	116.7	114.3	119.2 de	123.8 C
		WS	123.0	132.3	129.7	128.3 bc	
	G2	FI	126.3	116.0	113.7	118.7 e	121.3 C
		WS	122.0	126.3	123.8	124.0 cde	
	G3	FI	151.3	148.7	145.6	148.6 a	139.0 A
		WS	116.0	137.7	134.9	129.5 bc	
	G4	FI	128.0	138.3	141.6	136.0 b	132.0 B
		WS	130.0	125.0	129.2	128.01	

	Periods averages		126.2	129.8	128.4	$\text{Lsd}_{\text{fertilizer}}$*= 5.58 $\text{Lsd}_{\text{irrigation x fertilizer}}$*= 7.90 $\text{Lsd}_{\text{irrigation x period}}$*= 6.12	
	Irrigation levels averages	FI	129.8				
		WS	126.4				
Fruit Diameter (mm)	Fertilizer applications	Irrigation levels	Dap			Fertilizer × Irrigation	Fertilizers averages
			69	90	111		
	G0	FI	27.5	33.0	32.3	30.9	30.1 B
		WS	29.5	29.6	28.9	29.3	
	G1	FI	29.1	29.7	29.1	29.3	29.3 B
		WS	29.4	29.6	28.9	29.3	
	G2	FI	30.6	29.8	29.2	29.9	29.6 B
		WS	28.3	30.1	29.5	29.3	
	G3	FI	32.6	34.7	33.9	33.7	32.4 A
		WS	29.5	32.3	31.6	31.1	
	G4	FI	29.6	31.0	31.6	30.8	29.4 B
		WS	28.3	28.0	27.9	28.1	
	Periods averages		29.4 b	30.7 a	30.3 ab	$\text{Lsd}_{\text{fertilizer}}$*= 1.36 $\text{Lsd}_{\text{irrigation}}$*= 0.86 $\text{Lsd}_{\text{period}}$*= 1.05	
	Irrigation levels averages	FI	30.9 A				
		WS	29.4 B				
Fruit Volume (ml)	Fertilizer applications	Irrigation levels	Dap			Fertilizer × Irrigation	Fertilizers averages
			69	90	111		
	G0	FI	110.0	98.3	96.4	101.6 c	90.8 C
		WS	85.0	78.3	76.8	80.0 d	
	G1	FI	83.3	120.0	117.6	107.0 c	95.2 BC
		WS	88.3	81.7	80.0	83.3 d	
	G2	FI	108.3	115.0	112.7	112.0 bc	98.0 BC
		WS	96.7	78.3	76.8	83.9 d	
	G3	FI	101.7	140.0	137.2	126.3 a	115.0 A
		WS	100.0	106.7	104.5	103.7 c	
	G4	FI	116.7	123.3	129.5	123.2 ab	101.3 B
		WS	70.0	83.3	85.0	79.4 d	
	Periods averages		96.0	102.5	101.7	$\text{Lsd}_{\text{fertilizer}}$*= 8.0 $\text{Lsd}_{\text{irrigation x period}}$*=8.7 $\text{Lsd}_{\text{irrigation}}$*= 5.0 $\text{Lsd}_{\text{fertilizer × period}}$ *= 13.8 $\text{Lsd}_{\text{irrigation × fertilizer}}$*= 11.2	
	Irrigation levels averages	FI	30.9 A				
		WS	29.4 B				

1) Separate letters represent the differences between the averages,

2) N. S.: Not Significant; *P ≤ 0.05

The claim that, with respect to fruit length, diameter, and volume, G3 fertilization treatments usually produce better results resonates with the observations of Beyaert *et al.* (2007). These authors proved that marrying organic and inorganic fertilizer techniques proved effective in optimizing nutrient availability, resulting better growth. This multi-nutrient approach seems more convenient for a wholesome nutritional profile, as also recommended by Kaman *et al.* (2023) in their research regarding advanced nutrient management approaches. Overall, the findings of Omotade *et al.* (2019), together, emphasize the paramount significance of modified irrigation and fertilization schemes - to optimize fruit size as one of the critical hotlinks between cucumber marketability and yield. The combined insights from these studies underscore the importance of a holistic approach to cucumber cultivation, integrating both irrigation and nutrient management for optimal growth.

Physiological measurements

In this section, an assessment was made of the effects of different fertilization and irrigation techniques on the Pn, gs, and Ψl values (Table 5) of cucumbers, which were obtained from measurements made at 69, 90, and 111th dap.

Differences were noticed in Pn, gs, and Ψl in the different treatment combinations. Pn, Ψl, and gs values were consistently higher in the FI treatment as compared to the WS setup, highlighting the crucial role that water availability plays in maximizing plant physiology. The treatment with G3 was the best, with the highest values of Pn, Ψl, and gs. This is to suggest that the photosynthetic efficiency and gas exchange capacity would be better with this treatment. Conversely, in the control group (GO), Pn (9.79 μmol CO$_2$ m^{-2} s^{-1}) and gs (252 μmol CO$_2$ m^{-2} s^{-1}) were lowest under limited irrigation, corresponding to a significant reduction of physiological activity as a result of nutrient limitation and WS. The results were further supported by the Ψl measurements that identified the best water status under the conditions of combined fertilization and FI. This is also supported in the study by Parkash *et al.* (2021) with regard to cucumber physiology and irrigation levels. They further found that deficit irrigation could have substantial effects on stomatal conductance, transpiration rate, and photosynthesis rate, which suggests that the reduction in physiological activity of plants in WS conditions can be very marked. Regarding the findings that focused on the synergy of water and nutrient management, Rahil *et al.* (2015) also emphasize methods for conserving water in irrigation and the efficient use of water in harmony with this current study.

Table 5. The effects of different irrigation levels and fertilization treatments on cucumber physiological measurements

	Fertilizer applications	**Irrigation levels**	**Dap**			**Fertilizer × Irrigation**	**Fertilizers averages**
			69	**90**	**111**		
Pn (μmol CO$_2$ m^{-2} s^{-1})	G0	FI	14.67	12.13	10.80	12.53	11.85 D
		WS	12.73	11.00	9.79	11.17	
	G1	FI	15.10	12.70	11.30	13.03	12.29 C
		WS	12.77	11.57	10.29	11.57	
	G2	FI	15.13	13.40	11.93	13.49	12.61 BC
		WS	12.83	11.83	10.53	11.73	
	G3	FI	15.43	14.53	12.93	14.30	13.20 A
		WS	13.50	12.07	10.74	12.10	
	G4	FI	15.23	13.87	12.34	13.81	12.85 AB
		WS	13.10	11.93	10.62	11.88	
	Periods averages		14.05 a	12.50 b	11.13 c	Lsd$_{fertilizer}$*= 0.42	
	Irrigation levels averages	FI	13.43 A			Lsd$_{irrigation}$*= 0.26	
		WS	11.69 B			Lsd$_{period}$ *= 0.32	
gs (μmol m^{-2} s^{-1})	Fertilizer applications	Irrigation levels	Dap			Fertilizer × Irrigation	Fertilizers averages
			69	90	111		
	G0	FI	460	463	412	445	370 B
		WS	350	283	252	295	
	G1	FI	470	467	415	451	375 B
		WS	358	285	254	299	
	G2	FI	470	477	424	457	382 B
		WS	358	298	266	307	
	G3	FI	507	553	492	517	438 A
		WS	377	368	328	358	
	G4	FI	488	530	500	506	422 A
		WS	366	343	306	338	
	Periods averages		420 a	407 b	365 c	Lsd$_{fertilizer}$*= 17	
	Irrigation levels	FI	475 A			Lsd$_{irrigation}$*= 10	

	averages	WS	319 B			Lsd$_{\text{irrigation × period}}$*= 18 Lsd$_{\text{period}}$ *= 13 Lsd$_{\text{fertilizer × period}}$ *= 29	
Ψl (bar)	Fertilizer applications	Irrigation levels	Dap			Fertilizer × Irrigation	Fertilizers averages
			69	90	111		
	G0	FI	-7.07	-9.00	-12.27	-9.44	-10.67 D
		WS	-9.30	-11.0	-15.37	-11.89	
	G1	FI	-7.03	-8.93	-12.17	-9.38	-10.55 D
		WS	-9.17	-10.93	-15.10	-11.73	
	G2	FI	-7.00	-.867	-12.00	-9.22	-10.40 C
		WS	-9.03	-10.83	-14.90	-11.59	
	G3	FI	-6.83	-8.00	-11.40	-8.74	-9.87 A
		WS	-8.67	-10.0	-14.33	-11.0	
	G4	FI	-7.00	-8.33	-11.73	-9.02	-10.19 B
		WS	-9.00	-10.50	-14.57	-11.36	
	Periods averages		-8.01 a	-9.62 b	-13.38 c	Lsd$_{\text{fertilizer}}$*=0.13 Lsd$_{\text{period}}$*= 0.10 Lsd$_{\text{irrigation}}$*=0.08 Lsd$_{\text{irrigation × period}}$*= 0.15 Lsd$_{\text{fertilizer × period}}$*=0.23	
	Irrigation levels averages	FI	-9.16 A				
		WS	-11.51 B				

1) Separate letters represent the differences between the averages,

2) N. S.: Not Significant,* $P \leq 0.05$

The significant increases in photosynthesis and stomatal function, two important markers of plant health and efficiency, demonstrate the synergistic effect of an adequate water supply and balanced nutrient management. Moreover, interaction between fertilization and irrigation methods disclosed complex dynamics in cucumber physiology. Furthermore, our findings support those of Nikolaou *et al.* (2021) and Parkash *et al.* (2021), who have argued that the interaction of fertilization and irrigation is crucial in determining the physiological responses of cucumbers. Parkash *et al.* (2021) found that stomatal conductance, photosynthesis, and water use efficiency are all significantly impacted by varying degrees of water stress. These findings are consistent with our own research, which showed that limited irrigation had a negative impact on these physiological parameters.

Fertilization, especially with bottom fertilizers, somewhat reduced the negative effects of water stress in scenarios with limited irrigation (WS). The moderate Pn and gs values found in these treatments when compared to the control under comparable water conditions were indicative of this. The results also highlight the resilience of cucumbers to varying environmental conditions. Parkash *et al.* (2021) indicated that cucumber, though being in general a sensitive crop to water stress, has the potential to adapt to certain limits of water stress without a major loss in its yield capacity. In such water-limited environments, such an adaptation will be indispensable for sustainable cultivation. The combined fertilization treatments, however, did not entirely reproduce the physiological benefits of FI, which is interesting. This means that the role of water availability in eliciting plant physiological responses may be more dominant compared to nutrient supplementation. Apart from the above stressor-alleviating findings, these results also support the potential of combined fertilization to enhance resistance toward the stressor.

The observed increases in net photosynthesis (Pn) and stomatal conductance (gs) under full irrigation (FI) conditions are primarily attributed to optimal water availability. Adequate water supply supports stomatal opening and enhances gas exchange, enabling higher carbon dioxide assimilation and improved photosynthetic activity. Conversely, under deficit irrigation (WS), partial stomatal closure likely acted as a drought adaptation mechanism, reducing transpiration and limiting gas exchange to conserve water. Moreover, the combined fertilization treatment (G3), which integrates organic and inorganic fertilizers, further enhanced physiological responses. This synergistic effect is likely due to improved nutrient availability, which supports enzyme activity, chlorophyll synthesis, and overall metabolic efficiency. The balanced nutrient supply from G3 fosters optimal physiological functioning, amplifying photosynthetic efficiency even under varying irrigation conditions. These findings align with previous research demonstrating the interaction between water availability, nutrient management, and plant physiological processes, emphasizing the importance of integrated strategies for enhancing crop resilience and productivity.

These results underscore the importance of customized scheduling in irrigation and fertilization to get maximum physiology for cucumbers in growth and yield. Growers can ensure sustainable and efficient production even in the face of changing environmental conditions by optimizing plant physiological responses through an understanding of the interplay between these factors. Janoudi *et al.* (1993) and Nikolaou *et al.* (2021) particularly emphasized the need for improvement of fertigation and irrigation techniques in agricultural systems, with special reference to the semi-arid regions where there is water scarcity as one of the prime problems. Such results fit pretty well with current study findings that balanced fertilization and right irrigation serve for an essential increase in the photosynthetic efficiency and stomatal function in cucumbers.

Analysis of plant nutrients (%)

Table 6 evaluates the impact of varied irrigation and fertilization regimes on the nitrogen distribution (for roots, stems, leaves, and fruits) in cucumber plants.

Current research's findings showed that, under various treatments, there were notable differences in the distribution of N and K among the various plant parts (Table 6 and Table 7). The present study's results agree with the work of Bhogi *et al.* (2023) that it is through fertigation that an increase in yield and the efficiency of water and nutrient use in cucumber is achieved. It also indicates marked variations in N and K distribution between cucumber plant parts under different treatments. This was in line with the findings of Wang *et al.* (2019) and Kırnak and Demirtaş (2006), which underscored the benefits derived from the use of integrated fertigation techniques in the promotion of the uptake and distribution of nutrients.

All plant parts showed increased N and K availability under FI, which is important for photosynthesis and yield. This effect was particularly pronounced in treatments G3 and G4, which involve combinations of bottom fertilizer with either organic or chemical fertilizers. The findings correlate with those by Mao *et al.* (2022) and Qu *et al.* (2022), who found that the cucumber plants were affected differently due to different agronomic treatments. Furthermore, these results are in line with those reported by Bhogi *et al.* (2023), who supported that the integrated fertigation techniques enhanced the nutrient uptake in an effective manner. Differences in the way cucumber plants responded to the different irrigation and fertilization treatments also influenced the dynamics of nutrient partitioning. The study carried out by Ramirez-Peres *et al.* (2018) evidences improved nutrient distribution in growth-relevant areas due to proper irrigation practices. This research, especially, highlights the crucial role that water management plays in nutrient dynamics. This also implies that effective irrigation practices enhance the plant's capacity to distribute nutrients to growth-relevant regions as well.

Table 6. The effects of different irrigation levels and fertilization treatments on cucumber nitrogen (N) partitioning (%)

Root N (%)	**Irrigation levels**	**G0**	**G1**	**G2**	**G3**	**G4**	**Irr. levels averages**
	FI	1.01 c	1.03 c	1.11 b	1.19 a	1.13 b	1.09 A
	WS	0.80 g	0.82 fg	0.85 ef	0.91	0.89 de	0.85 B
	Fertilizers averages	0.90 D	0.93 D	0.98 C	1.05 A	1.01 B	
	Lsd$_{fertilizer}$*= 0.03 Lsd$_{irrigation}$* 0.02 Lsd$_{fertilizer \times irrigation}$*= 0.04						
Stem N (%)	Irrigation levels	G0	G1	G2	G3	G4	Irr. levels averages

	FI	1.80 c	2.01 b	2.03 b	2.21 a	2.15 a	2.04 A
	WS	1.02 g	1.05 fg	1.11 ef	1.22 d	1.14 e	1.11 B
	Fertilizers averages	1.41 D	1.53 C	1.57 C	1.72 A	1.64 B	
	Lsd$_{\text{fertilizer}}$*= 0.05 Lsd$_{\text{irrigation}}$*= 0.03 Lsd$_{\text{fertilizer × irrigation}}$*= 0.07						
Leaf N (%)	Irrigation levels	G0	G1	G2	G3	G4	Irr. levels averages
	FI	4.65	5.15	5.14	5.34	5.22	5.10 A
	WS	2.57	2.79	2.84	3.01	2.93	2.83 B
	Fertilizers averages	3.61 B	3.97 A	3.99 A	4.18 A	4.07 A	
	Lsd$_{\text{fertilizer}}$*= 0.33 Lsd$_{\text{irrigation}}$* 0. 21						
Fruit N (%)	Irrigation levels	G0	G1	G2	G3	G4	Irr. Levels Averages
	FI	2.03 bc	2.09 b	2.13 b	2.46 a	2.37 a	2.22 A
	WS	1.81 f	1.86 ef	1.88 ef	1.98 cd	1.93 de	1.89 B
	Fertilizers averages	1.92 D	1.98 CD	2.00 C	2.22 A	2.15 B	
	Lsd$_{\text{fertilizer}}$*= 0.07 Lsd$_{\text{irrigation}}$*= 0.04 Lsd$_{\text{fertilizer × irrigation}}$*= 0.09						

1) Separate letters represent the differences between the averages,
2) N. S.: Not Significant,* P ≤ 0.05

Table 7. The effects of different irrigation levels and fertilization treatments on cucumber potassium (K) partitioning (%)

	Irrigation levels	**G0**	**G1**	**G2**	**G3**	**G4**	**Irr. levels averages**
Root K (%)	FI	1.52 e	1.62 d	1.75 c	1.98 a	1.88 b	1.75 A
	WS	0.81 j	0.86 i	0.93 h	1.29 f	1.14 g	1.00 B
	Fertilizers averages	1.16 E	1.24 D	1.34 C	1.64 A	1.51 B	
	Lsd$_{\text{fertilizer}}$*= 0.03 Lsd$_{\text{irrigation}}$* 0.02 Lsd$_{\text{fertilizer × irrigation}}$*= 0.04						
Stem K (%)	Irrigation levels	G0	G1	G2	G3	G4	Irr. levels averages
	FI	3.54	3.63	3.79	3.94	3.85	3.75 A
	WS	1.79	1.85	1.95	2.08	2.00	1.93 B
	Fertilizers averages	2.66 E	2.74 D	2.87 C	3.01 A	2.93 B	
	Lsd$_{\text{fertilizer}}$*= 0.06 Lsd$_{\text{irrigation}}$*= 0.04						
Leaf K (%)	Irrigation levels	G0	G1	G2	G3	G4	Irr. levels averages
	FI	3.55 c	3.89 b	3.94 b	4.44 a	4.29 a	4.02 A
	WS	1.53 f	1.67 ef	1.72 e	1.93 d	1.85 de	1.74 B
	Fertilizers averages	2.54 C	2.78 B	2.83 B	3.18 A	3.07 A	
	Lsd$_{\text{fertilizer}}$*= 0.33 Lsd$_{\text{irrigation}}$* 0. 21						
Fruit K (%)	Irrigation levels	G0	G1	G2	G3	G4	Irr. levels averages
	FI	2.10 e	2.23 d	2.39 c	2.81 a	2.57 b	2.42 A
	WS	1.78 h	1.83 gh	1.87 gh	1.99 f	1.90 fg	1.87 B
	Fertilizers averages	1.94 E	2.03 D	2.13 C	2.40 B	2.24 A	
	Lsd$_{\text{fertilizer}}$*= 0.06 Lsd$_{\text{irrigation}}$*= 0.04 Lsd$_{\text{fertilizer × irrigation}}$*= 0.09						

1) Separate letters represent the differences between the averages,
2) N. S.: Not Significant,* P ≤ 0.05

On the other hand, WS decreased the uptake of N and K in every part of the plant. However, WS caused a noticeable reduction in N and K in the fruit and root but an unexpectedly higher decrease in the leaf and stem, indicating a possible stress-adapted survival mechanism, which is consistent with Shehata *et al.* (2019)'s observations about plant responses to stress. The inequality in nutrient uptake under different irrigation levels also enlightens physiological optimization in the resource allocation of plants. For instance, the case of limited water irrigation revealed relative stability in the N and K levels in the fruits in relation to the prioritization mechanism to support photosynthesis and growth despite the water stress. This aligns with Kirnak and Demirtaş (2006) and Wang *et al.* (2019), as they described similar nutrient prioritization strategies in stressed plants. All these studies indicate how plants adapt to such variant environmental and agronomic conditions, offering deep knowledge about the complex relationships among fertilization, irrigation, and plant physiological responses. In summary, these current research findings complement those of Mao *et al.* (2022) and Qu *et al.* (2022) in underpinning how efficient nutrient management optimization can be, not only in yielding better crops but also in enhancing crop quality across varying water availability. The adaptive mechanisms are the key players that future studies should keenly follow. The studies of Ramirez-Peres *et al.* (2018) and Wang *et al.* (2019) equally pointed out that such an approach would offer a direction for any such breeding and cultivation strategies to boost crop resilience. It is of great importance in the development of sustainable agricultural practices since it incorporates all the agronomic, physiological, and environmental factors.

Conclusions

This useful study on the realization of cucumber cultivation in controlled conditions presented an optimal strategy for fertilizing in terms of yield, irrigation efficiency, and crop quality through the correct use of smart irrigation systems and proper nutrient management, particularly the combination of organic and inorganic nutrients. The integration of organic and inorganic fertilizers (G3) with smart irrigation systems not only optimizes crop yield and water use efficiency but also holds significant implications for long-term soil health and sustainability. Organic fertilizers improve soil structure, increase microbial activity, and enhance nutrient retention, while inorganic fertilizers provide readily available nutrients for immediate plant uptake. This combination addresses both short-term nutrient demands and long-term soil fertility. When paired with precision water management through smart irrigation, the risk of nutrient leaching and soil degradation is minimized. This synergy promotes a sustainable agricultural system by maintaining soil organic matter levels, enhancing soil resilience to environmental stress, and reducing dependency on chemical inputs over time. These findings underscore the critical role of integrated nutrient and water management practices in achieving sustainable intensification of agriculture. This current research output further validates the importance of precision agriculture in sustainable food production. Future studies should focus on the necessity of sustainable practices in global agricultural systems by examining long-term effects and scalability in various climatic regions. This current research strategy contributes to environmental sustainability while optimizing resource use efficiency, which is important given the world's water scarcity and the rising demand for food production of superior quality. Future research should focus on scaling up the proposed strategies to larger agricultural systems, exploring their long-term feasibility and impact under diverse climatic and soil conditions.

Authors’ Contributions

EC: Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization, Supervision. MEC: Resources, Methodology, Investigation, Formal analysis, Funding acquisition. HE: Validation, Software, Visualization, Resources.

All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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