Improving Yield of Tomatoes Grown in Greenhouses using IoT based Nutrient Management System

Abstract:

Aims: This paper discuss, a study conducted to evaluate the developed automated IoT based fertigation control system for greenhouse for tomato (Solanum lycopersicum L.) crop.

Study Design: Different nutrient and irrigation water levels were used to evaluate developed system using three replications in a factorial randomized block design (RBD).

Methodology: An automated fertigation scheduling system was implemented in a greenhouse with soil moisture sensors at three depths (15, 30, and 45 cm) within the tomato root zone. R^2, RMSE, NSE and MAE values were used to establish the correlation between sensor values and actual soil moisture. Tomato crop biometric parameters were collected and analyzed to evaluate the system's performance.

Results: The results indicated strong correlation between sensor and observed soil moisture with R^2 (0.8642 to 0.9528), RMSE (1.0786 to 1.8328), NSE (0.8438 to 0.9463), and MAE (0.9729 to 1.7043) values. Highest plant height (255 cm), girth (2.29 cm), number of leaves (21), number of flowers (23.1), fruit length (8.05 cm), fruit weight (110 g), yield/plant (2.75 kg), yield (68.77 t/ha) and sugar (5.1°Brix) were observed with drip irrigation at the rate of 100% ETc and 100% recommended dose of fertilizer (RDF), while minimum values of these parameters were noted in the control treatment.

Conclusion: Using sensor-based drip irrigation at 100% ETc and 100% RDF led to a 62.92% increase in tomato yield and water saving of 14.84% compared to the control treatment. For tomato crop, the system required 2.27 l/plant/day water at 100% ETc. The developed automated fertigation system found suitable for greenhouse vegetable crops with the use of sensor based drip irrigation at 100% ETc and 100% RDF.

Keywords: Nutrient Management, Fertigation Scheduling, IoT, Sensors, Tomato.

1. Introduction

Agriculture has a major impact on the development of the nation. For the sake of the country's economy, farming and the profession related to agriculture should therefore be highly prioritized. For many years, the agricultural sector has been India's core infrastructure, and farmers have been lauded and highly appreciated **(Datta et al., 2017).** The growing urban population has increased the demand for agricultural product in and around the big cities.

Due to the increased need for food to feed the growing population and the limited water resources available for agricultural production, irrigation researchers and managers have recently been forced to utilize water saving irrigation technologies to raise water productivity **(Bowlekar et al., 2019)**. The conventional irrigation scheduling as well as water distribution systems can be improved using modern irrigation management technologies. One such modern technology for the proper use of water resources for enhanced crop yields is the automatic irrigation scheduling and nutrient management system. Automatic drip irrigation scheduling particularly with protected cultivation technology has shown very good result in improving crow water productivity particularly for horticultural crops **(Hasan, 2015).**

Protected cultivation technology deals with growing crops inside protected structures commonly known as greenhouse, net house, shade house etc. and it is now being used through the world and different parts of India by growers and formers mainly for horticultural crops **(Hasan, 2016).** Drip irrigation is mostly used inside protected structures for irrigating crops. Precision management of crops grown in protected cultivation based greenhouse can be done by adopting drip irrigation and fertigation **(Hasan et al., 2022).**

Drip irrigation is a precise method conserving water and nutrients, ideal for crops in challenging conditions. It reduces water use by 36-79%, sustaining optimal soil moisture near field capacity. By delivering filtered water directly to plant roots, it ensures efficient growth, utilizing 90-95% water application efficiency. This technique covers more land with less water due to non-irrigated row spaces. Drip irrigation maximizes water savings and productivity, making it vital for horticultural success **(Hasan, 2016).**

Automation of drip irrigation, aided by soil moisture and fertigation sensors, optimizes system management **(Hasan et al., 2022).** Sensor-driven scheduling curtails water losses, providing precise crop-specific irrigation, thereby enhancing water-use efficiency. Timely irrigation enhances yield per water unit, crucial in water-scarce areas. Sensor-guided daily cycle irrigation ups water-use efficiency by 25-38% through alternating irrigation and rest periods **(Ismail et al., 2007).** Tropical greenhouse tomato research indicates sensor-based drip fertigation outperforms open-field systems, yielding 20-40% higher water savings **(Nikolaou, 2019).** Wireless sensor networks further this research, spotlighting soil moisture and fertigation sensors for water-efficient greenhouse cultivation **(Hasan et al., 2022).**

Capacitive soil moisture sensors excel due to corrosion resistance, extended lifespan, and onboard voltage regulation. They operate within 3.3-5.5V for microcontrollers like Raspberry Pi, requiring an analog-to-digital converter (ADC). Unlike resistive sensors, they resist soil-induced corrosion and DC current, boosting durability **(Martinez and Byrnes,**

2001). Capacitive measurement surpasses resistance measurement by precisely detecting soil moisture and avoiding probe corrosion. It gauges relative dielectric permittivity through capacitance, which relates to soil's conductivity, accurately reflecting moisture. Such sensors find use in greenhouse cultivation, including crops like tomatoes. The dielectric permittivity of soil components ranges from 2 to 6, with water's at 80 **(Hrisko, 2020).**

Tomato *(Solanum Lycopersicum L)* is one of the most popular and commonly cultivated vegetables in the world. It is good for our health and contains provitamins, beta-carotene, and vitamin C. It also contains abundant amounts of lycopene, which is a powerful antioxidant that helps in the prevention of the spread of many forms of cancers and heart disease **(Xiukang and Yingying, 2016).** Greenhouse tomato crop requires a suitable temperature i.e. 22 to 27 ^{o}C and high humidity 49 to 60 percent for optimium production **(Shinde et al., 2018).** On an average, 186.821 million metric tonnes (Mt) of tomatoes were produced worldwide on 5,051,983 hectares, yielding an average of 37.1 t/ha **(Shinde et al. 2018).** India ranks first in canned vegetable production and second in terms of area and production of tomatoes globally after potatoes **(Mishra et al., 2013).** Tomato is widely grown around the world in more than 4.5 million acres due to the huge commercial demand **(Chand et al., 2020).** For ensuring year-round production and promoting higher water application efficiency, greenhouses protect crops from insects, pests, diseases, and the harmful impacts of extreme weather events **(Shinde et al., 2018).** In a greenhouse system, tomato production is influenced by various factors, such as the local climate (specifically, temperature, humidity, and light intensity), greenhouse infrastructure, suitable varieties and automatic fertigation system.

Automatic fertigation system includes fertigation control head and irrigation automation accessories with controller, venture injector, solenoid valves and field level system including pipes, lateral and valves. Accordingly, a fertigation control head should be designed and sensors values should be standardized to go ahead for automated fertigation scheduling **(Nikolaou, 2019).** Fertigation scheduling is the timely application of nutrients with drip irrigation in accordance with crop stages. Knowing exactly how much water and fertilizer should be given by drip is one of the most important components of drip fertigation. Fertigation is assisted by specialized fertilizer equipment (injectors) positioned at the system's head control unit and before the filter. For improving crop productivity and product quality, fertigation nutrient control is essential. Throughout all stages of growth, plants require appropriate dosage of water and nutrients. Sensors are used for automation of water nutrient supply through fertigation of greenhouse crops **(Hasan et al., 2022)**.

In this paper, sensor and Internet of Things (IoT) based fertigation scheduling system development and evaluation for tomato crop grown in forced ventilated greenhouse is discussed. The objectives of this work were (1) To develop control head for sensor-based automated fertigation system; (2) To standardize different sensors for fertigation scheduling of greenhouse tomato; and (3) To evaluate various parameters of greenhouse tomato crop based on standardized fertigation sensors.

2. Materials and Methods

2.1 Study Area

The present study was conducted at Centre for Protected Cultivation Technology (CPCT), Indian Council of Agricultural Research-Indian Agricultural Research Institute (ICAR-IARI), New Delhi during December 2021 to May 2022. The climate of Delhi is subtropical and semi-arid, with hot summers and cold winters. The average temperature can vary from 25°C to 46°C during the summer (April-July) and 22°C to 5°C during the winter (December-January). The average annual rainfall in Delhi is 71 cm. During the monsoon season, humidity levels are high. The driest months are April and May when relative humidity ranges from less than 20% in the afternoon to around 30% in the morning. Wind speeds range from 0.45 m s^{-1} to 3.96 m s^{-1} **(Chakraborty et al., 2014).** The soil of experimental site was sandy loam having field capacity, permanent wilting point and bulk density of 22.72%, 8.13% and 1.59 g cm^{-3}, respectively. The available nitrogen, phosphorus and potassium in soil of experimental field were 130.25 kg ha^{-1}, 39.29 kg ha^{-1} and 361.91 kg ha^{-1}, respectively. The location map of the study area is shown in Fig. 1.

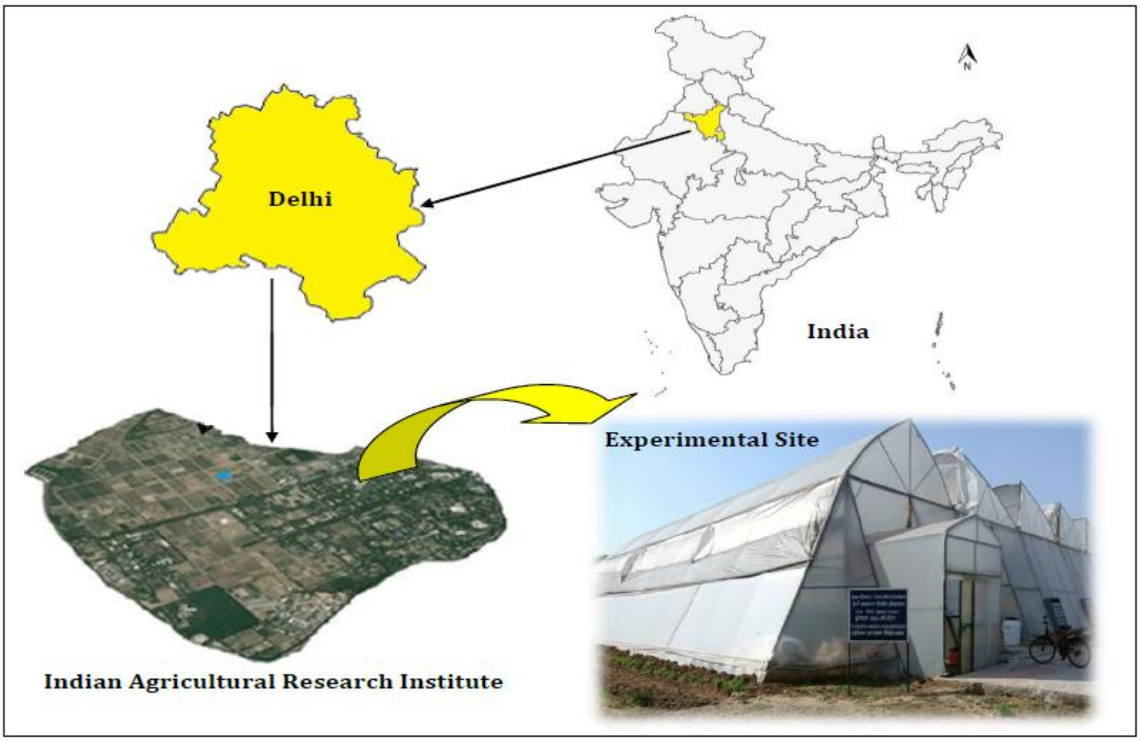


Fig. 1 Location map of the study area

2.2 Development of soil moisture characteristic curve

The soil moisture characteristic curve of the sandy loam soil was developed using Richard's Pressure Plate Apparatus **(Richards, 1944).** Six soil samples were collected from three different depths *viz.* 0-20 cm, 20-40 cm and 40-60 cm. The soil moisture content determined at different tension ranges between 0 to 15 kPa for each sample. The developed soil moisture characteristic curve of the sandy loam soil of experimental field is depicted in Fig. 2.

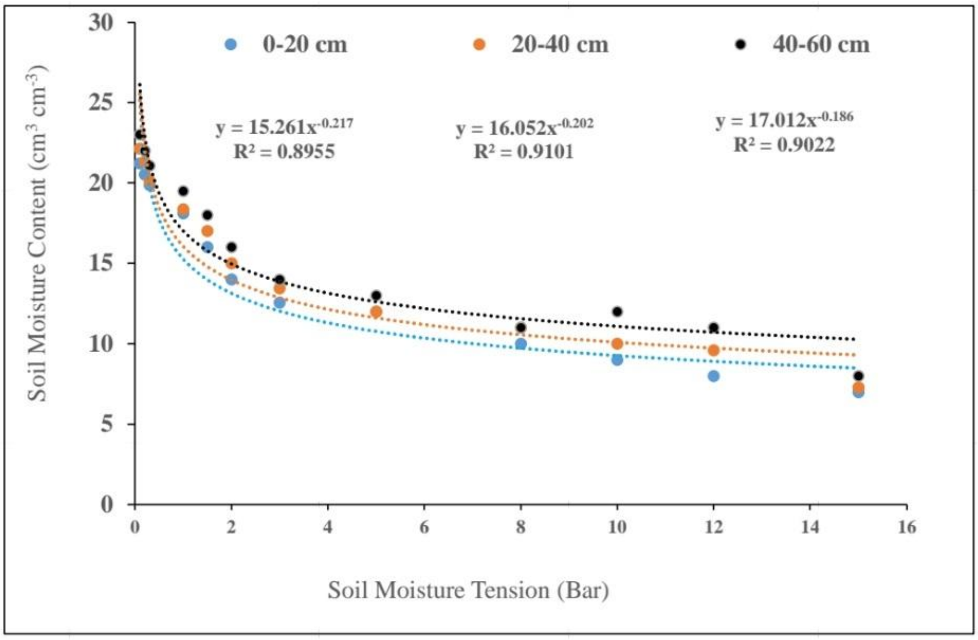


Fig. 2 Soil moisture characteristic curve of the sandy loam soil of experimental field

2.3 Treatment details

The present field experiment was conducted on greenhouse tomato crop (variety: Hechicero F1) to develop and evaluate sensor based fertigation system. Total area of experimental field was 20 m x 13.5 m (270 m^2). Both plant to plant and row to row distance was maintained at 60 cm. An individual treatment comprised of combination of irrigation level and percentage of Recommended Dose of Fertilizer (RDF) for tomato crop. First three treatments were given irrigation at the rate of 100% Crop Evapotraspiration (ETc) with fertilizer dose of 100% RDF, 80% RDF and 60% RDF, respectively. Another three treatments were given irrigation at the rate of 80% ETc with fertilizer dose of 100% RDF, 80% RDF and 60% RDF, respectively. Similarly, last three treatments were given irrigation at the rate of 60% ETc with fertilizer dose of 100% RDF, 80% RDF and 60% RDF, respectively. This combination of 9 treatments was executed in 3 replications using Factorial Randomized Block Design (FRBD). The recommended dose of fertilizer (RDF) for 1000 m^2 greenhouse tomato crop is urea phosphate (39 kg), urea (14 kg) and potassium sulphate (40 kg). Micronutrients were also applied for proper crop growth time to time during this experiment. The different biometric observations of tomato crop such as plant height, plant girth, number of leaves and number of flowers per plant were recorded at 30, 60, 90 and 120 days after transplanting. The yield parameters such as fruit weight, fruit length, yield per plant and yield per hectare were noted.

2.4 Development of fertigation control unit

2.4.1 Calibration and installation of the capacitive soil moisture sensor V2.0

Soil moisture sensors were calibrated using CoDeSys software. The probe of the sensor was inserted into the soil sample under the test. With the help of this software, the moisture content of the soil was set in the range of 0 to 100% by the scale on the system. The same process was repeated ten times with different soil samples, and the calibrated sensor values were used to validate the field sensors. For validation of sensors, the samples of soil were taken from the experimental field at different depths *viz.* 0-20, 20-40, and 40-60 cm before irrigation and after irrigation at 2, 4, 24, 48, and 72 hours before transplanting the tomato. The moisture content of these soil samples was determined by using gravimetric method, and converted into volumetric basis by multiplying with bulk density of soil. The obtained soil moisture content values were compared with sensor soil moisture values which were installed on same location at different depth of 15, 30, and 45 cm within the root zone of the tomato. Installation of the capacitive soil moisture sensors at different depths is shown in Fig. 3.

The capacitive soil moisture sensor V2.0 measures the soil moisture content by sensing the capacitive rather than the resistive. Nine sensors with pipe attached to their upper end for sturdiness and ease of installation were put at different desired locations such that they are equally distributed in all treatments. The sensor circuits were covered with water proof insulator material to prevent the damage of sensors from soil moisture. These sensors were installed near the root zone of tomato plants at three different depths, namely 15, 30, and 45 cm to determine the real time average soil moisture content at these depths. All nine sensors were in series with each other and connected to the 12-volt supply from the control unit. This module has an onboard voltage regulator that provides it with a 3.3-5.5V operational voltage range. Both 3.3V and 5V low-voltage MCUs used it well. It was provided with an ADC converter to be compatible with a microcontroller. These 3-pin interface compatible soil moisture sensors were connected to the input/output expansion shield.

Fig. 3 Installation of the capacitive soil moisture sensors at different depths

2.4.2 Components of automated fertigation control system

2.4.2.1 Data management and display unit

The soil moisture sensor values given by the system to the user were stored and analyzed for the soil condition and water requirement of the field crop by using data management unit. The observed data was evaluated to determine the efficiency and accuracy of the developed system. A liquid crystal display screen which is a type of electronic display module was used for displaying soil moisture content values obtained from all sensors on the LCD display unit.

2.4.2.2 Solenoid valves

The solenoid valves with a 24 volt AC current for operating at low pressure (range of 0.7 to 4.5 bar) applications were integrated with controller and used for autimated fertigation of tomato crop. These valves were operated by a relay based on a time interval where the signal received by the controller unit from the soil moisture sensors and then commands transmitted to the relay.

2.4.2.3 Relay module

A relay is one kind of electrical switch. The coil of the relay is energized by DC current so that contact switches can be opened or closed. A single-channel 5 volt relay module included a coil and two contacts, *viz.* normally open (NO) and normally closed (NC). NO contact connected to the circuit when the relay unit was activated and disconnected when the relay unit was inactive. A 5-volt relay is common automatic switch that is frequently used in automatic control circuits to regulate high-range currents to low-range current signals. The range of input voltage of relay signals used for automation was 0 to 5 volts.

2.4.2.4 NodeMCU

NodeMCU stands for Node Microcontroller Unit, and it is an open-source Lua-based firmware designed specifically for Internet of Things (IoT) applications. The ESP-12E module that runs this firmware is based on the 32-bit ESP8266 MCU. Its 2.4 GHz Wi-Fi supports WPA/WP2. Along with a 3.3-volt SMPS unit, the ESP-12E has a programmer. Therefore, this board can be readily operated directly on 5 volt from USB without the requirement for an extra programmer.

2.4.2.5 Control panel

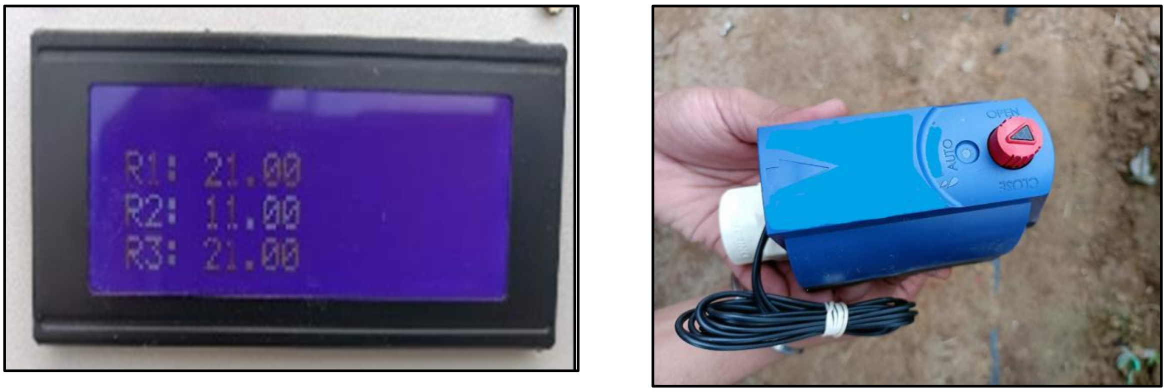
The control panel unit included a liquid crystal display, relay, NodeMCU, a microprocessor, an SD card and an emergency pull bottom. All the soil moisture capacitive type sensors were connected to the control panel through the circuit.

A self-priming monoblock electric pump was used for drip irrigation. It was 1.10/1.5 kW/HP, 220 AC, 50 Hz motor pump having discharge is 1800-5200 lph and total head 178 feet. The controller unit consisted of the relay, which received the signal from the capacitive soil moisture sensors. Whenever the soil moisture level lowered than the field capacity, the pump was turned ON and moisture level incresed to a preset level, then the pump was closed.

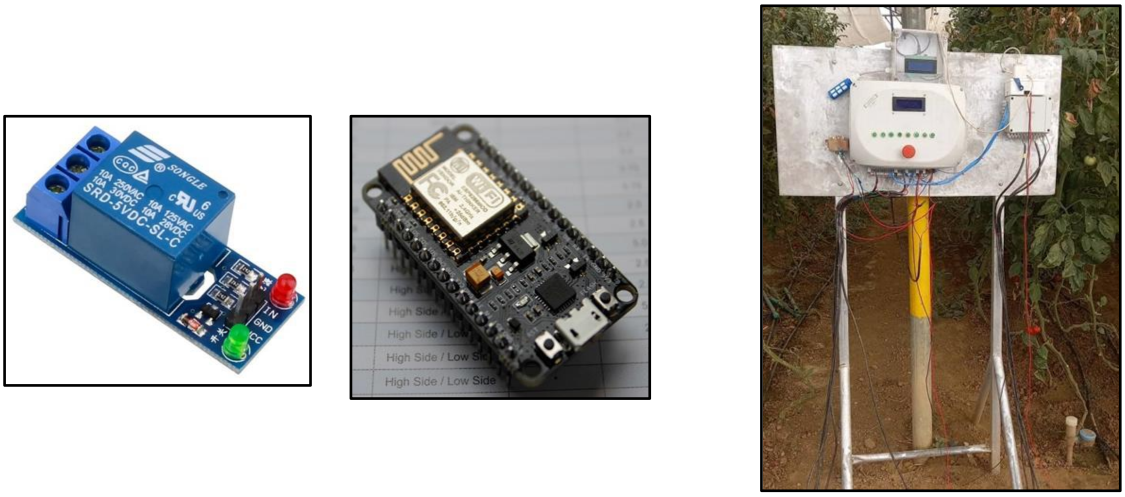
Components of automated fertigation system are shown in Fig. 4.

2.5 Performance evaluation of the capacitive soil moisture sensors

The performance of soil moisture sensors was evaluated using various statistical indices. Coefficient of Determination (R^2) measures the goodness of fit of the regression equation. The R^2 is a statistical measurement that examines how differences in one variable may be explained by variations in another. If R^2 approaches 1, then it indicates a better correlation between the sensor value and gravimetric soil moisture content. **Nash-Sutcliffe Efficiency (NSE)** indicates how well the curve of gravimetrically observed soil moisture verses sensor soil moisture fits linearly. The NSE ranges from to -∞ to 1. If it is closer to 1 then better fit to gravimetrically observed soil moisture with sensor value. Root Mean Square Error (RMSE) is the standard deviation of the difference between sensor moisture value and gravimetric observed soil moisture content (residuals). Lower value of RMSE is the better fit between sensor moisture content to gravimetric observed soil moisture content. Mean Absolute Error (MAE) is the average of absolute difference between the sensor soil moisture value and the gravimetric soil moisture content. The lowest value of MAE ascertains that the sensor value is approaching the gravimetric soil moisture content.



Display Unit **Solenoid Valve**



5V Relay Module **NodeMCU** **Control Panel**

Fig. 4 Components of automated fertigation system

3. Results and Discussion

3.1 Development of control head for sensor based automated fertigation system

This fertigation control setup consisted of three tanks each of 225 litres capacity, two disc filters, three venturi injectors and an electric water pump. All three tanks were connected with separate venturi injectors through PVC pipe. The electric water pump was operated by a relay and a control panel. There were nine sensors installed into the field at three locations (R1, R2, and R3). Each location consisted of three sensors at different depths of 15, 30, and 45 cm within the root zone of greenhouse tomato. The sensor senses the moisture content and sends it to the microcontroller to control the relay unit. The main principle of this setup was to apply the fertigation to the plant in appropriate quantity and within the root zone which can be controlled by microcontroller. The developed fertigation control head is depicted in Fig. 5 and 6.

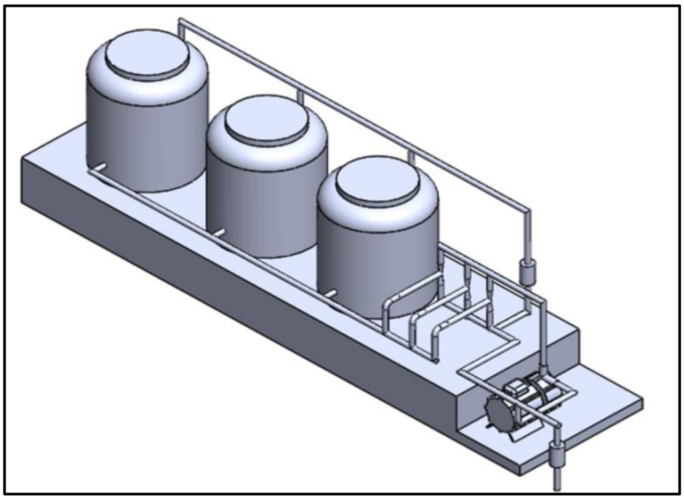


Fig. 5 Isometric view of developed fertigation control head

Fig. 6 Field view of developed fertigation control head

Three tanks of capacity 225 litres each were used for providing fertigation to the tomato plants. Two tanks used for stocking nutrient solution A and nutrient solution B and third tank was used as mixing tank from which fertigation was provided to the crop. The fertilizers having calcium source were kept in tank A and others in tank B. This is because calcium generally reacts with other nutrients and form precipitates which may block various drip components.

3.2 Standardization of different sensors values for fertigation scheduling of greenhouse tomato

The capacitive type soil moisture sensors were calibrated by using gravimetric method to the volumetric soil moisture content (cm^3 cm^{-3}) and sensor analogue values have been presented in Table 1. The calibrated equation was obtained to be linear in nature and it is shown in Fig. 7. The coefficient of determination was found to be 0.8617.

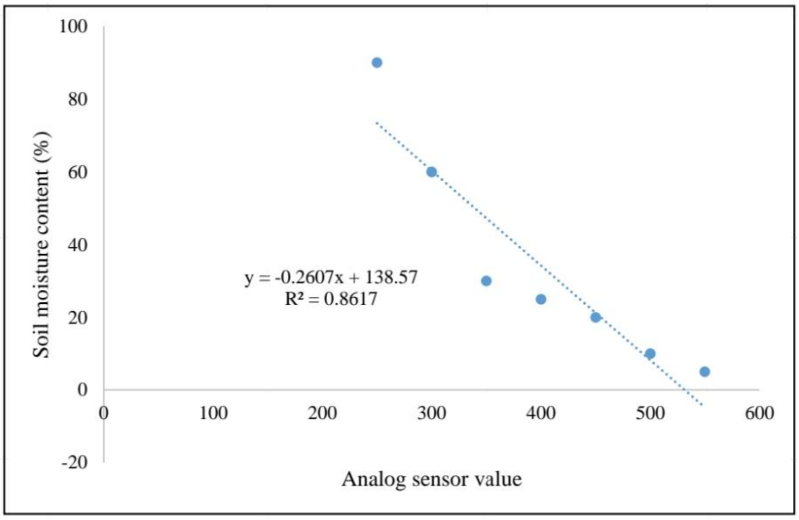


Fig. 7 Relationship between the volumetric soil moisture content and analogue values of the sensor

3.3 Calibration of capacitive type soil moisture sensors

The field experiment was carried out with the use of nine sensors placed at three locations on the experimental site at three different root zone depths of 15, 30, and 45 cm. A combination of three sensors were placed at each location. All sensors were calibrated by using standard gravimetric method by a regression relationship between observed soil moisture content calculated by the gravimetric method and sensor soil moisture at 15, 30, and 45 cm. The calibration curves for three sensors (S1, S2, and S3) installed at 15 cm are shown in Fig. 8 (a), 8 (b), and 8 (c) and the coefficient of determination (R^2) found to be 0.9495, 0.9385, and 0.9201, respectively. Similarly, calibration of three sensors at 30 cm and three sensors at 45 cm was carried out.

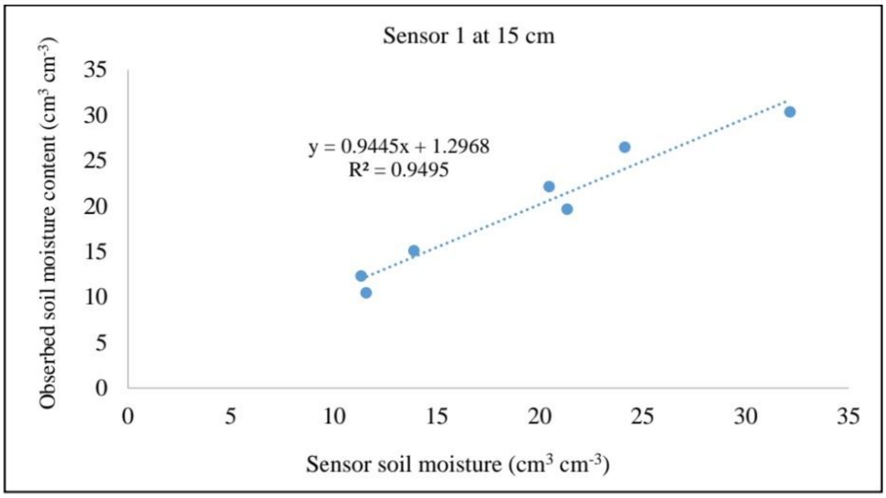


Fig. 8 (a) Relationship between gravimetrically observed soil moisture content and sensor 1 soil moisture content at a depth of 15 cm

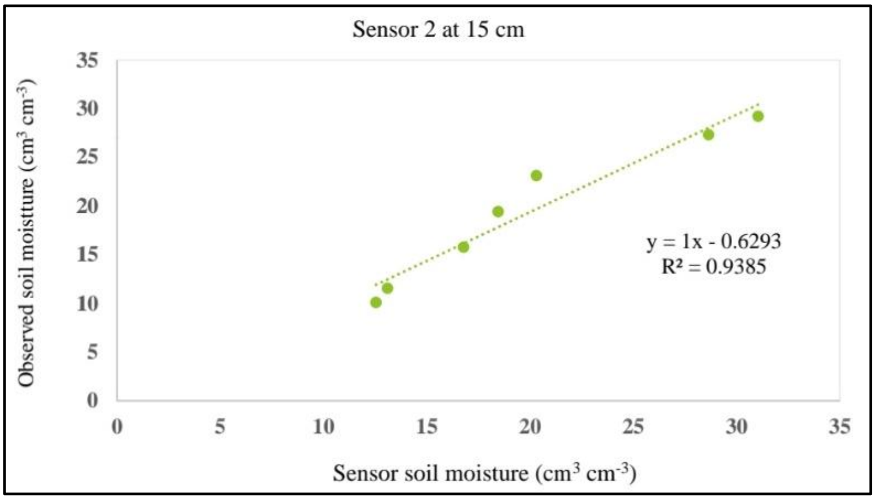


Fig. 8 (b) Relationship between gravimetrically observed soil moisture content and sensor 2 soil moisture content at a depth of 15 cm

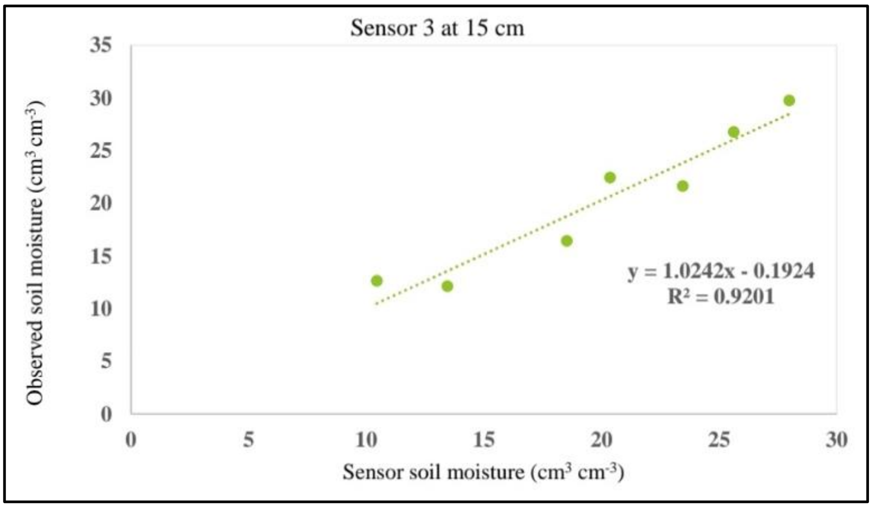


Fig. 8 (c) Relationship between gravimetrically observed soil moisture content and sensor 3 soil moisture content at a depth of 15 cm

3.4 Performance evaluation of all sensors

The statistical analysis parameters such as coefficient of determination (R^2), Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE) and Mean Absolute Error (MAE) were computed to check the performance of all capacitive soil moisture sensors and compared them with gravimetrically observed soil moisture content at depths of 15, 30 and 45 cm within the root zone of tomato (Table 1). The R^2, RMSE, NSE and MAE values varied from (0.8642-0.9528), (1.0786-1.8328), (0.8438-0.9463) and (0.9729-1.7043) respectively for soil moisture sensors placed at 15-45 cm depths in multiple field locations.

Table 1 Performance evaluation parameters for sensors at different depths

Sensor Location	Depth (cm)	Sensor Number	R^2	RMSE	NSE	MAE
1	15	S1	0.9495	1.5982	0.945	1.5371
	30	S4	0.9368	1.7883	0.921	1.4857
	45	S7	0.8642	1.8328	0.8438	1.5800
2	15	S2	0.9385	1.8242	0.9301	1.7043
	30	S5	0.9483	1.4759	0.9452	1.4029
	45	S8	0.9528	1.0786	0.9463	0.9729
3	15	S3	0.9201	1.8103	0.9187	1.7714
	30	S6	0.9227	1.7673	0.9073	1.5929
	45	S9	0.8968	1.5343	0.8975	1.4029

3.5 Evaluation of biometric parameters based on standardized sensors

3.5.1 Plant height

Greenhouse tomato plant height increased gradually during the first 120 days after transplanting (DAT) and became nearly constant after that. Among all treatments, T1 corresponding to 100% ETc and 100% RDF showed the highest plant height (255 cm) while the minimum plant height (202.5 cm) was obtained in control treatment. The variation of plant height with respect to treatments is shown in Fig. 9. Treatments 1 to 9 are denoted as T1 to T9.

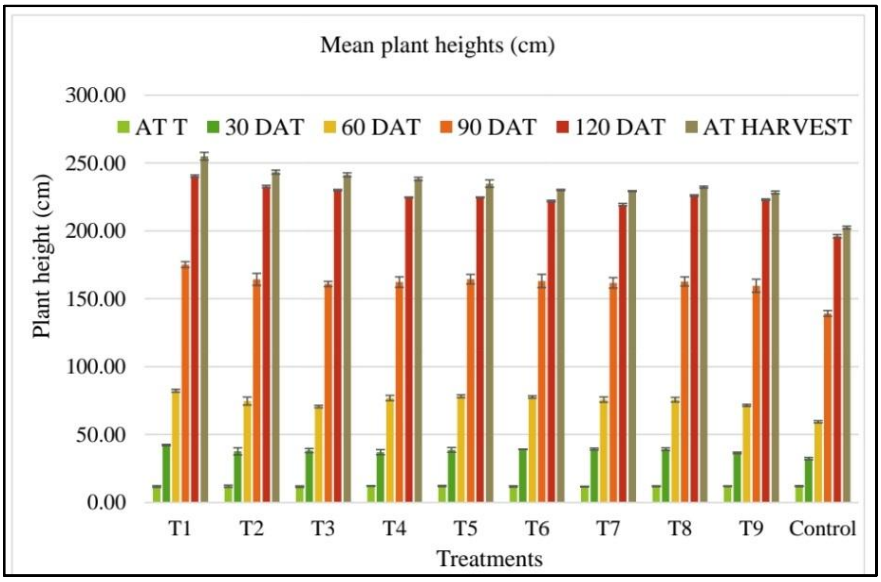


Fig. 9 Variation in plant height of greenhouse tomato with different treatments

3.5.2 Plant girth

The mean plant girth values for different treatments are shown in Fig. 10. Greenhouse tomato plant girth increased gradually during the first 120 days after transplanting (DAT) and became nearly constant after that. Among all treatments, T1 corresponding to 100% ETC and 100% RDF showed the highest plant girth (2.29 cm) while the minimum plant girth (1.70 cm) obtained in control treatment.

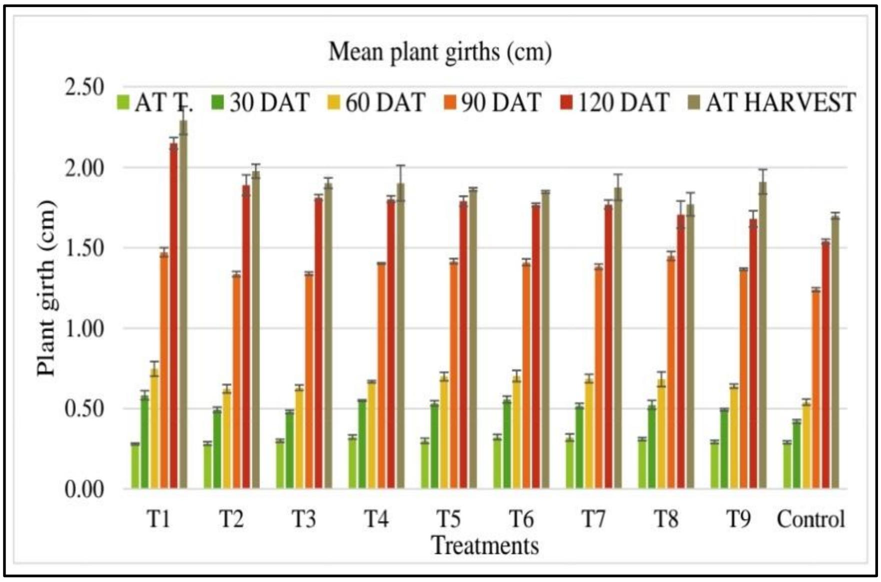


Fig. 10 Variation in plant girth of greenhouse tomato with different treatment

3.5.3 Plant leaves

The mean number of plant leaves for different treatments are shown in Fig. 11. The number of leaves increased continuously for the first 90 days after transplanting (DAT) and then began to decline gradually. Among all treatments, T1 corresponding to 100% ETC and 100%

RDF showed the highest number of leaves (21) while the minimum number of leaves (12.33) obtained in control treatment.

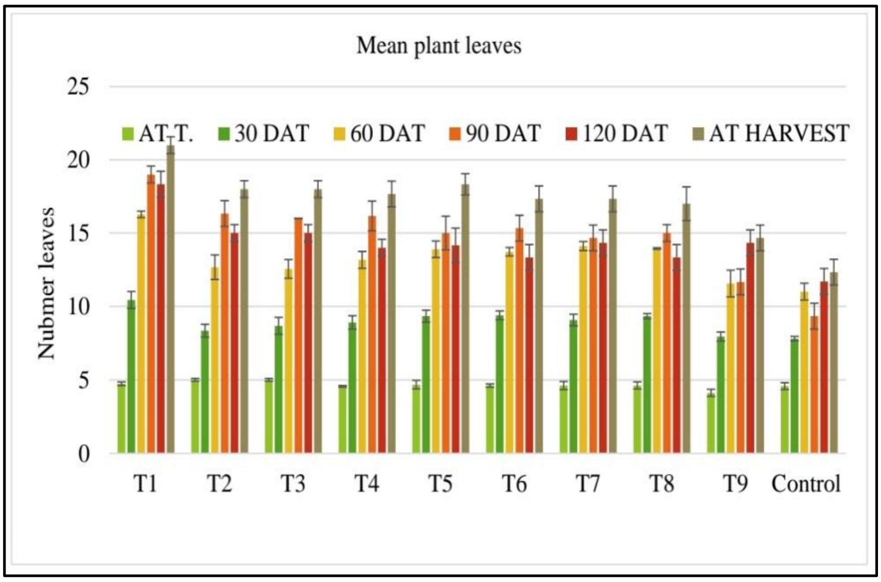


Fig. 11 Variation in number of leaves of greenhouse tomato with different treatments

3.5.4 Number of flowers

The mean number of flowers of greenhouse tomato for different treatments are shown in Fig. 12. The number of flowers increased continuously for the first 90 days after transplanting (DAT) and then began to decline gradually. Among all treatments, T1 corresponding to 100% ETC and 100% RDF showed the highest number of flowers (23.10) while the control treatment resulted in lowest values (10).

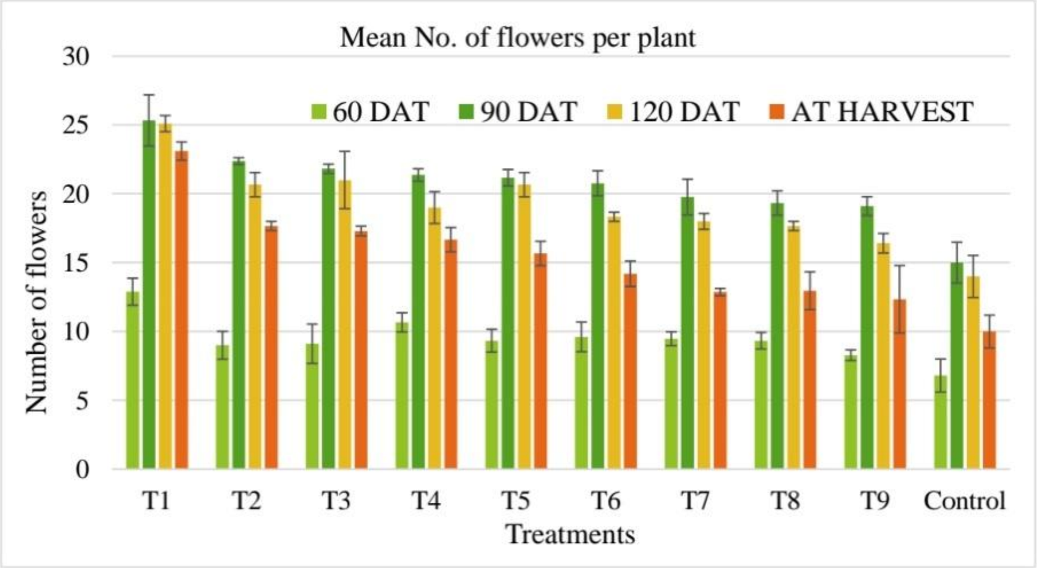


Fig. 12 Variation in number of flowers of greenhouse tomato with different treatments

3.6 Yield parameters

3.6.1 Fruit length

After was picking the full matured fruits from the tags plant, average fruit length of greenhouse tomato was recorded and shown in Fig. 13. Among all treatments, T1 corresponding to 100% ETC and 100% RDF showed the maximum average fruits length (8.05 cm) while the control treatment resulted in minimum values (5.93 cm). The irrigation and fertigation levels were significant at 5% and 1% level of significance but there was no interaction between them.

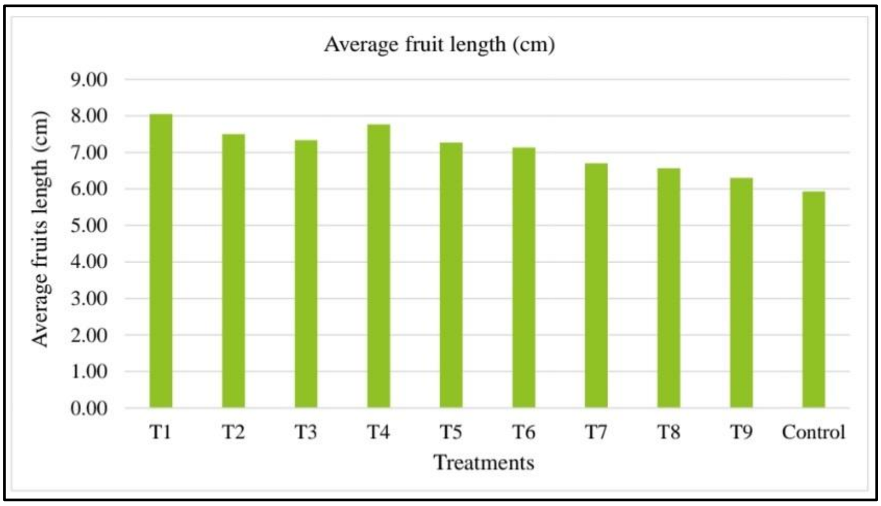


Fig. 13 Variation in average fruit length of greenhouse tomato

3.6.2 Average fruit weight

Among all treatments, T1 corresponding to 100% ETC and 100% RDF showed the maximum average fruits weight (110 gm) while the control treatment resulted in minimum values (65.33 gm). The irrigation and fertigation levels were significant at 5% and 1% level of significance but there was no interaction between them. The variation of average fruit weight of tomato with different treatments is shown in Fig.14.

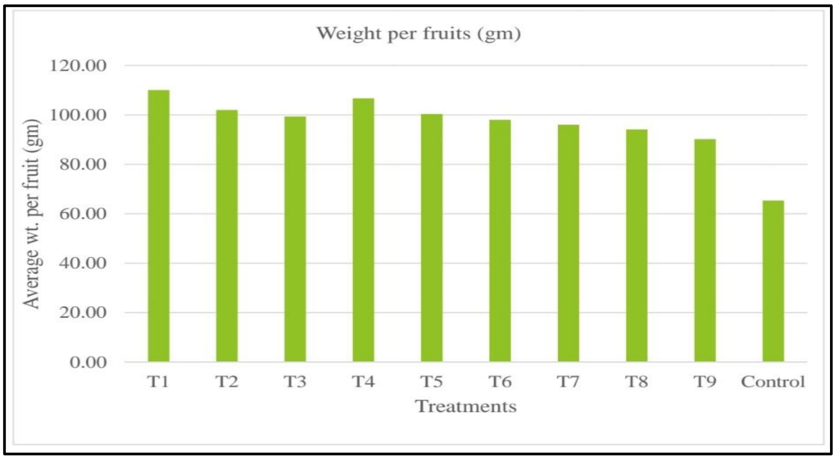


Fig. 14 Variation in weight per fruits of greenhouse tomato with different treatments

3.6.3 Yield per plant

T1 corresponding to 100% ETC and 100% RDF showed the maximum average fruits yield per plant (2.75 kg) while the control treatment resulted in minimum values (1.50 kg). From ANOVA, the irrigation and fertigation levels were significant at 5% and 1% level of significance and interaction between them was also significant. Variation of average fruits yield per plant shown in Fig.15.

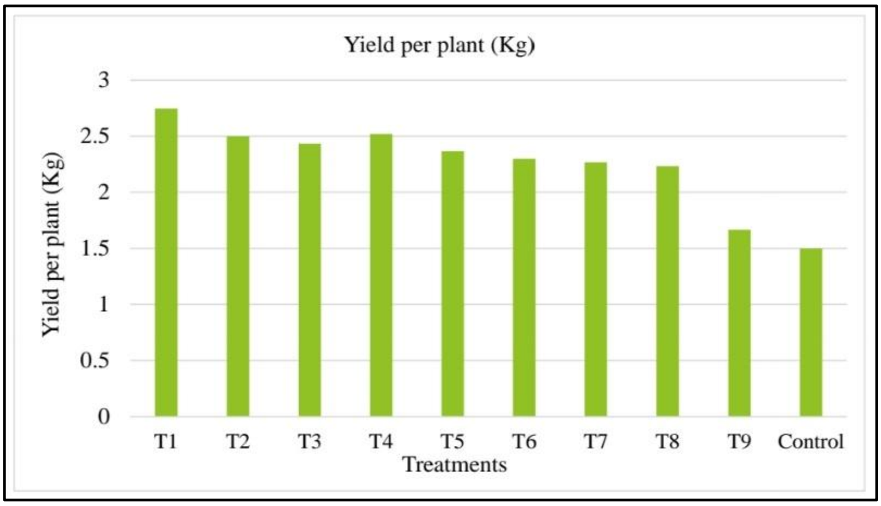


Fig. 15 Variation in yield per plant of greenhouse tomato with different treatments

3.6.4 Yield per hectare

Among all treatments, T1 corresponding to 100% ETC and 100% RDF showed the maximum yield per hectare (68.77 t/ha) while the control treatment resulted in minimum values (25.5 t/ha). From ANOVA, the irrigation and fertigation levels were significant at 5% and 1% level of significance and interaction between them was also significant. Variation of yield is shown in Fig. 15.

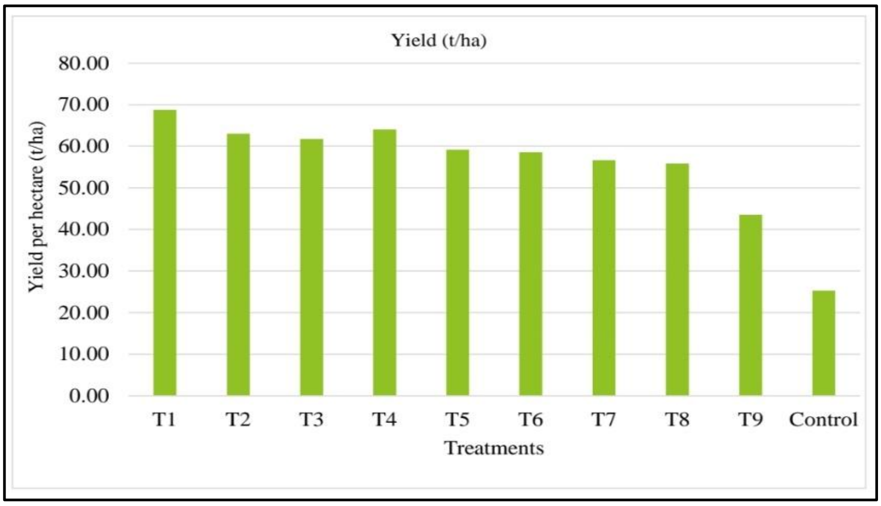


Fig. 16 Variation in yield per hectare of greenhouse tomato with different treatments

The overall view of developed automated fertigation system and yield of tomato crop obtained using this fertigation system are shown in fig. 17 and 18, respectively.

Fig. 17 Overall view of developed fertigation control head

Fig. 18 Yield of tomato

3.6.5 Total soluble solid (TSS)

T1 corresponding to 100% ETC and 100% RDF showed the maximum TSS (5.10 ^{o}Brix) while the control treatment resulted in minimum values (3.25 ^{o}Brix). The irrigation and fertigation levels were significant at 5% and 1% level of significance and interaction between them was also significant.

3.7 Sensor based and without sensor based monthly water requirement of greenhouse tomato

The total water requirement for tomato crop was 2.67, 2.14, and 1.60 l/plant/day at 100%, 80%, and 60% of ETc respectively without sensor-based drip irrigation and 2.27, 1.86, and 1.45 l/plant/day at 100%, 80%, and 60% of ETc respectively with sensor-based drip irrigation. Water saving in sensor-based irrigation varied from 9.62-14.84 % respectively from 60-100% ETC during the crop growth period (Fig.19). The crop coefficient values of greenhouse tomato varied from 0.6-1.20 during 150 days. The peak value of greenhouse crop coefficient reached after 82 days after transplanting.

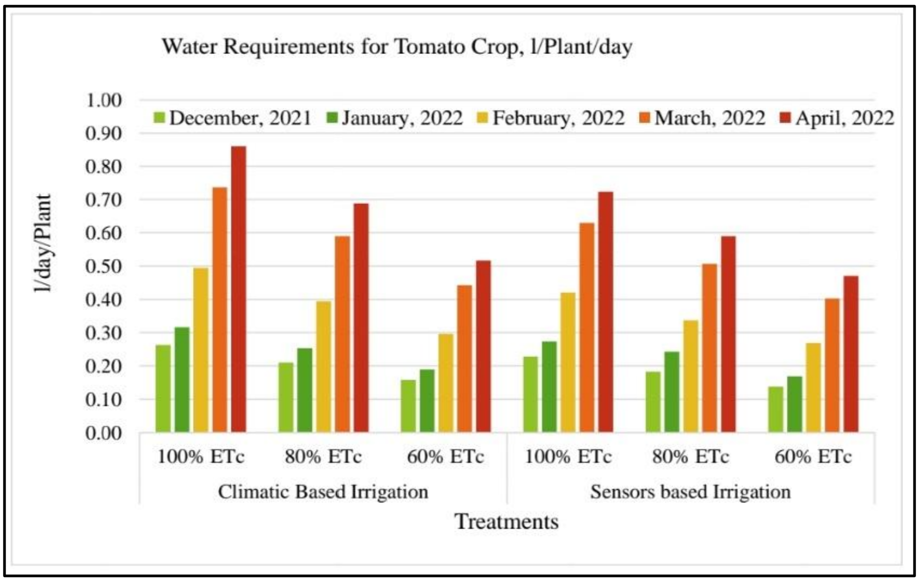


Fig. 19 Monthly wise crop water requirement of greenhouse tomato without sensor based and sensor-based irrigation scheduling

3.8 Conclusion

A sensor based automated fertigation system was developed in a greenhouse environment to optimize fertigation management for tomato crop. Real-time feedback on soil moisture levels was provided by automatic capacitance soil moisture sensors at depths of 15-45 cm. Among the capacitive sensors, Sensor 8 (S8) at 45 cm depth exhibited superior performance, closely aligning with gravimetrically determined moisture content. These sensors indicated 20-25% moisture content at field capacity. Statistical parameters, including R^2 (0.9528), RMSE (1.0786), NSE (0.9463), and MAE (0.9729), identified the 45 cm depth sensor as the most proficient. Implementing these sensors for drip irrigation in greenhouse tomato cultivation substantially curtailed water and fertigation demands compared to sensor-less drip irrigation. Water savings ranged from 9.62-14.84% across varied irrigation levels of 100% ETc (14.84%), 80% ETc (12.97%), and 60% ETc (9.62%). The most effective treatment for greenhouse tomatoes was determined as T1, involving full irrigation (100% ETc) and recommended fertilizer dosage (RDF). This regimen yielded optimal plant dimensions, flower and fruit quantities, as well as fruit dimensions, weight, and overall yield. Conversely, the control group exhibited inferior outcomes. Throughout the 150-day growth period, the developed fertigation system consistently achieved water savings of 9.62-14.84%. Greenhouse tomato's crop coefficient ranged from 0.6-1.20, peaking 82 days post-transplanting. The system's efficacy in conserving water and nutrients while enhancing crop yield underscores its suitability for greenhouse tomato cultivation. The prevailing approach to fertigation scheduling relies upon a retrospective analysis of existing literature and a predetermined temporal regimen. To enhance and advance this methodology, forthcoming endeavors should integrate a contemporaneous monitoring system that gauges the concentration of pivotal nutrients in the vicinity of the root zone. Subsequently, the actuation of fertigation should be contingent upon the identification of nutrient levels having fallen beneath the established threshold. The envisaged Internet of Things (IoT) framework must be adept at effecting this paradigm shift, with a pronounced emphasis on judicious nutrient allocation aimed at maximizing resource conservation.

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5. References

Bowlekar, A. P., Patil, S. T., Kadam, U. S., Mane, M. S., Nandgude, S. B. and Palte, N. K. (2019) Development, field testing and economic evaluation of automatic irrigation system. *Journal of Agricultural Engineering*, 56(4), 284-93.

Chakraborty, S. D., Yogesh Kant and Bharath, D. B. (2014) Study on land surface temperature in Delhi city to managing the thermal effect on urban developments. *International Journal of Advanced Scientific and Technical Research*, 1(4): 439-450.

Chand, J., Hewa, G., Hassanli, A., and Myers, B. (2020) Evaluation of deficit irrigation and water quality on production and water productivity of tomato in greenhouse. *Agriculture*, 10(7): 297.

Datta, S., Taghvaeian, S., and Stivers, J. (2017) Understanding soil water content and thresholds for irrigation management. Oklahoma Cooperative Extension Service.

Hasan, M. (2015) Protected Cultivation and drip fertigation Technology for sustainable food production. Souvenir of The Second International conference on bio resource and stress management held at Hyderabad, India during 07-10th Jan, 2015. ISBN 978-81-920073-8-0 pp 19-24.

Hasan, M. (2016) Protected Cultivation and Drip fertigation technology for sustainable food production. *International Journal of Economic Plants*, 3(3): 102-106.

Hasan, M., Indra Mani, Love Kumar, Atish Sagar, Vinayak Paradkar, Dhaval Chavda, Kishor Gavhane, Tarun Kumar Ametha and Prakash Bhai. (2022) Precision Management under Protected Cultivation and Vertical Farming. *Indian Journals of Fertilizers,* 18(4): 652-655.

Hrisko, J. (2020) Capacitive Soil Moisture Sensor Theory, Calibration, and Testing. no, 2, 1-12.

Ismail, S. M., Ozawa, K., and Khondaker, N. A. (2008) Influence of single and multiple water application timings on yield and water use efficiency in tomato (var. First power). *Agricultural Water Management,* 95(2): 116-122.

Martinez, A., and Byrnes, A. P. (2001) Modeling dielectric-constant values of geologic materials: An aid to ground-penetrating radar data collection and interpretation. *Current Research in Earth Sciences,* 1-16.

Mishra, A., Dash, B. B., Nanda, S. K., Das, D. and Dey, P. (2013) Soil test based fertilizer recommendation for targeted yield of tomato (Lycopersicon esculentum) under rice–tomato cropping system in an Ustochrept of Odisha. Environ. *Ecol,* 31: 655-658**.**

Nikolaou, G., Neocleous, D., Katsoulas, N., and Kittas, C. (2019) Irrigation of greenhouse crops. *Horticulturae,* 5(1): 7.

Richards, L. A. and Weaver, L. R. (1944) Moisture retention by some irrigated soils as related to soil moisture tension. *Journal of Agricultural Research,* 69(6): 215-235.

Shinde, D., and Siddiqui, N. (2018) IOT Based environment change monitoring & controlling in greenhouse using WSN. In 2018 International Conference on Information, Communication, Engineering and Technology (ICICET) (pp. 1-5). IEEE.

Xiukang, W., and Yingying, X. (2016) Evaluation of the effect of irrigation and fertilization by drip fertigation on tomato yield and water use efficiency in greenhouse. *International Journal of Agronomy*, 2016.