ग्रीनहाउस सिंचाई सूचीकरण के लिए टेंसियोमीटर स्वचालित प्रणाली

TENSIOMETER AUTOMATION DEVICE FOR GREENHOUSE IRRIGATION SCHEDULING

VENKATESH

DIVISION OF AGRICULTURAL ENGINEERING

ICAR–INDIAN AGRICULTURAL RESEARCH INSTITUTE

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TENSIOMETER AUTOMATION DEVICE FOR GREENHOUSE IRRIGATION SCHEDULING

A Thesis

By

VENKATESH

Submitted to
the faculty of Post-Graduate School,
ICAR–Indian Agricultural Research Institute, New Delhi
In partial fulfillment of requirements for the award of degree

MASTER OF TECHNOLOGY

IN

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Approved by:

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CERTIFICATE

This is to certify that the thesis entitled **"Tensiometer Automation Device for Greenhouse Irrigation Scheduling"** submitted to the Post-Graduate School, ICAR–Indian Agricultural Research Institute, New Delhi, in partial fulfillment of the requirements for the award of the degree of **Master of Technology in Agricultural Engineering**, embodies the results of *bona fide* research work carried out by **Mr. Venkatesh (Roll No. 20769)** under my guidance and supervision, and that no part of this thesis has been submitted for any other degree or diploma.

The assistance and help availed during the course of investigation as well as source of information have been duly acknowledged by him.

Date:
Place: New Delhi, India

(Dr. Murtaza Hasan)
Chairman, Advisory Committee

DEDICATED TO

BELOVED PARENTS

&

FARMERS …

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In every one's life, the day arises when one has to shape the feelings in words. Sometimes, the words become unable to express the feelings of the mind, because, the feelings of heart are beyond the reach of the words. When, I came to complete this manuscript, so many memories have rushed through my mind, which are full of gratitude to those who encouraged and helped me at various stages of this research. It gives me immense pleasure to record my feelings at this moment of time.

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CONTENTS

LIST OF TABLES

LIST OF PLATES

LIST OF FIGURES

LIST OF ABBREVIATIONS

%	Percentage
&	And
ARM	Acorn RISC Machines
ATC	Automatic Tension Control
AVR	Automatic Voltage Variation
BCM	Billion Cubic Meter
CAVS	College of Agricultural and Veterinary Science
CPCT	Center for Protected Cultivation Technology
CSSRI	Central Soil Salinity Research Institute
DC	Direct Current
DF	Degree of Freedom
ET	Evapotranspiration
GOI	Government of India
GPR	Ground penetrating radar
GSM	Global System for Mobile Communications
IARI	Indian Agricultural Research Institute
ICAR	Indian Council of Agricultural Research
IFAPA	Institute of Research and Training in Agriculture and Fisheries
IIT	Indian Institute of Technology
ISSS	Indian Society of Soil Science
IWUE	Irrigation Water Use Efficiency
LAI	Leaf Area Index
LCD	Liquid crystal display
lph	liters per hour

MCU	Micro controller unit
MEMS	Micro Electro Mechanical System
MIR	Marine Instrument
MOWR	Ministry of Water Resources
MSL	Mean Sea Level
NCIWRD	National Commission on Integrated Water Resources Development
PCB	Printed Circuit Board
PMKSY	Pradhan Mantri Krishi Sinchai Yojana
r	Correlation coefficient
RISC	Reduced Instruction Set Computing
SMP	Soil Matric Potential
SMS	Short Message Service
TDR	Time domain reflectometry
VMC	Volumetric soil moisture content
WUE	Water Use Efficiency

Chapter-1

INTRODUCTION

Water is the most critical resource for agriculture besides soil, light and air. India has only about 4% of the world's freshwater resources and supports 17.5% of world population. Moreover, about 690 billion cubic meter (BCM) of surface water and 433 BCM of ground water is available for use from the total precipitation of 4000 BCM occurring over the entire country (ISSS, 2017). Precipitation from monsoon lasts only for 3 to 4 month in a year and it varies from 100 mm at West Rajasthan to 1000 mm at Cherrapunji in Meghalaya indicating its pronounced spatio-temporal variability. As per the land use statistics 2015-16, India is seventh largest country in the world and the total geographical area of the country is 328.7 million hectares, out of which 141.4 million hectares is reported as net sown area and 200.9 million hectares is the gross cropped area with a cropping intensity of 142%. The net irrigated area is 68.2 million hectares. Further, about 64% of the net sown area in India is highly dependent on seasonal rainfall for crop cultivation, which not only hampers productivity but also requires adoption of high yielding varieties and other inputs. The gross sown area expected by 2025 is 210 million hectares considering the area sown is more than once. It is a potential challenge to bring the remaining net sown area under irrigation for sustainable agriculture (Anonymous, 2016). Estimates on water demand reported by Standing Sub-Committee of the Ministry of Water Resources (MOWR) and National Commission for Integrated Water Resources Development indicated that, by the year 2050, the demand for water will increase by 50% for irrigation 16 times for energy production, 5 times for industries and 2 times for drinking water (NCIWRD, 2016).

Irrigation is defined as the science of artificial application of water to the land, in accordance with the 'crop water requirements' throughout the 'crop period' for full-fledged nourishment of the crops (Garg, 1996). Irrigation has been the most important agricultural input for crop production throughout the world. It is prehistoric practice and can be traced with the beginning of human civilization. Importance of irrigation in agriculture is very well documented in *Narada Smriti XI,* which states that "no grain is ever produced without water, but too much water tends to spoil the grain; an inundation is as injurious to crop growth as the dearth of water." The irrigation requirement of a crop is the amount of water to be supplied to a diseases-free crop growing in field with adequate soil water and fertility status and achieving full production potential under prevailing soil and climatic conditions. Irrigation requirement of crop varies with soil characteristics *viz.* structure, texture, organic matter and climatic conditions like precipitation, temperature, humidity, wind velocity and crop growth stage.

Among the different methods of irrigation, Indian farmers are largely following the surface irrigation method for irrigating their field. It is having 30-40% efficiency as compared to drip irrigation system (80-95%). In order to enhance the irrigation efficiency, there is requirement of soil moisture measurement device for real time irrigation management.

Average irrigation efficiency in surface irrigation in India is about only 38% and water resources are limited with increased demand of agricultural products (Sharma *et al.*, 2010). This necessitates subsequent enhancement of the irrigation efficiency by using suitable irrigation scheduling devices. Such efforts in enhancing the irrigation application efficiency of the farm land would assist in bringing the remaining net sown area under irrigation to sustain the overall agricultural crop production and subsequently fulfill the prime objective of the "*Pradhan Mantri Krishi Sinchai Yojana*" (PMKSY) scheme by GoI to bring the entire farm area under irrigation. Associated objectives of PMKSY is to improve on farm water use efficiency; undertake sustainable water conservation practices; augmentation of water sources, arresting and conserving surface runoff and soil moisture conservation besides precision irrigation and water saving technology to ensure "per drop more crop" can be accomplished by judicious irrigation scheduling.

Green house is a covered structure that protects the plants from extensive external climatic conditions and diseases, creates optimal growth microenvironment, and offers a flexible solution for sustainable and efficient year-round cultivation. Greenhouse provides a suitable controlled environment to grow crops irrespective of season and increase the crop's productivity. Greenhouse automation is the right tool to fully monitor and control the environment and has a dramatic social and economic impact. Greenhouses are constructed with translucent glass or plastic for promoting crops growth. They allow for more effective use of water and the daylight. Proper irrigation is a key to improve quality and productivity of crops grown inside the greenhouses. The time, duration, type and amount of irrigation are essential to optimize the use of water. Different irrigation methods can be used such as: hand watering, overhead sprinkling system, movable irrigation boom, flood floor and drip irrigation. However, the drip irrigation is the most suitable for greenhouses in term of its efficient use of the available water (Hatem, 2017). Water supply during intensive farming activities in protected structures is very limited because of different timing as compared to open field agricultural activities. Scheduling of water application is very critical to make the most efficient use of drip irrigation systems, as excessive irrigation water reduces yield while inadequate irrigation causes water stress and reduces production (Rahil and Qanadillo, 2015). The soil moisture content determines the irrigation time; therefore, continuous monitoring is necessary to decide when to exactly start the irrigation besides the quantity of water to be applied.

There are many available methods to determine the soil moisture status viz. gravimetric method, tensiometers, watermarks, electrical resistance method, granular matrix, Time Domain Reflectometer and Frequency Domain Reflectometry (FDR) (Pariva et. al. 2012), which are widely applied in irrigation scheduling. The use of information and communication technology (ICT) in agricultural field has allowed to improve the concept of precision agriculture (Kruize et al., 2016; Achora, 2016). Among these the ICT, automation in irrigation is one of the major technological tool used for enhancing the irrigation efficiency ensuring the proper level of water for growing up the plants all through the season. Automatic irrigation system is usually designed for ensuring the proper level of water for growing up the plants all through the season.

An automated irrigation system refers to the operation of the system with no or minimum of manual intervention. Almost every irrigation system can be automated with the help of timers, sensors, computers, or mechanical appliances. Automatic irrigation system is usually designed for ensuring the proper level of water for growing the plants efficiently throughout the year. Automation of irrigation system may be accomplished using a combination of soil moisture sensors, data logger/microprocessor, controller, and regulatory valve with the help of a pressurized water source (Rahim *et al.,* 2013). The entire operational details of automated irrigation system can be either programmed through software or manually using a control unit. The most important component of the automated irrigation system is the soil moisture sensor. This system starts when the soil moisture attains a predetermined level and it stops irrigation when the desired soil moisture content or field capacity is achieved.

Tensiometers have been used for many years as the devices to give growers feedback on when to irrigate (Dukes *et al*., 2010). A tensiometer is a water-filled tube designed to simulate the soil moisture dynamics in the root zone of the crop. A porous ceramic cup is buried in the soil with a negative pressure (vacuum) gauge at the other end. As the soil dries, water is pulled out of the tensiometer to exhibit the equilibrium and indicates negative pressure reading. The more negative reading indicates presence of lesser moisture in the soil. Moreover, after the irrigation, the soil water re-enters the cup and the pressure becomes less negative. Therefore, to accomplish automated irrigation scheduling, the low cost tensiometer need to be coupled with an irrigation controller device. In this context, one of the possible solution could be to develop a low cost pressure transducer based automated tensiometer for different soil texture and crops. Further there is a need for standardizing different input and output parameters related to such developed device. Keeping in view the need and the current emphasis on enhancing water use efficiency through sensor based irrigation schedules, the present study is targeted towards development and testing of a "Tensiometer Automation Device for Greenhouse Irrigation Scheduling" under the following specific objectives:

1.1. Objectives

1) Design and development of piezo-resistive sensor for measurement of soil moisture tension.
2) Development of automated device for soil moisture tension measurement by integrating piezo-resistive sensor with the tensiometer.
3) Validation of the automated device for greenhouse irrigation scheduling.

Chapter-2

REVIEW OF LITERATURE

The availability of soil water for crop growth is one of the key factor that affect its yield. In areas where the precipitation is insufficient to fulfill the crop water requirements, there is a need to supply adequate irrigation to achieve optimum crop yield. Thus, an effective irrigation schedule considers when to irrigate and the quantity of water to be applied for maximizing the profit and water-use efficiency (Ayars and Phene, 2007; Pardossi *et al.,* 2009). In agriculture, many devices and methods *viz* tensiometers, resistance blocks, gravimetric methods, and granular matrix sensors have been used to monitor and measure the soil moisture and need to be widely used in irrigation scheduling. Supply of irrigation water based on the availability of soil moisture has been a practical solution for simplifying the on-farm irrigation scheduling. Availability of soil water to plants is a critical factor in the regulation of plant growth, which is determined by the soil water tension. A tensiometer device that can sense the in-situ soil water tension and produce an electrical output signal can be used to automate irrigation events.

Irrigation water management techniques and devices vary with respect to their accuracy, labour intensity, cost and their simplicity to use. A plethora of studies have been conducted to evaluate soil water monitoring devices both qualitatively and quantitatively in respect of their setup requirements, maintenance, initial cost, accuracy, data acquisition and interpretation. At the same time, the sensing devices coupled with recent computer technologies is gaining its applicability in judicious irrigation scheduling leading to efficient agricultural water management. The newly designed soil moisture sensing systems are also being used on a real-time basis for scheduling of irrigation in different crops. Sensors for soil moisture monitoring is being used in various natural resource management practices, such as crop growth and yield monitoring, precision agriculture and irrigation scheduling for enhancing water use efficiency and reductions in pollution by reducing the runoff and thereby leaching of nutrients (Zotarelli *et al.,* 2011).

This chapter includes the review of available information on design and testing of sensor based application in irrigation water management for enhancing water use efficiency besides its effect on the crop yield under micro irrigation system in both open and green house environment.

2.1 Design and development of soil moisture sensor for automatic irrigation scheduling

Sugiyama *et al*. (1983) developed an integrated piezoresistive sensor with both voltage and frequency output at Toyoto central research and development labs, Aichi, Japan. The chip was 3×3.8mm^2 in size and it measured the output voltage range about 1 to 4V for the pressure range of 0 to 750 mm of Hg. The sensitivity of the frequency output is about 30 kHz for a 750 mmHg change in pressure. Non linearity of the chip was 0.4%, temperature coefficient of sensitivity of the chip was 0.06%/^{o}C for temperature -20 to 110^{o}C in order to know the temperature effect on voltage measurement in an instrument.

Marthaler *et al.* (1983) developed a pressure transducer for coupling with the tensiometer at soil physical laboratory at the federal institute technology Zurich, Switzerland. The developed device consisted of pressure transducer, spring needle and a digital pressure indicator. Moreover, the pressure transducer comprised of a steel enclose with transducer membrane which separates the lower and upper part in the tensiometer. The upper part was open to atmosphere and with creation of vacuum the lower parts of tensiometer membrane gets deflected. Thus, the resistance of silicon semiconductor embedded in the membrane gets changed due to the deflection. It was observed that the change in pressure and resistance of the silicon embedded system were directly proportional to each other (R^2=0.99). Moreover, the developed system pertaining to the tensiometer was not calibrated under field situations.

Smajstrla *et al*. (1986) conducted an experiment on use of the tensiometer for irrigation scheduling of citrus under trickle irrigation at Florida agricultural experiment station, university of Florida, USA. The Irrometer vacuum gauge tensiometer type was equipped with magnetic pick up switches which performed the automatic irrigation scheduling activity. It was observed that with the decrease of soil water potential, the vacuum gauge needle and magnet rotates and closes the magnetic field leading to supply of irrigation water. The developed controller was provided with 24V AC power source for its operation. Thus, the developed system is operated for switching on and off the system under pre-set value of soil water potential. It was concluded that the magnetic switching tensiometers were suitable to initiate the irrigation as and when the soil moisture reaches the critical value.

Li *et al.* (1989) conducted an experiment on irrigation scheduling in a peach orchard using tensiometers and dendrometers at Gotheron experimental orchard of the Institute National de la Recherche Agronomique, Rhone, France. In the experiment, three trickle irrigation schedules using tensiometer, dendrometer and a schedule of restricted water supply to peach orchard were conceptualized. It was observed that the water applied using the restricted water supply treatment was more than the dendrometer based scheduling which accounted the daily stem concentration flow. Tree growth, fruit size and leaf water potential of the plot with dendrometer irrigation scheduling did not differ much from the tensiometer irrigation scheduling plot but affected the quality with premature fruit drop and fruit bud initiation. It was concluded that the dendrometer irrigation scheduling was more accurate and resulted in better fruit yield as compared to the tensiometer based irrigation scheduling.

Luthra *et al.* (1996) designed and developed an automatic irrigation system using auto control valve at Federal university of viscos, Brazil. In this system, the soil moisture tension was measured through a modified manometer type tensiometer designed to control irrigation at the pre-decided soil moisture tension using a programmed timer. It was reported that the water application through automatic control valve at pre-decided soil water tension was significant. Soil water stress was monitored in the root zone continuously using a soil moisture sensor and the irrigation scheduling was accomplished with automated irrigation controller with real time soil water tension for the entire crop duration.

Luthra *et al.* (1997) designed and developed an automatic irrigation system according to the crop evapotranspiration at the Institute farm of ICAR-CSSRI, Karnal, Haryana, India. In this system, the soil water tension was recorded using a modified manometer mounted tensiometer with electrical sensors. Gate valves, pumping units and timer were used to automatically control the drip irrigation system. The power requirement for the operation of the circuit was 12V. The developed auto irrigation system maintained the soil water tension at predetermined level in the root zone for efficient irrigation scheduling.

Meron *et al.* (1997) developed a tensiometer activated automatic micro irrigation for apple at Matityahu experimental station, Hebrew University of Jerusalem, Israel. The tensiometer and the vacuum transducer was interfaced with campbel micrologger (MIR 5000) for irrigation scheduling. Treatments were consisted of mini-sprinklers actuated at 25 kPa, single drip line per row actuated at 15, 25 and 35 kPa, and two (double) drip lines per row actuated at 15 and 25 kPa. It was observed that the pressure range of 15-20 kPa was found to be the appropriate actuation threshold for single lateral drip irrigation, and 20-25 kPa for two laterals drip irrigation system.

Kruger *et al.* (1999) conducted an experiment on the irrigation scheduling in strawberry using tensiometer and a climatic water balance model. The experiment was undertaken at Research Station Geisenheim, Germany for three years duration. It was reported that during dry periods, the soil moisture tension under non-irrigated strawberries increased to above 30 kPa at 20 cm soil depth. The hydraulic gradients calculated from tensiometer measurements showed that during irrigation, percolation did not occur below 40 cm soil depth. Therefore, leaching of mineral nitrogen out of the rooted area of strawberries could be excluded for both irrigation schedules. The positive influence of irrigation on the yield and fruit size of strawberries in comparison to non-irrigated plants was confirmed and also showed that climate balance model was best suitable for the decision making then the tensiometer based irrigation.

Joshi *et al.* (1999) developed a soil moisture based automated irrigation controller at IIT- Kharagpur, West Bengal, India. The tensiometer was designed in conjunction with a mercury manometer and two sensors were used to detect the change in mercury level due to variation in soil moisture. The developed irrigation controller was tested in laboratory and field plot irrigated through drip system operated with mono-block pump driven by electric motor. The irrigation controller actuated and de-actuated the irrigation pump according to the soil water tension during the field test. It was recommended that the developed irrigation controller could be successfully used for irrigation automation in drip systems.

Taylor *et al.* (2003) Conducted a study on use of a tensiometer-based irrigation control system to reduce effect of irrigation on the yield and quality of cut flower *dianthus caryophyllus* 'santorini' at college of agricultural and veterinary science (CAVS), Australia. Five treatments with soil water tension ranging from 15 kPa to 75 kPa was undertaken. It was found that the irrigation scheduling at soil moisture tension of 15 kPa produced highest number of long stem (>60 cm) but they had inconsistent quality. Irrigation scheduling carried out at 45 kPa produced most of the flowers with high quality without any reduction in stem length. Overall, there was no decline in flower quality or stem length, except when the soil moisture tension reached 75 kPa before irrigation. Moreover, it was also found that the tensiometer based irrigation scheduling not only consumed less quantity of water but also improved the flower quality and yield.

Wiedenfeld (2004) conducted an experiment on scheduling water application in drip irrigated sugarcane at Texas Agricultural Experiment Station, South Texas, USA. The amount of irrigation water required for the crop was determined by using four different methods such as Pan Evaporation (E_{pan}), Evapotranspiration (ET), Auto-Tensiometers and manual Tensiometer methods. The ET base irrigation scheduling consumed more water, number of stress days were more in first season of irrigation as compared to next season of irrigation. It also resulted in higher runoff from ET based irrigation scheduling field. Direct method of irrigation by using tensiometer was more reliable and most accurate for assessment of irrigation requirement in sugarcane with the yield in second rooting (11.1Mg/ha) was more as compared to ET based irrigation scheduling (8.9Mg/ha).

Vellame and Oliveira (2005) conducted an experiment at the Federal University of Bahia, at Cruz das Almas, State of Bahia, Brazil to develop and test a tensiometer based reading system for soil moisture measurement. The developed prototype consisted of pressure transducer and transmitter device as the prime component and digital display as the indicator device. Each component used in the instrument was calibrated separately and finally combined as a transmitter indicator device. A differential mercury manometer was used as reference for comparison of tension readings during the calibration process over a vacuum range from 0 to 75.5 kPa. It was observed to be with an overall accuracy within ±1.12% on output scale. The system was considered to be accurate and reliable for tension readings under field conditions as well. The cost of the developed instrument reduced to 120US$ as compared to a similar available model of 2,500 US$.

Munoz-Carpena *et al.* (2005) conducted an experiment on soil moisture based irrigation scheduling for tomato production at Pine island farm, Miami, Florida. The experiment consisted of seven treatments, out of which six treatments consisted of pressurized irrigation system and the other one was standardized commercial practice. Two treatment was based on the timer scheduling and one to supply 100% of maximum recommended crop water need in the area based on historical ET (ET-100%) and the other to supply 150% of ET. Four treatment were created by interfacing with tensiometer and granular matrix soil moisture sensors set at 2 moisture levels *i.e* wet at 10 kPa and optimal at 15kPa. It was observed that switching a tensiometer at 15kPa reduced the water use by 73% as compared to commercial practice and the reduction was 50% with respect to ET-100% based irrigation scheduling.

Hoppula and Salo (2007) conducted an experiment on tensiometer based irrigation scheduling in strawberry cultivation. The experiment consisted of three soil matric potentials *viz* -15,-30 and -60 kPa. Soil matric potential were selected based on the plant growth stage and irrigation was carried out using drip system. It was found that the irrigation scheduling carried out for cultivar ‘’Bounty’’ at tension of -30 kPa and -60 kPa gave higher yield and better fruit quality.

Klein (2010) compared the performance of automatic irrigation scheduling under different threshold-set of soil matric potential at the Institute of Soil, Water and Environmental Sciences, The Volcani Center, Israel. An automation device was connected to the tensiometer for irrigation scheduling in soilless culture and the experiment was conducted for a period of two years. Soil moisture sensors were used for continuously monitoring the soil moisture tension at pre-set soil water potential *viz*. -10, -20, -35 kPa and depth of irrigation was controlled by closing the automatic control valve at appropriate time after the supplying irrigation water so as to ensure the soil moisture tension at -5 kPa. The sensing device was used for automatic irrigation scheduling in cherry, peach, and Figure plants inside greenhouse besides grapes and olive planted under drip irrigation outside of the green house. The stem water potential, photosynthesis, stomatal conductance and transpiration (E) of daily drip irrigated grape were highly correlated (R^2 = 0.8833 – 1.000) in the morning hours to monitor the soil water tension (0 to – 27 kPa). Irrigating olive at low soil water tensions increased irrigation efficiency and saved 50% water as compared to current recommendations. Controlled deficit irrigation at -20 kPa threshold tension irrigation saved additional water, up to 75% of the recommended rate as compared to -10 kPa threshold tension irrigation.

Dursun *et al.* (2011) developed a wireless module of drip irrigation automation supported with soil moisture sensor at the department of electrical engineering, Ankara, Turkey. The data acquisition was performed by a solar operated wireless stations module. The system consisted of 3 units such as 1) Basic unit, 2) valve unit, and 3) sensor unit. It was observed that the system could save 35% of water loss by the percolation and evapotranspiration as compared to the conventional unit. Moreover, the wireless module of sensor-based site specific irrigation was having added advantages of preventing moisture stress of trees, diminishing of excessive water usage and arresting rapid growth of weeds.

Dobriyal *et al.* (2012) conducted an experiment to decide the best method for estimating soil moisture and its subsequent application for water resource management at wildlife institute of India, Dehradun. They found that the direct method (Gravimetric method) though time consuming was accurate and less expensive as compared to the indirect methods *viz.* Time domain reflectometry (TDR) and Ground penetrating radar (GPR) technique for measuring soil moisture. They concluded that the GPR was suitable for large area but it was not suitable for use in forest area as compared to the TDR and was expensive. Nonetheless, they suggested that the sensing systems should be selected based on the response time, cost, accuracy, effort involved in its installation and management.

Sanjukumar (2013) developed an advance technique for soil moisture content based automatic irrigation scheduling for agricultural crops at Institute of Science and Technology, Hyderabad. Experimental setup consisted of soil moisture sensor, microcontroller, LCD and irrigation pump. When soil moisture content reaches the predetermined level, microcontroller sends the signals to the motor, it will automatically on and pump and the water to the field, when the soil moisture reaches above the predetermined level of the soil moisture, the pump switch offs.

Sakthipriya (2014) developed an integrated sensing system by combining external sensors components viz. leaf wetness, soil moisture (gypsum block), soil pH, atmospheric pressure sensors and installed in the experimental farm of Bharath University, Chennai. Based on the soil moisture the system triggered irrigation through sprinkler irrigation system. Once the field was sprinkled with adequate water, sprinkler system was switched off automatically to attain judicious irrigation scheduling and optimize the use of irrigation water. Further, the data recorded by the soil pH sensor transmit to the base station which was further communicated to farmers *via* SMS using GSM modem. The soil pH displayed in mobile assisted farmers in deciding fertilizer doses for crops to reduce cost and enhance the fertilizer use efficiency. They concluded that the developed system would help stakeholders to achieve efficient management and utilization of agro ecological resources.

Chavan *et al*. (2014) developed a wireless system for monitoring soil moisture, temperature and humidity using Zigbee transmitter at Beed district, Maharashtra. A conventional approach of collection of data regarding soil moisture, humidity and temperature was tedious and time consuming, so a remote sensing Zigbee system was developed to collect, store, analyze the data. The wireless system transmit data to a central server, which stores and analyzes the data with provision of data display and subsequent communication to the mobile of the stakeholder.

Kim *et al.* (2015) designed and tested an automatic irrigation controller for precision water management in greenhouse crops at Research Institute for Agriculture and Life Sciences, Seoul National University, Seoul, South Korea. The developed prototype of automation irrigation system was based on the soil moisture status, it consisted of an 8-bit MCU, 12-bit AD converter and was tested for tomato crop in greenhouse. Two different algorithms for controlled automatic irrigation were programed using variable keep-pause method and water calculation method. In keep-pause method, the irrigation water was intermittently supplied to the root zone until sensors sends the signals to the controller to stop it as per the pre-set value of soil moisture. Whereas in water calculation method, the soil water status was measured by using a tensiometer and converts the soil matric potential (kPa) in to volumetric water content using a soil moisture characteristic curve and supply the required quantity of water to the plants. It was observed that in above two algorithms, water calculation method by using tensiometer provided simple irrigation operation without frequent irrigation events, and it supplied the amount of water actually needed by plant in each irrigation event.

Pathan and Hate (2016) developed an automated irrigation system using wireless sensor network at the Institute of Engineering, Wagholi, Pune, India. The automation system used temperature sensor, light sensor and soil moisture sensor for transmission of data to the microcontroller through the XBee wireless transmitter using radio-frequency. The MATLAB programming was used to display the threshold value of 25% of soil moisture Advanced RISC Machines (ARM) controller were used in decision making in order to irrigate the crop. The pump was made operational by ARM controller based on the threshold value of soil moisture content.

2.2 Performance evaluation of automated system for irrigation scheduling

In this section literatures related to studies on irrigation scheduling of different crop using sensor based automation irrigation system was reviewed and presented under following paragraphs.

Ibarra *et al.* (1997) conducted an experiment for calibration of tensiometer for scheduling irrigation in maize at the Macdonald Campus of McGill University, Montreal, Canada. Irrigation requirement were calculated using the rainfall and evapotranspiration data. The results were found that at irrigation requirement calculated at the root zone depth of 300 mm led to more water losses due to drainage, and therefore, it was recommended that 400 mm root zone depth be used for irrigation scheduling to apply 25 mm depth of irrigation, 50% moisture depletion was suggested as the time to start irrigation to avoid crop stress. The tensiometer were used to measure the tensions that the plant roots exerted to obtain water from the soi1 and tabulated as a guide for triggering the irrigation.

Shock *et al.* (2002) conducted a field experiment to test the evaluation of an automation in irrigation system using subsurface drip tape at Central Great Plains, Kansas, California, USA. Soil matric potential was measured using granular matric sensor installed at the depth of 0.2 m in onion and potato field crops. The data logger was programmed to read the granular matrix sensor reading in each irrigation treatment between 4 to 8 times in a day. The irrigations were controlled by data logger, signaling controller was connected to solenoid valve. The amount of water applied in each zone was recorded by water meter installed between the solenoid valve and drip tape. The results were found that estimated onion profits were highest with the soil, climate and onion market class tested with a calculated SWP of -17 kPa in 1997, and at –10 kPa in 1998.

Dukes *et al.* (2003) conducted an experiment on automatic soil moisture based drip irrigation for tomato crop at North Florida Research and Education Center, University of Florida, USA. Experiment was carried out to study the effect of irrigation on yield and seasonal irrigation volume, water use efficiency and soil moisture content in the root zone under sensor based irrigation system and thus was compared with seasonal based irrigation. Results were found that marketable yields ranged between 17,000 and 20,000 kg/ha similar to the seasonal volume daily irrigation and sensor based irrigation treatments, but sensor based irrigation was used approximately 50% less seasonal irrigation water. The irrigation water use efficiencies of sensor based irrigation and seasonal based irrigation were found as 1209-2316 kg/ha/m^3 and 703 to 1612 kg/ha/m^3, respectively. And also sensor installed at 15 cm and 30 cm, resulted in higher soil volumetric moisture levels.

Kukal *et al.* (2005) conducted a study on soil matric potential based irrigation scheduling for Rice at Punjab Agricultural University Research Farm, Ludhiana (India). Five tensiometers were installed in soil at a depth of 15-20 cm with tension of 8, 12, 16, 20, 24±2 kPa, in addition to this a recommended practice of alternate wetting and drying with an irrigation interval of 2 days after complete infiltration of ponded water was carried out. The results were found that the grain yield remain unaffected up to tension of 16±2 kPa but helped to save the irrigation water up to 30-35% as compared to irrigation given at 2 days interval.

Thompson *et al.* (2006) evaluated the Watermark 200SS sensor for the measurement of soil matric potential (SMP) with drip-irrigated vegetable crops at the field research station, Las Palmerillas of Cajmar, Spain. Pepper and melon crops were grown sequentially during autumn-winter and spring-summer, in a sandy loam soil in a greenhouse. Ranges of SMP were generated by applying three different irrigation treatments namely 100, 50 and 0% of crop water requirements, during two treatment periods (16 December 2002–7 January 2003; 20 January–10 February 2003) in pepper and one treatment period (26 May–6 June 2003) in melon. SMP was calculated from Watermark electrical resistance using the in-situ, and found that in rapidly drying soil, the Watermark-derived SMP responded considerably more slowly to continual drying and to drying between irrigations, regardless of the calibration equation used. The in-situ and re-parameterized equations were accurate for the conditions in which they were derived/re-parameterized. They suggested that the Watermark sensor can provide an accurate indication of SMP, provided that a suitable calibration equation was derived/verified for the specific cropping conditions.

Wang *et al.* (2007) conducted an experiment to investigate the effect of soil matric potential (SMP) on tomato yield, evapotranspiration (ET), water use efficiency

(WUE) and irrigation water use efficiency (IWUE) under drip irrigation condition. Five treatment of SMP *viz*.10 (S1), 20(S2), 30(S3), 40(S4), 50(S5) kPa were selected to irrigate the field. The results were found that ET of tomato and irrigation amount were affected by irrigation at different SWP. Irrigation amount decreased from 185 mm (S1) to 83.6 mm (S2) in 2004 and 165 mm to 109 mm in 2005 respectively but there was no significant difference in the tomato yield and IWUE, WUE increased as SWP decreased. Maximum IWUE of 620 and 406 kg/ha mm and WUE of 253 and 217 kg/ha mm were recorded for 50 kPa in the year 2004 and 2005 respectively. The 10 kPa treatment recorded minimum IWUE of 261 and 259 kg/ha mm and WUE of 178 and 155 kg/ha mm in 2004 and 2005 respectively. From the above results it was concluded that tomato crop can be irrigated when the soil moisture tension is 20 kPa at beginning stage, after its beginning stage it can be increased to up to 50 kPa.

Migliaccio *et al*. (2010) conducted an experiment to study the response of plant to evapotranspiration and soil water sensor based irrigation for the production of papaya in Tropical Research and Education Center, University of Florida, USA. Experiment consisted of Irrigation scheduling based on ET, Set schedule irrigation regime and soil tension of 10 kPa, 15 kPa, and 25 kPa. Irrigation scheduled at 25 kPa showed higher fruit yield and fruit weight and it was also observed that about 65% more water was consumed in case of set schedule irrigation as compared to other methods. It was revealed that irrigation schedule at soil moisture tension of 15 kPa was best in all aspects. Soil water sensor and ET based irrigation methods were identified as more sustainable practices.

Pinmanee *et al*. (2011) developed a low cost tensiometer driven irrigation control unit and also evaluated its suitability for irrigation of lychee tree in Mae Sa Valley, in the upland area North of Chiang Mai, Northern Thailand. An Automatic tension control (ATC) unit was developed to determine the soil matric potential for opening and closing of the valve for laterals of micro irrigation system. The field testing were carried out under following treatment *viz*. tensiometer, ATC (Automatic Tension Control), visual control, and excess irrigation. Tensiometer and ATC were installed at the depth of 30 cm and visual based irrigation fallowed the conventional based irrigation and excess irrigation based on owner observation. It was found that higher fruit yield (41.56 kg) was observed in case of ATC based irrigation.

Liu *et al*. (2012) carried out a research to investigate the irrigation management under drip irrigation and plastic mulch for Chili pepper at Wuwei City, China. Five treatments -10, -20, -30,-40 and -50 kPa were used in the experiment. LAI, plant height, soil water content, yield and TSS were measured, and crop evapotranspiration, irrigation water productivity, were computed regularly. The results were found that the treatments (10 to 40 kPa) conveyed similar results for LAI, Plant height, above-ground biomass, and crop yield (P>0.05) but the treatment of 50 kPa showed higher value (P<0.05) than these treatments. The threshold values with SMP value from -10 kPa to -30 kPa reduced the consumption of irrigation requirement by 22-43% and crop ET by 11-25%. Treatments consisting of 30 kPa and 40 kPa showed higher TSS and marketable fruits, IWP, water productivity in both growing seasons. It was recommended that for irrigation management of chili pepper under mulched-drip irrigation conditions in the arid region of Northwest China the SMP threshold range of −30 kPa to −40 kPa at 20 cm depth was more applicable.

Beraldo *et al*. (2012) developed a new methodology to evaluate the soil matric potential using mercury tensiometer and puncture digital tensiometer at an area of Faculty of Agriculture and Veterinary Sciences, Jaboticabal, State of São Paulo, Brazil. It was also compared with gravimetric soil moisture obtained by tensiometer and neutron probe meter. Four plot of different soil moisture content with three replications of tensiometer were installed at a depth of 0.20 meter. Based on soil moisture characteristic curve corresponding gravimetric soil water were determined. The results were found that both the tensiometric methods did not shows any difference, when soil moisture tension was greater than -40 kPa. However, under drier soil, when irrigation was carried out, the soil matric potential of the puncture digital tensiometer was less than that of the mercury tensiometer.

Letourneau *et al*. (2015) conducted a study on soil matric potential-based irrigation management of field-grown strawberry and its effects on yield and water use efficiency at Quebec City of Canada. Within each site, impact of soil matric potential on yield and WUE were evaluated. Matric potential based irrigation was compared with the common irrigation practice in each site irrespective of area. An IT (Irrigation Threshold) of -15kPa improved yield by 6.2% without any additional use of water relative to irrigation practice in site-1 having silty clay loam soil; then it was resulted that an IT between −10 and −15 kPa could optimize yield and WUE, from the all the site when irrigation threshold of -10 kPa appears to be a starting point for further optimizing irrigation in most of the field.

Gendron *et al*. (2016) conducted a study on strawberry at Oxnard, in the southern part of California, to compare WUE of conventional and tension (soil water potential) based irrigation methods. Conventional irrigation treatment included both the standard grower procedure and managements based on evapotranspiration (ET) of the crop (50, 75 and 100% ET). Irrigation management based on tension measurements used irrigation thresholds that varied from -8 to -35 kPa .The results of study was concluded that WUE increased from 7.5 to 8.3% in conventional and deficit irrigation strategy respectively whereas WUE increased from 33 to 93% in soil moisture potential based irrigation method as compared to conventional irrigation method.

Almeida *et al*. (2017) conducted a field experiment to study the performance evaluation of an irrigation controller through mechanically actuated by soil-water tension at Piracicaba-SP, Brazil. Tensiometer was used as a sensor to directly control the irrigation by six hydraulic valves, these valves were placed in 6 rows of the plant for 64 days in the field. Each line of drip lateral was controlled by the hydraulic valve. When the soil-tension reached the predetermined tension irrigation was initiated and was terminated at lower soil tension. The developed soil tension based irrigation controller was effective up to soil moisture tension of 30 kPa.

Contreras (2017) studied the effect of different soil matric potential level on the bio-productivity of greenhouse zucchini crop at the Institute of Research and Training in Agriculture and Fisheries (IFAPA), La Mojonera City, Almeria Province of Southeast Spain. Experiment was carried out with different threshold level of soil matric potentials like activation of irrigation to −10 kPa and application of volume of 1.5 lm^{-2} (T1), activation of irrigation to −25 kPa and application of volume of 2.0 lm^{-2} (T2) and activation of irrigation to −40 kPa and application of volume of water at 3.0 lm^{-2} (T3). Yield, leaf area, biomass, water consumption, WUE, nutrient use efficiency, drainage volume and physical-chemical parameters of the soil were determined. It was found that irrigation scheduling carried out at highest values of WUE and nutrients use efficiency were registered by T2 and T3. The soil matric potential of −25 kPa was the best among agronomic and environmental aspects, as the most efficient use of water and nutrients obtaining a commercial production of 15 kg m^{-2}

However the work on automation of irrigation on real time basis using piezo-resistive sensor based on moisture depletion in soil are available but are very few indicating the importance of the present study. Therefore present research project is proposed to develop low cost indigenous automated micro irrigation system to supply irrigation water on the basis of soil moisture.

In review of literature some of the researchers have described efforts toward this direction on different components of automation including soil moisture sensors and the software for linking weather and crop parameters, which might be helpful for automation.

Chapter-3

MATERIALS AND METHOD

The experiment was undertaken in the greenhouse of Center for Protected Cultivation Technology (CPCT) and the data was analyzed in the laboratory of Water Technology Centre, ICAR-Indian Agricultural Research institute (IARI), New Delhi for testing of the tensiometer automation device in scheduling of irrigation in tomato and chrysanthemum. Different materials used for fabrication of the device and the methods used for its testing under greenhouse environment is presented in this chapter.

3.1 Description of study area

3.1.1 Location

The greenhouse is located at CPCT, ICAR-Indian Agricultural Research Institute (IARI), New Delhi, between Latitude of $28^{o}37'22''$ to $28^{o}39'05''$ N and Longitude of $77^{0}08'45''$ to $77^{0}10'24''$ E, at an average elevation of 230 m above the Mean Sea Level (MSL). The general slope of the land is in north-west direction. The location map of the study site with satellite image is presented in the Figure 3.1.

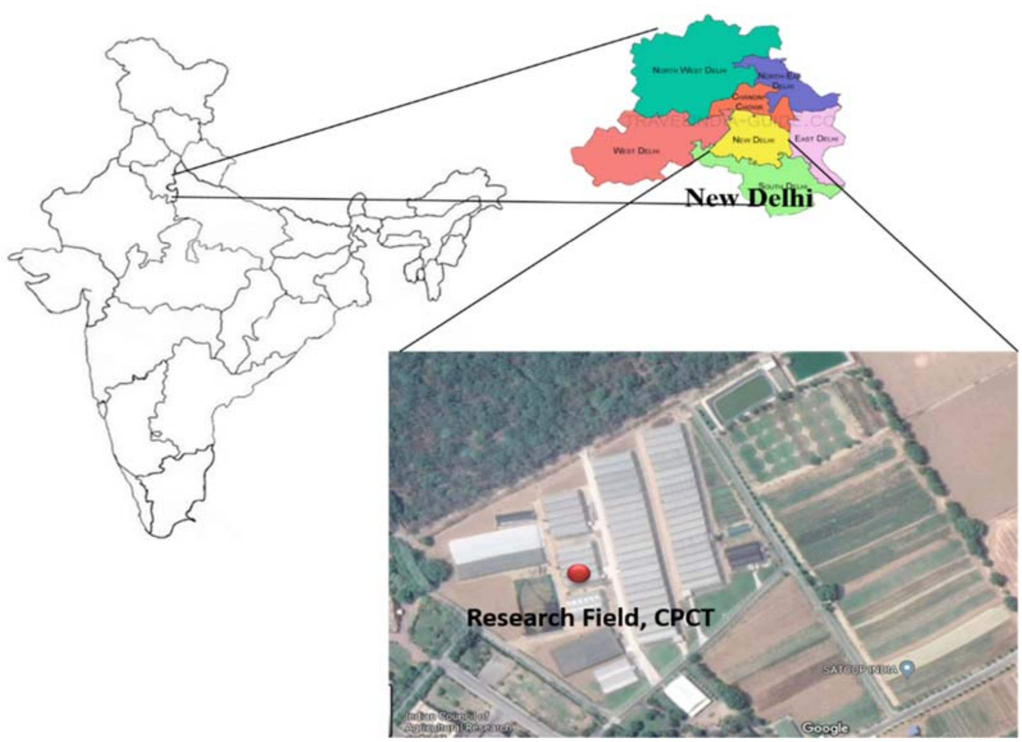

Figure 3.1 Location map of the experimental site

3.1.2 Climate

The climate of Delhi region is an overlap between monsoon-influenced humid subtropical and semi-arid with significant variation of summer and winter temperatures besides precipitation. It falls under the agro-climatic zone of "Trans-Gangetic plains" in the agro-ecological region-IV (Ajdary *et al*. 2007). Summer months spanning from May to June record maximum temperature ranging between 41^0C to 46^0C while temperature falls to its lowest (4^0C to 7^0C) during January. Average annual rainfall of Delhi is 740 mm and 75% of rainfall depth is received during the monsoon season between June to September and the remaining in winter. The average open pan evaporation ranges from 13.9 and 1.15 mm/day in the month of May and January, respectively. Average relative humidity varies from 34.1% to 97.9% and the average wind speed ranged from 0.45 to 3.96 m/s.

3.1.3 Soil

Soil samples were collected from varying soil depth of 0-15, 15-30 cm using a tube auger as per sampling scheduling for acquiring the physical and chemical properties of the soil. The soil texture, bulk density, field capacity, permanent wilting point, soil moisture, Soil matric potential, hydraulic conductivity, pH, and EC of collected samples were determined using the standard procedure as mentioned in Table 3.1. The soil of the experimental site was found to be of sandy loam texture and other physical and chemical properties of the soil are presented in Table 3.2 and 3.3.

Table 3.1 Methodology for soil analysis

Parameters	**Methodology/Instrument**	**References**
Soil Texture	Hydrometer	Bouyoucos, 1927
pH	pH meter	Jackson, 1973
Electrical Conductivity	Conductivity bridge	Jackson, 1973
Bulk Density	Gravimetric method	Jackson, 1973
Hydraulic Conductivity	Constant head permeameter	Jackson, 1973
Field Capacity and Permanent Wilting Point	Pressure plate apparatus	Richards and Weaver, 1944

Table 3.2 Physical properties of soil

Soil Layer depth (cm)	Particle size distribution (%)			Soil texture class	BD (g/cc)	FC % (m^3 m^{-3}) on gravimetric	PWP % (m^3 m^{-3})
	Sand	Silt	Clay				
0-15	67.5	12.5	20	Sandy Loam	1.32	30.5	9.8
15-30	66.1	13.1	20.8	Sandy Loam	1.38	30.1	9.3

Table 3.3 Chemical properties of soil

Soil Layer depth (cm)	EC (dSm^{-1})	pH
0-15	0.35	5.8 - 6.1
15-30	0.38	5.6 -5.9

Moreover, the soil moisture characteristic curves of sandy loam soil in the greenhouse at various metric potentials were determined by Richard's Pressure Plate Apparatus (Richard, 1944). The data related to soil moisture characteristic curve for the sandy loam soil is presented in Appendix-I.

3.2 Fabrication of the Piezo-resistive based soil moisture sensor

Tensiometer is an instrument used to measure the energy status (or potential) of soil moisture present in the soil column. It consists of water filled plastic tube with hollow ceramic cup attached to its bottom and fitted with an airtight vacuum gauge on top (Figure, 3.2). The porous cup is generally made up of ceramic because of its structural strength as well as permeability to flow of water. The Bourdon tube vacuum gauge is commonly used for measurement of vacuum created in the tube. This device is installed at desired depth in the soil with the ceramic cup in good contact with soil particles. The water in the tensiometer eventually comes to equilibrium pressure with the surrounding soil through the ceramic tip. Moreover, with drying of soil the water present in the tube flows out through the ceramic cup creating a vacuum which is indicated by the mounted pressure gauge. Further, with addition of water to the soil, the reverse flow from the soil to the tube occurs through the ceramic cup, thereby reducing the vacuum pressure which is measured by the pressure gauge (Shock and Wang, 2011). Tensiometer cannot provide the instant readings of soil moisture content. Thus, the reading of the vacuum pressure in the tensiometer need to be calibrated with the soil moisture content, so that the soil moisture data from tensiometer reading can be obtained for subsequent irrigation scheduling. Also, moisture characteristic curve, which is drawn by plotting soil moisture versus soil metric potential (Allen, 2011).

Most tensiometers are manufactured with a measuring scale from 0-100 centibars out of which the range from 0 to 80 centibars is considered for irrigation management. A lower (near 0 centibars) reading indicates saturated soil condition and the limitations of the tensiometers are cavitation, mechanical failure problem. Tensiometer requires careful installation and maintenance to insure reliable results. Installations should be protected from field hazards and need to have good soil contact with the ceramic cup. After extreme drying/wetting cycles, refilling with water may be necessary to replenish evaporated water and remove entrapped air. Tensiometer require no site-specific calibration and are, therefore, well suited for a wide range of applications in soil hydrology and irrigation water management. Vacuum gauge has limitation that it does not provide output in form of electrical signal, which is used as input for automatic irrigation system. Thus to overcome this problem, the present investigation was carried out for replacement strategy for vacuum gauge and related automation.

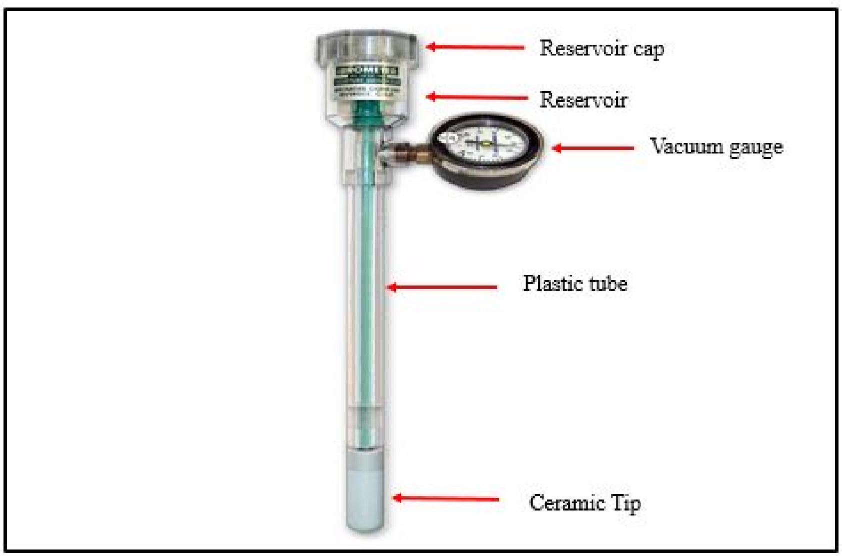

Figure 3.2 Tensiometer and its different parts

3.5 Design Approach of Piezo-resistive based soil moisture sensor

Piezo-resistive based soil moisture sensor is developed using the tensiometer to measure the soil water potential and replacing the vacuum gauge component in tensiometer by a piezo-resistive sensor. Development of Piezo-resistive soil moisture sensor consisted of systematic integration of ceramic cup, acrylic pipe, piezo-resistive sensor, Silicon cork, Printed Circuit Board (PCB), Zigbee (XBee) transmitter and receiver. Development of sensor parts and its assembly are shown in the pictures (Figure 3.3 to 3.7). Such type of modification is technically sound, low cost and with minimal manual intervention. Modified design of tensiometer consist of water filled acrylic pipe with porous ceramic cup in contact with soil at one end and at a Piezo-resistive sensor is connected to acrylic pipe with the help of silicon cork at the top. The developed sensor is shown in Plate.3.1

Plate 3.1 Development of sensor at field

When tensiometer is installed in the soil, the moisture content within the soil matrix come into equilibrium with the water present in the porous cup, and since the system is closed, vacuum is created and thus transmitted to the Piezo-resistive sensor. The piezo-resistive sensor is connected to printed circuit board (PCB) and both of these are powered by battery source. Different gadgets used in development of sensor are discussed below:-

3.5.1 Piezo-resistive Sensor

A pressure sensor can be as simple as a spring scale, which swings an arrow when pressure is applied to it. Piezo resistive pressure sensors are one of the preliminary products of Micro Electro Mechanical System (MEMS) technology. Those products are widely used in biomedical applications, automotive industry and household appliances. A piezo-resistive pressure sensor contains several thin wafers of silicon embedded between protective surfaces. The surface is usually connected to a Wheatstone bridge, a device for detecting small differences in resistance. The Wheatstone bridge runs a small amount of current through the sensor. When the resistance changes, less current passes through the pressure sensor. The Wheatstone bridge could detects this change and indicates a change in pressure. Most of the pressure sensors use semiconductor silicon devices as piezo-resistive sensor. The Piezo-resistive sensor is shown in Figure 3.3.

The type of sensor used for this application is the piezo resistive differential pressure transducer MPX4250DP selected from Free scale Semiconductor company with integrated temperature compensation and signal amplification circuits, providing a linear voltage output for a differential pressure ranging from 0 to 250 kPa. The sensitivity of the sensor corresponds to 18.8 mV/kPa, according to the official product datasheet. The MPX4250DP sensor requires a power supply of 5 V and provides an output voltage with a full-scale span of 4.5 V and a maximum output of 4.8 V. MPX4250DP sensors have been used for various scientific tensiometer applications for more than a decade. The detailed specification of piezo-resistive sensor are given in appendix-II

3.5.2 Printed Circuit Board (PCB)

Printed Circuit Board (PCB) was used for housing the electronic components to make a circuit compact and simple for operation of the piezo-resistive sensor. PCB is actually a sheet of bakelite (an insulating moulded plastic material) on the one side of which copper patterns are made with holes and soldered to the copper points on the back. Such copper patterns provide circuits for joining of electronic components to complete the electronic circuitry. All the components as per the circuit diagram (Figure 3.5) were placed on the printed circuit board and soldered properly in the laboratory. The designed PCB for the operation of the system is presented in the Plate.3.2.

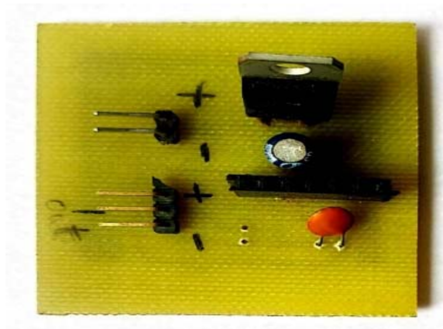

Plate 3.2 PCB mounted with electronic gazettes

Figure 3.3 Piezo- resistive sensor

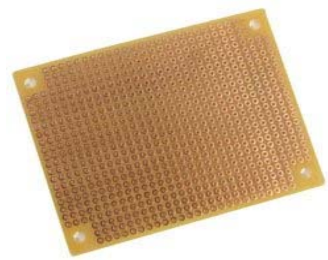

Figure 3.4 Simple circuit board

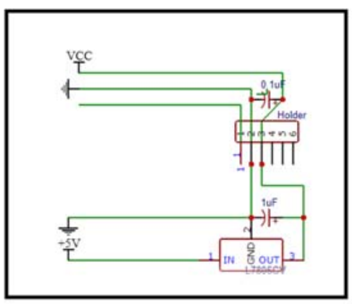

Figure 3.5 Electrical circuit connection

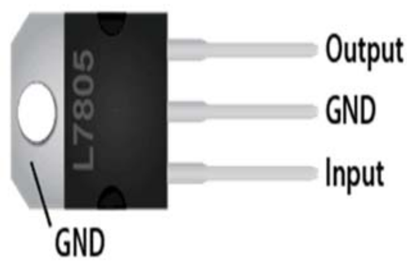

Figure 3.6 Voltage regulator

Figure 3.7 XBee Transmitter and Receiver

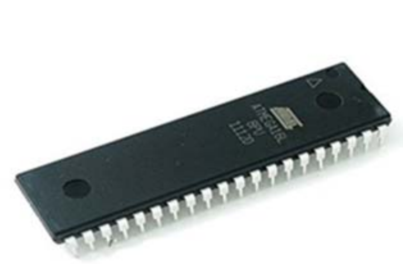

Figure 3.8 Microcontroller

3.5.3 Voltage regulator

The voltage regulator is an electronic circuit that provides a stable DC voltage independent of the current, temperature and AC line voltage fluctuations. The voltage regulator ensures a constant supply of 5V, which is required for operation of the piezo-resistive sensor. In the study, the L7805CV, a step down type of voltage regulator was used to supply constant voltage from 12V input supply to 5V in electrical circuits of the sensing device. It can generate a fixed output voltage that only remain constant for any change in an input voltage or load condition but also act as a buffer for protecting components from damage. The voltage regulator is shown in Fig 3.6.

3.5.4 Capacitor

A capacitor is a passive two-terminal electrical component that stores potential energy in an electric field and add capacitance to the circuit. Ceramic type aluminum electrolytic capacitor with capacitance range of 0.1µF and 01µF were used in the design of PCB to filter the noise generated by the electrical signals in circuits and also to store and discharge electric current.

3.5.5 XBee Transmitter and Receiver

XBee is a RF (Radio Frequency) module, which are embedded to provide wireless end-point connectivity to devices. Digi XBee 52C was selected for the operation of the system due to its lower power, low cost, having wireless sensor and control network (Chaitanya *et al*. 2013). It is a serial communication which allows to design an XBee network, inbuilt analog to digital converters which can be directly interfaced to the sensors which have analog values. It uses the radio frequency ranging from 20 kHz to 300 kHz for its communication between transmitter and the receiver. When analog input is received from the Piezo-resistive sensor, it convert the signal from analog to digital format and send to the receiver end in the form of radio frequency. It transfers the data in the range of 30m-100m distance and required input voltage of 3.3V for its operation. However, before connection of XBee with piezo-resistive sensor there is a need of establishment of communication between transmitter and receiver. For communication between transmitter and receiver, a XCTU software was used. At one end, Xbee transmitter interfaced with Piezo-resistive sensor and PCB (Figure 3.7) and on the other end XBee receiver was interfaced with microcontroller ATMEGA16L for the automation of irrigation system. The detailed specifications of the XBee module is given in Appendix-III. After integration of above components on the PCB, to collect the voltage reading in order to know the soil moisture content as shown in the plate 3.3

Plate 3.3 Recording of analog voltage readings in the tomato field

3.6 Components of automated irrigation system

An automated irrigation system refers to the operation of the system with almost nil or minimal manual intervention beside the surveillance. Almost every irrigation system (*i.e.* drip, sprinkler and surface) can be automated with help of timers, sensors or computers or mechanical appliances. Advantages of automatic irrigation system are its low initial cost, reduce monitoring hassle, reduce labour cost, require low power, and save a significant quantity of water. The XBee receiver, micro-controller, LCD (Liquid Crystal Display), pump and water meter were the prime components of automatic irrigation system.

3.6.1 Microcontroller

Microcontroller serves as heart of automatic irrigation system. It is a compact integrated circuit designed to govern a specific operation in an embedded system. In general, the microcontroller includes a processor, memory and input/output (I/O) peripherals on a single chip. Microcontroller is equipped with an input device in order to receive the input signal and an output device (such as LED or LCD Display) to display the acquired and processed information. The microcontroller used in the system design for automation or taking decision was with model No ATMEGA16L and was connected with electrical circuits. ATMEGA16L is an 8-bit high performance microcontroller of Atmel's Mega AVR product with low power consumption. It is a 40 pin microcontroller based on enhanced RISC (Reduced Instruction Set Computing) architecture. Most of the instructions gets executed in one machine cycle. It can work on a maximum frequency of 16MHz. The microcontroller used in development of the device is shown in the figure 3.8.

3.6.2 Liquid Crystal Display

Liquid Crystal Display (LCD) screen is an electronic display module. A 16×2 LCD indicates a display of 16 characters per line and there are 2 such lines in the controller. In the developed device, the, 16×2 LCD display unit was selected for displaying the moisture content and total amount of water supplied to the crop, in first and second row, respectively. Moisture content and amount of water released to field corresponding to each irrigation event was displayed in terms of percentage and litters of water respectively. The LCD for displaying moisture content, volume of water supplied to the field shown in figure 3.9.

3.6.3 Water meter

Water meter was used to measure flow velocity in the pipe flow. The velocity is measured by a multi-blade conical propellers, made of metal plastic, rubber, rotating in a vertical plane and geared to a totalizer in such a manner that numerical counter can totalize the flow in desired volumetric units. The speed of the propeller is proportional to the velocity of flow of water. There are two basic requirements for accurate operation of water meter such as the pipe must flow full at all times and rate of flow must exceed the minimum rated discharge. Based on the water requirement for the crop, water meter was selected, which can measure the flow rate in the range of 2 to 100 l/min, and can withstand a pressure ≤2.0MPa. Water meter selected for design of automatic irrigation system is shown in figure 3.10.

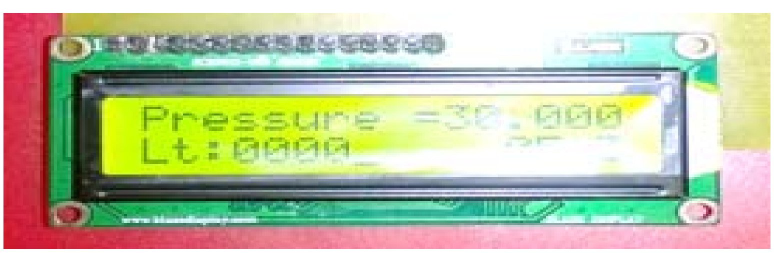

Figure 3.9 Liquid Crystal Display

Figure 3.10: Water meter

Figure 3.11: Light Emitting Diodes

Figure 3.12 and 3.13: Resistors

3.6.4 Light Emitting Diodes

The light emitting diodes (LEDs) in the circuit was used to give a visual indication of whether the circuit was working or not. One LED was connected to the voltage regulator in the circuit to indicate power supply to the circuit and another one was connected before the relay unit in circuit to indicate whether the relay was on or off. In the design of circuit, microcontroller enabled relay device gets activated when the tensiometer reading exceeds the threshold value of soil metric potential. LEDs selected for design of automatic irrigation system is shown in Figure 3.11.

3.6.5 Resistors

Resistors (Figure 3.12 and 3.13) are electronic components which have a specific and fixed electrical resistance. The resistance limits the flow of electrons through a circuit. Resistors are usually added to circuits where they complement active components like microcontrollers, and other integrated circuits.

Generally resistors are used to limit the flow of current, divide voltages, and pull up I/O lines. In the designed electrical circuit, 10 K resistors were used, for the proper operation of LCD. On LCD, the resistor is used to adjust the contrast level.

3.6.6 Programmer device and programming code for the developed device:

A programming language is a formal language consist a set of instructions that can be used to produce various kinds of output. Programming languages generally consist of instructions through well-defined algorithms for operation of the microcontroller. Atmel studio7.0 software was used for the programing and embedding in the microcontroller connected with the automation device. Atmel studio is the integrated development platform (IDP) for developing and debugging all Automatic Voltage Variation (AVR) and Software Management (SAM) microcontroller applications written in C/C++ or assembly code. . The detailed program developed for the automation irrigation controller is presented in the Appendix-V. To accomplish these tasks, the USB programmer is used to program the Atmel AVR microcontrollers. Besides this, jumper wire are required to interface the microcontroller and the USB programmer which can provide +5 volt power supply to the microcontroller so that microcontroller can be programmed without any external power source. The USB programmer components are shown in the Figure 3.14.

Figure 3.14 Components of USB Programmer

3.7 Irrigation Pump

A self-priming mono block centrifugal irrigation pump were used for irrigating the experimental field. It is a 2 HP motor having discharge capacity is 19.4 l/ sec at 6 m suction head. Motor was operated by the 12 V DC relay, which used 9.5 A AC current having 230 V voltage.

3.8 Relay unit

Relays are switches that open and close circuits electromechanically or electronically. The contacts of a relay can be either Normally Open (NO), Normally Closed (NC) or change over the contact. NO contacts connect the circuit when the relay is activated. The circuit was disconnected when the relay was inactive. The relay was powered with 12 V DC and was used to operate the pump. The microcontroller passes signal to the relay unit (Figure 3.15), which then activates the irrigation pump for supply of water to the field

.

Figure 3.15 Relay unit for operation of electrical motor

All these above components were fixed on the PCB, which transmits signals and instructions mechanically and electronically to all components for irrigating the field. The designed PCB for the operation of irrigation system is shown in the Plate.3.4

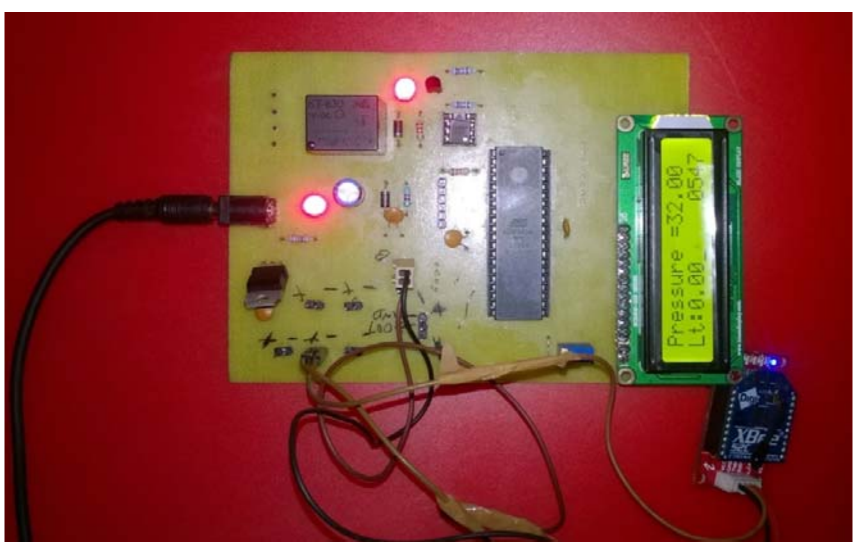

Plate 3.4 Designed PCB for the operation of irrigation system.

The flow chart for working of “Tensiometer Automation Device for Greenhouse Irrigation Scheduling” is shown in Figure 3.16. Sequential steps for its operation are presented below:

- Tensiometer need to be installed at a required depth based on the effective root zone of crop by following the standard procedure. Moreover, it should be ensured that the Xbee transmitter and receiver should be within the data transferable range of 1-100 m.
- After installation of tensiometer, the piezo-resistive sensor need to be connected with the tensiometer to measure the vacuum pressure caused by soil moisture tension of the soil.
- The piezo-resistive sensor and all other components should be connected with power source for its operation.
- The vacuum pressure sensed by the piezo-resistive sensor transfer the data to a Xbee receiver and convert the analog reading to digital format and transmit data to a Xbee receiver located within specified range 1-100 m.
- Microcontroller receives data from the Xbee receiver to ensure whether the crop requires irrigation or not based on the pre-set moisture content pertaining to manageable allowable deficit. Further, if irrigation is triggered, then the microcontroller with it’s embed programme quantify the amount of irrigation water to be supplied to the crop.

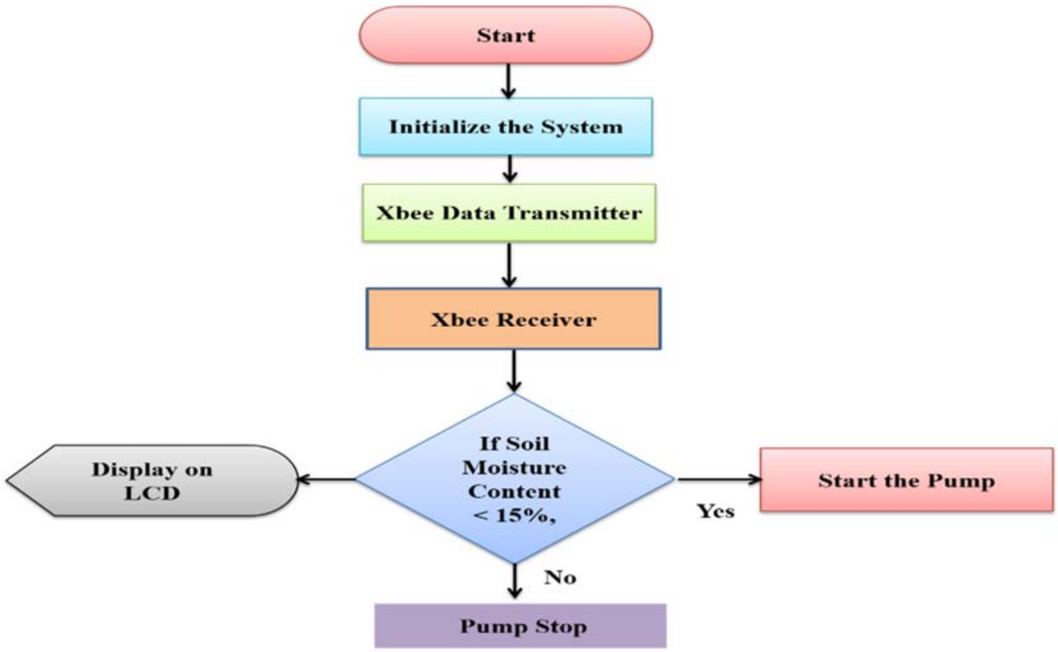

Figure 3.16 System architecture depicting the operation of tensiometer automation device for greenhouse irrigation scheduling

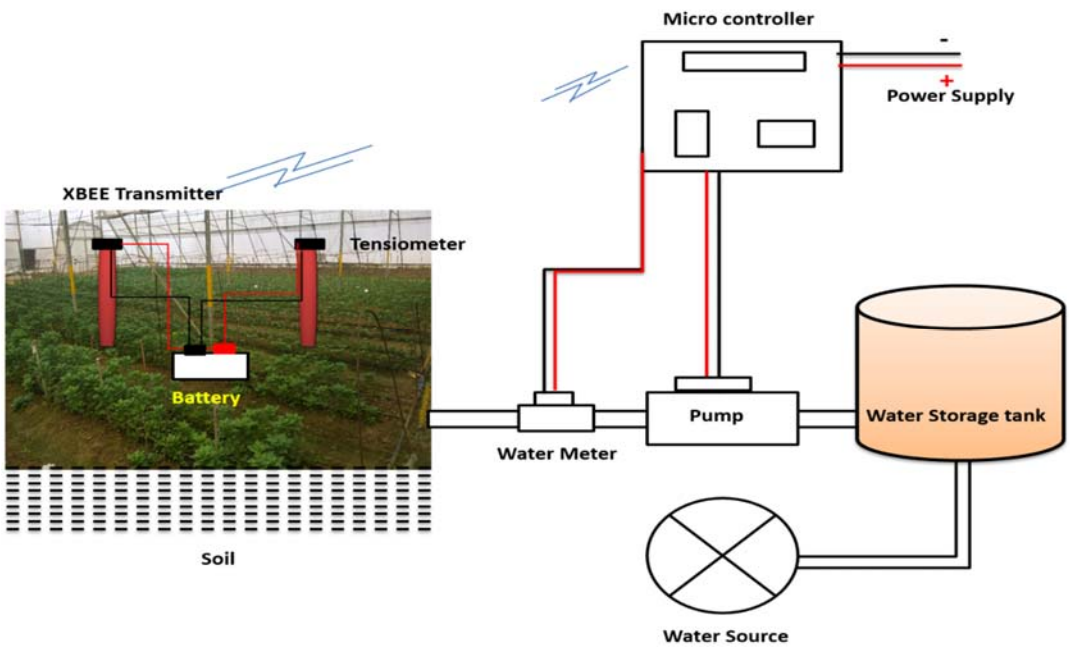

Figure 3.17 Block diagram indicating the arrangement of irrigation components in the greenhouse irrigation scheduling.

- ❖ The display unit is also provided at the receiver end to read the soil moisture content on real time basis.
- ❖ After quantification of water requirement by the microcontroller, the signal is transmitted to the relay unit which switches on the pump to supply water.

- ❖ The pumped water passes through the flow meter which quantifies water discharged to the field.
- ❖ The microcontroller is programmed to ascertain the estimated volume of water supplied through the water meter and when the estimated water is supplied to the field, the microcontroller send signal to the relay to switch of the pump to stop the irrigation event.
- ❖ A pause time is programmed based on response time of tensiometer for next irrigation, so as to enhance the irrigation efficiency. However, there is provision of display of the soil moisture content at every five minutes interval.

Same procedure is repeated for the next irrigation event, which depends on the soil moisture depletion as per the pre-set MAD value. The system architecture depicting the functioning of tensiometer automation device for greenhouse irrigation scheduling is shown in Figure 3.16.

3.9 Experimental set up for testing of the developed device

The experiment was conducted during rabi season of 2017-18. An experimental area of 300 m^2 was selected to grow tomato and chrysanthemum crops irrigated by drip irrigation system. The area was divided in to two plots of size 10 × 15 m (150 m^2) each. Each plot was irrigated with 9 drip lines having 16 mm in diameter, distances between drip lines was 300 mm with emitter discharge of 2 lph.

The experimental plot was equipped with tensiometer and Piezo-resistive based soil moisture sensor installed at a depth of 15 and 30 cm. Eight tensiometers were installed, out of which four were installed at 15 cm and the other four at 30 cm depth as shown in Figure 3.18. Soil moisture readings were recorded on daily basis and at regular interval of 5 minutes. The developed sensors were installed along with drip line and between two plant rows to monitor the variability in soil moisture available to the plants in tomato and Chrysanthemum crops. The sensor installation process and operational procedures were performed according to the manufacturer's recommendations and instructions.

Sensors reading were recorded daily at 10:00 AM and at the same time soil samples were collected for quantifying the soil moisture content using gravimetric analysis. The gravimetric analysis was undertaken to calibrate the developed sensor. To reduce mass flow of soil water to the soil sampling holes made by augur, the holes were immediately refilled with soil from similar profiles taken from a site at 10 m apart.

Further, the gravimetric sample sites were marked with flags so that no repeated soil samples were taken from the same point.

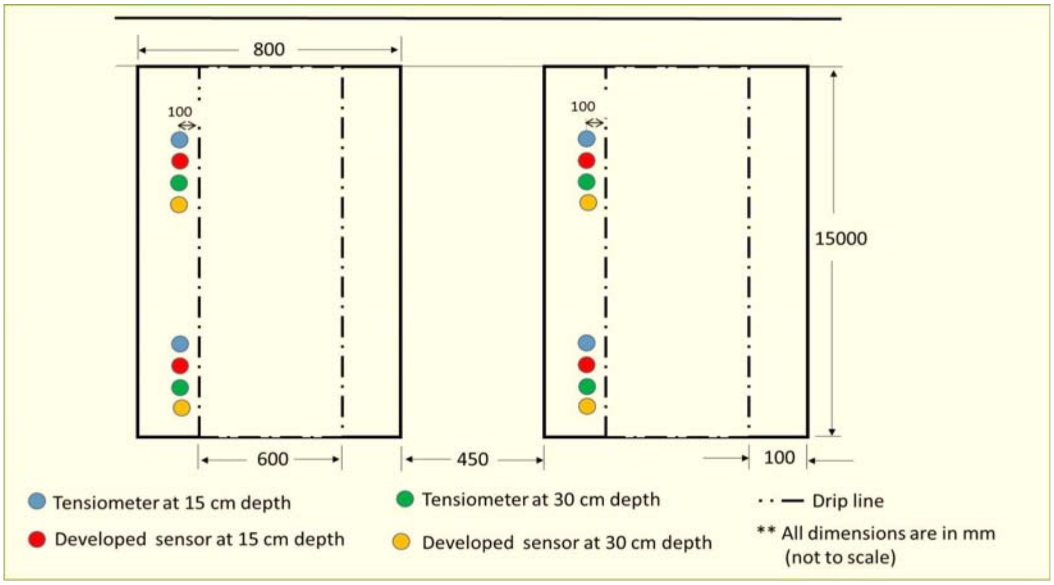

Figure 3.18 Field layout of installed sensor in the greenhouse.

3.10 Testing of Piezo-resistive soil moisture sensor

The Piezo-resistive soil moisture sensor requires no assembling as it is pre-assembled. However, some instructions must be followed for its calibration and installation, which is presented in Appendix IV.

3.10.1 Gravimetric method of soil moisture measurement

Gravimetric soil moisture measurement is one of the oldest and widely adopted method for soil moisture measurement, sometimes it is also called as direct moisture measurement method (Charlesworth, 2005). Gravimetric method is generally used for one time moisture content data acquisition and also for calibrating the soil moisture measurement device. Gravimetric method measures soil moisture content on weight basis by dividing the weight of water in the sample by the dry weight of the sample. An auger is used for obtaining soil sample from various depths of field and kept in air tight aluminum cans which are weighed and kept in an oven at 105-110^{0}C for 24 hours and weighed again.


Plate 3.5 Collection of soil sample for soil moisture determination

Moisture content (M.C) on dry basis can be calculated by the using following formula:

$$\mathrm{M.C}\ (\%) = \frac{\text{Weight of wet soil} - \text{Weight of dry soil}}{\text{Weight of dry soil}} \times 100 \qquad \ldots 3.1$$

3.11 Performance evaluation of the Piezo-resistive soil moisture sensor

The performance of Piezo-resistive soil moisture sensor in measurement of soil moisture content is compared with the gravimetric method using three statistical tests, which are:

a) Mean Difference (MD)

MD describe the average difference between sensor measurements and the corresponding gravimetric measurements of soil moisture content, it is expressed as:

$$MD = \frac{\sum_{i=1}^{n}(M_{si} - M_{gi})}{n} \qquad \ldots 3.2$$

Where,

M_{si}= the i^{th} measurement of soil moisture obtained by a sensor.

M_{gi}= the i^{th} measurement of soil moisture obtained with gravimetric method.

n = the number of samples.

The lowest value of MD ascertains that the sensor measurement is in line with the gravimetric measurement of soil moisture content.

b) Coefficient of Determination (R^2)

It provides a measure of how well the observed outcomes are replicated by the model, based on the proportion of total variation of outcomes explained by the model.

The coefficient of determination, is denoted R^2 and it is the proportion of the variance in the dependent variable that is predictable from as the independent variable(s). It is estimated by the formula:

$$R^2 = \left[\frac{1}{n}\ \frac{\Sigma\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sigma_x \sigma_y}\right]^2 \qquad \text{...3.3}$$

Where

n = number of observations

X_i= x value for i^{th} observation

$\overline{X}$= mean of x value

Y_i= y value for i^{th} observation.

$\overline{Y}$= mean of y value

σ_x = standard deviation of x

σ_y = standard deviation of y

The Coefficient of Determination R^2 approaching one indicate a better correlation between the sensor and the gravimetric measurement of soil moisture content.

C) Relative Root Mean Square Error (RRMSE)

Relative root mean square error calculates the total difference between Piezo-resistive based soil moisture sensor and gravimetric method of soil water content as a percentage of the mean gravimetric moisture content value. The RRMSE is similar to the coefficient of variation. Equation for calculation of RRMSE is given as follows

$$\text{RRMSE} = \sqrt{\left[\sum_{i=1}^{n} \langle M_{si} - M_{gi} \rangle^2\right]} \times \frac{100}{M_g} \qquad \text{... 3.4}$$

Where M_{gi} = the corresponding mean of Gravimetric measurement was calculated by equation 3.5.

$$M_g = \frac{1}{n} \sum_{i=1}^{n} M_{gi} \qquad \text{...3.5}$$

d) Paired T-test

A paired T-test is generally used to compare two population means in which observations in one sample can be paired with observations in the other sample. This test is used under two different situations *viz.* before and after observations on the same subjects and to compare two different methods of measurement or two different treatments where the measurements/treatments are applied to the same parameter. Assumption for the paired t-test in a present experiment, there was no significant difference in the mean value of tensiometer and Piezo-restive based soil moisture sensor. If the value of P, when compared between tensiometer and piezo-resistive based soil moisture sensor is less than 0.05 then it implies that there is a significant difference in mean value of both treatment. Value of T-statistic was calculated by using the formula:

$$T = \frac{\overline{D}}{\text{SE}\ (\overline{D})} \qquad \ldots 3.6$$

Where:

$\overline{D}$ = Mean difference between the tensiometer and gravimetric measurements of soil moisture content

$SE\ (\overline{D})$ = Standard error of mean difference

Chapter-4

RESULTS

The present research entitled “Tensiometer automation device for greenhouse irrigation scheduling” was undertaken during the *rabi-season* of 2017-18 in the greenhouse situated at Center for Protected Cultivation Technology (CPCT), ICAR-Indian Agricultural Research Institute (IARI), Pusa, New Delhi, India. The Piezo-resistive based soil moisture sensor was designed to measure soil matric potential further it was calibrated and validated for irrigation scheduling of greenhouse. The results obtained from the field experiment are presented in the following sections.

The experiment was laid out in two plots installed with drip irrigation system in greenhouse for testing the developed Piezo-resistive based soil moisture sensor for automated system for Chrysanthemum and Tomato crop during Rabi season of 2017-18. In each plot, at 10 cm from drip lines, two tensiometers were installed at 15 and 30 cm depth along with the developed Piezo-resistive based soil moisture sensor for automated irrigation system at the same depth. The soil matric potential based irrigation scheduling in the field was done by using Piezo-resistive based soil moisture sensor consisted of Piezo-resistive sensor, which was calibrated with standard gravimetric method. The Piezo resistive sensor actuated and de-actuated the irrigation pump exactly at the pre-set position of the sensors during field test. The Piezo-resistive based soil moisture sensor successfully used for automation of the irrigation system on the real time basis.

4.1 Design and development of Piezo-resistive transducer for measurement of soil moisture tension

The design and development of Piezo-resistive soil moisture sensor was based on the working principle of tensiometer and Piezo-resistive effect. The experiment was conducted for development of automatic irrigation scheduling in greenhouse using Piezo-resistive based Soil moisture sensor. The developed Piezo-resistive based Soil moisture sensor consisted of systematic integration of ceramic cup, acrylic pipe, Piezo-resistive sensor, Silicon cork, Printed Circuit Board (PCB), Zigbee (XBee) Transmitter and Receiver. Piezo-resistive based soil moisture sensor was installed in the field. When soil matric potential was created in soil, then vacuum was created in the acrylic pipe. The quantum of Vacuum created was measured by the Piezo-resistive sensor located on the tensiometer, which converts the pressure reading in to voltage reading by changing the resistance of electric current. The developed output voltage was connected to the Xbee transmitter for transformation of data to the receiver end located at within the data transferable range of microcontroller. This mechanism leads to development of a user friendly, low cost, indigenous automatic irrigation system. Prototype of Piezo-resistive based soil moisture sensors and its associated components is shown in plate 4.1.

Plate 4.1 Prototype of Piezo-resistive based soil moisture sensors and its associated components

After design, the developed prototype of Piezo-resistive based soil moisture sensor was installed in the greenhouse for its performance evaluation as shown in plate 4.2.

Plate 4.2 Developed Piezo-resistive based soil moisture sensor installed in Greenhouse

4.2 Development of automated device for soil moisture tension measurement by integrating Piezo-resistive transducer with the tensiometer

The automated irrigation system comprised of Piezo-resistive sensor, tensiometer, Xbee transmitter, receiver, water meter and irrigation pump. The vacuum pressure caused by change in soil matric potential was sensed by the Piezo-resistive sensor was transmitted through Xbee transmitter to the receiver located at or near microcontroller. The X-bee receiver after receiving the data, converted in to moisture content by microcontroller using soil moisture characteristic curve equation. Based on the soil moisture status it decides whether to irrigate the crop or not. If the soil moisture is less than the pre-stated value, it quantifies the amount of water needed to replenish the soil moisture content at effective root zone of the crop. After calculating the amount of water required for the crop, micro controller communicates the signal to the relay unit, which automatically starts the pump i.e. “Pump ON”.

While running of irrigation pump, water passes through the flow meter and it quantifies the amount of water passing through it. After passing the quantified amount of water it interfaces the signal to relay unit to stop the pump i.e. “Pump OFF”. Based on the response time of the tensiometer, the above process was repeated for automatic irrigation scheduling of greenhouse tomato and chrysanthemum crops.

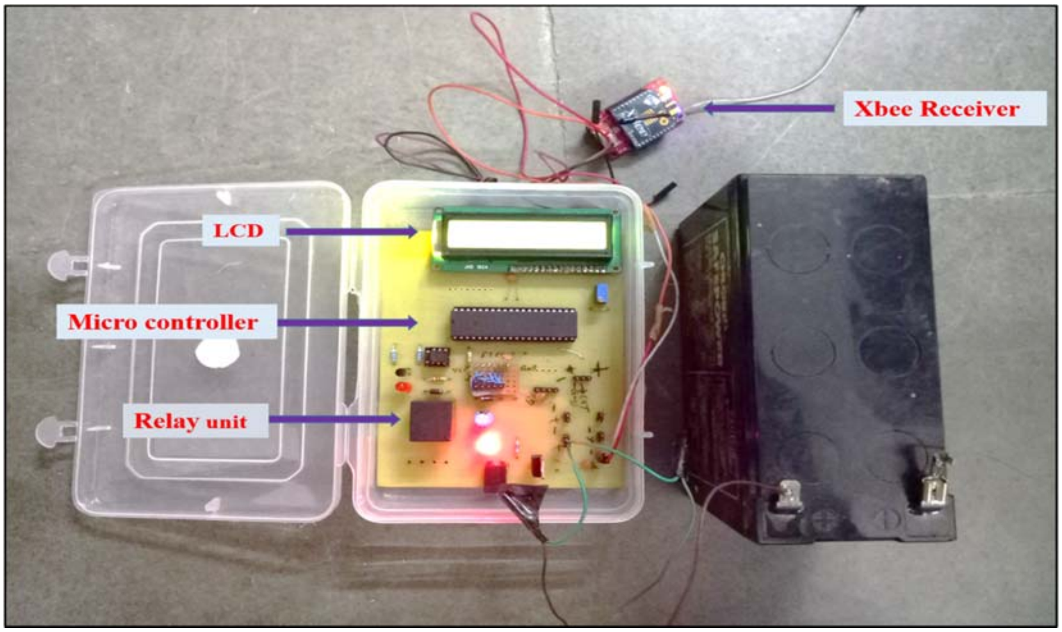

Plate 4.3 Developed microcontroller for automated irrigation system and greenhouse irrigation scheduling.

Plate 4.4 Microcontroller integrated with Irrigation pump for automation system

4.3 Soil moisture characteristic curve

Soil moisture characteristic curve at various soil matric potential were determined by pressure plate apparatus (Richards, 1944). It was used for determination of soil moisture content at a particular depth by using the Piezo-resistive based Soil moisture sensor reading, installed in the field.

This curve was used to develop relationships between the soil matric potential and moisture content at corresponding depths. The soil moisture content readings were plotted on y-axis and soil matric potential for various layers in soil profile was plotted on x-axis up to the root zone depth of 30 cm (Figure 4.1). Moreover, soil moisture content varies with respect to different depths of soil profile at constant matric potential. These curve change with change in bulk density, soil texture and soil structure. The coefficient of determination (R^2) was found to be 0.9611 and 0.957 for 0-15 cm and 15-30 cm depth, respectively.

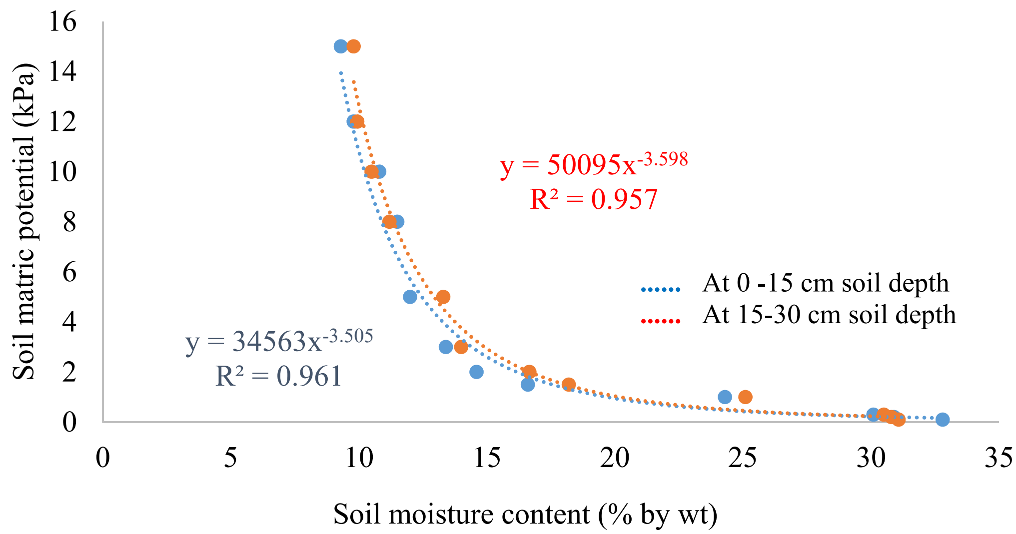

Figure 4.1 Soil moisture characteristic curve at 15 and 30 cm depth of soil

4.4 Performance evaluation of Piezo-resistive based soil moisture sensor

The experiment was carried out in sandy loam soil. The tensiometer and Piezo-resistive based Soil moisture sensor were installed at 15 and 30 cm depth and replicated thrice. The developed sensor and tensiometer were evaluated in the field by comparing sensor's reading with correlation of soil moisture content using standard gravimetric method.

The soil moisture content measured by gravimetric method was converted into volumetric moisture content by multiplying the corresponding bulk density of soil layers at 15 cm and 30 cm depth. Regression relationship between volumetric soil moisture content measured by standard gravimetric method and volumetric soil moisture content by tensiometer at 15 and 30 cm depth in chrysanthemum plot were developed and are represented in Figure 4.2 and Figure 4.3 respectively.

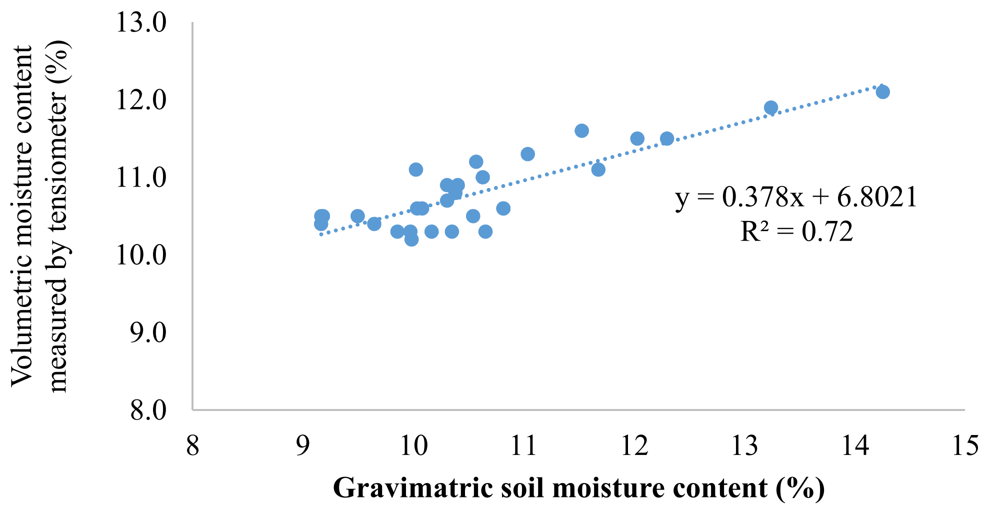

Figure 4.2 Regression relationship between volumetric soil moisture content by standard gravimetric method and tensiometer at 15cm depth in chrysanthemum.

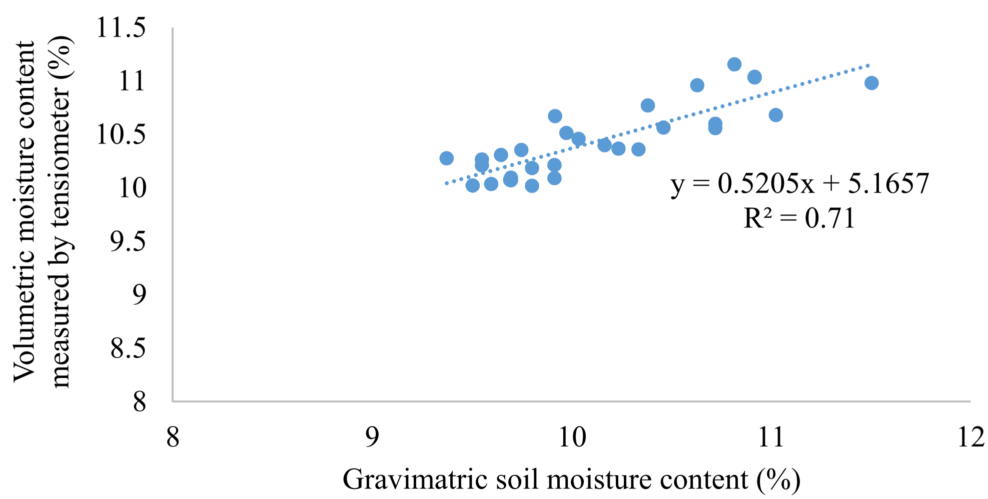

Figure 4.3 Regression relationship between volumetric soil moisture content by standard gravimetric method and tensiometer at 30 cm depth in chrysanthemum

Figure 4.2 and 4.3 shows the relationship between tensiometer with moisture content measured by gravimetric method for chrysanthemum crop at a depth of 15 and 30 cm. The coefficient of determination (R^2) was found to be 0.72 and 0.71 between tensiometer and gravimetric method at 15 cm and 30 cm depths, respectively.

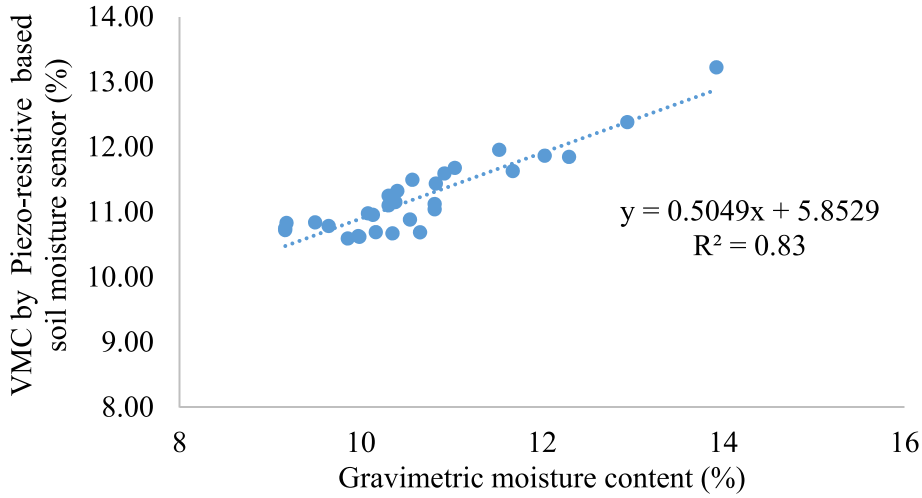

Figure 4.4 Regression relationship between volumetric soil moisture content (VMC) by standard gravimetric method and Piezo-resistive soil moisture sensor at 15 cm depth in chrysanthemum

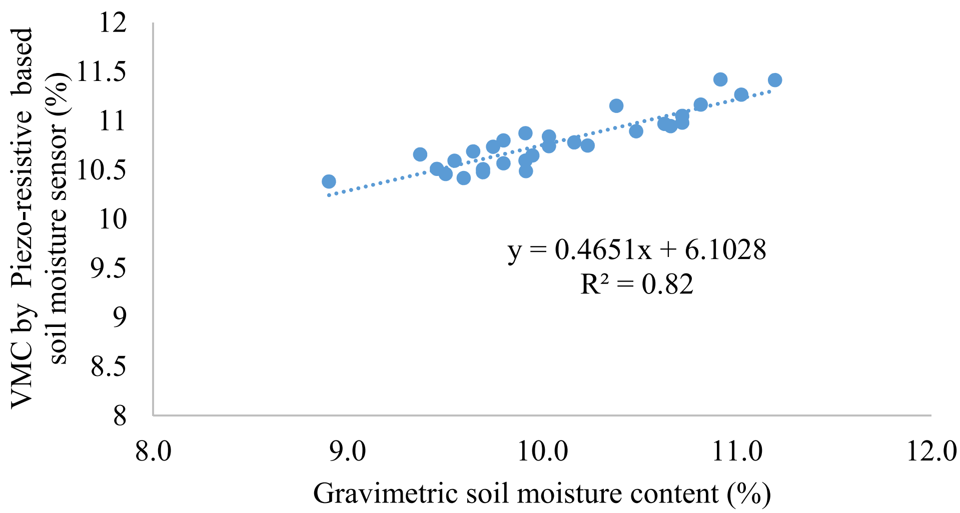

Figure 4.5 Regression relationship between volumetric soil moisture content (VMC) by standard gravimetric method and Piezo-resistive based Soil moisture sensor at 30 cm depth in chrysanthemum crop

Regression relationship (figure 4.4 and 4.5) between volumetric soil moisture content measured by gravimetric method and Piezo-resistive based soil moisture sensor installed at 15 and 30 cm depth in chrysanthemum plot were recorded and thus were retrogression against each other.

Figure 4.4 and 4.5 shows the relationship between tensiometer with moisture content measured by gravimetric method for chrysanthemum crop at a depth of 15 and 30 cm. The coefficient of determination (R^2) was found to be 0.83 and 0.82 between piezo-resistive based soil moisture sensor and soil moisture content measured by the gravimetric method at 15 cm and 30 cm depths, respectively.

Regression relationship between volumetric soil moisture content measured by standard gravimetric method and volumetric soil moisture content calculated by tensiometer at 15 and 30 cm depth in tomato plot were developed and are represented in Figure 4.6 and Figure 4.7 respectively.

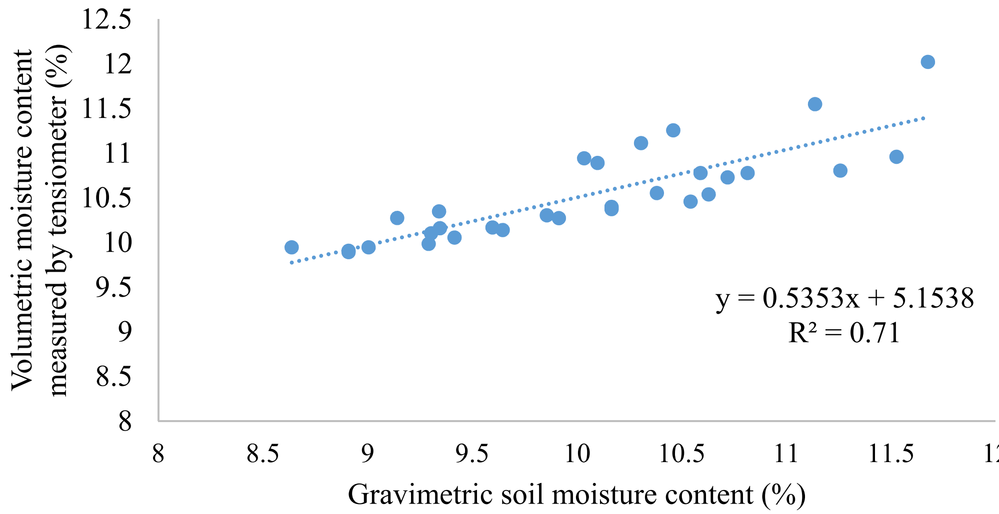

Figure 4.6 Regression relationship between volumetric soil moisture content by standard gravimetric method and tensiometer at 15cm depth in tomato crop

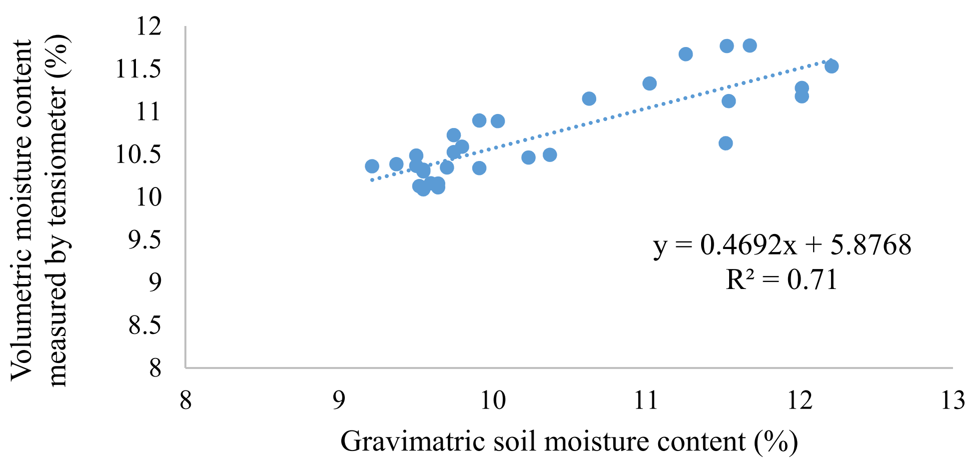

Figure 4.7 Regression relationship between volumetric soil moisture content measured by standard gravimetric method and tensiometer at 30 cm depth in tomato crop

Figure 4.6 and 4.7 shows the relationship between piezo-resistive based soil moisture sensor with moisture content measured by gravimetric method for tomato crop at a depth of 15 and 30 cm. The coefficient of determination (R^2) was found to be0.71 and 0.71 between piezo-resistive based soil moisture sensor and soil moisture content measured by the gravimetric method at 15 cm and 30 cm depths, respectively.

The soil matric potential by piezo-resistive based soil moisture sensor and gravimetric method at 15 and 30 cm depth in tomato plot were recorded and thus were retrogressed against each other. The Figure 4.8 and Figure 4.9 represent the regression relationship between them.

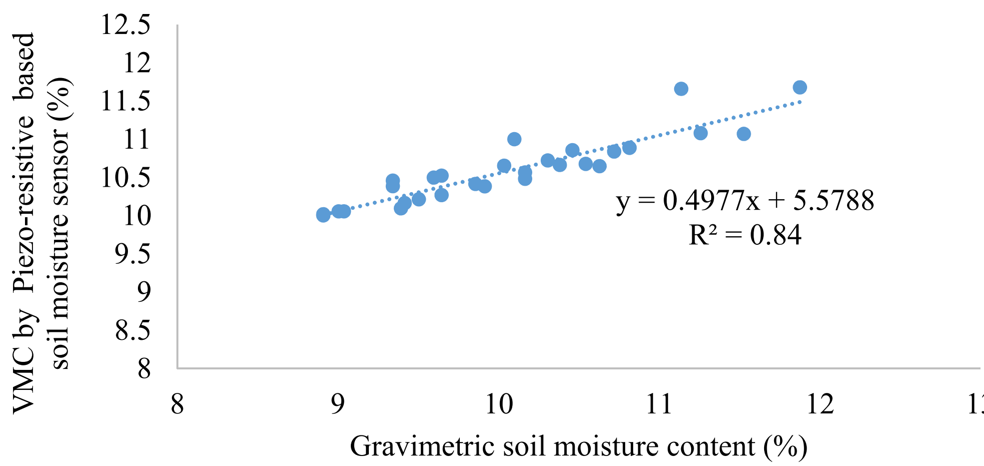

Figure 4.8 Regression relationship between volumetric soil moisture content by standard gravimetric method and Piezo-resistive based soil moisture sensor at 15 cm depth in tomato crop

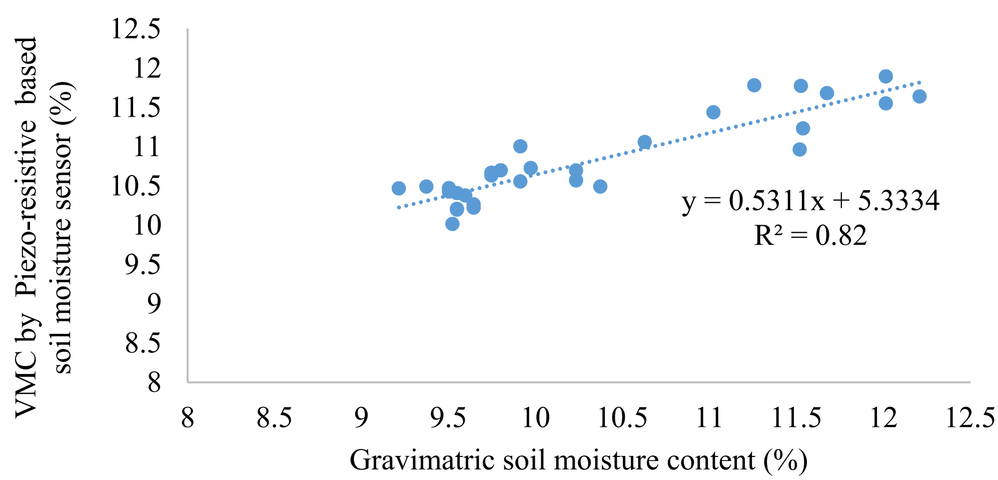

Figure 4.9 Regression relationship between volumetric soil moisture content by Standard gravimetric method and Piezo-resistive based Soil moisture sensor at 30 cm depth in tomato crop.

The coefficient of determination (R^2) was found to be 0.84 and 0.82 between developed tensiometer and soil moisture content measured by the gravimetric method at 15 cm and 30 cm depths, respectively. Figure 4.8 and 4.9 shows the relationship between tensiometer with moisture content measured by gravimetric method for tomato crop at a depth of 15 and 30 cm.

The voltage readings recorded by Piezo-resistive sensor were noted down on daily basis with their corresponding soil moisture content. The voltage reading and soil moisture content were recorded in both the crops *viz.* Chrysanthemum and Tomato at 15 cm and 30 cm depth as given in the Table 4.1 and 4.2, respectively.

Table 4.1 Temporal variation of voltage reading and its corresponding soil moisture content recorded by Piezo-resistive sensor in Chrysanthemum

Day	At 15 cm Depth		At 30 cm Depth	
	Voltage Reading(mV)	Soil Moisture Content (%)	Voltage Reading (mV)	Soil Moisture Content (%)
1	126.5	11.63	183.7	10.74
2	142.8	11.04	194.8	10.57
3	130.66	11.32	174.6	10.89
4	156.75	10.75	200.9	10.48
5	137.85	11.15	207.6	10.38
6	163.71	10.62	198.61	10.51
7	158.28	10.72	186.97	10.69
8	163.15	10.63	193.15	10.59
9	160.84	10.67	184.1	10.74
10	152.76	10.83	165.3	11.27

Table 4.2 Temporal variation of voltage reading and its corresponding soil moisture content recorded by Piezo-resistive sensor in Tomato

DAY	At 15 cm Depth		At 30 cm Depth	
	Voltage Reading (mV)	Soil Moisture Content (%)	Voltage Reading (mV)	Soil Moisture Content (%)
1	177.9	10.84	184.5	10.72
2	188.66	10.66	190.4	10.64
3	200.59	10.48	205.7	10.40
4	205.37	10.41	216.2	10.26
5	168.68	10.99	220.59	10.20
6	197.81	10.52	201.5	10.47
7	229.76	10.09	201.2	10.47
8	199.55	10.49	199.8	10.49
9	207.5	10.38	153.6	11.89
10	232.9	10.05	156.40	11.23

The voltage reading and its corresponding soil moisture content recorded by developed Piezo-resistive sensor in greenhouse Chrysanthemum crop varied inversely from (126.5-163.71 mV)/ (11.63-10.62 %) and (165.3-207.6 mV)/ (11.27-10.38 %) for 15 and 30 cm depth respectively for the 10 continuous recorded period during vegetative stage. The voltage reading and its corresponding soil moisture content recorded by developed Piezo-resistive sensor in greenhouse tomato crop varied inversely from (177.9-232.9 mV)/ (10.99-10.05 %) and (153.6-220.59 mV)/ (11.89-10.20 %) for 15 and 30 cm depth respectively for the 10 continuous recorded period during fruiting stage.

4.3 Statistical analysis of sensor and tensiometer performance

The statistical measures such as the coefficient of determination (R^2), mean and Standard deviation were computed to evaluate the performance of tensiometer and Piezo-resistive based Soil moisture sensor by comparing with volumetric moisture content obtained by gravimetric method at 15 and 30 cm depth in both chrysanthemum and tomato plots separately. Paired T-test and Average absolute deviation for the recorded set of data were carried out to find the significance difference between the different methods. Statistical summary of the performance of the different methods incorporated in the experiment at different depths and in different plots are presented in the tables 4.3 and 4.4.

Table 4.3 Comparative Statistical analysis of Tensiometer and Piezo-resistive based Soil moisture sensor at different soil depth for Chrysanthemum and Tomato

Sensor	Crop	Depth (cm)	RRMSE	R^2	r
Tensiometer	Chrysanthemum	15	19.38	0.72	0.85
		30	9.47	0.71	0.84
	Tomato	15	18.21	0.71	0.84
		30	14.18	0.71	0.84
Piezo-resistive based Soil moisture sensor	Chrysanthemum	15	18.28	0.83	0.91
		30	7.44	0.82	0.91
	Tomato	15	14.16	0.84	0.92
		30	9.88	0.82	0.91

Table 4.4. Paired t-test of volumetric soil moisture content recorded by tensiometer and Piezo-resistive based Soil moisture sensor

Sl.no	Paired sample test					
Tensiometers placed in Chrysanthemum plot at 15 cm depth.						
	Type of Sensor	**Mean**	**SD**	**t-value**	**DF**	**5 % level of Significance**
Pair-1	Tensiometer	10.79	.51230	-68.384	29	.000
	Piezo-resistive based Soil moisture sensor	11.1846	.50881.			
Tensiometers placed in Chrysanthemum plot at 30 cm depth						
Pair-2	Tensiometer	10.4308	.33207	-32.651	29	.001
	Piezo-resistive based Soil moisture sensor	10.8184	.30433			
Tensiometers placed in Tomato plot at 15 cm depth						
Pair-3	Tensiometer	10.5215	.51575	-8.558	29	.0006
	Piezo-resistive based Soil moisture sensor	10.6495	.48970			
Tensiometers placed in Tomato plot at 30 cm depth						
Pair-4	Tensiometer	10.7184	.52664	-5.635	29	.00001
	Piezo-resistive based Soil moisture sensor	10.8208	.54657			

Paired t-test was performed to check the statistical significance between Piezo-resistive based Soil moisture sensor and tensiometer. If the P- value is less than 0.05 at 5% significance level, then the values were significant. It was concluded that at 15 and 30 cm depth in both chrysanthemum and tomato crop, there was significant difference between observations of tensiometer and developed Piezo-resistive based Soil moisture sensor, the mean performance of tensiometer and Piezo-resistive based Soil moisture sensor were significant at 5% level of significance.

4.4 Cost Estimation

Design and development of automated device for irrigation scheduling in greenhouse was done using a locally available electronic components and low cost materials. The following table indicates the materials used and their respective rate along with the total cost incurred during the development of automated irrigation device.

Table 4.5 Cost Estimation of the developed device

Sl. No	Particulars	Quantity (No.)	Rate (Rs.)	Amount (Rs.)
1	Piezo-resistive sensor	1	1650	1650
2	Tensiometer	1	3000	3000
3	Resistors kit	1	250	250
4	Capacitors kit	1	150	150
5	XBee transmitter and receiver	2	1300	2600
6	PCB (Printed circuit board)	2	200	400
7	Silicon cork	3	25	75
8	Female adopter (5 piece)	1	150	150
9	Micro controller (ATMEGA)	1	300	300
10	LCD	1	200	200
11	LEDs kit	1	250	250
12	USB Programmer	1	500	650
13	Relay unit	1	200	200
14	Water meter	1	1000	1000
15	Installation cost (Skilled Labour)	3	1500	4500
	Total			**15,625/-**

Chapter-5

DISCUSSION

Precision agriculture techniques focus on the existence of in-field variability of natural components, including chemical leaching, runoff, drainage, water content, nutrients, and soil components (Giacomin, 2006). The goal of precision agriculture is to utilize new technologies, such as GPS, satellites, aerial remote sensing and sensors to assess the variations in a field more accurately. Accordingly, farming practices, including sowing, irrigation and fertilizer management, and pest control, can be scheduled autonomously according to the assessment of the field. The concept of precision irrigation can be applied to all form of irrigation but extensively used for drip irrigation system through which water is applied either on surface or at subsurface near the crop root zone occupied by the plant root zone. Drip irrigation system are designed in such a way that, which only wet the soil zone occupied by plant root and maintain this zone at near an optimum or at saturation condition (Lyle, 1981).

The concept of automation in irrigation system plays an important role in order to get higher yield and for higher water productivity through utilizing the irrigation water efficiently. The automation irrigation system consist of piezo-resisitive sensor, flow meter, Xbee transmitter and receiver. The sensor systems must provide irrigation managers information on crop water status, crop water use and soil water status on a continuous basis. The specific objective of the study was to develop an automatic irrigation control system using soil matric potential to determine when to irrigate and soil water status to determine how much to apply. In this chapter, the performance of piezo-resistive based soil moisture sensor is discussed and also comparison of piezo-resistive based soil moisture sensor is made with gravimetric method.

5.1 Soil moisture characteristic curve

The soil moisture content readings were plotted on y-axis and soil matric potential for various layers in soil profile were plotted on x-axis as shown in Figure 4.1 for 15 and 30 cm depth of soil. The developed curves were found similar in trend of the standard one but varied with soil depth because of different soil moisture tension observed at different depths due to change in soil properties like bulk density, soil texture and soil structure. The coefficient of determination (R^2) was found to be 0.957 and 0.961 for 0-15 cm and 15-30 cm depth respectively showing accurate and better correlation between the actual and developed sensor predicted moisture content. Coarse soils have many large pores that release water molecules at lower matric potentials all at once. From these curves, it is possible to determine the volumetric water content for any of these soils at matric potentials of interest.

5.2 Development of tensiometer device for automation in greenhouse irrigation scheduling

The experiment was conducted to design and develop tensiometer automation device for greenhouse irrigation scheduling with the help of piezo-resistive based soil moisture sensor. This work was done to overcome the limitations of tensiometer (cavitation, mechanical failure, organic growth problems etc.) and also some modifications were made in tensiometer for using it in automation irrigation system. Therefore development of piezo-resistive based soil moisture sensor was done without vacuum gauge to reduce the cost and subsequently it was used in automation irrigation system. It was done by using local material *viz*, Piezo-resistive sensor, acrylic pipe, ceramic cup, and rubber cork. The working principle of piezo-resistive based soil moisture sensor is based on the soil matric potential using soil moisture characteristic curve developed for different soil depth. Efforts were made in this direction using tensiometer to sense the vacuum created in the tensiometer due to soil matric potential and was measured through the piezo-resistive sensor. After development of piezo-resistive based soil moisture sensor, it was integrated with microcontroller for development of automatic irrigation system for precision irrigation scheduling.

The developed piezo-resistive based soil moisture sensor for irrigation scheduling was done using low cost, indigenously available material including electronic components. The developed automatic tensiometer device can be used by farmer and grower for efficient irrigation scheduling.

5.2 Performance evaluation of piezo-resistive based soil moisture sensor

The experiment was laid out in two sub plots with drip irrigation system under greenhouse Chrysanthemum and Tomato crop. Piezo-resistive based soil moisture sensor was installed in each subplot at 15 and 30 cm depth for automatic irrigation scheduling. The Piezo-resistive based soil moisture sensor was developed in such a way that the piezo-resistive sensor was installed at the top of conventional tensiometer which measures the vacuum pressure created by soil metric potential of the soil. The

Piezo-resistive based soil moisture sensor was connected with a microcontroller for activation or deactivation of irrigation pump exactly at the pre-set value of moisture content during the field test to facilitate automatic irrigation scheduling. The vacuum pressure measured by the piezo-resistive based soil moisture sensor was measured and calibrated with the gravimetric method and also compared with the conventional tensiometer observation.

Hence, it represent the variability of each sensor when correlated with gravimetric methods. The reading of matric potential obtained from the tensiometer and piezo-resistive based soil moisture sensor were converted to volumetric water content using soil moisture characteristic curve of different soil profile layers to compare with the gravimetric method.

The figures 4.2 to 4.9 depicts the graphical representation of volumetric soil moisture content measured by standard gravimetric method and calculated volumetric moisture content by Piezo resistive based soil moisture sensor and tensiometers. The coefficient of determination was calculated to infer the significance and to find the similarity between the methods. The coefficient of determination (R^2) was found to be 0.83 and 0.82 between volumetric soil moisture content calculated by piezo-resistive based soil moisture sensor (based on its voltage readings) and soil moisture content measured by the gravimetric method in Chrysanthemum at 15 cm and 30 cm depths, respectively, while, for Tomato the coefficient of determination at 15 and 30 cm depth were 0.84 and 0.82, respectively for same methods.

The coefficient of Determination (R^2) between volumetric soil moisture content calculated by tensiometer readings and volumetric soil moisture content measured by standard gravimetric method for chrysanthemum at 15 and 30 cm depth were found to be 0.72 and 0.71, respectively, while for Tomato the coefficient of determination at 15 and 30 cm depth were 0.71 and 0.71, respectively for moisture content measured by tensiometers and standard gravimetric method. Simil

ar findings were found reported by Leib *et al.* (2003)

The voltage readings measured by the piezo resistive sensor were noted down on daily basis, and with respect to which volumetric soil moisture content was calculated. The volumetric soil moisture content between different methods was correlated and conclusions were drawn. Table 4.1 and 4.2 reveal the voltage readings recorded by the piezo resistive sensor in both the crops *viz.* Chrysanthemum and Tomato at 15 and 30 cm depth. The voltage readings were in inverse relation with the soil moisture status i.e higher the voltage reading, lower was the soil moisture content. The results obtained by the experiment were in accordance with the results obtained by Thalhemer, 2013.

5.3 Statistical Analyses

5.3.1. Statistical analysis of Tensiometer and developed tensiometer at different soil depth in Chrysanthemum and Tomato crop

Tensiometer and piezo-resistive based soil moisture sensor were evaluated in Chrysanthemum and Tomato crop at 15 and 30 cm depth. Several statistical parameters such as mean deviation, standard deviation, Relative root mean square error (RRMSE), Coefficient of determination (R^2) were used to assess the degree of coincidence and association between the tensiometer and piezo-resistive based soil moisture sensor. The degree of coincidence indicates how well piezo resistive based soil moisture sensor measurement matched the actual soil moisture content measured by Gravimetric method. The RRMSE of soil moisture content for tensiometer and piezo-resistive based soil moisture sensor varied from 9.47 to 19.38 and 7.44 to 18.28, respectively. The lower the RRMSE values and higher the R^2 values may indicate acceptable sensor performance. R^2 of moisture content varied from 0.71 to 0.72 and 0.82 to 0.84 for tensiometer and piezo resistive based soil moisture sensor respectively. The correlation coefficient of piezo-resistive based soil moisture sensor was better and higher than tensiometer. It because of better estimation of soil moisture by piezo-resistive based soil moisture sensor. In piezo-resistive soil moisture sensor pressure is directly converted to voltage leading to minimum mechanical losses as compared to tensiometer. From the Table 4.1, it can be concluded that piezo resistive based soil moisture sensor performed superior and better as compared to tensiometer at 15 and 30 cm depth for both the greenhouse crops.

5.3 Paired t-test data of different piezo-resistive based soil moisture sensors in chrysanthemum and tomato crop

Paired t-test was performed to check the statistical significance between piezo-resistive based soil moisture sensor and tensiometer. If calculated p-value is less than 0.05 then the treatments are significant at 5% level. The null hypothesis for tensiometer and Piezo-resistive based soil moisture sensor means were rejected since, p-values were less than 0.05. From the table 4.4 it was concluded that at 15 and 30 cm depth in both chrysanthemum and tomato crop, there was significant difference between observations of tensiometer and developed piezo resistive based soil moisture sensor. Both the methods were significant at 5% level. Similar results were also found and reported by Kumar (2016) for tensiometer based automatic irrigation system.

***Chapter*-6**

SUMMARY AND CONCLUSION

Irrigation water use, in irrigation water management, represents a considerable opportunity for agriculture water savings. Automation of irrigation based on soil moisture sensor system has the potential to provide maximum water use efficiency by maintaining soil moisture at optimum levels (Mohammad *et al.,* 2011). Sensor based automated irrigation system has many applications in natural resource management, crop yield forecasting, watershed management etc. The focus of this research was development and testing of Piezo resistive based soil moisture sensor for greenhouse irrigation scheduling automation in Chrysanthemum and Tomato crops.

The present research entitled "Tensiometer Automation Device for Greenhouse Irrigation Scheduling" was carried out in Rabi season of 2017-18 at Green-house, located in Center for Protected Cultivation Technology, Indian Agricultural Research Institute, New Delhi. The main objective of the Study was to design, develop and evaluate the performance of Piezo resistive based soil moisture sensor in green house irrigation scheduling under Chrysanthemum and Tomato crops. The experimental soil was found as sandy loamy soil. An experimental area of 300 m^2 was selected to grow tomato and chrysanthemum crops irrigated by drip irrigation system. The area was divided in to two plots of size 10 × 15 m (150 m^2) each. Each plot was irrigated with 9 drip lines having 16 mm in diameter, distances between drip lines was 300 mm with emitter discharge of 2 lph.

Tensiometer and piezo resistive based soil moisture sensor were used in this study to measure soil matric potential. To evaluate the performance of sensors, both developed piezo resistive based soil moisture sensors and tensiometers were installed at 15 cm and 30 cm depth, respectively. The sensor readings and corresponding soil samples were taken on daily basis to measure the volumetric soil moisture content. The volumetric soil moisture content was measured by referring standard gravimetric method. The volumetric soil moisture content were calculated from the corresponding voltage readings recorded by the piezo resistive based soil moisture sensor and tensiometer using Soil characteristic curve and compared with soil moisture content obtained by gravimetric method.

The automated irrigation system refers to the operation of the system with minimum manual intervention beside the surveillance. The developed piezo resistive based soil moisture sensor played a major role in irrigation scheduling automation. It was developed with the low cost and locally available electronic components. A piezo-resistive pressure sensor consisted of several thin wafers of silicon embedded between protective surfaces. The surface was usually connected to a Wheatstone bridge, a device for detecting small differences in resistance. It works on the principle of piezo resistive effect. The limitations of the conventional tensiometer like cavitation, high cost, manual handling, use in automation irrigation scheduling etc. were addressed successfully by piezo resistive based soil moisture sensor. Paired t-test was performed to check the statistical significance between piezo-resistive based soil moisture sensor and tensiometer. The results showed that the piezo resistive based soil moisture sensor measured soil moisture tension efficiently than the normal tensiometer for both greenhouse Chrysanthemum and Tomato crops.

Based on the study conducted, following conclusions were drawn:

1. An indigenous piezo-resistive based soil moisture sensor was designed and assembled with the total developed sensor cost of Rs. 15,625 (Fifteen thousand six hundred twenty five only) for use in automation of greenhouse irrigation scheduling.
2. Soil moisture characteristic curves were developed for greenhouse sandy loam soil for 15 and 30 cm depth. The developed regression equation and coefficient of determination for 15cm and 30 cm depth are $y = 34563x^{-3.505}$ ($R^2 = 0.957$) and $y = 50095x^{-3.598}$ ($R^2 = 0.961$) respectively.
3. The regression equation and coefficient of determination for volumetric soil moisture content between standard gravimetric method and tensiometer for greenhouse chrysanthemum at 15 and 30 cm depth are $y = 0.378x + 6.802$ ($R^2 = 0.72$) and $y = 0.520x + 5.165$ ($R^2 = 0.71$) respectively.
4. The regression equation and coefficient of determination for volumetric soil moisture content between standard gravimetric method and tensiometer for greenhouse tomato at 15 and 30 cm depth are $y = 0.5353x + 5.1538$ ($R^2 = 0.71$) and $y = 0.4692x + 5.8768$ ($R^2 = 0.71$) respectively.
5. The regression equation and coefficient of determination for volumetric soil moisture content between standard gravimetric method and piezo-resistive

based soil moisture sensor for greenhouse chrysanthemum at 15 and 30 cm depth are y = 0.504x + 5.852 (R^2 = 0.83) and y = 0.4651x + 6.1028 (R^2 = 0.82) respectively.

6. The regression equation and coefficient of determination for volumetric soil moisture content between standard gravimetric method and piezo-resistive based soil moisture sensor for greenhouse tomato at 15 and 30 cm depth are y = 0.4977x + 5.5788 (R^2 = 0.84) and y = 0.531x + 5.333 (R^2 = 0.82) respectively.
7. The voltage reading and its corresponding soil moisture content recorded by developed Piezo-resistive sensor in greenhouse Chrysanthemum crop varied inversely from (126.5-163.71 mV)/ (11.63-10.62%) and (165.3-207.6 mV)/ (11.27-10.38%) for 15 and 30 cm depth respectively for the 10 continuous recorded period during vegetative stage.
8. The voltage reading and its corresponding soil moisture content recorded by developed Piezo-resistive sensor in greenhouse tomato crop varied inversely from (177.9-232.9 mV)/ (10.99-10.05%) and (153.6-220.59 mV)/ (11.89-10.20%) for 15 and 30 cm depth respectively for the 10 continuous recorded period during fruiting stage.
9. Paired t-test at 5% significance level showed significant difference between Piezo-resistive based Soil moisture sensor and tensiometer at 15 and 30 cm depth in both chrysanthemum and tomato crop.

Tensiometer Automation Device for Greenhouse Irrigation Scheduling

ABSTRACT

The rapid increase of human population is putting an incredible strain on our environment. Water demand already exceeds supply in many parts of the world and more areas are expected to experience this imbalance in near future. Agriculture is by far the largest consumer of the Earth's available freshwater. Due to shrinking fresh water resources, micro irrigation plays an important role in sustainable use of water in agriculture. Automation of irrigation further helps in conserving the water by timely even distribution of water and thus prevents wastage of water. Hence, the present research entitled "Tensiometer Automation Device for Greenhouse irrigation Scheduling" was carried out in Rabi season of 2017-18 at farm Green-house, Centre for protected cultivation technology, Indian Agricultural Research Institute, New Delhi. The main objective of the Study was to design, develop and evaluate the performance of Piezo resistive based soil moisture sensor in green house irrigation scheduling under Chrysanthemum and Tomato crops. The experimental soil was found as sandy loamy soil. An experimental area of 300 m^2 was selected to grow tomato and chrysanthemum crops irrigated by drip irrigation system. The area was divided in to two plots of size 10 × 15 m (150 m^2) each. The piezo-resistive based soil moisture sensor was designed and was incorporated in automation of greenhouse irrigation scheduling. To evaluate the performance of sensors, both developed piezo resistive based soil moisture sensors and tensiometers were installed at 15 cm and 30 cm depth. The sensor readings and corresponding soil samples were taken on daily basis to measure the volumetric soil moisture content. The volumetric soil moisture content were calculated from the corresponding voltage readings recorded by the piezo resistive based soil moisture sensor and tensiometer using Soil characteristic curve and then they were compared with soil moisture content obtained by gravimetric method. The results revealed that the coefficient of determination (R^2) was found to be 0.83 and 0.82 between volumetric soil moisture content calculated by piezo-resistive based soil moisture sensor (based on its voltage readings) and soil moisture content measured by the gravimetric method in Chrysanthemum at 15 cm and 30 cm depths, respectively, while, for Tomato it was 0.84 and 0.82, respectively for same methods. The coefficient of Determination (R^2) between volumetric soil moisture content measured by tensiometer and volumetric soil

moisture content measured by standard gravimetric method for chrysanthemum at 15 and 30 cm depth were found to be 0.72 and 0.71, respectively, while for Tomato it was recoded as 0.71 and 0.71. The results also revealed that the voltage readings were in inverse relation with the soil moisture status. The RRMSE of soil moisture content for tensiometer and piezo resistive based soil moisture sensor varied from 9.47 to 19.38 and 7.44 to 18.28, respectively. Lower RRMSE values and higher coefficient of determination (R^2) were recorded by the piezo resistive based soil moisture sensor as compared to tensiometer indicating higher degree of accuracy. The paired t-test indicated that both piezo resistive based soil moisture sensor and tensiometer were significantly different at 5% significance level. The results showed that piezo resistive based soil moisture sensor measured soil moisture tension efficiently than the normal tensiometer for both greenhouse Chrysanthemum and Tomato crops.

"ग्रीनहाउस सिंचाई सूचीकरण के लिए स्वचालित टेंसियोमीटर प्रणाली"

सार

मानव आबादी की तीव्र वृद्धि हमारे पर्यावरण पर अविश्वसनीय तनाव डाल रही है। पानी की मांग पहले से ही दुनिया के कई हिस्सों में आपूर्ति से अधिक है और अधिक क्षेत्रों में निकट भविष्य में इस असंतुलन का अनुभव होने की उम्मीद है। कृषि पृथ्वी के उपलब्ध ताजे पानी का सबसे बड़ा उपभोक्ता है। ताजा जल संसाधनों को कम करने के कारण, कृषि में पानी के सतत उपयोग में सूक्ष्म सिंचाई एक महत्वपूर्ण भूमिका निभाती है। सिंचाई का स्वचालन पानी के समय पर वितरण के समय पानी को बचाने में मदद करता है और इस प्रकार पानी की बर्बादी को रोकता है। इसलिए, वर्तमान शोध "ग्रीनहाउस सिंचाई सूचीकरण के लिए स्वचालित टेंसिओमेटेर प्रणाली" 2017-18 के रबी सीजन में ग्रीन हाउस, में संरक्षित खेती प्रौद्योगिकी केंद्र, भारतीय कृषि अनुसंधान संस्थान, नई दिल्ली में किया गया था। अध्ययन का मुख्य उद्देश्य गुलदावदी और टमाटर फसलों के तहत ग्रीन हाउस सिंचाई शेड्यूलिंग में पिइज़ो प्रतिरोधी आधारित मिट्टी नमी सेंसर के प्रदर्शन को डिजाइन, विकसित और मूल्यांकन करना था। प्रयोगात्मक मिट्टी रेतीले लोमी मिट्टी के रूप में पाया गया था। ड्रिप सिंचाई प्रणाली द्वारा सिंचाई की गई टमाटर और गुलदावदी फसलों को विकसित करने के लिए 300 वर्ग मीटर 2 का एक प्रयोगात्मक क्षेत्र चुना गया था। क्षेत्र को 10 × 15 मीटर (150 वर्ग मीटर) आकार के दो भूखंडों में विभाजित किया गया था। पीजो-प्रतिरोधी आधारित मिट्टी नमी सेंसर डिजाइन किया गया था और ग्रीनहाउस सिंचाई शेड्यूलिंग के स्वचालन में शामिल किया गया था। सेंसर के प्रदर्शन का मूल्यांकन करने के लिए, दोनों विकसित पीजो -प्रतिरोधी आधारित मिट्टी नमी सेंसर और टेंसियोमीटर 15 सेंटीमीटर और 30 सेंटीमीटर गहराई में स्थापित किए गए थे। वॉल्यूमेट्रिक मिट्टी नमी सामग्री को मापने के लिए सेंसर रीडिंग और संबंधित मिट्टी के नमूने दैनिक आधार पर लिया गया था। वॉल्यूमेट्रिक मिट्टी नमी सामग्री की गणना पीजो-प्रतिरोधी आधारित मिट्टी नमी सेंसर और टेंसिओमीटर द्वारा मृदा विशेषता वक्र का उपयोग करके दर्ज किए गए इसी वोल्टेज रीडिंग से की जाती है और फिर उन्हें ग्रेविमेट्रिक विधि द्वारा प्राप्त मिट्टी नमी सामग्री से तुलना की जाती है। नतीजे बताते हैं कि दृढ़ संकल्प (आर 2) गुणांक (आर 2) 0.83 और 0.81 पाया गया था जो पीजो-प्रतिरोधी आधारित मिट्टी नमी सेंसर (इसकी वोल्टेज रीडिंग के आधार पर) द्वारा गणना की गई वॉल्यूमेट्रिक मिट्टी नमी सामग्री और गुलदावदी में गुरुत्वाकर्षण विधि द्वारा मापा गया मिट्टी नमी सामग्री के बीच पाया गया था। क्रमशः 15 सेमी और 30 सेंटीमीटर गहराई पर, जबकि टमाटर के लिए क्रमशः 0.84 और 0.82 था, क्रमशः उसी विधि के लिए। 15 और 30 सेंटीमीटर गहराई पर गुलदावदी के लिए मानक ग्रेविमेट्रिक विधि द्वारा मापा गया मात्रात्मक मिट्टी नमी सामग्री के बीच मात्रात्मक मिट्टी की नमी सामग्री के बीच निर्धारण (आर 2) क्रमशः 0.72 और 0.71 पाया गया था, जबकि टमाटर के लिए इसे रिकोड किया गया था 0.71 और 0.71। नतीजे यह भी पता चला कि वोल्टेज रीडिंग मिट्टी की नमी की स्थिति के साथ विपरीत संबंध में थे। टेंसिओमीटर और

पीजो-प्रतिरोधी आधारित मिट्टी नमी सेंसर के लिए मिट्टी नमी सामग्री का आरआरएमएसई क्रमश: 9.47 से 19.38 और 7.44 से 18.28 तक भिन्न है। निचले आरआरएमएसई मूल्य और दृढ़ संकल्प के उच्च गुणांक (आर 2) को पायजो प्रतिरोधी आधारित मिट्टी नमी सेंसर द्वारा दर्ज किया गया था, जो टेन्सीमीटर की तुलना में सटीकता की उच्च डिग्री दर्शाता है। जोड़ा गया टी-टेस्ट इंगित करता है कि दोनों पायजो प्रतिरोधी आधारित मिट्टी नमी सेंसर और टेन्सीमीटर 5% महत्व स्तर पर काफी अलग थे। इस प्रकार यह अनुमान लगाया जा सकता है कि पेजो प्रतिरोधी आधारित मिट्टी नमी सेंसर की परिशुद्धता दोनों गहराई और दोनों फसलों के नीचे टेंसिओमीटर की तुलना में अधिक थी।

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Appendix-I

Relationship between Matric Potential versus Volumetric Water Content (%)

Soil Water Potential (kPa)	Soil Water Content cm^3/cm^3 at different depths (cm)	
	0-15	**15-30**
0.1	31.08	32.8
0.2	30.8	30.9
0.3	30.5	30.1
1	25.1	24.3
1.5	18.2	16.6
2	16.66	14.6
3	14	13.4
5	13.3	12.0
8	11.2	11.5
10	10.5	10.8
12	9.94	9.8
15	9.8	9.3

Appendix-II

The detailed specifications of the XBee module

Specification	XBee S2C
Supply voltage	2.1 - 3.6 V for programmable version
Operating current	45 mA
Dimensions	surface-mount: 2.199 x 3.4 x 0.305 cm (0.866 x 1.33 x 0.120 in)
Operating temperature	-40 to 85 °C (industrial
Data rate	RF 250 Kbps, Serial up to 1 Mbps
Data transferable range	30-100 meter

Appendix-III

The detailed specification of Piezo-resistive sensor

Characteristics	Measurement
Pressure Range	0 – 250 kPa
Supply Voltage	4.85 - 5.35 V
Supply Current	10 mA
Full Scale Output	4.844 - 4.974 V
Accuracy	±1.4 of % full scale voltage supply
Sensitivity	18.8 mV/kPa
Response Time	1.0 ms
Operating Temperature	-40 to 85 ºC
Max error	±3.45 kPa

Appendices-IV

Tensiometer installation procedure and its maintenance

Before installation:-

- Fill the tensiometer with clean, fresh water. Water that has been boiled (to remove air) and allowed to cool is best. Fill the tensiometer slowly to avoid adding air to the tube.
- Remove the reservoir cap and leave the tensiometer to soak overnight in a bucket of clean water, stand the tensiometers up in the bucket.
- Remove air from the gauge and tube using a vacuum pump or by pumping the reservoir of the 'jet fill' types.
- Refill the reservoir with clean water, add a few drops of chlorine to inhibit algal growth and replace the cap.
- Wrap the tip in a wet towel to prevent it drying out during transport

Tensiometer installation procedure:-

- Ensure there are no air leaks. The gauge and ceramic tip should be screwed on firmly but not over tight
- Check the ceramic tip is not blocked. Water should be able to move freely through the tip.
- Position the tensiometer correctly. The ceramic tip should be within the active root zone of the plant.
- Auger or drive a hole into moist soil within the drill with a piece of 13 mm pipe. This will ensure good contact with the soil and minimal root disturbance.
- If the soil is dry, prepare a slurry of soil and water and pour it down the hole. Insert the tensiometer, pushing on the reservoir, not the gauge making sure it reaches the bottom of the hole.
- Leave at least 50 mm between the bottom of the gauge and the soil.
- Hill up the soil around the tube and pack it firmly to ensure good soil contact and allow surface water to drain.
- Service tensiometer 2-3 times in the first week after installation and then every time a reading is taken.
- Fill the reservoir as required and ensure that the fluid level after an irrigation is no more than 2-3 cm below the gauge