Pak. J. Agri. Sci., Vol. 59(1), 105-116; 2022
ISSN (Print) 0552-9034, ISSN (Online) 2076-0906
DOI: 10.21162/PAKJAS/22.502
http://www.pakjas.com.pk

Application of indigenized soil moisture sensors for precise irrigation of wheat crop under various irrigation methods

Usman Iqbal[1,*], Allah Bakhsh[1], Muhammad Adnan Shahid[1,2], Syed Hamid Hussain Shah[1] and Shoukat Ali[3]

[1]Department of Irrigation and Drainage, Faculty of Agricultural Engineering and Technology, University of Agriculture, Faisalabad, Pakistan; [2]National Center of GIS and Space Applications – Agricultural Remote Sensing Lab (NCGSA – ARSL), University of Agriculture, Faisalabad, Pakistan; [3]Institute of Agricultural Extension, Education and Rural Development, Faculty of Social Sciences, University of Agriculture, Faisalabad, Pakistan.
[*]Corresponding author's e-mail: usmaniqbaluaf@yahoo.com

Real time soil moisture monitoring using sensors has potential to save irrigation water and improve water productivity. Field experiments were carried out for two successive years (2016-17 and 2017-18) to produce wheat crop at the Water Management Research Center, Postgraduate Agricultural Research Station, University of Agriculture, Faisalabad. Field irrigation methods included flood irrigation (canvas pipe), perforated pipe irrigation, and drip irrigation under different planting geometries and irrigation designs. The sensor-based irrigation systems were developed using locally available material to minimize the cost of equipment development and energy consumption for crop irrigation. Seven wheat crop treatments used in this experiment were T_1-flood irrigation flat sowing by rabi-drill, T_2-flood irrigation bed furrow planting with 0.254 m furrow, T_3-perforated pipe irrigation bed furrow planting with 0.254 m furrow, T_4-perforated pipe irrigation bed furrow planting with 0.203 m furrow, T_5-perforated pipe irrigation bed furrow planting with 0.152 m furrow, T_6-drip irrigation flat with 0.914 m lateral spacing and T_7-drip irrigation on beds with 0.914 m lateral spacing. An IT-based web server was developed for monitoring soil moisture status to serve as decision support system for applying irrigation to the crops. The developed sensors sent soil moisture signals on cloud for data storage, reuse and sharing purpose using coding. The irrigation was applied based on soil moisture status. The system based on micro-controller was tested for irrigating wheat crop. Raspberry Pi-3 (Model B) controlled hardware in distribution box (DB) made excellent use of indigenized soil moisture sensors for calibration and irrigation water management. Type-I (Single probe) and Type-II (Double probe) steel sensors performed best due to high R^2 values of about 0.99 and RMSE in the range of 3.30% - 3.50% during calibration. The calibration further improved the accuracy of both steel and copper sensors. Since the sensors were designed, developed, and calibrated during the 1st year (2016-17) and properly installed in 2nd year (2017-18), therefore, have affected crop and soil parameters positively. Drip irrigation treatments (T_6 = 359.56 mm and T_7 = 358.65 mm) required significantly lowest mean amount of water than those by all the other treatments and the flood irrigation treatments (T_1 = 431.55 mm and T_2 = 424.95 mm) required significantly greatest ($\alpha = 0.05$) amount of mean irrigation depth. Drip irrigation treatments (T_6 and T_7) produced high mean water productivity values (14.30 and 14.20) than those under flood irrigation treatments (T_1 = 9.6 and T_2 = 10.30) and perforated pipe irrigation treatments (T_3 = 12.66, T_4 = 12.43 and T_5 = 12.30). The mean yield of wheat grain over two years was greater under drip irrigation treatments (T_6 = 5145.1 kg/ha and T_7 = 5091 kg/ha) than those under flood (T_1 = 4139 kg/ha, T_2 = 4371 kg/ha) and perforated pipe irrigation treatments (T_3 = 4969 kg/ha, T_4 = 4872 kg/ha, T_5 = 4775.7 kg/ha). Perforated pipe irrigation treatments had significantly greater ($\alpha = 0.5$) wheat grain yield than those under flood irrigation treatments.

Keywords: Wheat, irrigation methods, soil moisture sensors, precision irrigation.

INTRODUCTION

Agriculture being the largest sector of Pakistan's economy, contributes about 20.9% of GDP. The agricultural production in Pakistan depends on adequate availability of irrigation water supplies because majority of its production land lies in the arid to semi-arid region (GOP, 2014-15). Water shortage, witnessed over the last several decades, has crippled agricultural productivity and compelled the scientists to redirect their research efforts towards an efficient use of

Usman Iqbal, Allah Bakhsh, Muhammad Adnan Shahid, Syed Hamid Hussain Shah and Shoukat Ali. 2022.Application of indigenized soil moisture sensors for precise irrigation of wheat crop under various irrigation methods. Pakistan Journal of Agricultural Sciences. 59:105-116.
[Received 14 Apr 2021; Accepted 7 Feb 2022; Published 18 Mar 2022]

available water supplies. Falkenmark *et al.* (1989) wrote that a country having per capita water resources less than 1700 m^3 would be a water-stressed country (Falkenmark Indicator). As water availability per capita basis falls below 1000 m^3, the country becomes water scarce, and falling below 500 m^3 per capita, the country experiences an absolute-water scarcity. Ashraf (2016) wrote that according to Falkenmark Indicator, Pakistan already crossed the water scarcity line during 2005 and, with the continued situation; the country might touch the absolute water scarcity line by 2025. Improvements in agricultural irrigation efficiencies are available through a variety of existing solutions. Christian-Smith *et al.* (2012) performed an inventory of presently available options for ‘‘enhancing the efficiency of water use in California agriculture’’, and pointed out that all solutions fall under one of three categories: efficient irrigation technologies, modified irrigation scheduling, and / or deficit irrigation. Osman (2000) reported that perforated pipe irrigation method with precision land leveling improved water distribution uniformity resulting in water saving of 29.24% and 12% for wheat and cotton respectively. Drip irrigation is a highly efficient irrigation method providing about 90-95% irrigation efficiency. However, the main constraint in its adoption is high initial cost as well as the energy requirements to operate it. Nevertheless, the benefits of this method in terms of water savings and yield increase due to on spot irrigation and thus improving overall water use efficiency cannot be overlooked. Burt and Styles (2007) reported that drip irrigation allows increasing water use efficiencies by providing precise amounts of water directly to root zone of individual plants. The WSN, a network of small sensing devices, has a potential for representing inherent variability of soil profile present at the experimental site. Akyildiz *et al.* (2002) found that WSN over wired system is a significant cost reduction and simple in wiring. The wired networks are very stable and reliable systems for control and communication because they provide smooth communication as compared to wireless system. Farmer’s organizations and planners are more conscious about water utilization efficiency as the water resources are getting scarcer.

The localized irrigation substantially reduces deep percolation and runoff losses, thus attaining higher irrigation efficiency is considered as a water-saving technology. There is a reduction in operating and labor costs, as human intervention is reduced to the periodic inspection of equipment and proper operation of drippers. Hartz (1999) reported many factors that affect proper drip irrigation management viz; system design, soil characteristics, crop and its growth stage, environmental conditions, etc. The effects of these factors can be integrated into a practical efficient scheduling system to determine quantity and timing of drip irrigation. Nahla and Hemdan (2003) and Gameh *et al.* (2004) reported that the drip irrigation management maximized the production of some crops (sorghum, sunflower, faba bean, pea, cowpea and squash) under the Western Desert conditions in Egypt. Mateos *et al.* (1991) reported that drip irrigation improved soil water regimes and water application efficiency by 30% resulting in increased crop yields. Based on literature cited, this study was designed to fulfill the following objectives for wheat production during two successive wheat crop seasons.

1. To evaluate indigenized sensor-based soil moisture monitoring setup for achieving precision irrigation.
2. To evaluate irrigation techniques under flood, perforated, and drip irrigation for improving water productivity, water use efficiency, and crop productivity.

A poor management of irrigation methods in the past typically results in lower water use efficiency and increased cost of crop production. The REAL TIME management of resources like water, energy, and data to meet the task of high crop yields at par with those obtained by the developed countries like USA, France, Germany, Japan etc. has been the need of the time in Pakistan. Field experiments were designed and experiments performed for two successive years (2016-17 and 2017-18) to produce wheat at the Water Management Research Center (WMRC), Postgraduate Agricultural Research Station (PARS), University of Agriculture, Faisalabad (UAF). The field irrigation methods included flood irrigation, perforated pipe irrigation, and drip irrigation.

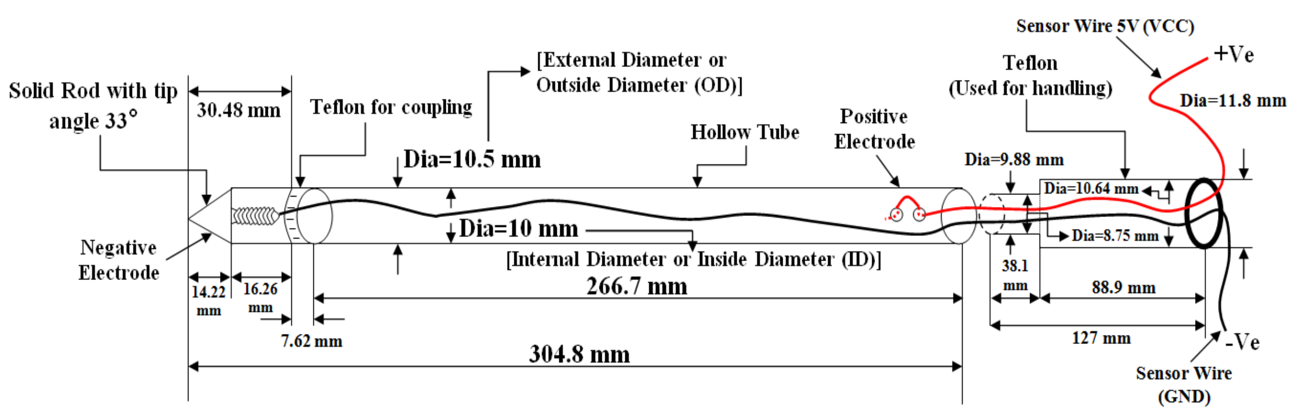

Figure 1. Type-I single probe indigenized soil moisture sensor (Iqbal *et al.*, 2020)

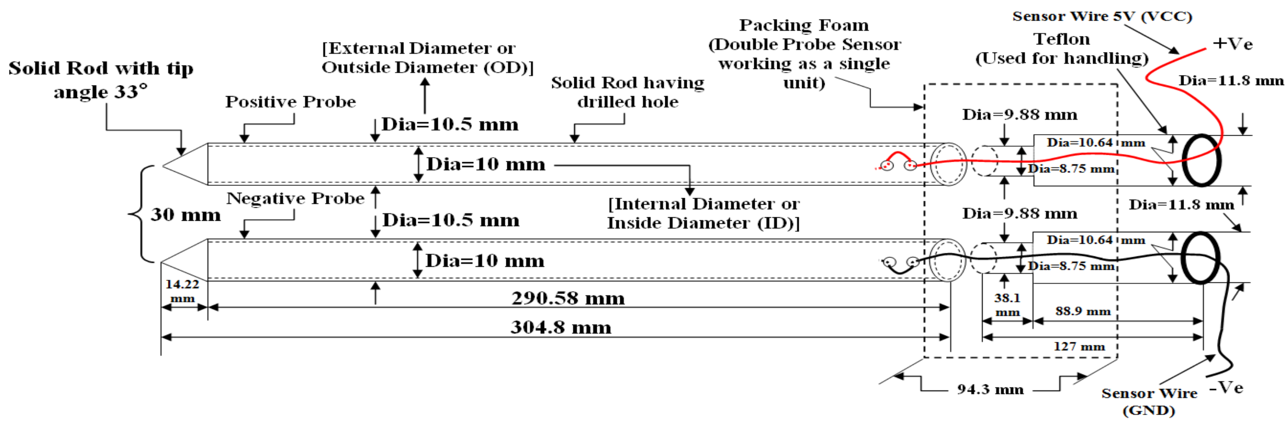

Figure 2. Type-II double probe indigenized soil moisture sensor (Iqbal *et al.*, 2020)

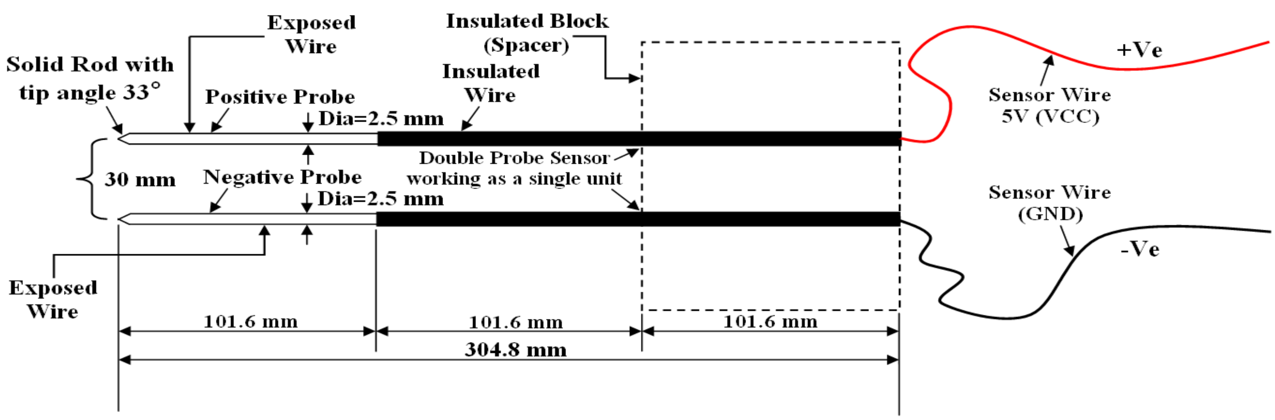

Figure 3. Type-III double probe indigenized galvanized steel wired soil moisture sensor (Iqbal *et al.*, 2020)

MATERIALS AND METHODS

Iqbal *et al.* (2020) procured low cost locally available material for developing and fabricating sensors viz; Type-I single probe indigenized soil moisture sensors of Copper, Brass and Steel (15.24 cm and 30.48 cm lengths) (Fig. 1); Type-II double probe indigenized soil moisture sensors of Copper, Brass, Steel (15.24 cm and 30.48 cm lengths) (Fig. 2) and Type-III double probe indigenized galvanized steel soil moisture sensors (15.24 cm and 30.48 cm lengths) (Fig. 3). The indigenized sensor development and fabrication work was performed at the Water Management Research Center, Postgraduate Agricultural Research Station, University of Agriculture, Faisalabad (WMRC-PARS, UAF). These sensors were calibrated, validated with gravimetric method for online soil moisture data and evaluated for their performance in the 2nd year of crop production.

The steel is fully resistant but copper and brass dissolve with the passage of time inside the soil. The properties of sensor fabrication materials have been presented in Table 1.

The experimental fields for growing wheat crop and installing required indigenized sensors were selected as shown in Figure 4 & 5. The field experimental areas had medium to moderately coarse soils. These soils were permeable and low in organic matter (7.0 - 7.9 pH). The soil areal topography was flat and adopted for different crops (Ahmad, 2002).

Prior to tillage operations, a Laser Land Leveler (LLL) was used to precisely level the field. Disc plough was used for primary tillage operations. Secondary tillage operations were performed employing rotavator, cultivator, and planker. After

Table 1. Properties of sensor fabrication materials.

Materials	Electrical conductivity (10.E6 Siemens/m)	Electrical resistivity (10.E-8 Ohm.m)	Thermal Conductivity (W/m.k)	Thermal expansion coef.10E-6(k-1) from 0 to 100°C	Density (g/cm³)	Melting point or degradation (°C)
Copper	58.50	1.7	401.0	17.0	8.9	1083
Brass	15.90	6.3	150.0	20.0	8.5	900
Steel	1.37	73.0	16.3	16.5	7.9	1450

land preparation, a recommended quantity of "Millat" wheat variety was sown in two successive growing seasons on December 31, 2016 and on December 31, 2017 by Rabi drill for treatments "T_1" and "T_6", Bed planter for treatments "T_2-T_5" and "T_7". The plots were randomly distributed in the experimental field under the Completely Randomized Design (CRD). Statistical package SAS was employed for ANOVA to determine the effects of treatments on crop and soil parameters (SAS, 2009). The quantity of water for each application of irrigation applied to all experimental fields of seven treatments was recorded. Wheat crop treatments and specifications have been presented in Figure 4 and Figure 5. Basel dose of Di-Ammonium Phosphate (DAP) and SOP fertilizer at the rate of 50 kg/ac was applied at the time of sowing uniformly on all experimental area.

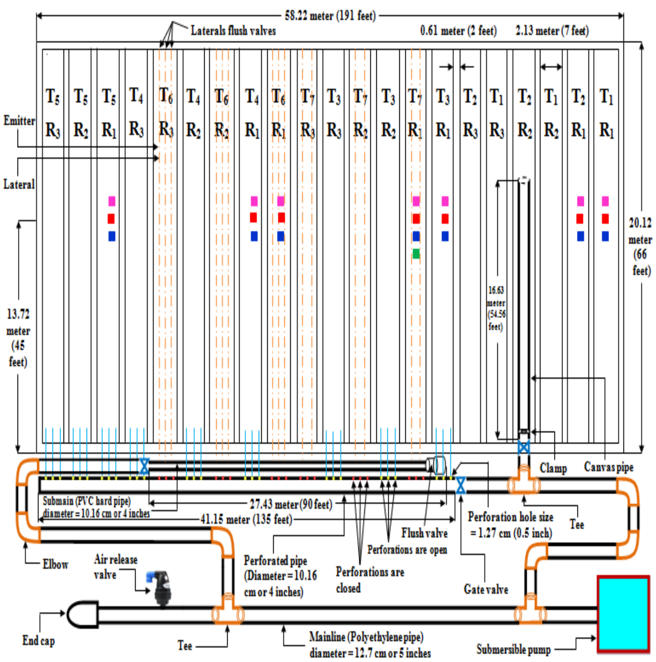

Figure 4a: Wheat 2016-17 treatments and replications

5.08 cm (2 inches) probe length installed seven (7) soil moisture sensors at 30.48 cm (1 foot) soil depth for irrigation scheduling.

5.08 cm (2 inches) probe length installed seven (7) soil moisture sensors at 45.72 cm (1.5 feet) soil depth for irrigation scheduling.

5.08 cm (2 inches) probe length installed seven (7) soil moisture sensors at 60.96 cm (2 feet) soil depth for irrigation scheduling.

[5.08 cm (2 inches) probe length installed twenty one (21) soil moisture sensors at 30.48 cm (1 foot), 45.72 cm (1.5 feet) and at 60.96 cm (2 feet) soil depths for irrigation scheduling].

30.48 cm (1 foot or 12 inches) probe length installed indigenized copper soil moisture sensor in T_7R_1 for testing and irrigation scheduling using laptop installed Arduino 1.8.5 sketch.

Wheat Crop Treatments and Specifications:

T_1 = Flat Sowing By Rabi Drill;
T_2 = Bed Furrow Planting (10" Furrow);
T_3 = Bed Furrow Planting with Perforated Pipe Irrigation (10" Furrow);
T_4 = Bed Furrow Planting with Perforated Pipe Irrigation (8" Furrow);
T_5 = Bed Furrow Planting with Perforated Pipe Irrigation (6" Furrow);
T_6 = Drip Irrigation Flat (Lateral Spacing = 3');
T_7 = Drip Irrigation on Beds (Lateral Spacing = 3').

Wheat Crop: (Sowing: 31-12-2016, **Harvesting:** 7-05-2017)

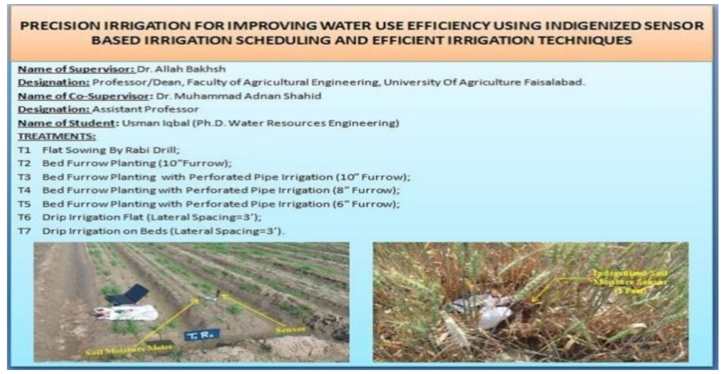

Figure 4b.Wheat 2016-17 experimental field treatments

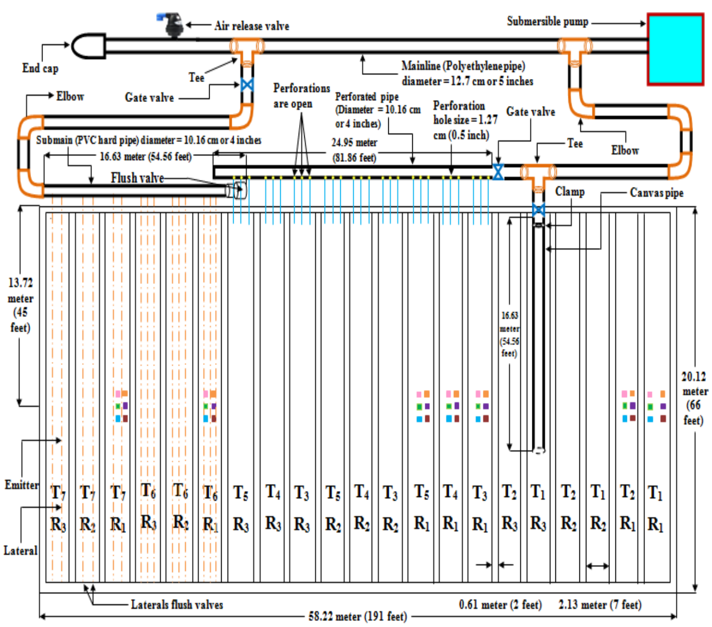

Figure 5a. Wheat 2017-18 treatments and replications

Wheat Crop Treatments and Specifications:

T_1 = Flat Sowing By Rabi Drill;
T_2 = Bed Furrow Planting (10" Furrow);
T_3 = Bed Furrow Planting with Perforated Pipe Irrigation (10" Furrow);
T_4 = Bed Furrow Planting with Perforated Pipe Irrigation (8" Furrow);
T_5 = Bed Furrow Planting with Perforated Pipe Irrigation (6" Furrow);
T_6 = Drip Irrigation Flat (Lateral Spacing = 3');
T_7 = Drip Irrigation on Beds (Lateral Spacing = 3').

Wheat Crop: (**Sowing:** 31-12-2017, **Harvesting:** 30-04-2018)

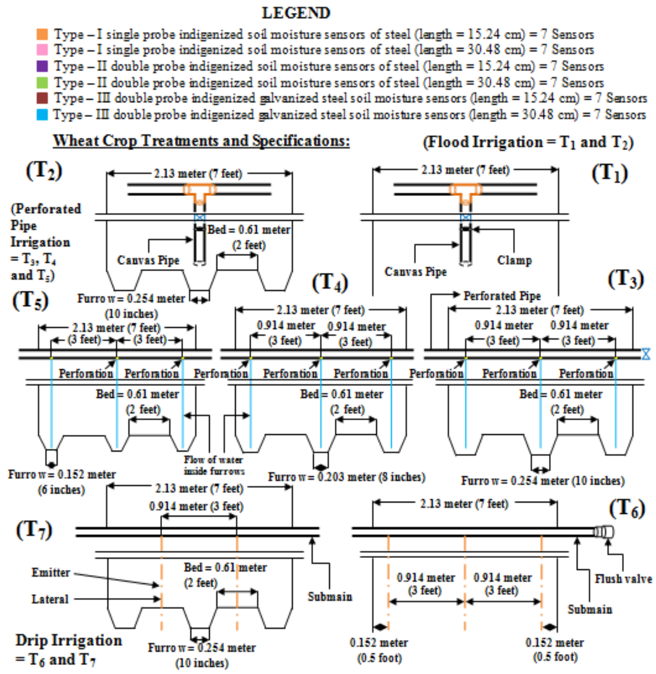

Figure 5b. Wheat 2017-18 experimental field treatments

Irrigation scheduling for precision irrigation was performed using twenty one (21) double probe (length = 5.08 cm) market available soil moisture sensors for soil moisture monitoring in the crop root zone (sowing to harvesting) to observe and record soil moisture data through laptop daily at 8:00 am, 12:00 pm and 4:00 pm during the year 2016-17. The volumetric soil moisture (%) values were displayed on serial monitor in Arduino 1.8.5. On the other hand, during the year 2017-18, irrigation scheduling was performed installing forty two (42) indigenized soil moisture sensors in the wheat crop root zone (sowing to harvesting); including fourteen (14) single probe steel soil moisture sensors (Type-I length = 15.24 cm, 30.48 cm), fourteen (14) double probe steel soil moisture sensors (Type-II length = 15.24 cm, 30.48 cm), and fourteen (14) double probe galvanized steel soil moisture sensors (Type-III length = 15.24 cm, 30.48 cm). These indigenized soil moisture sensors and irrigation method were integrated with Arduino Microcontroller and Raspberry Pi 3 (Model B) for irrigating the crop. Arduino Mega was coupled with Arduino Ethernet Shield and LCD 16×2 for transformation of volumetric soil moisture (%) readings on cloud wirelessly and to display volumetric soil moisture (%) values on LCD 16×2. All volumetric soil moisture (%) values were monitored using LCD 16×2 display and daily emails were received as moisture dropped below a specified level. The indigenized sensor network used to receive data and send it to ThingSpeak (http://thingspeak.com) and mobile using Raspberry Pi 3 (Model B).

The MAD Level set for the treatments had been presented in Table 2.

Irrigation time - The time required to irrigate a plot up to the required depth was calculated employing a universally standardized equation.

$$Q.t = A.d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where: Q = Discharge, cusec, ft^3/s; t = Time, hr; A = area, acre and d = Depth of water applied, in

$$\boldsymbol{Q}\left(\frac{1.ft^3}{s}\right).\boldsymbol{t}(1.hr) = \boldsymbol{A}(1.acre).\boldsymbol{d}(1.inch)$$

$$Q\left(\frac{1.ft^3}{s}.\frac{(30.48cm)^3/s}{\frac{1.ft^3}{s}}\right)x\ t(hr)$$

$$= A\left(1acre.\frac{43560ft^2x(\frac{30.48cm}{1.ft})^2}{1acre}\right).d(1.inch\frac{2.54cm}{1.inch})$$

$$28316.85\ xQ\left(\frac{cm^3}{s}\right)xt(hr)$$

$$= 102790153\ xA\left(\frac{cm^3}{s}\right)xd\ (cm)$$

Table 2. MAD levels for wheat 2016-17 and 2017-18.

Name of Irrigation Method	Treatments	MAD (%)	FC (%)	PWP (%)	AW (%)	AW (%) at 40% MAD, 20% MAD and 15% MAD	LL
Canvas/flood irrigation	T_1-T_2	40	21	8	13	5.2	15.8
Perforated pipe irrigation	T_3-T_5	20	21	8	13	2.6	18.4
Drip irrigation	T_6-T_7	15	21	8	13	1.95	19.05

MAD = Management Allowed Deficit, FC = Field Capacity, PWP = Permanent Wilting Point, AW = Available Water, LL = Lower Limit

$$Q\left(\frac{cm^3}{s}\right)xt(hr) = 3630\ xA(cm^2)xd\ (cm)$$

$$t(hr) = 3630x\frac{A(cm^2)xd(cm)}{Q(cm^3/s)}$$

$$t(s) = 217800x\frac{A(cm^2).d(cm)}{Q(cm^3/s)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

Water use efficiency/water productivity: Water use efficiency was measured employing the following relationship (Khurram, 2008).

$$\text{WUE} = \frac{\text{CY,(kg/ha)}}{\text{TIW,(mm)}} \ldots\ldots\ldots\ldots\ldots\ldots .3$$

Where, WUE = Water Use Efficiency/Water Productivity (kg/ha/mm); CY = Crop Yield (kg/ha) and TIW = Total Irrigation Water Applied during growing season (mm).

Water conveyance efficiency: Water conveyance efficiency, the ratio of amount of irrigation water that reaches a farm to the amount of water diverted from the water source, was determined using the relationship:

$$\text{Ec} = \frac{\text{Vf}}{\text{Vt}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

Where; Ec = Conveyance Efficiency of Water (%); Vf = Volume of Irrigation Water that reaches to farm experimental area (m^3) and Vt = Volume of Water received from the source (m^3).

Water application efficiency: Water application efficiency was measured by the following mathematical relationship:

$$\text{Ea} = \frac{\text{Vs}}{\text{Vf}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .5$$

Where; E_a = Water application efficiency (%), Vs = Volume of water stored in the root-zone of crop (m^3). V_f = Volume of irrigation water at the point of entrance to field (m^3).

For the estimation of application efficiency, crop rooting depth (RD) was measured at 30.48 cm, 45.72 cm and 60.96 cm in wheat for both years. The soil moisture meter (PMS-714) and indigenized soil moisture sensors (Type-I, Type-II and Type-III) were used for determining available soil water storage capacity (ASWC) and thus total soil water storage (SWS) was calculated as:

SWS = RD (m) × ASWC (mm/m)…………6

Where; SWS = soil water storage (mm), RD = crop rooting depth (m) and ASWC = Available soil water storage capacity (mm/m).

Field irrigation efficiency: The saving of water for drip and perforated pipe irrigation were calculated by comparison with conventional irrigation system and then the field irrigation efficiency was calculated using following relationship.

$$Ei = \frac{CWR}{WA} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{-----------}\ldots\ldots .7$$

Where: Ei = Irrigation efficiency (%), CWR = Crop water requirement (mm) and WA = Water applied (mm).

Crop yield - Wheat crop was manually harvested from seven locations (one meter square for each) under each treatment and yield was estimated using the following relationship.

$$Y = \frac{W_g, kg}{A, m^2} \times \frac{10{,}000\ m^2}{1ha} x \frac{1\ ton}{1000\ kg} \ldots\ldots\ldots\ldots\ldots .8$$

Where; Y = Crop grain yield (ton/ha), W_g = Grain weight per m^2 (kg), A = Area (1-m^2).

RESULTS

Sensors evaluation, calibration and validation: The increased use of precision technology like sensor has become a part of many irrigation systems due to its potential to increase efficiencies and reduced costs (Stubbs, 2016). Iqbal *et al.* (2020) developed, calibrated and evaluated validation of indigenized soil moisture sensors. The results of evaluation

Table 3. Evaluation and calibration of Type-I, Type-II and Type-III indigenized soil moisture sensors.

Materials and lengths	Calibration equation	Sample size (n)	R^2	MBE (%)	RMSE (%)	k
A. Type-I (Single probe) indigenized soil moisture sensors						
Copper-30.48 cm (304.8 mm)	$y = 0.009x^2 + 0.596x$	376	0.993	1.67	32.29	2.66
Copper-15.24 cm (152.4 mm)	$y = 0.352x^{1.328}$	376	0.908	-0.31	5.98	1.23
Brass-30.48 cm (304.8 mm)	$y = 0.308x^{1.341}$	376	0.886	-0.48	9.31	1.26
Brass-15.24 cm (152.4 mm)	$y = 0.435x^{1.230}$	376	0.892	-0.42	8.05	1.24
Steel-30.48 cm (304.8 mm)	$y = 1.013x$	376	0.991	2.30	3.50	0.94
Steel-15.24 cm (152.4 mm)	$y = 0.993x$	376	0.992	2.10	3.30	0.89
B. Type-II (Double probe) indigenized soil moisture sensors						
Copper-30.48 cm (304.8 mm)	$y = -0.031x^2 + 1.618x$	504	0.968	-10.30	231.32	5.81
Copper-15.24 cm (152.4 mm)	$y = 0.016x^2 + 0.485x$	504	0.991	4.33	97.12	1.47
Brass-30.48 cm (304.8 mm)	$y = -0.035x^2 + 1.913x$	504	0.939	-7.33	164.60	-5.11
Brass-15.24 cm (152.4 mm)	$y = 0.841x$	504	0.963	0.08	1.74	0.68
Steel-30.48 cm (304.8 mm)	$y = 1.608x^{0.866}$	504	0.996	2.20	3.40	0.91
Steel-15.24 cm (152.4 mm)	$y = 0.644x^{1.119}$	504	0.999	1.90	3.30	0.87
C. Type-III (Double probe) indigenized soil moisture sensors						
Galvanized Steel-15.24 cm (152.4 mm)	$y = 1.018x$	509	0.997	1.80	3.28	0.83
Galvanized Steel-30.48 cm (304.8 mm)	$y = 1.049x$	509	0.998	2.10	3.37	0.68

Source: Iqbal *et al.*, (2020)

and calibration of indigenized soil moisture sensors have been presented in Table 3.

Table 3 depicted that both Type-I and Type-II sensors, steel sensors performed best due to high R^2 values of about 0.99 and RMSE in the range of 3.30% - 3.50% during calibration. The calibration further improved the accuracy of both steel and copper sensors, but the performance of brass sensors was further affected after applying calibration equations.

Mean water use efficiencies: The perforated pipe irrigation and drip irrigation helped achieving high water use efficiency by reducing water application losses. The integration of all the technologies along with soil moisture monitoring sensors for irrigation scheduling helped achieving precise irrigation. Table 4 depicted that during 2nd year water use efficiencies were enhanced for flood, perforated pipe, and drip irrigation methods.

Effect of treatments over two years on wheat crop production parameters: Wheat crop was grown for two years 2016-17 and 2017-18 for exploring the effects of irrigation management practices on crop growth parameters. Seven treatments comprising different field geometries and irrigation methods were compared. Crop production data were collected and analyzed employing CRD statistical design with General Linear Model (GLM) of SAS/STAT 9.1 (SAS, 2009). The statistically analyzed results of wheat are discussed and presented in the following paragraphs. Wheat crop production treatments included:

T_1 = Flood irrigation flat sowing by rabi drill with flood irrigation, T_2 = Flood irrigation bed furrow planting with 0.254 m (10”) furrow, T_3 = Perforated pipe irrigation bed furrow planting with 0.254 m (10”) furrow, T_4 = Perforated pipe irrigation bed furrow planting with 0.203 m (8”) furrow, T_5 = Perforated pipe irrigation bed furrow planting with 0.152 m (6”) furrow, T_6 = Drip irrigation flat with 0.914 m (3’) lateral spacing, T_7 = Drip irrigation on beds with 0.914 m (3’) lateral spacing.

Table 4. Water use efficiency improvement for wheat crop.

Treatments	Mean Water use efficiency (MWUE)		Increased MWUE during 2017-18 (%)
	Wheat 2016-17	Wheat 2017-18	
T1	9.1	10.0	9.9
T2	9.8	10.8	10.2
T3	12.4	12.9	4.0
T4	12.2	12.7	4.1
T5	12.0	12.6	5.0
T6	14.2	14.4	1.4
T7	14.1	14.3	1.4

Table 5 showed that irrigation water depth (W) requirement was significantly affected ($\alpha = 0.05$) by treatments over both the years. Drip irrigation treatments (T_6 and T_7) required significantly lowest mean amount of water (359.55 mm and 358.65 mm) than those by all the other treatments. This indicated best consumption of water by growing roots of wheat crop under drip irrigation treatments. Graphical presentation in Figure 6 clearly showed the significant difference ($\alpha = 0.05$) among different treatments for their water requirement of wheat production.

Table 5. Effect of treatments on irrigation depth requirements for wheat production over two years (2016-17 and 2017-18).

Treatments	W		Mean	LSD (0.05)
	Y1	Y2		
T_1	440.8^{a}_{a}	422.3^{a}_{b}	431.55^{a}	9.068
T_2	434.8^{b}_{a}	415.1^{b}_{b}	424.95^{b}	8.0149
T_3	391.6^{c}_{a}	393.5^{c}_{a}	392.55^{c}	6.809
T_4	390.6^{c}_{a}	392.1^{cd}_{a}	391.35^{cd}	6.809
T_5	388.4^{c}_{a}	387.7^{d}_{a}	388.05^{d}	6.809
T_6	354.4^{d}_{b}	364.7^{e}_{a}	359.55^{e}	6.809
T_7	354.2^{d}_{b}	363.1^{e}_{a}	358.65^{e}	6.809
Mean	393.54_{a}	391.21_{b}	379.38	2.0484
LSD (0.05)	5.8081	5.5378	3.8322	

Superscripts (a, b, c etc.) for vertical comparison in columns and subscripts (a, b, c etc.) for comparison along rows.

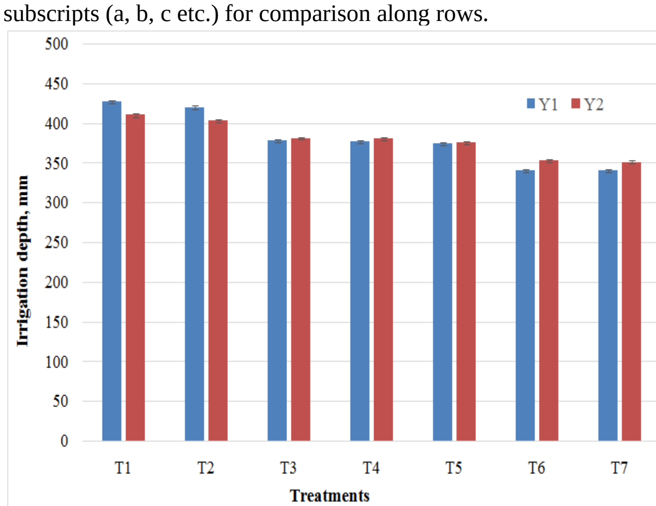

Figure 6. Effect of treatments on irrigation depth requirements for wheat production over two years (2016-17 and 2017-18)

Table 6 depicted that mean yield of wheat grain (YD) over two years was significantly greater ($\alpha = 0.5$) under drip irrigation treatments (T_6 = 5145.1 kg/ha and T_7 = 5091 kg/ha) than those under flood irrigation treatments (T_1 = 4139 kg/ha, T_2 = 4371 kg/ha) and perforated pipe irrigation treatments (T_3 = 4969 kg/ha, T_4 = 4872 kg/ha, T_5 = 4775.7 kg/ha). Figure 7 more clarified pictorially the yield significance differences among various treatments.

Table 6. Effect of treatments on wheat grain yield (kg/ha) over two years (2016-17 and 2017-18).

Treatments	YD		Mean	LSD (0.05)
	Y1	Y2		
T_1	4040^{f}_{b}	4238^{f}_{a}	4139^{g}	68.09
T_2	4272^{e}_{b}	4470^{e}_{a}	4371^{f}	49.873
T_3	4870^{b}_{b}	5068^{b}_{a}	4969^{c}	68.09
T_4	4773^{c}_{b}	4971.3^{c}_{a}	4872^{d}	171.65
T_5	4677^{d}_{b}	4875^{d}_{a}	4775.7^{e}	132.83
T_6	5046^{a}_{b}	5244.1^{a}_{a}	5145.1^{a}	46.339
T_7	4992^{a}_{b}	5190^{a}_{a}	5091^{b}	18.136
Mean	4667.16_{b}	4865.16_{a}	4766.16	26.08
LSD (0.05)	72.249	67.25	48.79	

Superscripts (a, b, c etc.) for vertical comparison in columns and subscripts (a, b, c etc.) for comparison along rows.

Table 7 showed almost the same trend of straw yield (SY) as that for wheat grain yield production discussed previously. Mean yield (SY) yield (kg/ha) under flood irrigation treatments (T_1, T_2) was significantly ($\alpha = 0.5$) lowest (6645 kg/ha, 7133 kg/ha) and significantly greatest (9435 kg/ha, 9053.3 kg/ha) under drip irrigation treatments (T_6, T_7). The perforated pipe irrigation treatments stood at intermediate positions for SY production when compared with flood and drip irrigation treatments. The graphical presentation in figure 8 clearly showed the difference of SY production among all the treatments. The significance difference of SY yield over two years has been clearly shown in the Table 7.

Table 7. Effect of treatments on wheat straw yield (t/ha) over two years (2016-17 and 2017-18).

	SY		Mean	LSD (0.05)
	Y1	Y2		
Treatments				
T_1	6590^{g}_{b}	6700^{g}_{a}	6645^{g}	22.67
T_2	7078^{f}_{b}	7188^{f}_{a}	7133^{f}	49.873
T_3	8670^{c}_{b}	8780^{c}_{a}	8725^{c}	68.009
T_4	8403^{d}_{a}	8513^{d}_{a}	8458^{d}	250.69
T_5	8093^{e}_{b}	8203^{e}_{a}	8148^{e}	10.389
T_6	9380^{a}_{b}	9490^{a}_{a}	9435^{a}	45.339
T_7	8998^{b}_{a}	9108^{b}_{a}	9053.3^{b}	217.23
Mean	8173.2_{b}	8283.2_{a}	8228.19	36.484
LSD (0.05)	101.07	101.07	68.25	

Superscripts (a, b, c etc.) for vertical comparison in columns and subscripts (a, b, c etc.) for comparison along rows.

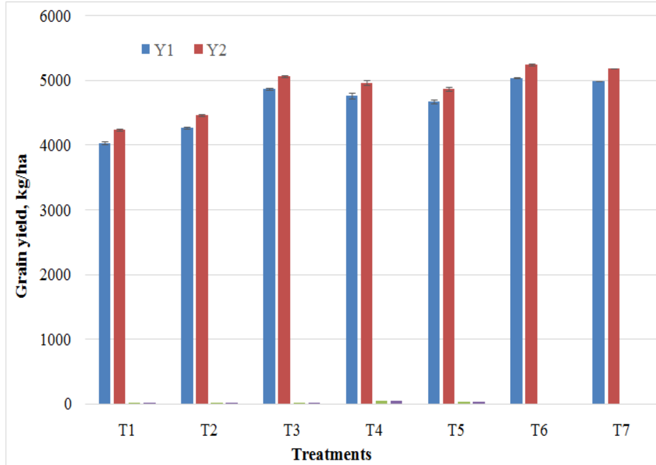

Figure 7. Effect of treatments on wheat grain yield production over two years (2016-17 and 2017-18)

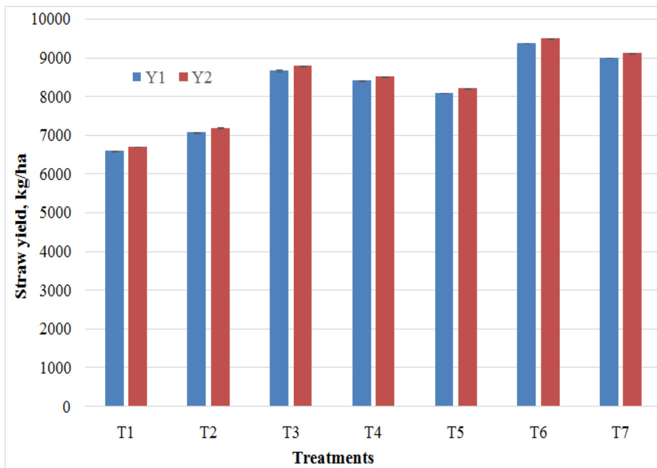

Figure 8. Effect of treatments on wheat straw yield production over two years (2016-17 and 2017-18)

Table 8 showed that drip irrigation treatments had significantly high mean water productivity (WP) values than those under flood irrigation treatments (T_1 and T_2) and perforated pipe irrigation treatments (T_3, T_4 and T_5). Flood irrigation treatments T_1 and T_2 had 9.6 and 10.30 mean WP (wheat grain yield kg/ha/mm irrigation depth of water) respectively. Perforated pipe irrigation treatments T_3, T_4 and T_5 had 12.66, 12.43, and 12.30 mean WP values respectively. The drip irrigation treatments T_6 and T_7 had mean WP values of 14.30 and 14.20, respectively. The effects of treatments on water productivity of wheat over two years have been presented in Figure 9.

Table 8. Effect of treatments on water productivity (wheat grain yield kg/ha/mm irrigation depth of water) over two years (2016-17 and 2017-18).

Treatments	WP		Mean	LSD
	Y1	Y2		(0.05)
T_1	$9.16^e{}_b$	$10.03^e{}_a$	9.6^e	0.3463
T_2	$9.83^d{}_b$	$10.76^d{}_a$	10.30^d	0.3463
T_3	$12.43^b{}_b$	$12.9^b{}_a$	12.66^b	0.0925
T_4	$12.2^c{}_b$	$12.66^c{}_a$	12.43^c	0.2449
T_5	$12.03^c{}_b$	$12.56^c{}_a$	12.30^c	0.4139
T_6	$14.23^a{}_b$	$14.37^a{}_a$	14.30^a	0.1309
T_7	$14.1^a{}_a$	$14.3^a{}_a$	14.20^a	0.2267
Mean	12.0_b	12.51_a	12.25	0.0784
LSD (0.05)	0.2058	0.2261	0.146	

Superscripts (a, b, c etc.) for vertical comparison in columns and subscripts (a, b, c etc.) for comparison along rows.

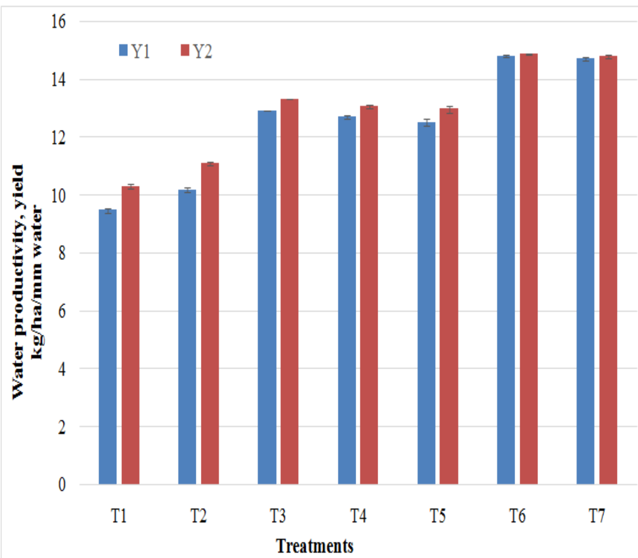

Figure 9. Effect of treatments on water productivity of wheat over two years (2016-17 and 2017-18)

The effect of treatments on irrigation efficiency, Ei (%) for wheat over two years presented in Table 9 showed the drip irrigation treatments (T_6, T_7) had significantly greatest Ei values (87.95%, 88.1%), perforated pipe treatments (T_3, T_4, T_5) had intermediated values of Ei (80.5%, 80.75%, and 81.45%) and flood irrigation treatments had significantly lowest Ei values (73.25%, 74.4%). The flood irrigation had the lowest Ei values. Most of the treatments had significantly greater Ei values during 2nd year wheat cropping than those under 1st year wheat cropping. Overall treatment mean Ei value was 80.82% during the 1st year and 81% during the 2nd year. Figure 10 explained pictorially the differences of Ei values both over treatments and years.

Table 9. Effect of treatments on irrigation efficiency, Ei (%) for wheat over two years (2016-17 and 2017-18).

Treatments	Ei		Mean	LSD
	Y1	Y2		(0.05)
T_1	$71.7^e{}_a$	$74.8^e{}_a$	73.25^e	6.8009
T_2	$72.7^c{}_a$	$76.1^{bc}{}_a$	74.4^c	9.068
T_3	$80.3^b{}_a$	$80.3^{bc}{}_a$	80.5^b	8.0149
T_4	$80.9^b{}_a$	$80.6^b{}_a$	80.75^b	8.0149
T_5	$81.4^b{}_a$	$81.5^{ab}{}_a$	81.45^b	8.0149
T_6	$89.2^a{}_a$	$86.7^a{}_a$	87.95^a	8.0149
T_7	$89.2^a{}_a$	$87.0^a{}_a$	88.1^a	8.0149
Mean	80.82_a	81.0_a	80.91	2.235
LSD (0.05)	6.7824	5.5378	4.181	

Superscripts (a, b, c etc.) for vertical comparison in columns and subscripts (a, b, c etc.) for comparison along rows.

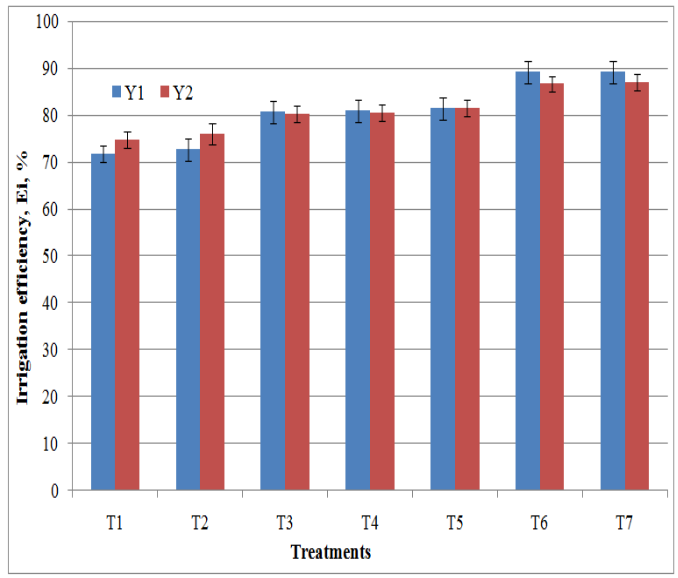

Figure 10. Effect of treatments on irrigation efficiency in wheat over two years (2016-17 and 2017-18)

The Table 10 showed the effects of all seven treatments on water application efficiency (Ea) over both year wheat crop productions. Mean Ea values over years were 55.5%, 64.5%, 61.5%, 66.5%, 75.5%, 83.0% and 84.5% under T_1, T_2, T_3, T_4, T_5, T_6, and T_7 treatments respectively. Most of the treatments under 2nd year wheat production significantly excelled in Ea values over those of 1st year. Figure 11 presented the effects of treatments on water application efficiency in wheat over two years.

Table 10. Effect of treatments on water application efficiency, Ea (%) for wheat over two years (2016-17 and 2017-18).

Treatments	Ea		Mean	LSD (0.05)
	Y1	Y2		
T_1	55^{c}_{a}	56^{g}_{a}	55.5^{e}	8.0149
T_2	64^{b}_{a}	65^{f}_{a}	64.5^{ed}	9.0678
T_3	61^{bc}_{a}	62^{f}_{a}	61.5^{d}	8.0149
T_4	66^{b}_{a}	67^{d}_{a}	66.5^{c}	8.0149
T_5	75^{a}_{a}	76^{c}_{a}	75.5^{b}	8.0149
T_6	78^{a}_{b}	88^{b}_{a}	83.0^{a}	8.0149
T_7	79^{a}_{b}	90^{a}_{a}	84.5^{a}	8.0149
Mean	68.28_{b}	72.0_{a}	80.91	2.279
LSD (0.05)	6.3141		4.264	

Superscripts (a, b, c etc.) for vertical comparison in columns and subscripts (a, b, c etc.) for comparison along rows.

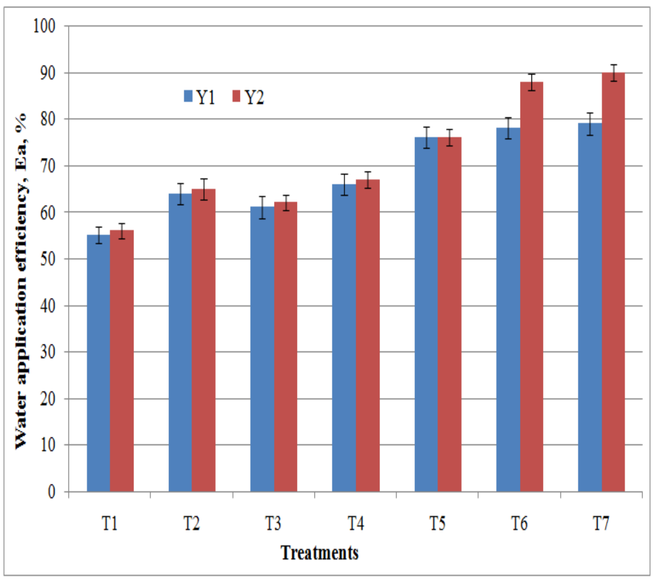

Figure 11. Effect of treatments on water application efficiency in wheat over two years (2016-17 and 2017-18)

DISCUSSION

The results found during this study have been discussed in the following paragraphs.

Table 3 depicted that the steel material was found the best for manufacturing both Type-I and Type-II sensors. The performance evaluation of Type-III galvanized steel sensors was also found at par with Type-I and Type-II sensors. Since the fabrication of Type-I and Type-II sensors is much laborious involving operation of Lathe Machine for developing probes and other soldering operations, therefore, it increased their cost. The indigenized steel sensors of all the three types were found acceptable for use in soil moisture monitoring for precision irrigation. The galvanized steel rod sensors (Type-III) being the lowest in cost and easy to fabricate with best performance may be promoted for sustainable commercialization. The use of sensors for irrigation scheduling have been supported by Stubbs (2016), who reported that sensor networks can be used to monitor volumetric water content of the soil. The use of real-time data and information gathered from sensor networks can be used for irrigation system automation for adjusting the amount and frequency of water applied.

The use of low cost but efficient perforated pipe technology, high water use efficiency was achieved with less energy consumption and economical cost. This has been supported by Bakhsh *et al.* (2015) who experimentally found that perforated pipe irrigation technique resulted 77% efficiency with water savings of 18%.

The flood irrigation treatments, T_1 and T_2 required significantly greatest ($\alpha = 0.05$) amount of mean irrigation depth (431.55 mm and 424.95 mm) for plant growth (Table 5). This indicates wastage of water as evaporation from free surface or deep percolation into deep soil layers. The perforated pipe irrigation treatments T_3, T_4, and T_5 had intermediate position for the consumption of irrigation water indicating more loss of water than those required for drip irrigation treatments and less loss than those of flood irrigation treatments T_1 and T_2. The results are in line with Bakhsh *et al.* (2015) who experimentally found that 25% to 60% water savings and a 60% increase in wheat yield under the drip irrigation method compared with conventional surface irrigation methods. Stubbs (2016) also reported that drip irrigation is more efficient irrigation method compared to sprinkler and gravity irrigation because it applies water directly to the root zone of crops. Therefore, it could safely be concluded that water requirements for flood irrigation are the largest and least for drip irrigation. Even though the table 5 showed significant difference between two years but the error bars in figure 6 showed negligible significant difference of water consumption between two years for flood, perforated pipe, and drip irrigation treatments. Anonymous (2012) reported that drips operate at relatively low pressure as compared with large irrigation systems delivering water onto the soil surface near the plant into the plant root zone, hence reduces plant evaporation and water loss.

Significantly higher mean yield of wheat grain (Table 6) over two years observed under drip irrigation treatments (T_6 and T_7) than those under flood (T_1 and T_2) and perforated pipe irrigation treatments (T_3, T_4 and T_5) have been found in line with the findings of Bakhsh *et al.* (2015) who experimentally found 60% increased wheat yield under drip irrigation method as compared with conventional surface irrigation methods. Table 6 also depicted that perforated pipe irrigation treatments had significantly greater ($\alpha = 0.5$) wheat grain yield than those under flood irrigation treatments. Horizontal comparisons between years indicated that the grain yield was significantly greater in 2nd year (2017-18) than those of 1st year under all the treatments. This could have been because the sensors were designed, fabricated, tested and installed properly during the 2nd year which might have controlled and regulated required water needs in the crop root zone. The plants might have favorable air and water environment for flourishing and developing root structure.

Mean straw yield (SY) yield under flood irrigation treatments (T_1, T_2) was found significantly (α = 0.5) lowest and significantly greatest under both T_6 and T_7 drip irrigation treatments (Table 7). The comparison of straw yield (SY) among three perforated pipe irrigation treatments (T_3, T_4 and T_5) showed that treatment T_5 had significantly lowest SY yield. This could have been due to less furrow width in T_5 treatment which might have decreased air circulation around plants that decreased flourishing plants resulting in reduced crop straw yield.

Drip irrigation treatments resulting in high mean WP values (Table 8) than those under flood irrigation treatments (T_1 and T_2) and perforated pipe irrigation treatments (T_3, T_4 and T_5) have been well supported with the findings of Bakhsh *et al.* (2015) who experimentally found that drip irrigation had been the efficient irrigation technique which resulted in greater value of WP for wheat than that produced by perforated pipe irrigation technique. Figure 9 clearly depicted that the 2nd year had significantly greater WP values than those of 1st year under all the treatments which might had been due to good water management with sensor-based irrigation in the 2nd year.

The sensor-based irrigation in the 2nd year wheat production increased benefits over uncontrolled irrigation in enhancing crop yield, dry matter yield and Ei values. The results are in line with the findings of Stubbs (2016) who reported that sensor irrigation methods is becoming more acceptable among farmers because of its potential to increase efficiencies and reduced costs.

Overall mean Ea value under drip irrigation was 39% and 23% greater than those of flood irrigation and perforated pipe irrigation treatments respectively (Figure 11). The mean Ea value of perforated pipe irrigation treatments excelled 13% more than the mean Ea value under flood irrigation treatments. All these results have been found in line with findings Stubbs (2016) who found that irrigation application efficiency (Ea) of gravity systems (flood irrigation) is generally less than pressure systems, drip irrigation and perforated pipe irrigation methods.

Conclusions: Type-I (Single probe) and Type-II (Double probe) steel sensors performed best due to high R^2 values of about 0.99 and RMSE in the range of 3.30% - 3.50% during calibration. Drip irrigation treatments (T_6 = 359.56 mm and T_7 = 358.65 mm) required significantly lower mean amount of water than those by all the other treatments, and the flood irrigation treatments (T_1 = 431.55 mm and T_2 = 424.95 mm) required significantly greatest (α = 0.05) amount of mean irrigation depth. These results present water savings under drip irrigation and other improved irrigation methods in comparison with treatment T1, as the sensor based scheduling was performed in all the 7 treatments. However, it can be seen from results that total depth of water applied in T1 was 431.55 mm which is normally near to 600 mm when farmers apply irrigation without scheduling using sensors. This indicated that the use of sensors also resulted in water savings in all the 7 treatments. Drip irrigation treatments (T_6 and T_7) produced high mean water productivity values (14.30 and 14.20) than those under flood irrigation treatments (T_1 = 9.6 and T_2 = 10.30) and perforated pipe irrigation treatments (T_3 = 12.66, T_4 = 12.43 and T_5 = 12.30). The mean yield of wheat grain over two years was greater under drip irrigation treatments (T_6 = 5145.1 kg/ha and T_7 = 5091 kg/ha) than those under flood (T_1 = 4139 kg/ha, T_2 = 4371 kg/ha) and perforated pipe irrigation treatments (T_3 = 4969 kg/ha, T_4 = 4872 kg/ha, T_5 = 4775.7 kg/ha). The results are in line with Bravdo *et al.* (1992) who reported that the soil matric potential sensors installed in the root zone controlled the size of root system and root environment resulting in increased fruit yield and quality. Perforated pipe irrigation treatments had significantly greater (α = 0.5) wheat grain yield than those under flood irrigation treatments.

***Conflict of Interes*t:** All the authors have no conflicts of interest.

***Authors' Contribution statement*:** The application of indigenized soil moisture sensors designed and developed by authors helped in precision irrigation of wheat crop under various irrigation methods. A lot of irrigation water was saved and crop yield was boosted up.

***Acknowledgements*:** The authors express thankfully acknowledge to Higher Education Commission (HEC), Islamabad, for funding under its Technology Development Fund (TDF-035) project. Also the support extended by WMRC staff for carrying out the project activities is highly acknowledged.

REFERENCES

Ahmed, I. 2002. Water and New Technologies. Global change impact studies centre (GCISC), Islamabad, Pakistan.

Akyildiz, I.F., W.S.Y. Sankarasubramaniam and E. Cayirci. 2002. Wireless Sensor Networks: A Survey, Computer Network, 38:393-422.

Anonymous. 2012.Water saving potential in agriculture in Europe: Findings from the xisting studies and application to the case studies. Final Report of European commission DG ENV. Biological intelligence service in collaboration with Cranfield University RPA.

Ashraf, M. 2016. Managing Water Scarcity in Pakistan: Moving Beyond Rhetoric. Proceedings of AASSA-PAS Regional Workshop on Challenges in Water Security to Meet the Growing Food Requirement. Pakistan Academy of Sciences, Islamabad.pp.:3-14.

Bakhsh, A. M. Ashfaq, A. Ali, M. Hussain, G. Rasool, Z. Haider and R. H. Faraz. 2015. Pakistan. The Pakistan Strategy Support Program (PSSP). Economic Evaluation of Different Irrigation Systems for Wheat Production in Rechna Doab, Pakistan International Food Policy Research Institute (IFPRI). Working Paper 028 – March 2015.

Bravdo B, I. Levin and R. Assaf. 1992. Control of root size and root environment of fruit-trees for optimal fruit production. Journal of Plant Nutrition. 15:699-712.

Burt, C.M., and S.W. Styles. 2007. Drip and Micro Irrigation Design and Management for Trees, Vines, and Field Crops.Practice plus Theory (4th ed.). ISBN 978-0-9643634-4:396.

Christian-Smith. J, H. Cooley and P.H. Gleick. 2012 - Water Policy, 2012 - Potential water savings associated with agricultural water efficiency improvements: A case study of California, USA. iwaponline.com.

Flakenmark, M., J. Lundquist, and C. Widstrand. 1989. Macro-scale water scarcity requires micro scale approaches: Aspects of vulnerability in semi-arid development. Natural Resources Forum. 13:258-267.

Gameh, M.A., K.K. Attia, H.M.A. Ragheb and N.A. Hemdan. 2004. Water Regime of Some Crop Grown Under Drip Irrigation at El-Kharga Oasis. I. Yield and Water Use Efficiency. Proceedings of the Egyptian Soil Science Society (ESSS) 7th National Conference on New Approaches in Soil Technology, Cairo, Egypt. December. 27-28.

GOP. 2014-15. Pakistan economy survey. Finance division, Economy advisor's wing, Government of Pakistan, Islamabad, Pakistan.

Hartz, T.K. 1999. Water management in drip-irrigated vegetable production. UC Davis, Vegetable Research and Information Center, Department of Vegetable Crops, University of California. pp. 37-38.

Iqbal, U., A. Bakhsh, M.A. Shahid, S.H.H. Shah and S. Ali. 2020. Development of low cost indigenized soil moisture sensors for precision irrigation. Pakistan Journal of Agricultural Sciences.57:205-217.

Khurram, S. 2008. Use of CROPWAT model to improve water use efficiency. Unpoblished M.Sc. Thesis, Faculty of Agricultural Engineering and Technology, University of Agriculture, Faisalabad, Pakistan.

Mateos, L., J. Berengena, F. Orgaz, J. Diz and E. Fereres .1991. A comparison between drip and furrow irrigation in cotton at two levels of water supply. Agricultural water management, ELSEVIER, Science Direct. 19:313-324.

Nahla, A. and Hemdan. 2003. Water regime of some crops grown under drip irrigation at El- Kharga Oasis. Unpublished M.Sc. Thesis, Assiut. University,Egypt. pp.497-499.

Osman, H.E. 2000. Gated pipe techniques for improved surface irrigation. Annals of Agriculture Science (Cario), 1(Special):145-155.

SAS. 2009. SAS/STAT® 9.2 User's Guide, (2nd ed.). Cary, NC: SAS Institute Inc., Cary, NC, USA., ISBN-10 :1607644398.

Stubbs. M. 2016. Irrigation in U.S. Agriculture: On-Farm Technologies and Best Management Practices. Irrigation in U.S. Agriculture: Congressional research service. 7-5700 www.crs.gov R44158.