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# DEVELOPMENT OF LOW COST INDIGENIZED SOIL MOISTURE SENSORS FOR PRECISION IRRIGATION

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Indigenized soil moisture sensors can be viable tools to improve water productivity through precision irrigation application. This study was conducted at Water Management Research Center, Postgraduate Agricultural Research Station, University of Agriculture, Faisalabad. Three types of soil moisture sensors were designed and fabricated using copper, brass, and steel. These sensors comprised a bottom tapered tip, middle tube/rod, and top handling part (packing foam). The length of the sensors was 30.48 cm, with bottom tip tapered at 33º over the length of 14.22 mm. The working principle was based on soil dielectric property through +ve electrode at the top and –ve electrode at bottom tip of the sensor tube. Type-I sensor had one probe, Type-II had two probes and Type-III had two insulated probes of galvanized steel. The electric current (mA) measured in response to the soil moisture status in the root zone was converted into digital form using microcontroller. These sensors were tested and calibrated against Gravimetric Method. The evaluation of Type-I, II, and III sensors showed that MBE (Mean Bias Error) was found to be within the acceptable limit of 2.5%, whereas RMSE (Root Mean Square Error) was lesser than 5% only in case of steel sensors and was out of the limit for all other sensors. The cost incurred on the indigenized sensors manufacturing was 10 times lesser than that of the imported. These research findings indicate that indigenized soil moisture sensors made of steel is relatively more accurate and can monitor real time soil moisture for promoting precision irrigation to improve water productivity.

**Keywords**: Soil moisture, monitoring, single probe, double probe, sensor, copper, brass, steel, galvanized steel, low cost.

## INTRODUCTION

Surface water supplies are decreasing, in contrast to the irrigation water requirements which are increasing in the Pakistan. Adequate availability of water supplies in future is becoming a challenge. The canals water supplies have decreased due to shortage in river flows. For example, Rabi season 2018-19 experienced water shortage of 38%, as reported by Indus River System Authority (IRSA, 2019). In such scenario, there is a need to improve water use efficiency. Improving irrigation efficiency can contribute to improving water productivity and making agriculture more competitive and sustainable. Through precision irrigations, average crop yields can be improved by minimizing water losses caused by excess water applications and subsequent leaching. Precision irrigation scheduling can offer one of the options to apply irrigation water efficiently based on continuous monitoring of the soil moisture in the root-zone. Recent technological advances have made soil water sensors available for efficient scheduling of precision irrigations. Soil moisture sensors can be installed at representative places in the agricultural field to provide data on continuous monitoring of the soil moisture during growing season that can be used for precision irrigation scheduling. The rapid variations, however, in the soil water contents of these soils are sometimes not correctly captured by some types of sensors (Irmak and Haman 2001; Muñoz-Carpena *et al.,* 2002; Muñoz-Carpena *et al.,* 2005). Most of the sensors, which work on volumetric basis currently available for irrigation, are dielectrics in nature while estimating the soil water content by measuring the soil mass permittivity. The dielectric constant of liquid water is much larger than that of the other soil constituents; whereas the total permittivity of the soil or of the mass permittivity is mainly controlled by the presence of soil water. Phene and Howell (1984) used a soil potential sensor tailored to control subsurface drip irrigated tomatoes and found the yields of the automated system similar to those of irrigated tomatoes based on evaporation by using less irrigation water. Smajstrla and Locascio (1996) reported that the tensiometers installed at 15 cm depth and fixed at 10 and 15 kPa in sandy soils in Florida reduced the irrigation needs of tomatoes by 40-50% without affecting crops yields. Efficient water management can play an important role in irrigated agricultural systems (Kim and Evans, 2009). Irrigation control systems based on Wireless

Sensor Network (WSN) and real time soil moisture data are potential solution to optimize water management by remotely assessing in – field soil water conditions and then site specifically controlling irrigation sprinklers (Hedely and Yule, 2009; Kim and Evans, 2009). There are numerous soil water tension based sensors (granular matrix based, tensiometer and soil moisture content based sensors i.e. TDR, FDR, VH400, etc.) available today for soil moisture estimation (Francesca *et al.,* 2010).

Granular Matrix Sensors (GMS) measure variations in soil water content in correspondence to the variation in resistance between electrodes (Berrada *et al.,* 2001). Irmak *et al.* (2006) reported that this resistance is inversely related to soil water. The GMS are less expensive and need less maintenance than tensiometers (Shock *et al.,* 1998) and measure irrigation needs automatically (Munoz-Carpena *et al.,* 2005). These GMS have mostly been used for estimation of soil moisture content for cotton, onion, potato and maize (Munoz Carpena *et al.,* 2005; Irmak *et al.,* 2006). These show different responses for different soil types (Enciso-Medina *et al.,* 2007). However, due to poor soil and sensor contact, these sensor measurements are erroneously high in heavy soils (Berrada *et al.,* 2001). Evett *et al.* (2006) reported that the soil moisture sensors must be accurate around 0.051-0.101 cm/cm.

In addition to accuracy, another issue in the adoption of sensor-based precision irrigation applications is the high cost of imported sensors, which may be addressed by promoting indigenized sensors. Currently, there is lack of technically viable indigenized soil moisture monitoring setup, and there is an urgent need of such systems from the technical professionals.

Specific objectives of this study were to design and fabricate low cost indigenized soil moisture sensors of different materials, and test and validate them in the field to achieve real time and accurate soil moisture monitoring for precision irrigation. Soil moisture-based irrigation scheduling is a preferable approach in which the soil moisture contents are determined using soil moisture monitoring devices (Garg *et al.,* 2016). Another goal of the study was to integrate the developed sensors with telemetry for continuous real time measurement delivery to irrigation managers through computer or using cloud.

## MATERIALS AND METHODS

***Soil Dielectric Properties*:** Dielectric measurements are sensitive to soil moisture, bulk density, temperature, and soil type, etc. The dielectric instruments are promoted for measuring volumetric soil moisture content. Therefore, to determine their accuracy and response to changes in soil moisture content, we compared the readings of locally developed soil moisture sensors with Gravimetric Method. Locally designed soil moisture sensors consist of one probe with two pin electrodes or two probes that function as a capacitor, with the surrounding soil serving as the dielectric (Figures 1 to 3). Dielectric permittivity (ε) is the ability of a substance to hold an electrical charge. The dielectric constant (Ka) is the ratio of the permittivity of a substance to free space. The value of $K_a$ in air is 1 and in water $K_a$ is approximately 80. The signals in mAs proportional to the soil's dielectric permittivity are converted to output signal i.e. a reading in digital form. The dielectric permittivity of soil water is much higher than that of air, soil minerals and organic matter. The close contact between soil particles and sensor is important and sensor's accuracy may be affected due to presence of stones and air pockets. The sensor may respond erroneously due to difference in dielectric permittivity and therefore, special care is taken not to install sensor near the metal.

***Specifications of the Sensors*:** Single probe and double probe indigenized soil moisture sensors with detailed dimensions are shown in Figs 1, 2, and 3. The packing foam was used for Type-II & Type-III sensors when double probe soil moisture sensors were behaving as a single unit.

***Mechanical work for the development of indigenized soil moisture sensors*:** Keeping in view the basic property of direct relationship of electricity conductance with soil moisture content, indigenized soil moisture sensors of Type-I (Single Probe), Type-II (Double Probe) and Type-III (Double Probes of Galvanized Steel Wire) were developed using locally available materials.

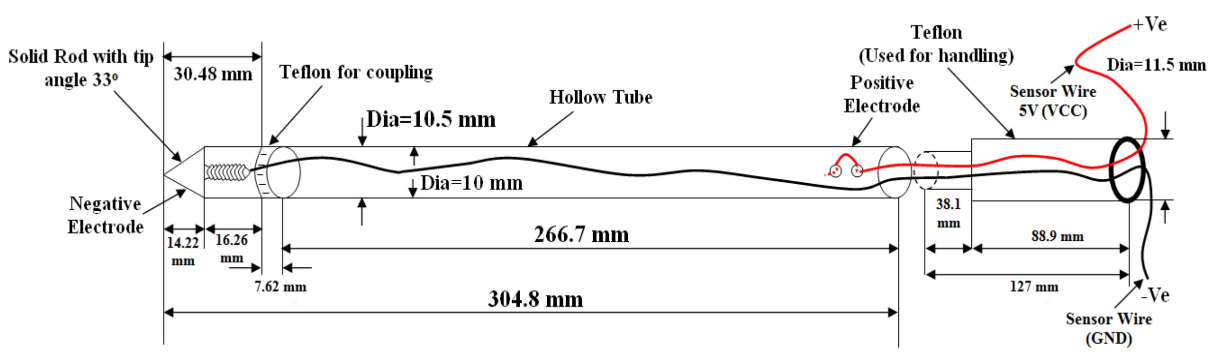



**Figure 1. Single probe (Type-I) indigenized soil moisture sensor.**

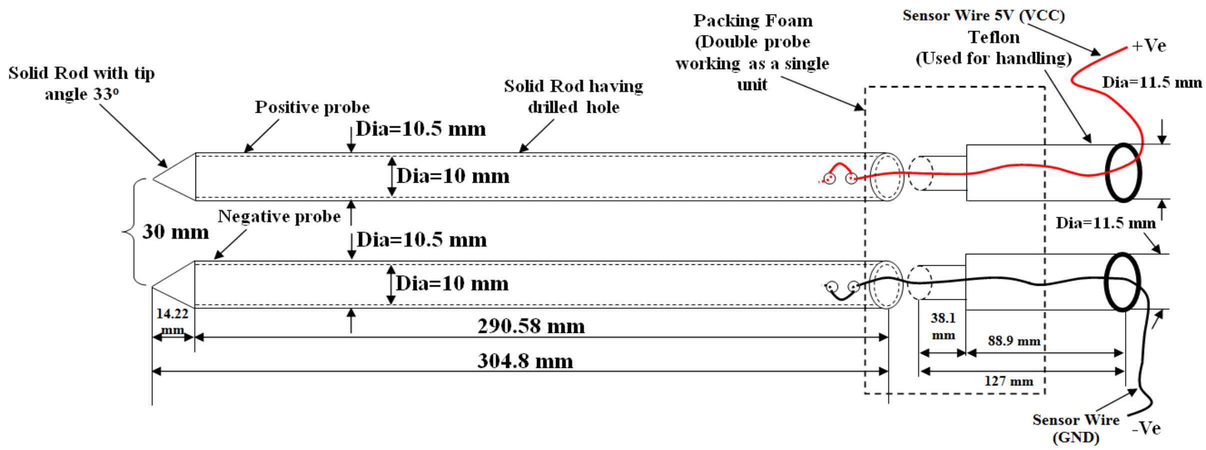



**Figure 2. Double probe (Type-II) indigenized soil moisture sensor.**

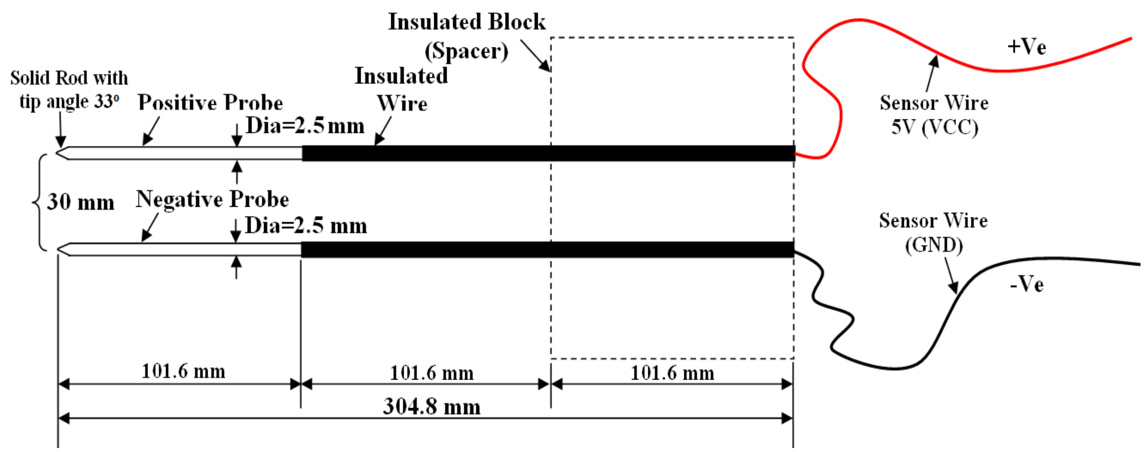



**Figure 3. Double probe (Type-III) galvanized steel wired soil moisture sensor.**

Copper, brass, and steel materials were selected on the basis of their soil properties as shown in Table 1. Copper and brass take time to dissolve inside the soil, while steel is fully resistant to dissolve while being inside the soil. Aluminum material was not selected because it is dissolved being in contact with soil very quickly.

The development of low-cost indigenized soil moisture sensors is very important for small scale farmers, because imported sensors are very expensive and without sensors the decision of field irrigations mostly results in the wastage of water. This study is important because the indigenized sensors-based irrigation decisions may result in mega water savings and sensor-based irrigations is a need of time. The details of development and fabrication of different types of soil moisture sensors are given in the following sections:

***Type-I (Single Probe) Sensors*****:** Type-I (Single Probe) Sensors were fabricated for two-pin electrodes for measuring soil conductivity along-with a converter to the soil moisture percentage. A hollow sensor tube (10-mm internal dia. and 266.7-mm long) was coupled with solid bottom tip (10-mm dia. 30.48 mm tip length with bottom tip of 14.22 mm, and tapered at angle 33° tip angle) using Teflon material. Thus, Type-I sensor with overall dimensions of 10-mm dia. length of coupling material of 7.62 mm, tube length of 266.7 mm and overall length of sensor as 304.8 mm was manufactured locally (Figure 1). Figures 1 to 3 are showing schematic of

**Table 1. Properties of 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 | 58,5 | 1,7 | 401 | 17 | 8,9 | 1083 |
| Brass | 15,9 | 6,3 | 150 | 20 | 8,5 | 900 |
| Steel | 1,37 | 73,0 | 16,3 | 16,5 | 7,9 | 1450 |

sensors. CNC Lathe machine work for fabrication of probe was performed in collaboration with the local industry. For Type-I sensor, Red wire was connected with Steel Tube (+ve electrode) and Black wire with Probe/Tip (-ve electrode); other operations like soldering, and coupling of sensor tube and rod using Teflon, etc. and the water proofing of sensor was performed using Alfee Rod using Hot Gun.

***Type-II (Double Probe) Sensors*:** Type-II sensors were also fabricated using the mentioned three materials. For each sensor of this type, a hole was drilled in the solid rod up to 290.58 mm (29.06 cm) length leaving remaining 14.22 mm (1.42 cm) for developing 33$^{o}$ tip using CNC Lathe machine.

For Type-II, double probe soil moisture sensors of 152.4 mm and 304.8 mm, lengths were manufactured by connecting Positive (Red) and Negative (Black) wires with two different probes by passing them through Foam Block, while sensor rod and tip of one probe working as a single unit.

***Type-III (Double Probe) Sensors*:** For Type-III, double probe galvanized steel soil moisture sensors were developed using galvanized wire (12 gauge of 2.5 mm) cut into 152.4 mm and 304.8 mm lengths for preparing of sensors of two different lengths. Probes were insulated by inserting them into the sleeve material, while 50.8 mm and 101.6 mm lengths of the probes were left exposed for 152.4 mm and 304.8 mm long sensors, respectively. These un-insulated portions were left for sensing soil moisture content, while the insulated portion was prepared in the form of packing foam block (50.8 mm long, 50 mm wide and 50 mm thick for 152.4 mm sensor and 101.6 mm long, 50 mm wide and 50 mm thick for 304.8 mm sensor) for developing top of the soil moisture sensor.

Two probes were kept 30 mm apart for filling soil in between the probes. The probes were insulated except where the portion needed for soil moisture sensing (50.8 mm and 101.6 mm). Resistors of 57-100 K were tested and resistance variation was found strongly dependent on soil moisture condition. The 100 K resistor was used when a sensor was directly inserted inside water either in field or in glass jar. Two digital pins from Arduino were used to flip-flop voltage (running current forward or in reverse direction). This back and forth current helped canceling out the electrolysis in order to check mechanism of electrolysis and break out crust created during electrolysis. This process elongated soil moisture sensor's working period.

***Electronic work for development of indigenized soil moisture sensors*:** Figure 4 shows the electronic work done for transmitting the voltage to soil through sensors and getting back the reading of soil moisture content in digital form. For this purpose, the Arduino Mega was coupled with Arduino Ethernet Shield for sending volumetric soil moisture (%) data on cloud wirelessly. Arduino Mega and Arduino Ethernet Shield both were operated using 5V-2AMP power supply from chargers. All the sensors were connected to Arduino Ethernet Shield and LM 393 voltage regulator. The code was uploaded into Arduino Mega from laptop installed Arduino 1.8.5 and received raw readings from soil moisture sensors were converted into volumetric soil moisture (%) data in

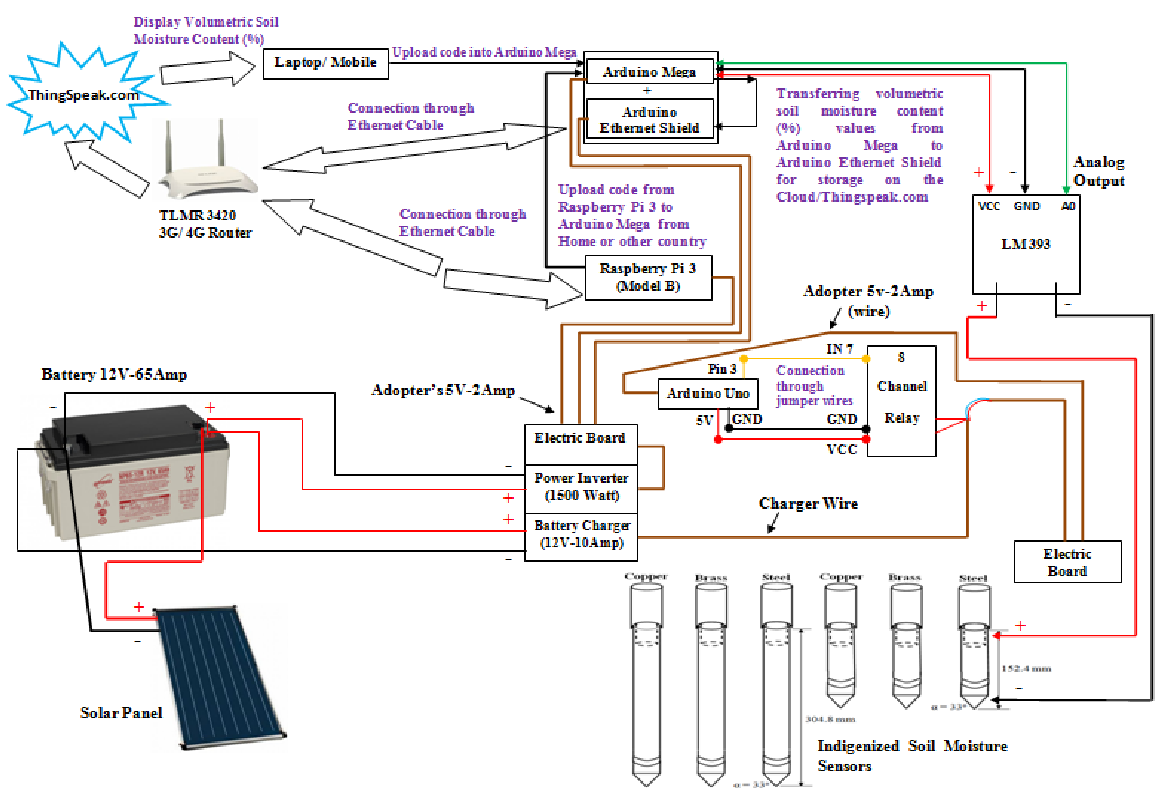



**Figure 4. Transmission of volumetric soil moisture data on "ThingSpeak.com" (Thematic process diagram).**

Arduino Mega. These volumetric soil moisture (%) readings were stored on cloud through Arduino Ethernet Shield with the interval of 30 minutes (interval defined in coding).

Instead of sending volumetric soil moisture (%) values on cloud, another better arrangement was the use of Raspberry Pi 3 (Model B). In this case, the developed sensors worked for measuring the current variation and then the analog values were converted immediately into corresponding digital values at appropriate raw scale (0-1023). Analog to Digital Converter (ADC) fetched these values into the microcontroller with built-in memory and storage that provided the flexible room for implementation of digital logic and other controls and limit. Raspberry Pi 3 (Model B) was used to control the working of hardware including Arduino Mega and Arduino Ethernet Shield.

To ensure communication of soil moisture data (volumetric based) on cloud, as well as on LCD, Arduino Mega was coupled with Arduino Screw Shield, which performed following three functionalities (Figure 5):

1. Display of volumetric soil moisture content readings on LCD.
2. Storage of volumetric soil moisture content readings on cloud.
3. Storage of volumetric soil moisture content readings on local memory card.

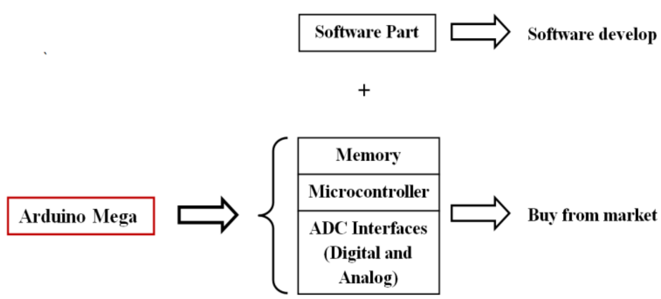



**Figure 5. Hardware Components.**

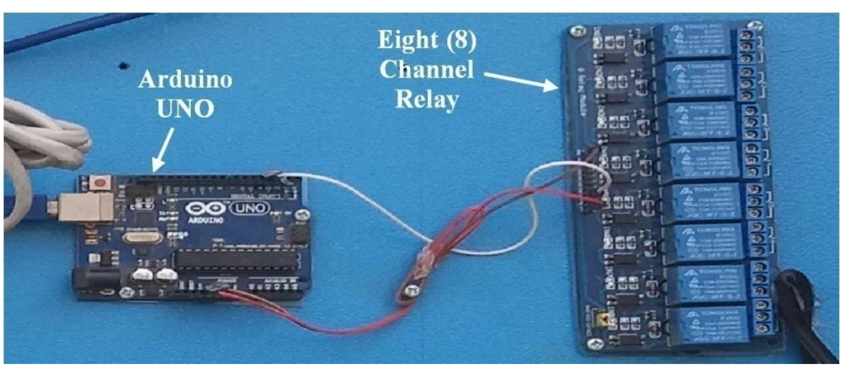
To ensure uninterrupted power supply to the setup, the battery was converted into smart UPS using Arduino UNO and Eight (8) Channel Relay Module, when code from laptop installed Arduino 1.8.5 was uploaded into Arduino UNO using USB cable. The time limit i.e. 1 hour (60 minutes) was defined inside code for charging. After 3 hours of continuous working the battery was automatically shifted on charging for period of 1 hour and this phenomenon was continued. The hardware components connections for conversion of battery into smart UPS have been presented in Figure 6.

***Calibration and validation of sensors*****:** The indigenously developed soil moisture sensors were tested, calibrated, and the validated employing Gravimetric Method at Water Management Research Center, Postgraduate Agricultural Research Station, University of Agriculture, Faisalabad (WMRC-PARS, UAF). For this purpose, soil samples were randomly collected from the upper 0-30 cm layer of soil in the field (Sandy loam). The soil was oven dried for 24 hours at 105 °C (Ramachandran and Jesudas, 2017) and passed through 2 mm sieve in-order to get homogeneous soil strata within each bucket (14 No; six for Type-I and Type-II each and two for Type-III sensors) with the assumption that every where the soil moisture content would be same. The holes (15 mm dia.) were drilled at the base of each bucket (101.6 mm upper dia. and base dia. 350.20 mm depth) for drainage of excess water. A low thickness filter paper was placed at the bottom of each bucket for drainage of excess water and stopping soil movement out of the bucket. Fourteen buckets were filled up-to 343 mm depth with oven dry soil for calibration and validation of all types of sensors.

The oven dried soil was poured in plastic buckets and compacted in layers so that the bulk density of 1.55 g/cm$^3$ is achieved, which is similar to the field bulk density of study site. Soil bulk density is the mass of dry soil per unit of bulk volume, including the air space, as described in Equation 1.

Bulk density (g/cm$^3$) = Dry soil weight (g) /Soil volume (cm$^3$)  (1)

Bulk density is usually expressed in megagrams per cubic meter (Mg/m$^3$), but the numerically equivalent units of g/cm$^3$and t/m$^3$ are also used (1 Mg/m$^3$ = 1 g/cm$^3$ = 1 t/m$^3$) (Cresswell and Hamilton, 2002). Using Equation 1 and the dimensions of buckets to calculate volume, mass of the oven dried soil to be filled in each bucket was calculated. The same mass of soil was filled in the buckets by gradual compaction,




| Arduino UNO | 8 Channel Relay |
|---|---|
| Digital (Pin 3) | IN 7 |
| 5V | VCC |
| GND | GND |

**Figure 6. Connections of Arduino UNO and 8 Channel Relay for battery conversion into smart UPS.**

finally resulting in bulk density equal to that field, i.e. 1.55 $g/cm^3$.

During calibration cycle, measured quantity of water was applied from the bottom of each bucket by putting the buckets of 350.20 mm height in the canes of 50 L capacity for homogenous water movement from bottom to top, throughout soil profile (Figure 7). The excess water was drained from bottom of buckets after saturation. The sensors were installed in the middle of each bucket, which was kept open to atmosphere for water evaporation from soil surface. During validation cycles, water was applied from bottom of the buckets similarly in the same way as during calibration.

**Figure 7. Water application from bottom of buckets.**

Following equations were employed for soil moisture content determinations (Black, 1965).

$$MC\%(db) = \frac{W_w - W_d}{W_d} x\ 100 \quad (2)$$

$$MC\%(dbv) = \frac{W_w - W_d}{W_d} x \frac{\rho_b}{\rho_w} x100 \quad (3)$$

$$MC\%\ (db) = \frac{W_{w1} - W_{d1} - W_{ISM} - W_{FP}}{W_{d1} - W_{ISM} - W_{FP}} x100 \quad (4)$$

Where, $W_w$=soil sample wet weight; $W_d$=soil sample oven dried weight; $\rho_b$=soil bulk density; $\rho_w$=water density; MC%(db)=% soil sample moisture content on dry weight basis; MC%(dbv)=% soil moisture content on dry volume basis; MC%(db1)=% soil moisture content of whole bucket on dry weight basis; $W_{w1}$=wet weight of soil, sensor and filter paper in bucket; $W_{d1=}$oven dried weight of soil in bucket; $W_{ISM}$=weight of Soil Moisture Sensor; $W_{Filter\ Paper}$=weight of filter paper

Soil moisture on Gravimetric basis was calculated using above mentioned formula and compared with that of sensors readings to develop correction factors/equations for each of sensors. The readings of volumetric soil moisture (%) were sent with the interval of 30 minutes on cloud (48 readings for 24 hours). The volumetric soil moisture (%) readings were stored on cloud continuously, but only those online readings of sensors were considered for calibration against which the weight readings were collected manually. The calibration and validation cycles time spans for different types of sensors have been presented in Table 2.

**Table 2. Calibration and validation time spans for different types of sensors.**

| Sensor Type | Calibration period | Validation period |
|---|---|---|
| Single probe (Type-I) | 7-07-2017 To 11-08-2017 | 12-08-2017 To 25-08-2017 |
| Double probe (Type-II) | 14-12-2017 To 1-02-2018 | 2-02-2018 To 21-03-2018 |
| Double probe (Type-III) | 16-12-2017 To 1-02-2018 | 2-02-2018 To 19-03-2018 |

***Real time data acquisition from sensors during calibration*:** An arrangement was made by creating an account on ThingSpeak.com to get real time data from soil moisture sensors. The soil moisture signals were transferred from indigenized soil moisture sensors to Arduino Mega. The output signal was converted through Arduino 1.8.5 coding into volumetric soil moisture and displayed on internet through Raspberry Pi 3 (Model B) and Zong-4G, TLMR 3420 Router arrangement. For connecting Raspberry Pi 3 (Model B), power (5V-2AMP) was provided to Raspberry Pi 3 (Model B) using a Micro USB Cable, Raspberry Pi 3 (Model B) Ethernet port was connected with 3G/4G (TLMR 3420) Router port using Ethernet cable and finally Raspberry Pi 3 (Model B) was connected with Arduino Mega using USB Cable in-order to upload code inside Arduino Mega.

Type-I, II, and III soil moisture sensors were calibrated through the adoption of online procedure when bucket installed soil moisture sensors values/readings of volumetric soil moisture content (%) were transferred on cloud at the interval of 30 minutes. The excel file was generated automatically on website containing readings of indigenized soil moisture sensors with an interval defined within code. At the same time the weight of buckets were recorded using digital balance at 30 minutes intervals and volumetric soil moisture content (%) for each sensor was calculated using Equation 3.

The error between sensors online readings and Gravimetric Method readings were calculated. Indigenized soil moisture sensors calibration curves were drawn between volumetric soil moisture content (%) readings and Gravimetric Method based volumetric soil moisture content (%) and then best fit equation i.e. linear/power/polynomial were sought out for each sensor. The calibration equations for copper, brass, and steel (152.4 mm, 304.8 mm) soil moisture sensors were applied to indigenously developed soil moisture sensors installed in the experimental field for performing validation and achieving precision irrigation scheduling.

A total of 376 data points (n = 376) were used for calibration of single probe Type-I sensors (152.4 mm, 304.8 mm). Similarly, number of data points (readings) used for calibration of double probe Type-II soil moisture sensors (152.4 mm, 304.8 mm), and double probe Type-III soil moisture sensors (152.4 mm, 304.8 mm) were 504 and 509, respectively.

***Evaluation criteria and statistical analysis for indigenized sensors*:** Four statistical measures were computed to compare and evaluate each model predicted (P) moisture content with that observed (O) by Gravimetric Method (bucket method). These include, mean bias error (MBE), root mean square error (RMSE), and index of agreement (k), as defined by Willmot (1982). The coefficient of determination ($R^2$) was also determined. The coefficient of correlation (r), which indicates the comparison between the calculated and the actual water content; Root Mean Square Error (RMSE), which indicates accuracy of calibration equation to predict actual water content; and the Mean Bias Error (MBE), which is an indicator of sensor's accuracy in the form of the difference between means of the calculated and actual water contents, were calculated using following equations.

***Mean bias error:***

$$MBE = n^{-1} \sum_{i=1}^{n} (P_i - O_i) \quad (5)$$

***Root mean square error:***

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \quad (6)$$

***Index of agreement:***

$$k = 1 - \left[ \frac{\sum_{i=1}^{n} (P_i - O_i)}{\sum_{i=1}^{n} \left( IP_i^{/} I - IO_i^{/} I \right)^2} \right] \quad (7)$$

Where n is the sample size, $P_i^{'}=P_i-O^{-}$ and $O_i^{'}=O_i-O^{-}$. The units of MBE and RMSE are volumetric water content (%), where as k is dimensionless. Many researchers indicated that in most agricultural and research applications the measurement accuracy needs to be within 0.01 to 0.02 cubic meter per cubic meter ($m^3\ m^{-3}$). Hence, MBE under 2.5% and RMSE less than 5% fit this criterion. The scale of k ranges between 0-1, with higher numbers representing greater correlation between the model prediction and observations.

Soil moisture measurement by Type-I, II, and III soil moisture sensors was completed with reference to the Gravimetric Method. Complete measurement of soil moisture content was done on volumetric basis. The final results of soil moisture measurement are represented by $y_n$ and $x_n$ i.e. percent volumetric moisture content measured with Gravimetric Method and Type-I, II & III sensors respectively.

## RESULTS AND DISCUSSION

Statistical analysis of the laboratory calibration data collected for performance of the various indigenized sensors has been presented in Table 3. As per recommendations of Willmot (1982) the statistical parameters measured were; the coefficient of determination ($R^2$), mean bias error (MBE), root mean square error (RMSE) and index of agreement (k).

***Type-I (Single Probe) Indigenized Soil Moisture Sensors*:** The online soil moisture status/values are presented in Figure 8 (a to f) depicted that single probe steel soil moisture sensors responded well to amount of water application from bottom of bucket and calibration equations resulted in water content levels similar to values determined from Gravimetric measurements. The data collected during calibration of single probe soil moisture sensors have been presented in Figure 8 (a to f), whereas regression equations are for sensors based soil moisture monitoring; have been presented in Figure 9 (a to f).

**Table 3. Evaluation of Type-I, Type-II and Type-III indigenized soil moisture sensors (CALIBRATION).**

| Material and length | 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 |

The high values of coefficient of determination ($R^2$) indicated that best fit models for the data were achieved.

**Table 4. Evaluation of Type-I, Type-II and Type-III indigenized soil moisture sensors (VALIDATION).**

| Material and length | Sample size (n) | MBE (%) | RMSE (%) | k |
|---|---|---|---|---|
| **A. Type-I (Single probe) indigenized soil moisture sensors** | | | | |
| Copper-30.48 cm (304.8 mm) | 140 | 2.58 | 30.48 | 2.56 |
| Copper-15.24 cm (152.4 mm) | 140 | -0.24 | 2.89 | 1.32 |
| Brass-30.48 cm (304.8 mm) | 140 | -0.50 | 5.91 | 1.28 |
| Brass-15.24 cm (152.4 mm) | 140 | 0.69 | 8.22 | 0.69 |
| Steel-30.48 cm (304.8 mm) | 140 | -0.10 | 1.21 | 0.78 |
| Steel-15.24 cm (152.4 mm) | 140 | -0.04 | 0.50 | 0.67 |
| **B. Type-II (Double probe) indigenized soil moisture sensors** | | | | |
| Copper-30.48 cm (304.8 mm) | 478 | -5.82 | 127.32 | 23.59 |
| Copper-15.24 cm (152.4 mm) | 478 | 3.89 | 85.02 | 2.55 |
| Brass-30.48 cm (304.8 mm) | 478 | -11.51 | 251.66 | -1.24 |
| Brass-15.24 cm (152.4 mm) | 478 | -40.27 | 880.41 | -0.22 |
| Steel-30.48 cm (304.8 mm) | 478 | -0.03 | 0.45 | 0.96 |
| Steel-15.24 cm (152.4 mm) | 478 | -0.02 | 0.48 | 0.91 |
| **C. Type-III (Double probe) indigenized soil moisture sensors** | | | | |
| Galvanized Steel-15.24 cm (152.4 mm) | 472 | 1.78 | 3.22 | 0.81 |
| Galvanized Steel-30.48 cm (304.8 mm) | 472 | 1.98 | 3.34 | 0.66 |

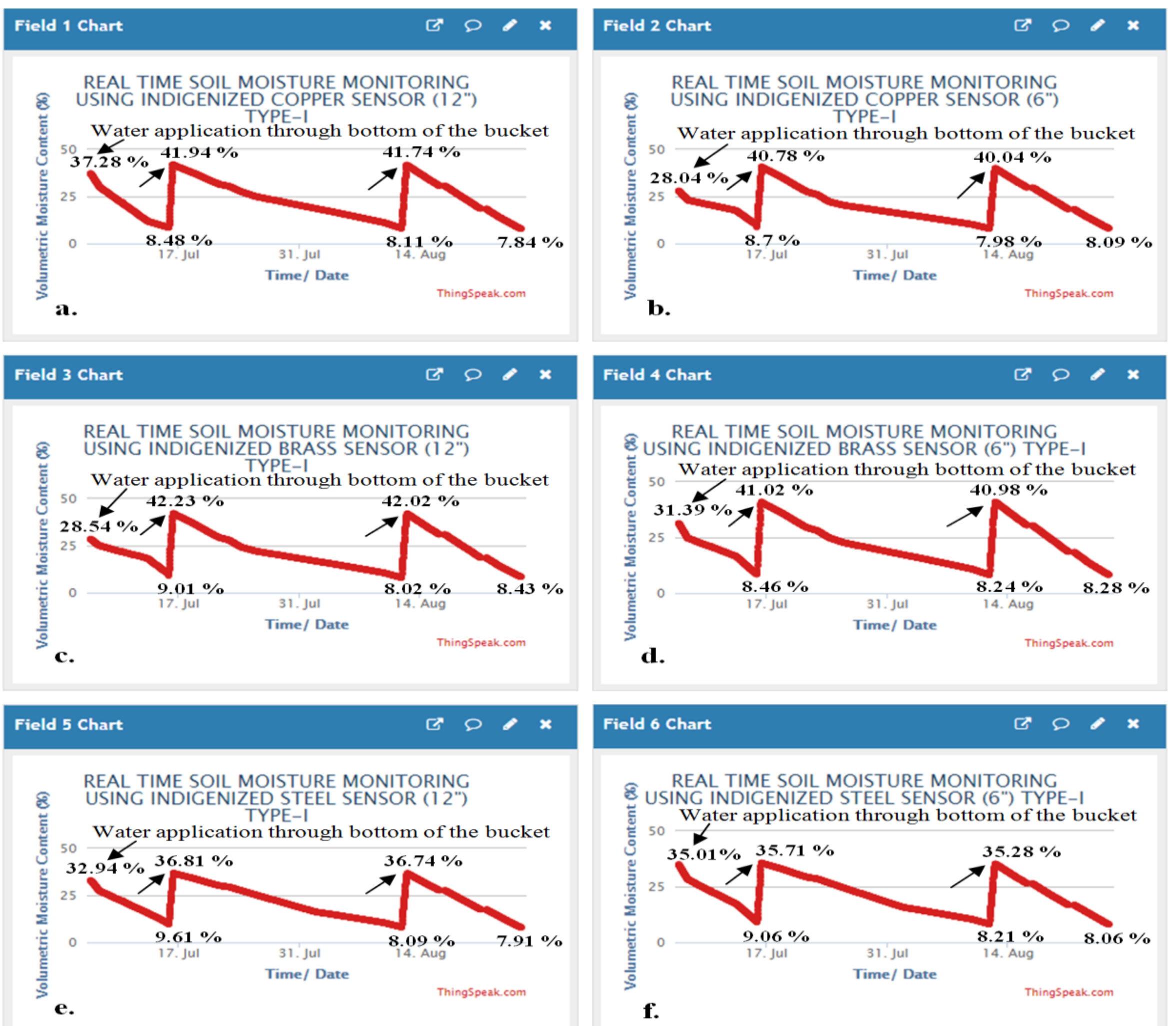



**Figure 8 (a to f). Real time volumetric soil moisture data for Type-I (single probe) indigenized soil moisture sensors.**

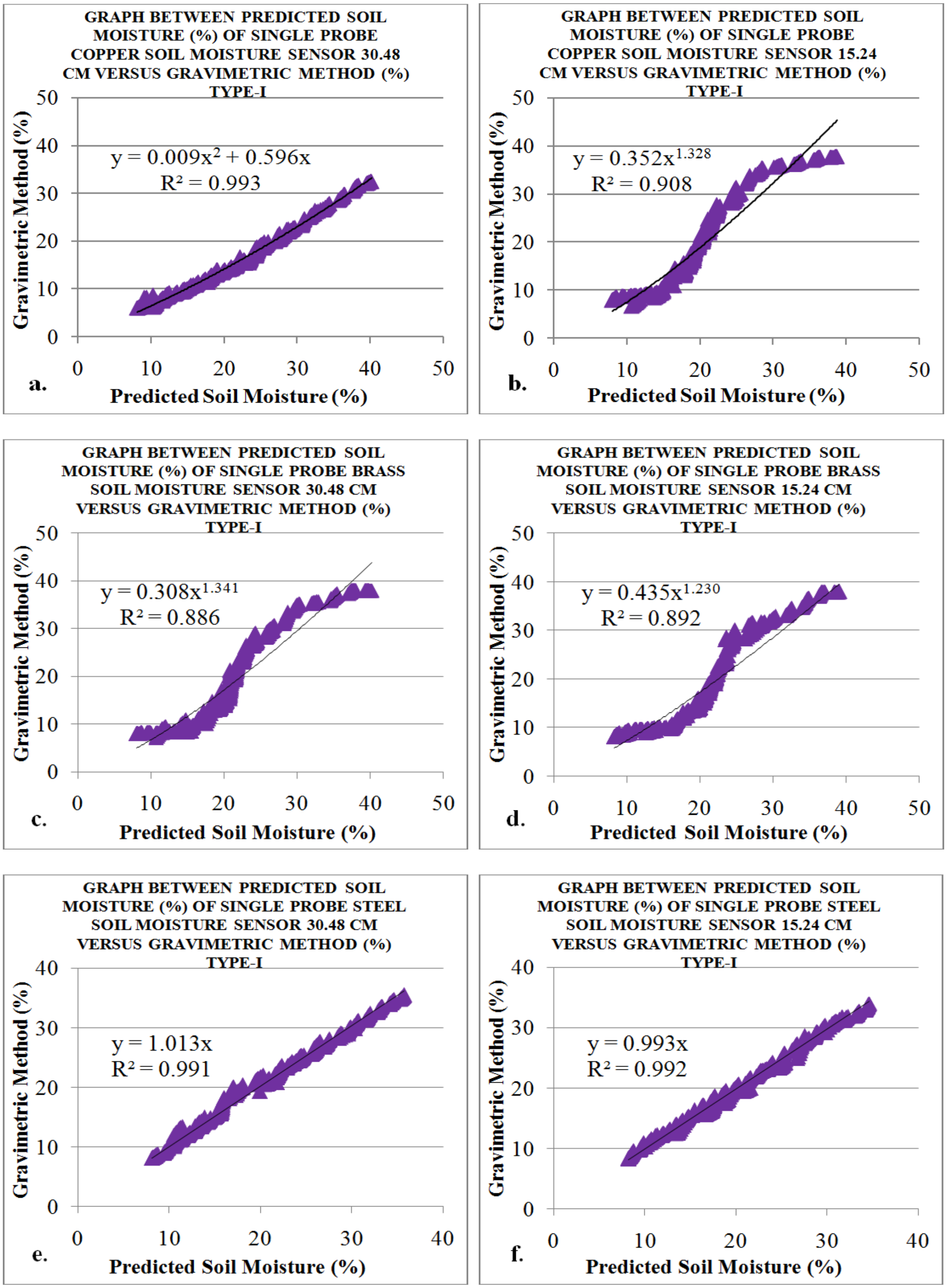



**Figure 9 (a to f). Regression Analysis indicating best-fit lines for single probe indigenized soil moisture sensors of copper, brass, and steel (15.24 cm and 30.48 cm).**

High values of coefficient of determination ($R^2$) ensured the implementation of best fit linear/power/polynomial models for the data observed. Soil moisture status values were observed through bucket installed indigenized soil moisture sensors for the complete soil saturation cycle i.e. from the time when soil moisture was at saturation, at field capacity (FC) and then to the time it was at permanent wilting point (PWP). It was also assumed that right after water application inside bucket, the soil around the soil moisture sensors reached the complete saturation.

***Type-II (Double Probe) Indigenized Soil Moisture Sensors*:** Figure 10 (a to f) depicts the real time soil moisture status monitored by Type-II (double probe) soil moisture sensors, while the calibration equations along with $R^2$ values are presented in Figure 11 (a to f). Figure 10 show that the soil moisture status was observed from the time when bucket soil moisture was at saturation to the time when it was at Permanent Wilting Point (PWP). It was observed that double probe indigenized soil moisture sensors had good response at all the stages, i.e. saturation, at Field Capacity and PWP during calibration and validation phases. The high values of cofficient of determinations ($R^2$ = 0.939 to 0.999) depicted that most suitable regression equations (linear/power/ polynomial) for the data were achieved, as shown in Figure 11 (a to f).

***Type-III (Double Probe) Galvanized Steel Soil Moisture Sensors*:** The real time soil moisture status presented in Figure 12 (a & b) depicted that Type-III (double probe) galvanized soil moisture sensors responded well to small amount of irrigation and calibration equations resulted in water content levels similar to values determined from Gravimetric measurements. The regression or calibration equations presented in Figure 13 (a & b) were developed for soil moisture sensors data collected during calibration showed high values of coefficient of determination ($R^2$ = 0.997 & 0.998) which ensured implementation of the best fit linear models for the data observed.

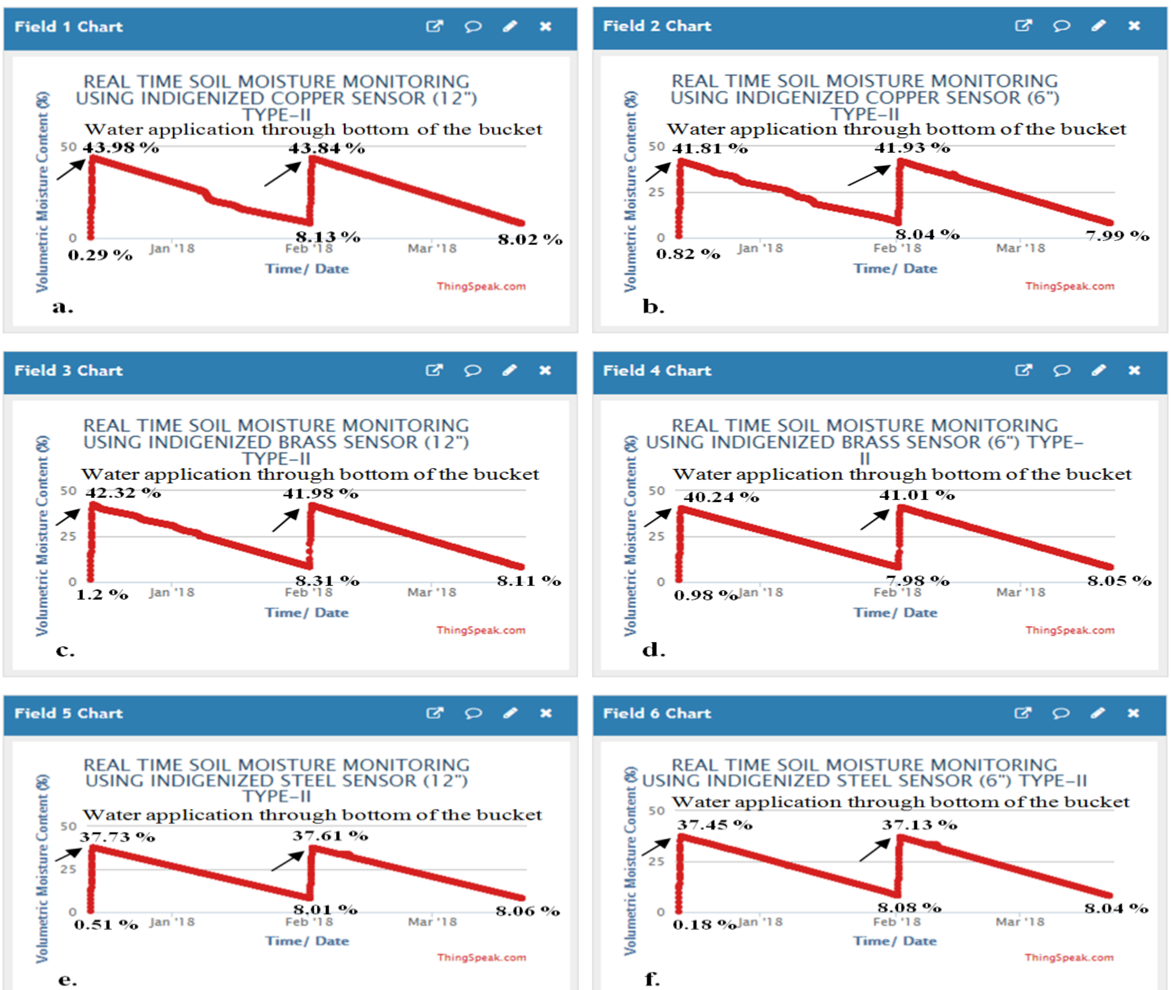



**Figure 10 (a to f). Real time volumetric soil moisture data for Type-II (double probe) indigenized soil moisture sensors.**

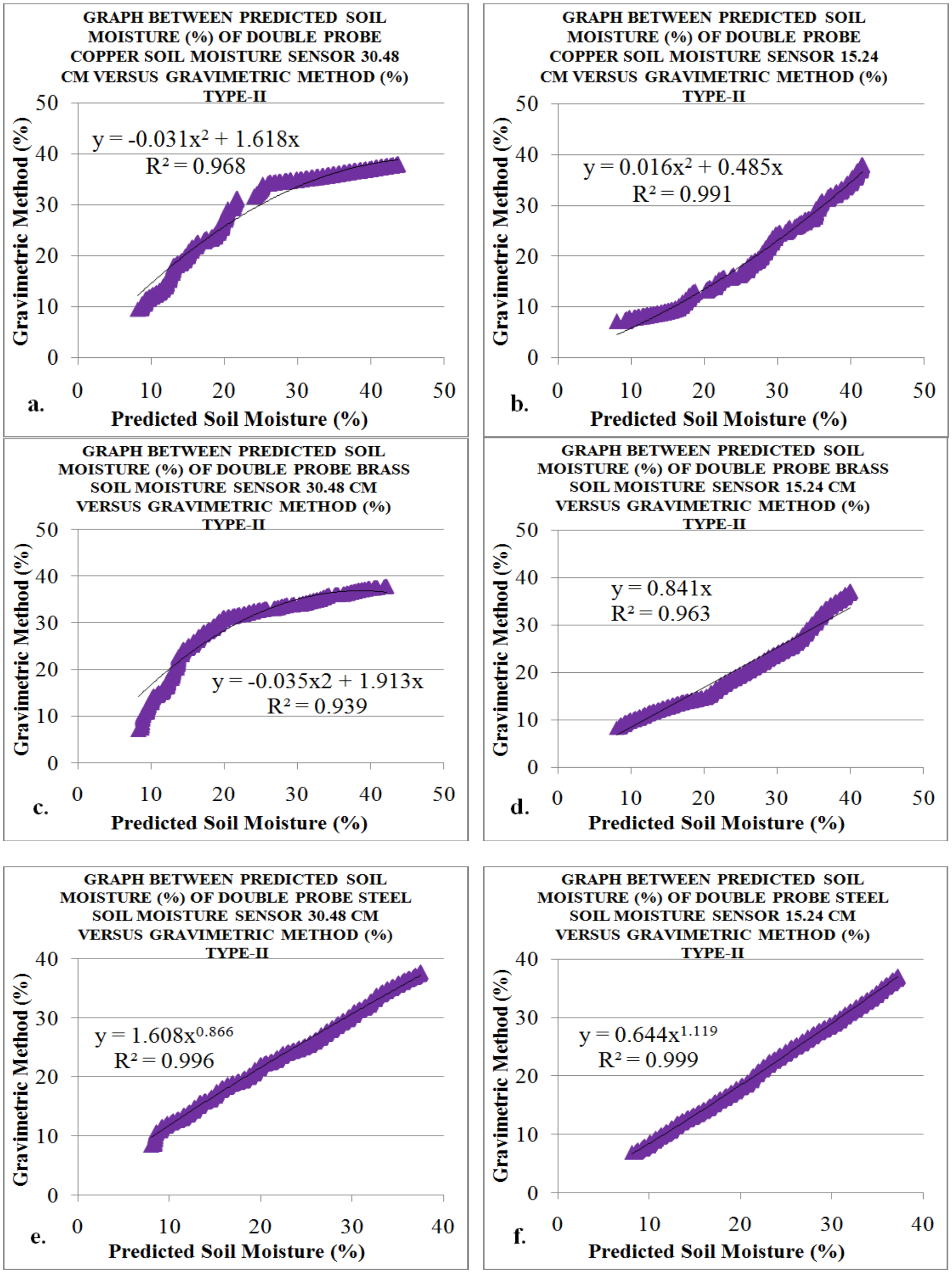



**Figure 11 (a to f). Best fit prediction equations for double probe indigenized soil moisture sensors of copper, brass, and steel (15.24 cm and 30.48 cm).**

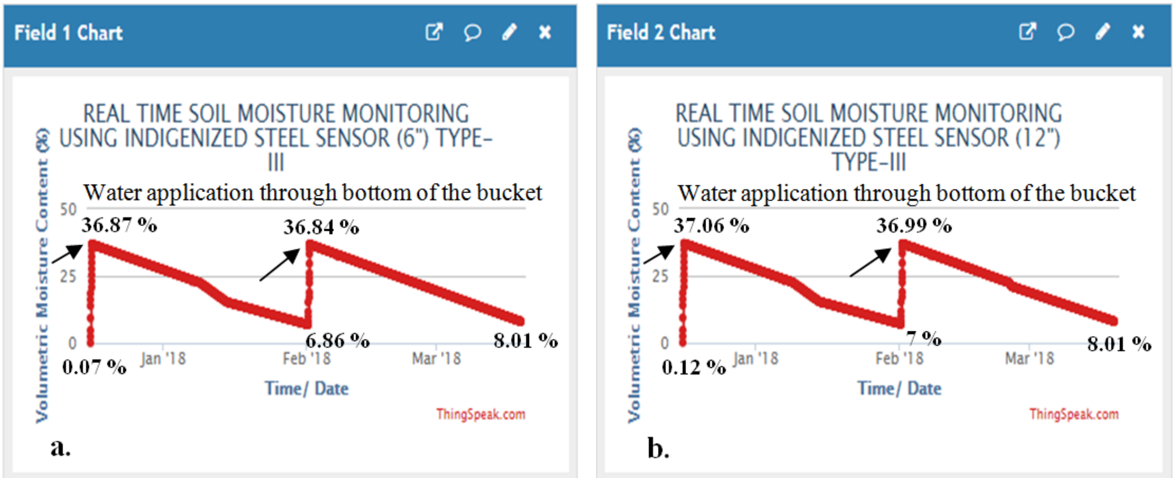



**Figure 12 (a & b). Real time volumetric soil moisture data for Type-III (double probe) galvanized steel soil moisture sensors.**

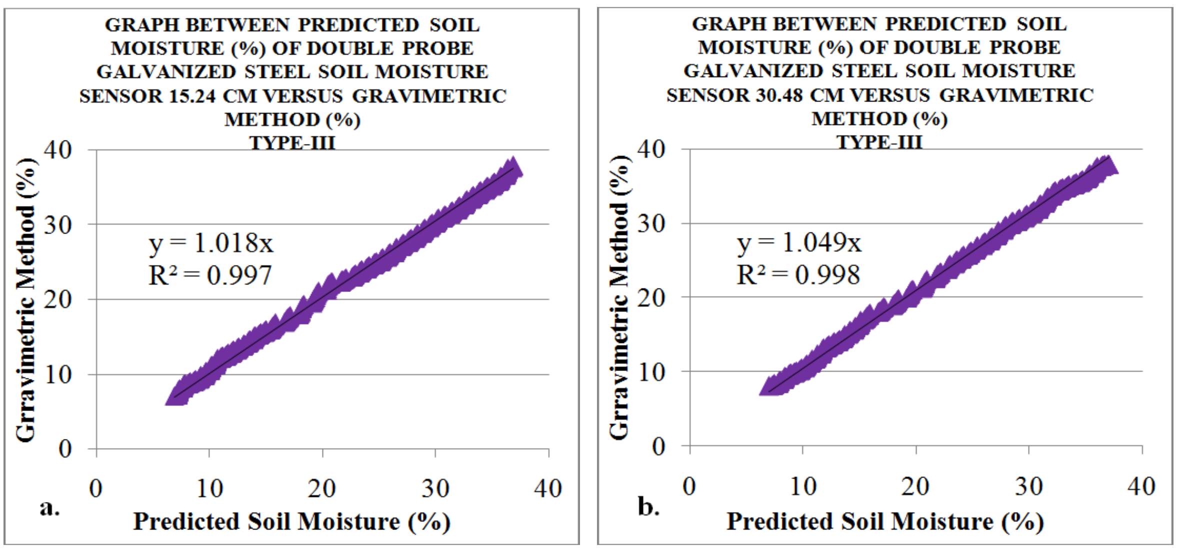



**Figure 13 (a & b). Regression Analysis indicating best-fit lines for double probe indigenized soil moisture sensors of galvanized steel (15.24 cm and 30.48 cm) calibration curves.**

The calibration equations were applied to the field installed sensors and the results compared with field sensors moisture content values (θv) for scheduling irrigation to produce fruitful results. The indigenized galvanized steel soil moisture sensor for double probe (30.48 cm), was found best as per calibration and validation as compared to indigenized double probe steel sensor of 15.24 cm length.

From the above results, it can be seen that for both Type-I and Type-II sensors, steel sensors performed best with $R^2$ values of about 0.99 and RMSE in the range of 3.30 to 3.50 percent during calibration. It was observed that 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. In short, steel material was found the best for manufacturing both Type-I and Type-II sensors. The performance of Type-III galvanized steel soil moisture sensors was also found at par with Type-I and Type-II sensors. However, the fabrication of Type-I and Type-II sensors is laborious involving operation of CNC Lathe Machine for developing probes and other soldering operations, which also increases their cost. Compared with this, Type-III sensors require only two pieces of galvanized steel rod, and are, therefore, low cost and easy to fabricate. Overall, indigenized steel sensors of all the three types were found acceptable for use in soil moisture monitoring for precision irrigation, with about 10 times less cost as compared to imported sensors. 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.

***Conclusions*:** The results of this study support the following conclusions, the low-cost indigenized sensors, designed, developed and fabricated with locally available material, helped in soil moisture determination properly. Steel (152.4 mm, and 304.8 mm) was found as best material as per long life and also with respect of its accurate results in laboratory as well as in experimental fields. Among the tested sensors, steel sensors of both Type-I (single probe) and Type-II (double probe), as well as the Type-III double probe galvanized steel rod sensors performed the best. 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. Indigenization and fabrication of sensors from locally available material be encouraged for sustainable promotion of soil moisture monitoring for precision irrigation.

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