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Standardization of Frequency Domain Reflectometry and Watermark Sensors for Soil Moisture Measurement at Field Level

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ABSTRACT

A field experiment with spilt plot design was carried out for standardization of Frequency Domain Reflectometry (FDR) and Watermark sensors in drip irrigated broccoli (*Brassica oleracea var. italica*). The experiment included three levels of irrigation frequencies: N_1 (once every day), N_2 (once every 2 days) and N_3 (once every 3 days) with three irrigation regimes of 100, 80 and 60 % of crop evapotranspiration (ET_c). For evaluating the performance of different soil moisture sensors, the sensors' readings were taken from the plot on a daily basis and these readings were compared with gravimetric method (standard). It was observed that the calibration of two sensors (FDR and Watermark) give a similar calibration equation with low RMSE after field calibration. The value of coefficient of determination (R^2) for FDR was observed 0.85, 0.86, 0.89 and 0.86 for 0-15, 15-30, 30-45 and 45-60 cm soil depths whereas, the value of coefficient of determination (R^2) for Watermark sensor was observed as 0.76, 0.83, 0.84 and 0.85 for 0-15, 15-30, 30-45 and 45-60 cm soil depths, respectively. The Watermark sensors curves observed less sensitive at low soil moisture tension, whereas FDR sensors performed better in wet as well as dry conditions. Thus field calibration of soil moisture sensors is a prerequisite to measure soil moisture content in the soil.

KEYWORDS

Broccoli, Crop evapotranspiration, FDR, Watermark, Split-plot design

INTRODUCTION

Water is a critical element of sustainable development that sustains all life on earth. In India, agriculture consumes around 80% of our available water resources and becomes the prime consumer of freshwater resources (Anonymous, 2017). Thus, in the agriculture sector, there is an excellent potential to enhance crop water productivity, which necessitates the implementation of judicious water management technologies. Mostly, farmers irrigate their fields manually at regular intervals through various surface irrigation methods with irrigation efficiency very low (about 40%). The ultimate aim of farmers is to always maximize farm profit by improving input use efficiency. The adoption of precise water application can achieve higher irrigation efficiency in the range of 75 to 95% through micro-irrigation like sprinkler and drip, respectively (CWC, 2011). In this regard, the modernization of agricultural practices at the field level is crucial for improving crop water productivity, which can be achieved by pressurized micro-irrigation systems with sensor-based irrigation scheduling. Sensor-based micro-irrigation and fertigation scheduling achieve very high water use efficiency as well as nutrient use efficiency (Patel and Rajput, 2001). Appropriate irrigation scheduling during crop growth is very vital for achieving crop-specific water requirements and enhancing crop water productivity. Irrigation scheduling is primarily based on when and how much water is to be applied to the field as per crop water need. Maintaining the soil moisture near about field capacity during the entire crop season is expected to result in more crop growth and high yields (Andrade *et al*., 2001).

Orthodoxly, irrigation scheduling is mainly performed either by soil moisture measurement or by using soil water balance calculations, which is difficult and time-consuming. Sensor-based irrigation scheduling provides the most precise and time effective on real-time basis. Apart from it, sensor-based irrigation scheduling has been demonstrated to address the challenges of higher productivity with greater resource-use efficiency by applying water as per the temporal and in-season variability, particularly in developed countries and it is not in infancy yet the widespread use of sensors is now picking up fast in India. The practice of gypsum resistance blocks as soil moisture sensor was first suggested by Shull and Dylla (1980). Francesca *et al*.(2010) compared the performances of two capacitance sensors and one Time Domain Reflectometer (TDR) sensors with gravimetric data. Results showed that the capacitive sensors could be used in each category of soil with the same calibration equation, independent of depth, whereas soil moisture determination with TDR probes showed a dependence on depth.

Similarly, Varble and Chavez (2011) examined the performance of three soil moisture sensors (CS616, TDT, 5TE) and a soil water potential sensor (watermark 200SS) in laboratory as well as field conditions and soil moisture/ potential values measured by the sensors were compared with corresponding volumetric water content values obtained from gravimetric soil sampling. They found that the measurement of soil moisture sensor reading was affected by increasing soil electrical conductivity. Results also revealed that the performances of CS616, 5TE and watermark sensors were influenced by diurnal fluctuation in soil temperature. Similarly, Girisha *et al.* (2012) have also evaluated the accuracy of three low-cost soil moisture sensors (ECH2O-5TE, watermark 200SS and tensiometer model R) and

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observed that the sensors needed site-specific calibration to improve their accuracy in determining soil moisture data. Keeping in view of the researchable issues pertaining to soil moisture sensor-based irrigation scheduling indicated that though some researchers have introduced and used few soil moisture sensors for irrigation scheduling, no significant adoption has taken place in the field. For an appropriate understanding of soil moisture distribution, research is needed on sensor-based drip system to improve irrigation scheduling strategy. The performance of soil moisture sensors is also affected by number and type of sensors, depth of placement, etc. Apart from it, research for the use of sensors in irrigation scheduling in the open field conditions is lacking in India. The most prominent constraint for the adoption of this technology is the cost of soil moisture sensors, which restrict its use to the poor farming community in India. Based on the gaps stated on the above phrases, an experiment was conducted for standardization of Frequency Domain Reflectometry (FDR) and Watermark sensors in drip-irrigated Broccoli (*Brassica oleracea var. italica*) at field level.

MATERIALS AND METHODS

Study location

Laboratory and field experiments were conducted at a field with well-levelled topography at Precision Farming Development Centre (PFDC), Water Technology Centre, Indian Agricultural Research Institute (IARI), New Delhi to compare soil moisture measured with FDR and Watermark sensors in drip-irrigated Broccoli. Indian Agricultural Research Institute (IARI) is situated in Delhi between the latitudes of 28º37'22″N and 28º39'05″N and longitudes of 77º8'45″ and 77º10'24″E at an average elevation of 228.6 m above the mean sea level. The climate of the study area is semi-arid with dry and hot summers as well as cold winters. The average annual rainfall of Delhi is about 750 mm, of which 74% is received during active south-west monsoon months, *viz.* July, August and September. The average wind speed is 0.13 to 1.1 km/h.

Frequency Domain Reflectometry (FDR) and Watermark

FDR sensor mainly consists of a pair of circular metal rings that are formed into a capacitor and the soil act as a dielectric. The probes measure the soil moisture content on a volumetric basis by measuring dielectric constant. Its main advantages are faster response time and wider operating range. The electronics of the system measures the frequency shift rather than a change in time. Whereas the watermark sensor is mainly electrical resistance blocks that measure the resistance between the electrodes buried into the soil and directly correlated to soil moisture tension. The working range of the watermark is 0-200kPa. It is user-friendly, robust, frost proof and low cost as compared to FDR.

Experimental design

A field experiment was carried out on a plot with dimensions of 29m x 15m (435 m^2). Texture of the field plot was sandy loam with moderate water holding capacity. The entire field was divided into three equal parts of dimension 9 m x 15 m and a buffer strip of 1 m was provided in between the two plots for separating one plot from another. The main and sub-main lines were laid on the buffer strip. The irrigation in each plot was performed with 16 mm diameter of 9 laterals. Each lateral is equipped with 9 in-line drippers' with 50 cm spacing and discharge of 2 lph. The experiment was planned in a split-plot design with 9 treatments and 3 replications. The layout representing different treatments is shown in Fig. 1.

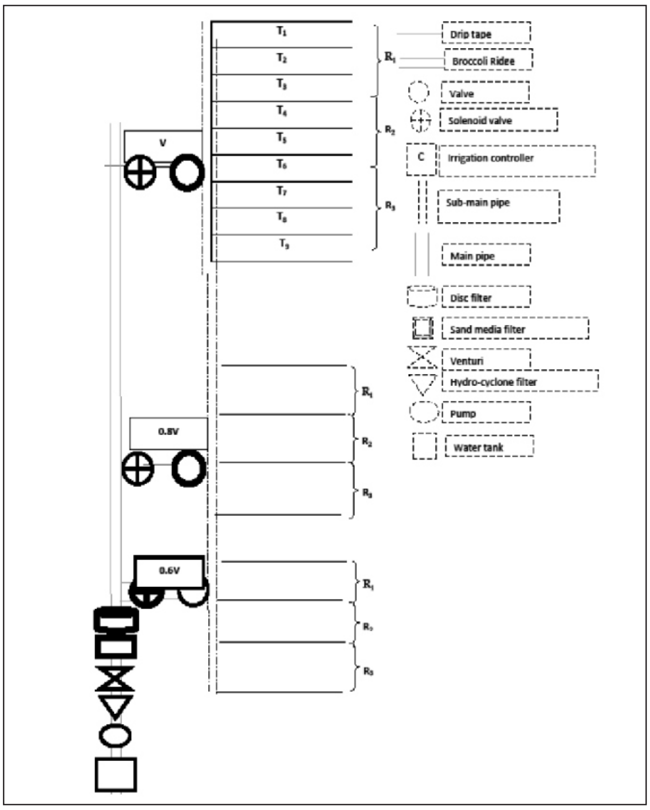

Fig. 1: Layout of different treatments and replication with Broccoli crop

Soil moisture sensors namely FDR and watermark sensors, were installed in one replication of each treatment at different depth up to 60 cm (Fig. 2). The treatments considered in the study are given below:

- T_1: 100% water requirement of ET_c with daily irrigation
- T_2: 80% water requirement of ET_c with daily irrigation
- T_3: 60% water requirement of ET_c with daily irrigation
- T_4: 100% water requirement of ET_c with irrigation once in 2 days
- T_5: 80% water requirement of ET_c with irrigation once in 2 days
- T_6: 60% water requirement of ET_c with irrigation once in 2 days
- T_7: 100% water requirement of ET_c with irrigation once in 3 days
- T_8: 80% water requirement of ET_c with irrigation once in 3 days
- T_9: 60% water requirement of ET_c with irrigation once in 3 days

Fig. 2: Field installation of a) Access tube for FDR and b) Watermark sensors

The sensors' readings were regularly taken in different treatments of each replication. At the same time, soil samples were collected and their moisture content was determined by gravimetric methods to calibrate the sensors. The soil samples were also analyzed for determining the physical properties of soils like bulk density, field capacity, permanent wilting point and hydraulic conductivity (Table1).

Table 1: Physical properties of the soil of PFDC, WTC

Depth (cm)	Particle size distribution (%)			Hydraulic conductivity	Bulk density	Field capacity	Permanent wilting
	Sand	Silt	Clay	(cm/h)	(g/cm^3)	(%)	point (%)
0-15	67.3	14.7	18.0	1.65	1.63	17.42	7.78
15-30	65.6	13.7	20.7	1.12	1.48	19.65	9.10
30-45	65.4	13.2	21.4	1.06	1.48	18.16	10.36
45-60	64.8	13.5	21.7	1.55	1.61	18.22	10.71
Avg.	65.8	13.8	20.45	1.345	1.55	18.36	9.49

The soil moisture content in a volumetric basis was expressed by multiplying gravimetric moisture content measured in weight basis with the corresponding bulk density of soils at different depths. Soil moisture characteristic curves at various matric potentials were also determined by using the pressure plate apparatus. The sensors' reading of Watermark (in matric potential) was converted into volumetric moisture content with the help of a calibration chart, whereas FDR measures the soil moisture content on a volumetric basis. Now, Watermark sensors and FDR were calibrated by fitting a regression relationship between the soil moisture measured by the gravimetric method to that of FDR and Watermark sensors up to a soil depth 60 cm.

The statistical parameters, i.e. coefficient of determination (R^2), root mean square error (RMSE), relative root mean square error (RRMSE) and mean difference (MD) was used to assess the performance of each sensor against the moisture measured by gravimetric method. The mean deviation (MD) indicates whether the sensors are over/ underestimating and the value of MD equal to zero signifies perfect measurement. The Root mean square error (RMSE) measures the average precision of the sensors and it should be as small as possible. The MD and RMSE were calculated by equations.

$$MD=\Sigma_{i=1}^{n}(P_i-O_i)/n \quad (1.1)$$

$$RMSE = \sqrt{\sum_{i=1}^{l} P_i - O_i)^2 / n} \quad (1.2)$$

P_i= Volumetric moisture content obtained by soil moisture sensors;
O_i= Volumetric moisture content obtained by gravimetric methods:
O= Mean of volumetric moisture content obtained by gravimetric methods;
n = Total no of samples

The coefficient of determination (R^2) was used for calculating the degree of similarity between the sensors' readings and gravimetric measurements. The values of MD and RRMSE being close to zero indicate a better performance of sensors. A paired *t*-test was also employed to calculate the mean of the difference between calibrated sensors.

RESULTS AND DISCUSSION

The wide range of irrigations applied during different treatments ensured a wide range of soil moisture variability in the field, suitable for the calibration process. Soil moisture characteristic curve is shown in Fig. 3. The regression relationship between soil moisture content measured by gravimetric method (standard) and moisture content obtained by FDR installed at different soil depth up to 60 cm are shown in Figs. 4 to 7. The regression relationship between the soil moisture measured by the gravimetric method to that of watermark sensors up to soil depth 60 cm was developed and is shown in Figs. 8 to 11.

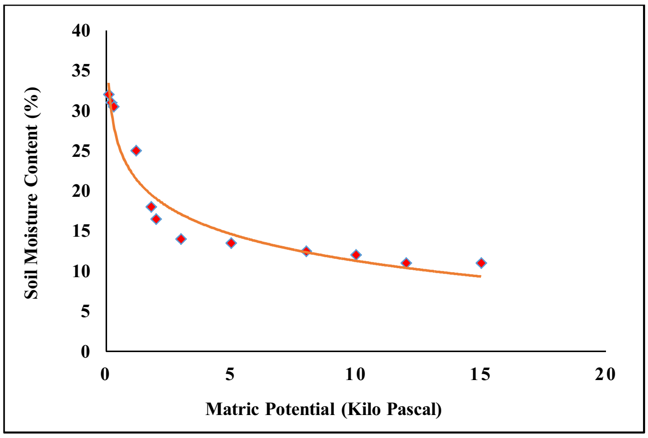

Fig. 3: Soil Moisture Characteristic curve

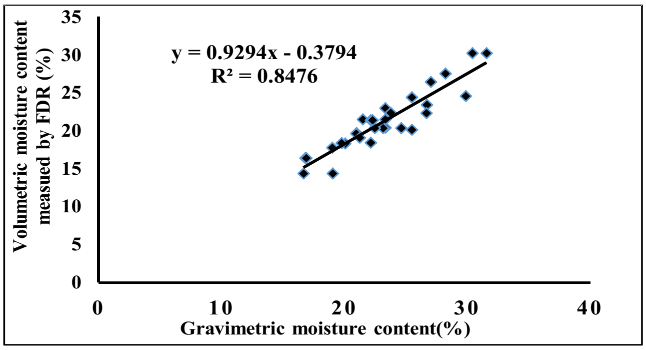

Fig. 4: Regression relationship between moisture measured by gravimetric and FDR sensor at 15 cm soil depth

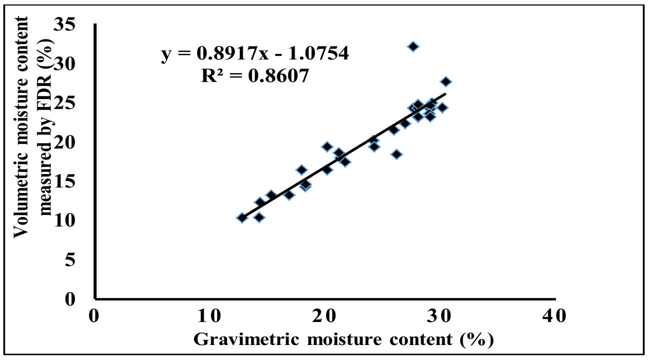

Fig. 5: Regression relationship between moisture measured by gravimetric and FDR sensor at 30 cm soil depth

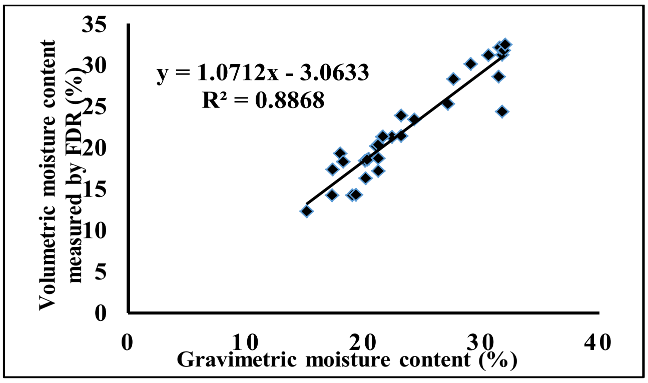

Fig. 6: Regression relationship between moisture measured by gravimetric and FDR sensor at 45 cm soil depth

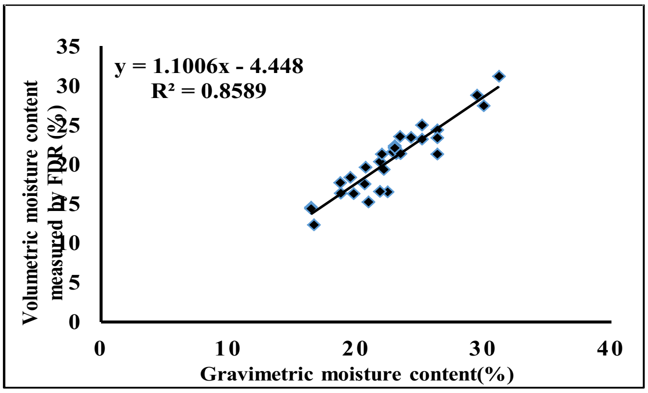

Fig. 7: Regression relationship between moisture measured by gravimetric and FDR sensor at 60 cm soil depth

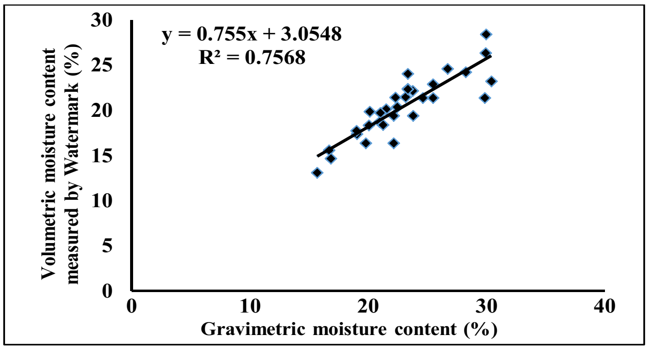

Fig. 8: Regression relationship between moisture measured by gravimetric and Watermark at 15 cm soil depth

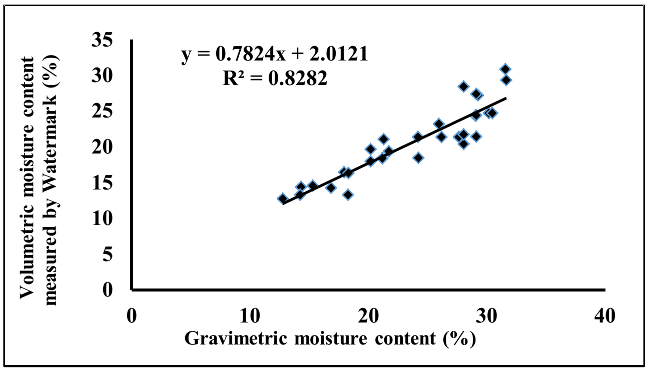

Fig. 9: Regression relationship between moisture measured by gravimetric and Watermark at 30 cm soil depth

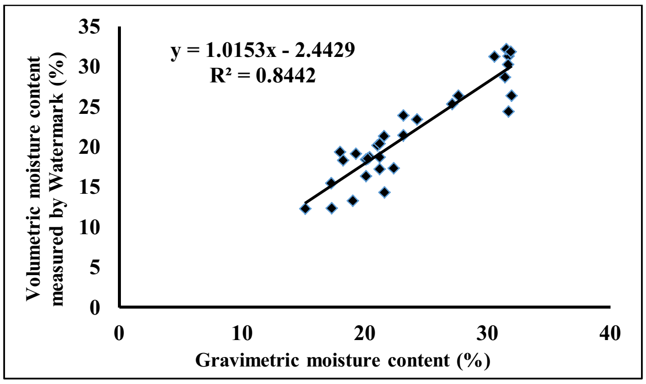

Fig. 10: Regression relationship between moisture measured by gravimetric and Watermark at 45 cm soil depth

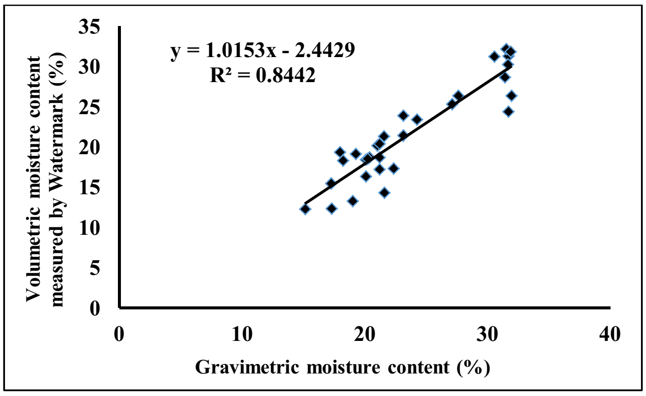

Fig. 11: Regression relationship between moisture measured by gravimetric and Watermark at 60 cm soil depth

Statistical analysis of sensors' performance at different soil depths up to 60 cm

The statistical measures such as the coefficient of determination (R^2), Mean difference (MD), root mean square error (RMSE) and relative root mean square error (RRMSE) were computed for comparative study of performance evaluation of different soil moisture sensors (FDR and Watermark) in terms of their outputs correlated with standard method of soil moisture measurement, i.e., gravimetric method. The statistical summary of the sensors' performance at different soil depths is shown in Table 2.The sensors were evaluated in broccoli crop up to 60 cm depth. There gression relationship between moisture measured by gravimetric method and volumetric moisture content obtained by FDR sensor installed at different soil depth showed the value of the coefficient of determination (R^2) 0.85, 0.861, 0.89 and 0.859 for 0-15, 15-30, 30-45 and 45-60 cm soil depth, respectively. Whereas, the value of the coefficient of determination (R^2) for Watermark was estimated as 0.76, 0.83, 0.84 and 0.85 for 0-15, 15-30, 30-45 and 45-60 cm soil depth, respectively (Table 2).

Table 2: Statistical analysis of the sensors' performance at different soil depths in Broccoli

Sensor	Depth (cm)	RMSE	RRMSE (%)	R^2	The correlation coefficient between sensors &gravimetric measurements
FDR	15	2.52	10.87	0.85	0.921
	30	4.17	17.60	0.861	0.928
	45	2.45	10.39	0.89	0.942
	60	2.72	11.93	0.859	0.927
Watermark	15	3.20	13.94	0.76	0.870
	30	3.98	16.65	0.83	0.910
	45	3.11	13.15	0.84	0.919
	60	2.13	9.06	0.85	0.923

The Mean Difference (MD) and the Relative Root Mean Square Error (RRMSE) resulting from the statistical analysis were used to evaluate the degree of coincidence of the sensor's readings with that obtained by gravimetric method. The negative/positive value of MD shows that the soil moisture sensors underestimated or overestimated. A smaller RRMSE indicates better performance. The value of RRMSE was obtained lesser at depth 45 cm for FDR and 60 cm for Watermark sensors. Therefore, it was inferred from the measured data that watermark captured the major pattern of soil moisture distribution variation with time in dry conditions, whereas FDR sensors consistently captured the variations of the soil moisture distribution with increasing soil depth. Thus, FDR sensors performed better both in wet as well as dry conditions as compared to watermark sensors. Paired *t-Test* was also performed to check the statistical significance between FDR and Watermark (Table 3).

Table 3: Paired t- Test of different soil moisture sensors up to depth 60 cm in Broccoli

Depth (cm)	Type of sensor	Mean	SD	t-value	d.f.	Sig. (2-tailed)
	Paired samples test					
0-15	FDR	21.17	3.88	1.27	30	0.056*
	Watermark	20.40	3.40			
15-30	FDR	20.04	5.29	-1.15	30	0.26
	Watermark	20.74	4.98			
30-45	FDR	22.17	5.9	1.54	30	0.134
	Watermark	21.55	5.94			
45-60	FDR	20.62	4.36	-1.67	30	0.106
	Watermark	22.14	4.32			

*Significant at 10% ($p \leq 0.10$); SD: Standard Deviation

The estimation of soil moisture content is a critical factor in achieving correct irrigation schedules and maintaining an optimum level of soil moisture in the crop root zone. It is also essential for precise and reliable irrigation scheduling. There are various sensors available for obtaining soil moisture including, FDR and watermark. Comparative study of gravimetric (standard) and sensors' readings demonstrated that field calibration is preferable than using the manufacturers supplied calibration. Similar results were observed by the other researchers for the same or different dielectric sensors and found that the sensors needed site-specific calibration to improve their accuracy in estimating soil moisture content data (Soulis *et al.,* 2015; Datta *et al.,* 2018; Kargas and Soulis, 2019).

Again, it was inferred from the measured data that Watermark sensors captured the major pattern of soil moisture distribution variation with time in dry conditions, whereas FDR captured soil moisture well both in wet and dry conditions. Thus, FDR displayed the best performance; however, the sensor is the most expensive as compared to watermark sensors and also not very convenient in-field operation because of fixing of access tubes when profile measurements and multi-point measurements are required. Whereas Watermark being the low cost to purchase but the reason responsible for the under performance of the resistance type sensors and the resistance type needs to calibrate every time, more temperature-sensitive. But the sensor is simple, light, and easy to handle in fieldwork. Being easily connected to a data logger, the watermark sensor can be applied to obtain temporal and spatial measurements of soil water contents at the root zone. Apart from it, the field calibration of different soil moisture sensors improves their accuracy for measuring the soil moisture content. It was recommended to use field-based calibrations developed over laboratory-based calibrations or manufacturers supplied calibrations to improve their accuracy in estimating soil moisture content.

CONCLUSION

It was concluded that at 15 cm soil depth, the mean performance of FDR and Watermark are significant at 5% level of significance but non-significant at 30-60 cm depth and inferred that any one of pair used at above-mentioned depth. It was also observed that the calibration of two sensors (FDR and Watermark) gave similar calibration equations, having quite low RMSE and ensuring good performance after field calibration. In this experiment, it was found that the sensors behaved differently at different soil depths and were more influenced by diurnal soil moisture variations. Thus, the depth of placement of sensors in the crop root zone is more critical for irrigation scheduling. The field calibration equations developed were unique for each sensor and soil conditions.

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