A Laboratory Procedure for the Calibration of EC-10 and EC-20 Capacitance Sensors in Coir

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Summary

A new laboratory calibration procedure is presented to calibrate soil water sensors in coir. Water content was measured gravimetrically with load cells during a drying cycle determined by the evaporative demand of the environment as well as the water retention characteristics of the growth medium (coir). Sample mass and capacitance sensor output (mV) was measured and logged hourly. Excellent precision fits, indicated by R^2 values greater than 0.99, for sensor response versus volumetric water content (θ_v) were achieved by 4th degree polynomial curves. Accuracy of sensor-specific calibration was within 0.002 to 0.005 $m^3\ m^{-3}$ root mean squared error (RMSE) for the EC-10 sensors and 0.002 to 0.003 $m^3\ m^{-3}$ RMSE for the EC-20 sensors. This indicated that the instruments are very reliable and capable to measure water content of coir over the entire range from saturation to the lower limit of plant available water. Accuracy of a universal coir calibration was 0.05 and 0.025 $m^3\ m^{-3}$ RMSE for the EC-10 and EC-20 sensors, respectively. Although the universal equations were less reliable than the individual equations, they still outperformed the equations provided by the manufacturer. The manufacturer's default calibration for soil underestimated θ_v of coir by a large margin of 0.25 to 0.29 $m^3\ m^{-3}$ RMSE for the EC-10 sensors and 0.27 to 0.33 $m^3\ m^{-3}$ RMSE for the EC-20 sensors. It was therefore strongly recommended that the manufacturer's equations should be replaced by the universal equations when using coir. Regular re-calibration was found to be important for organic growth mediums, since they may deteriorate over time. In conclusion, it stressed the need for a reliable and accurate determination of calibration equations.

Key words. capacitance – growth medium – soil water sensors – water content

Introduction

Worldwide, soil water sensors have changed the landscape of managing irrigation water in crops. Recent advances in soil water sensor technology provide a large variety of soil water sensors on the market. The most commonly used types of soil water sensors include dielectric sensors (e.g. time domain reflectometry and capacitance sensors), neutron scattering and tensiometers (Leib et al. 2003; Dorais et al. 2005; Fares and Polyakov 2006). Of these, capacitance techniques have become very popular because of their low cost, simplicity, sensitivity to water content, speed of measurements, continuous monitoring, and lack of radiation (van Rensburg 2010). However, development of new and improved calibration procedures has lagged behind rapid changes in instrument technology. This leaves scope for improvement on current calibration procedures.

The standard calibration procedures for soil water sensors are based on the principle that instrument output is measured against a gravimetric value of water content. This can be done either in the field or the laboratory. The calibration procedure for soil water sensors has changed little since the development of these instruments. A detailed discussion of the calibration procedure for capacitance sensors can be found in Starr and Paltineanu (2002) and

Cobos and Chambers (2010). The procedure basically comprises measuring sensor readings in the field, or in an undisturbed soil core or soil packed to original bulk density in the laboratory. These readings are calibrated against gravimetric water content values attained from weighing samples collected close to the sensor, before and after drying. The sampling for gravimetric water content is destructive and therefore the soil used for laboratory calibration must often be repacked to attain the next calibration point. Similarly, calibration in the field requires re-installation of the sensor in a new position after the collection of a sample. The procedure is repeated at several water contents until saturation is reached, to attain a calibration curve (Starr and Paltineanu 2002; Cobos and Chambers 2010).

Disadvantages of field calibration are labour- and time-intensiveness, which is mainly due to the destructive sampling as well as the waiting period required to reach the desired soil water content (Starr and Paltineanu 2002). In addition, spatial variation in the field may be large over small areas. Repacking of soil in the laboratory also makes this calibration procedure time-intensive although less than field calibration. In field and laboratory calibration, these factors lead to a calibration curve developed from very few data points. This may create doubt with regard to consistency of the instruments and measure-

ments, since calibration equations are derived from single data points while the sensor response over time is not considered. Sensitivity of sensors to salinity, bulk density and texture is frequently explored and incorporated into multiple regressions (TOMER and ANDERSON 1995), although these factors may also vary between single data points. All of the above-mentioned factors may create concern with regard to the precision and accuracy of calibration.

The use of coir as a growth medium in hydroponic production is gaining popularity due to improved yields of hydroponic crops (COLLA et al. 2003; HALMANN and KOBRYŃ 2003). However, coir varies greatly from soil and other growth mediums with regard to water availability and therefore knowledge on irrigation scheduling in coir is limited and irrigation usually managed poorly. As a result, research with coir and soil water sensors commenced, because of good results achieved in soil (THOMPSON et al. 2007).

As soil water sensor technology has advanced swiftly, it has become necessary to develop a new calibration procedure which directly addresses these concerns. Therefore, the objectives of this study were, i) to propose a laboratory procedure for calibrating ECH_2O capacitance water sensors (EC-10 and EC-20), and ii) to evaluate the proposed and manufacturer calibration equations for use in coir.

Material and Methods

Water content measurement

Sixteen ECH_2O capacitance sensors, comprising eight EC-10 and eight EC-20 sensors from Decagon Devices Inc., were used in this experiment. The probe dimensions for EC-10 is 14.5 cm × 3.17 cm × 0.15 cm and for EC-20 is 25.4 cm × 3.17 cm × 0.15 cm. Half of the sensors for both EC-10 and EC-20 were used for calibration and the other half for evaluation of the calibration equations as well as the manufacturer's equations. The frequency of the sensors is ~8 MHz, which makes readings vulnerable to salts in the water and relatively insensitive to temperature (PALTINEANU and STARR 1997). According to CAMPBELL (2001) the EC-10 and EC-20 sensor circuitry minimizes effects due to temperature variation, while the sensor coating somewhat minimizes salinity effects. For the purpose of developing a new calibration procedure, calibration was done at a constant temperature in a climate controlled chamber; while the growth medium used (salt content) were representative of that for crop production conditions. A data logger, model CR1000 of Campbell Scientific, was used to record hourly water content measurements of the sensors in millivolts (mV).

The manufacturer recommends the following linear equations for the calibration of the EC-10 and EC-20 sensors, where θ_v is the volumetric water content and mV is the raw electrical output (DECAGON DEVICES 2006):

EC-10: θ_v (m³ m⁻³) = 0.000936 mV − 0.376
EC-20: θ_v (m³ m⁻³) = 0.000695 mV − 0.290

Use of the water characteristic curve to define boundaries for calibration

The water characteristic curve is a function of water content and absolute values of matric suction of the growth medium. It was determined to define boundaries between which irrigation management will take place, namely saturation and the lower limit (a reference value of 1500 kPa) of plant available water. Large errors resulting from calibration equations that fall outside of these boundaries, especially at the lower end of θ_v (CHANZY et al. 1998), are not considered to be critical for production conditions.

Samples were analysed in the suction range between 0 and 10 kPa by means of a hanging water column apparatus, and by pressure plate apparatus in the suction range between 10 and 1500 kPa. Samples were packed to a bulk density (D_b) of 100 kg m⁻³ and saturated in a vacuum chamber. D_b was previously determined by packing a known volume with coir similar to the density at which a growing bag would be filled and a mass to volume ratio was found. Individual samples were repeatedly equilibrated to a certain suction head for different values below 10 kPa with the hanging water column. For pressures of 10 kPa and more, the pressure of the air phase needed to be increased and this was achieved by placing the samples in a pressure chamber. A range of suction values was applied successively and water content measured repeatedly at each suction pressure.

Equipment and material to calibrate ECH_2O sensors

Equipment comprised (i) a perforated cylinder in which the growth medium was packed to a known bulk density, (ii) a vacuum chamber to saturate the sample, (iii) load cells and a data logger for monitoring mass loss, and (iv) a controlled climate chamber for controlling temperature.

Eight 50 cm long × 10.5 cm diameter PVC pipe was perforated manually with random holes at a density of approximately two holes per cm² (Fig. 1). In order to obtain relatively homogenous packing of the growth medium in the cylinder, the oven dried medium was moistened with approximately 10 % water determined on a mass basis. Thereafter it was packed into the cylinder in separate portions, each with the same bulk density. One EC-10 sensor and one EC-20 sensor was inserted into either sides of the cylinder. A radial and axial distance of approximately 10 cm and 5 cm, respectively, were allowed for each sensor (PALTINEANU and STARR 1997). These distances were small enough to allow sensors to measure the water content of the total cylinder volume.

The cylinders were saturated by submersion in distilled water for 24 hours. This produced a water content of 0.72 m³ m⁻³. Complete saturation of a smaller sample of coir using a vacuum chamber in the laboratory produced a θ_v of 0.91 m³ m⁻³.
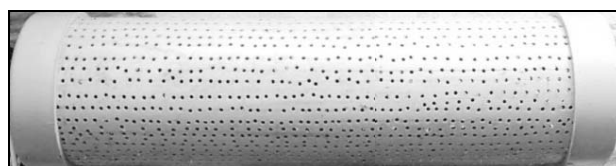

Fig. 1.   A 500 mm long calibration cylinder constructed from a standard 10.5 cm diameter PVC pipe and lids. The 6 mm holes were manually drilled at a density of approximately 2 holes per cm² to create uniform drying of the growth medium packed in the cylinder.

Load cells were calibrated by increasing the mass on the cells by known increments and finding a linear relationship between the mV reading from the load cells and the mass on the cells. The cylinders packed with the growth medium were suspended on the load cells as shown in Fig. 2. Hourly mass readings were recorded for the duration of the experiment with a Campbell Scientific (CR1000) data logger. The θ_v within a cylinder at any given time was determined by dividing the mass of the water by the dry mass of the growth medium, and multiplying this with the bulk density of the coir (HILLEL 2004).

A controlled climate chamber was used to maintain a constant temperature of 28 °C for the duration of the drying cycle to eliminate the diurnal effect of temperature on the dielectric constant of water and sensor electronics.

Measurements

The mass of the cylinders with medium and equipment were recorded manually with an electronic balance, model UX6200 Shimadzu, at the start of the experiment and once they were removed at the end of the experiment. A data logger, model CR1000 of Campbell Scientific, was used to record hourly water content measurements of the sensors and load cells in mV.
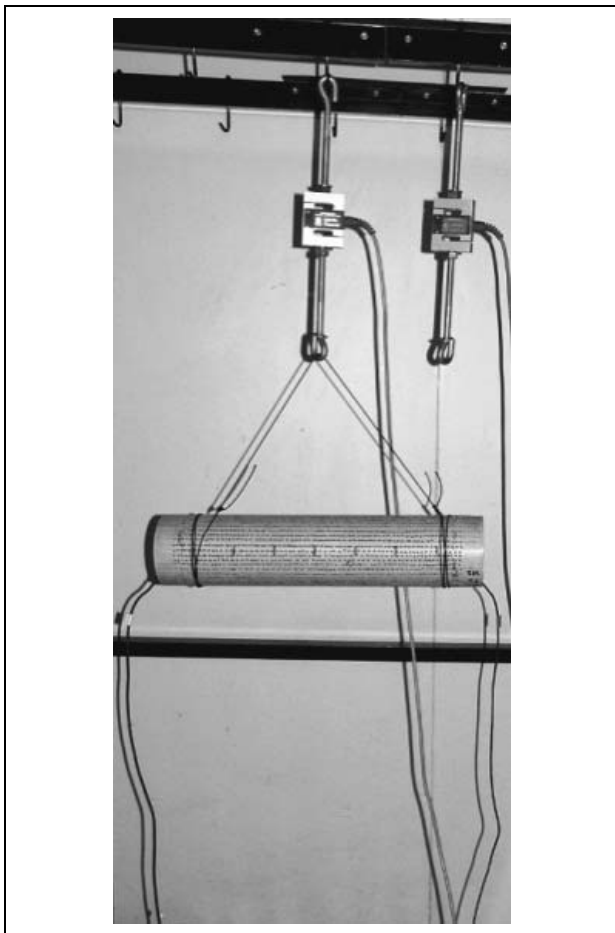

Fig. 2. The calibration cylinder hanging from a load cell mounted in the controlled climate chamber.

Statistical analysis

Volumetric water content predicted from the manufacturer's equations, and the coir specific laboratory determined calibration equations were compared using statistical analysis. Statistical analysis comprised the determination of the root mean squared error (RMSE), the index of agreement or D-index (WILLMOTT 1982) and the regression coefficient (R^2). The following formula was used to calculate the RMSE (WILLMOTT 1982):

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

Where P_i = predicted, O_i = observed and n = sample size. The RMSE indicates the absolute fit of the model to the data, i.e. how close the observed data points are to the model's predicted values, or in other words, how accurately the model predicts the response. WILLMOTT (1982) used the RMSE to determine the D-index:

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P'_i| - O'_i)^2} \right]$$

Where P_i = predicted, O_i = observed and n = sample size.

$P'_i = P_i - \overline{O}$, $O'_i = O_i - \overline{O}$, $\overline{P}$ = mean of predicted and

$\overline{O}$ = mean of observed.

The D-index indicates the accuracy of prediction compared to a 1:1 line, while the R^2 values only give an indication of the goodness of fit of the model (precision with which data points lie on the fitted regression line). For a good fit the D-index and R^2 values should approach one, while lower values of RMSE indicate better fit.

Results and Discussion

Laboratory procedure to calibrate ECH$_2$O sensors

Most calibration procedures use only a few gravimetric soil samples to calibrate soil water sensors (STARR and PALTINEANU 2002; COBOS and CHAMBERS 2010). Such results may not reflect detailed sensor response to water content changes in the growth medium and often result in linear regression equations due to a lack of data points. Even with a high R^2 (precision) achieved with these calibrations, accuracy of prediction of water content may be poor (deviation of predicted values from observed values).

The procedure proposed in this paper was based on the principle of continuous measurement of mass loss of a saturated coir sample during a drying cycle of at least one week. Drying is created by evaporation and the length of the drying period depends on the evaporative demand of the environment as well as the water retention characteristics of the growth medium.

The drying cycle employed was long enough for the growth medium to dry out beyond the lower limit of plant available water, which was determined from the water characteristic curve. It was therefore assumed that the cali-

bration between saturation and the air dried state achieved from the drying cycle would be sufficient, since irrigation scheduling will mostly occur between these points. The average θ_v observed for the lower limit and saturation was 0.274 and 0.910 $m^3\ m^{-3}$, determined from the water characteristic curve and vacuum saturation, respectively.

The response of water content determined gravimetrically over the drying cycle was non-linear (Fig. 3). This graph shows that variation between cylinders was small. Differences were probably due to variation in saturation values, but could also have been the result of spatial variations in bulk density (the packing of the coir), density of the perforations between cylinders, and/or the relative positions of cylinders in the controlled climate chamber.

Characterisation of sensors

The sensor response, expressed in mV, was non-linear over the complete drying cycle for both EC-10 and EC-20 sensors (Fig. 4). Variation in sensor response between three of the four EC-10 sensors was small. The third EC-10 sensor behaved differently in the wet range between day zero and day three of the drying cycle (Fig. 4a). Compared to the EC-10 sensors, the four EC-20 sensors showed increased variation in sensor response (Fig. 4b). EC-20 sensor 1 generally gave a lower reading than the

others over the first six days of the drying cycle. No obvious reason could be found for this phenomenon except that it indicated that some sensors responded uniquely to water content changes. These results strongly suggested that sensors must be calibrated individually.

Evaluation of the proposed calibration procedure for individual sensor calibration

Calibration equations determined from the proposed calibration procedure comprised the mathematical relation of mV response of individual sensors to the θ_v (Table 1). Regression coefficient (R^2) values greater than 0.99 proved that a 4th degree polynomial equation provided the best fit for the relationship for all the EC-10 and EC-20 sensors. The RMSE values nearing zero and D-index values of one indicated that the proposed calibration procedure delivered highly accurate calibrations for individual sensors in coir. Although small, some variation in the function equations indicated that individual sensors are unique and should therefore be calibrated separately. Individual calibration may be especially valuable in situations where very high accuracy in the determination of soil water content is required, e.g. in research. However, once the laboratory technique has been established, the proposed calibration procedure is not time or labour intensive and can be conducted with a large number of sensors simultaneously. Therefore individual sensor calibration is fast, easy and accurate, and should not be limited only to research.

Universal equation for coir

For conditions where some variation may be allowed for the prediction of soil water content, universal calibration equations may be useful. Because of the high accuracy (RMSE values <0.005 $m^3\ m^{-3}$) of the individual calibrations, equations of sensors 1–4 of EC-10 and EC-20 were combined to create a universal calibration equation for each sensor type in coir. A visual representation of the fit is shown in Fig. 5, while the equations and statistical results are summarised in Table 1. In contrast to all other equations, a 3rd degree polynomial equation proved to be the best fit for the universal EC-10 calibration. The RMSE values were 0.05 and 0.025 $m^3\ m^{-3}$ for the EC-10 and EC-20 sensors, respectively. This indicated good accuracy of the universal calibrations, if it is considered that the
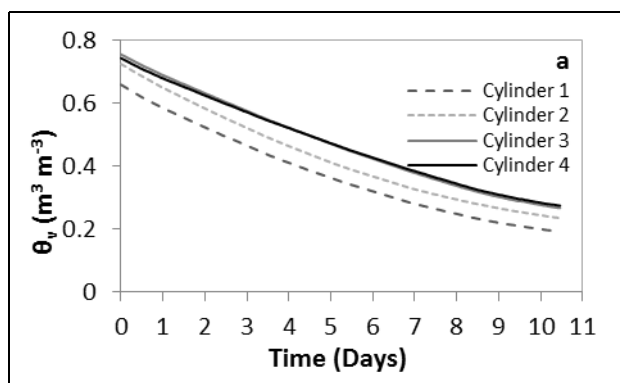

Fig. 3. Volumetric water content (θ_V) of coir measured continuously and gravimetrically (n = 252) over the duration of a drying cycle for four different calibration cylinders each containing one EC–10 and one EC-20 sensor.
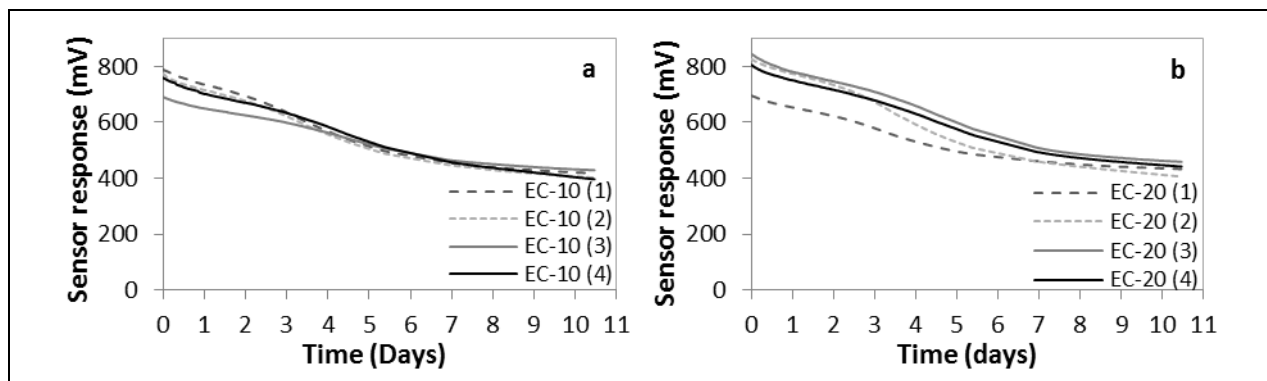

Fig. 4. a) EC-10 and b) EC-20 ECH$_2$O sensor response (mV) to changes in the water content of coir (n = 252) measured over the duration of a drying cycle.

Table 1. The 4th degree polynomial equations that describe the relationships between sensor response (mV) and volumetric water content (θ_v) of coir for 4 EC-10 and 4 EC-20 sensors used for the laboratory calibration (y = θ_v and × = mV) (n = 255).

| Sensor	Polynomial equation	n	R^2	RMSE ($m^3\ m^{-3}$)	D-index
EC-10 (1)	$y = -8.0591 + 0.0500x - 1.11E^{-4}x^2 + 1.10E^{-7}x^3 - 3.95E^{-11}x^4$	252	1.00	0.002	1.00
EC-10 (2)	$y = -4.7757 + 0.0287x - 5.92E^{-5}x^2 + 5.29E^{-8}x^3 - 1.62E^{-11}x^4$	252	1.00	0.003	1.00
EC-10 (3)	$y = -27.6857 + 0.1901x - 4.82E^{-4}x^2 + 5.41E^{-7}x^3 - 2.24E^{-10}x^4$	252	1.00	0.003	1.00
EC-10 (4)	$y = -6.2035 + 0.0412x - 9.75E^{-5}x^2 + 1.03E^{-7}x^3 - 4.03E^{-11}x^4$	252	0.99	0.005	1.00
Universal	$y = -0.5906 + 2.0187E^{-3}x + 7.39E^{-7}x^2 - 1.61E^{-9}x^3$	1008	0.88	0.050	0.97
EC-20 (1)	$y = -22.1022 + 0.1454x - 3.53E^{-4}x^2 + 3.79E^{-7}x^3 - 1.51E^{-10}x^4$	252	1.00	0.002	1.00
EC-20 (2)	$y = -1.5884 + 0.0063x - 1.45E^{-6}x^2 - 1.15E^{-8}x^3 + 9.90E^{-12}x^4$	252	0.99	0.003	1.00
EC-20 (3)	$y = -16.0411 + 0.0990x - 2.23E^{-4}x^2 + 2.23E^{-7}x^3 - 8.23E^{-11}x^4$	252	1.00	0.003	1.00
EC-20 (4)	$y = -13.0985 + 0.0829x - 1.91E^{-4}x^2 + 1.96E^{-7}x^3 - 7.40E^{-11}x^4$	252	1.00	0.002	1.00
Universal	$y = -0.3671 - 1.4866x + 1.48E^{-5}x^2 - 2.40E^{-8}x^3 + 1.24E^{-11}x^4$	1008	0.97	0.025	0.99
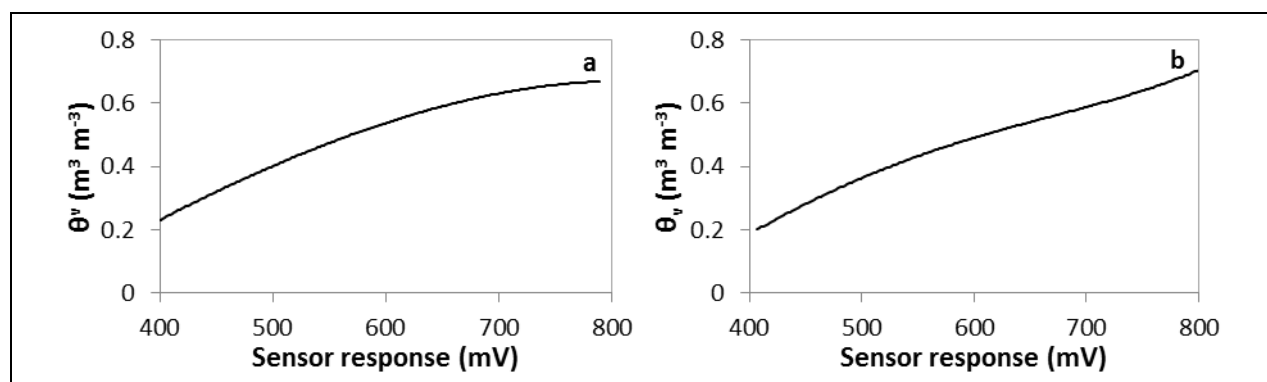
Fig. 5. The relationship between sensor response (mV) and volumetric water content (θ_v) of coir for the combined sensors of (a) EC-10 and (b) EC-20; and the equations that describe the curves (y = θ_v and × = mV).

water content of coir ranges between a lower limit of 0.274 and saturation at 0.910 $m^3\ m^{-3}$.

Evaluation of the proposed calibration and manufacturer's calibration equations

For evaluation, the universal and manufacturer equations were applied to eight independent sensors and statistical parameters compared (Table 2). Graphs of all sensors of EC-10 and EC-20 are plotted in Fig. 6.

Compared to the manufacturer's prediction, the accuracy and precision of the universal calibration equations proved to be very reliable for all sensors. Statistical results clearly indicated that the proposed laboratory calibration for coir yielded much lower RMSE and higher D-index values than the manufacturer's prediction (Table 2). Although prediction of water content by the proposed laboratory calibration equations was good enough, results for individual calibration was even better and since it is such a simple procedure, it must be considered the norm for irrigation scheduling.

The low D-index values was a result of the under estimation of water content by the manufacturer's calibration equations. Poor predictions achieved by the manufacturer's calibration equations was attributed to the difference in water retention characteristics between coir and other growth mediums such as different soils. To illustrate this, the water retention characteristics of coir and a sandy soil (8.6 % clay) (CHIMUNGU 2009) were plotted together in Fig. 7. Coir was saturated at 0.910 compared to 0.410 $m^3\ m^{-3}$ for the sandy soil. The high value for coir was ascribed to its high porosity, reported as approximately 94 % by KANG et al. (2004). The drained upper limit for coir was reached at 0.607, approximately 0.270 $m^3\ m^{-3}$ more than the equivalent value for the sandy soil. From the large difference in water retention characteristics between these two mediums, it was concluded that for capacitance sensors such as those used in this study, predictions of θ_v from equations developed for soils, will probably generally under estimate the θ_v of coir. This can lead to the mismanagement of irrigation practices in organic growth mediums such as coir.

Conclusions

A simple but sound scientific laboratory procedure was developed and tested to calibrate ECH$_2$O (EC-10 and EC-20) capacitance sensors. The procedure may be referred

Table 2. Comparison of statistical parameters of the universal laboratory and manufacturer calibrations for volumetric water content predictions conducted with independent EC-10 and EC-20 sensors (n = 446).

Sensor	Laboratory calibration			Manufacturer calibration		
	R^2-value	RMSE (m³ m⁻³)	D-index	R^2-value	RMSE (m³ m⁻³)	D-index
EC-10 (5)	0.97	0.041	0.99	0.97	0.292	0.57
EC-10 (6)	0.96	0.039	0.99	0.97	0.275	0.63
EC-10 (7)	0.94	0.057	0.97	0.98	0.254	0.64
EC-10 (8)	0.96	0.044	0.98	0.98	0.274	0.60
EC-20 (5)	0.94	0.079	0.97	0.97	0.276	0.65
EC-20 (6)	0.99	0.125	0.92	0.99	0.267	0.62
EC-20 (7)	0.99	0.072	0.97	0.99	0.296	0.58
EC-20 (8)	0.97	0.055	0.98	0.99	0.330	0.53
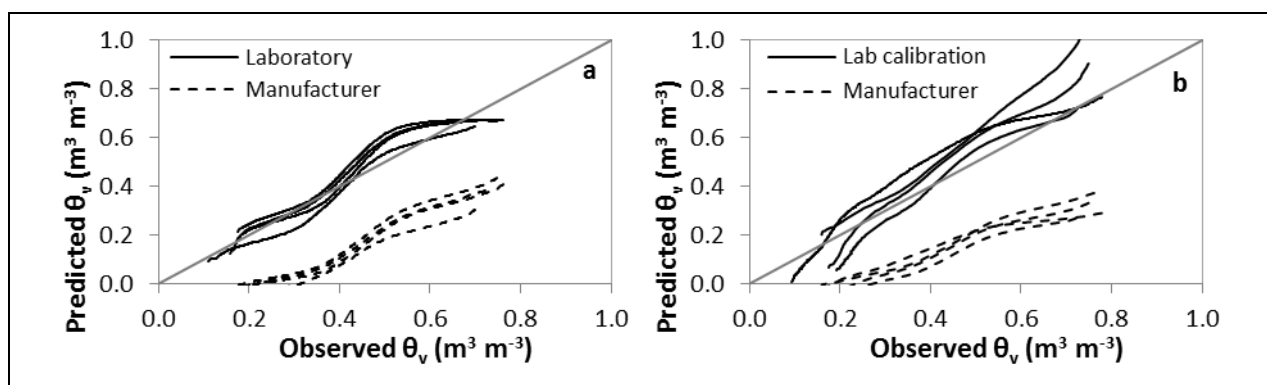
Fig. 6.   The relationship between observed volumetric water content (θ_v) of coir (n = 252) and θ_v predicted using the manufacturer's and the proposed laboratory calibration equations for four independent sensors of (a) EC-10 and (b) EC-20. The 1:1 line is also presented.
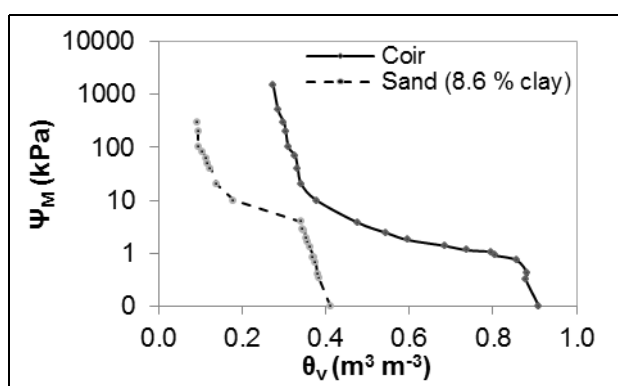
Fig. 7.   Water retention characteristics of coir and a sandy soil (8.6 % clay), as described by the absolute values of growth medium matric suction (Ψ_M) and volumetric water content (θ_v).

to as the evaporative desorption calibration method, and was based on the continuous weighing of a coir sample, packed in a perforated PVC cylinder, during a drying cycle after the sample had been saturated. The procedure showed

that both EC-10 and EC-20 sensors were able to measure water content of coir over the entire range from saturation to the lower limit of plant available water.

The procedure further allowed for the determination of precision (R^2) and accuracy (RMSE and D-index) of the sensors. The R^2 and D-index values were >0.99 and equal to one, respectively, for both EC-10 and EC-20. Further, RMSE values were between 0.002 and 0.005 m³ m⁻³ for the EC-10 sensors and between 0.002 and 0.003 m³ m⁻³ for the EC-20 sensors. Given this, it may be concluded that the instruments are very reliable and capable to measure water content of coir.

In the absence of a laboratory, it is recommended that the established universal equations are used when working with coir. However, users must be aware that the accuracy of the universal equations is much lower compared to the individual sensor calibrations. This was reflected in RMSE values of 0.05 and 0.025 m³ m⁻³ for the EC-10 and EC-20 sensors, respectively.

Although the universal calibration equations were less reliable than the individual calibration equations, they still outperformed the equations provided by the manufacturer. It is therefore strongly recommended that the manufacturer's equations should be replaced by the universal equations for coir.

Finally, organic growth mediums such as coir may deteriorate over time, since they are often re–used for a few production seasons. This may influence the accuracy of the calibration equations and accentuate the importance of regular re–calibration of sensors. In conclusion, it stresses the need for a reliable and accurate determination of calibration equations, which may be achieved through the use of the evaporative desorption calibration method.

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