EVALUATION OF EC-5 SOIL MOISTURE SENSORS FOR REAL-TIME DETERMINATION OF POULTRY MANURE OR LITTER MOISTURE CONTENT

L. B. Mendes, H. Li, H. Xin, J. W. B. Nascimento

ABSTRACT. *Moisture content (Ψ) of poultry manure or litter is an important property of the material. Relating manure or litter Ψ to its ammonia (NH_3) emission is conducive to assessing and/or controlling real-time ammonia emissions from the manure or litter. However, means to measure manure or litter Ψ on a real-time basis is lacking. This study was carried out to characterize the operational performance of a commercially available soil moisture sensor for measuring Ψ of meat-bird (broiler and turkey) litters and laying-hen manure. The Ψ tested ranged from 27.1% to 65.7% for broiler litter, 22.8% to 56.1% for turkey litter, and 11.0% to 75.0% for layer manure. Bulk density (ρ) ranged from 318 to 468 kg m^{-3} (20 to 29 lb ft^{-3}) for the broiler and turkey litters and from 151 to 943 kg m^{-3}(9 to 55 lb ft^{-3}) for laying-hen manure. Linear regression equations were developed to relate the sensor output to Ψ and ρ for the meat-bird litters and to Ψ for the laying-hen manure, all yielding good fit (R^2=0.95 – 0.99). An uncertainty analysis performed on the developed calibration equations revealed average errors in the Ψ estimation of ±7.1% estimated value for the poultry litters and ±6.7% estimated value for the laying-hen manure. Litter temperature was found to have a small impact on Ψ measurement by the sensor, 0.31% of measured mV per °C (0.17% per °F) deviation from the mean operating temperature over the range of 4°C to 24°C (39°F to 75°F). Results of the study indicate that when properly calibrated, the soil moisture sensor offers a reasonable means for real-time measurement of poultry litter or manure moisture content.*

Keywords. *Poultry, Litter, Manure, Ammonia emission, Real-time measurement.*

It is well known that ammonia (NH_3) emissions from poultry production facilities are strongly influenced by the animal manure properties and management practices. One of the factors ruling NH_3 emissions from poultry manure/litter is its moisture content (Ψ). The dependence of NH_3 emission rate on Ψ stems from its influence on the microbial activities, and the level of moisture in poultry manure is a key factor affecting uric acid degradation into NH_3. The standard method to determine manure/litter Ψ is oven-drying samples and measuring the weight changes, which takes 1-2 days and yields time-delayed results. Real-time measurement of Ψ is much more desirable where quick responses and actions are needed in animal housing management, such as increasing ventilation to dry wet litter/manure. However, the challenge has been to find a suitable sensor that is able to provide reasonably accurate real-time Ψ measurement.

The closest candidate for continuous and instantaneous monitoring of poultry manure or litter Ψ is a soil moisture sensor. In recent years, an arsenal of soil moisture sensors have been developed, tested, and validated for different types of soils. A dielectric sensor is an example of available technology for measuring soil Ψ that has been successfully applied over the years. It responds to the dielectric constant (ε) of a medium (soil, manure, or litter) affected by Ψ and has been tested for sensitivity to other properties such as bulk density (ρ), temperature, electrical conductivity, and pH of soils (Starr et al., 2000; Cobos, 2009; Casanova et al., 2012; Mittelbach et al., 2012; Ye et al., 2012; Qu et al., 2013). The change in ε is then reflected in electrical signal (mV) output of the sensor, which is correlated to soil Ψ through calibration procedures (Starr et al., 2000; Nemali et al., 2007; Cobos, 2009; Kodešová et al., 2011; Sakaki et al., 2011; Qu et al., 2013; Rowlandson et al., 2013). A typical calibration procedure for dielectric sensors used to measure soil Ψ has been described by Starr and Paltineanu (2002). The developed calibration equations are then validated with field data (Chow et al., 2009; Cardenas-Lailhacar and Dukes, 2010; Abbas et al., 2011; Casanova et al., 2012; Mittelbach et al., 2012; Majone et al., 2013;

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Rowlandson et al., 2013), followed by an analysis of uncertainty. For instance, Abbas et al. (2011) determined calibration equations for dielectric EC-5 sensors (Decagon Devices, Pullman, Wash.) with clay, clay-loam, and loam soils that yielded root mean square errors (RMSE, a measure of uncertainty) ranging from 0.011 to 0.054 m^3_{water} m^{-3}_{soil} (or 0.388 to 0.054 ft^3 ft^{-3}) when applied *in situ*. Mittelbach et al. (2012) compared the lab-developed linear calibration equations of four different soil Ψ dielectric sensors (TRIME-IT/-EZ, IMKO GmbH, Munchen, Germany; 10HS, Decagon Devices, Pullman, Wash.; CS616,Campbell Scientific, Logan, Utah; and the SISOMOP, SMG University of Karlsruhe, Germany) in the field with the standard method of time-domain reflectometry (TDR) for determination of volumetric water content with clay-loam and loam soils over a 2-year period, yielding RMSE values of 0.200 to 0.300 m^3_{water} m^{-3}_{soil} (or 7.063 to 10.594 ft^3_{water} ft^{-3}_{soil}). These results suggest that use of the dielectric sensors for Ψ determination requires development of media-specific calibration equations, as opposed to using factory or generic calibration equations. A review of literature found meager information concerning use of the soil moisture sensor for Ψ measurement of poultry litter or manure. In a study quantifying gaseous emissions from laying-hen manure, Li and Xin (2010) did use EC-20 sensors (Decagon Devices, Pullman, Wash.) to estimate Ψ of laying-hen manure and showed a good promise for the sensor.

Therefore, the objective of this study was to assess the suitability of a commercially available dielectric soil moisture sensor for instantaneous Ψ determination of laying-hen manure and meat-bird (broiler and turkey) litter (mixture of bedding and manure) from poultry houses under commercial operation conditions.

Materials and Methods

Moisture Content Sensor and Instrumentation

The soil moisture content sensor evaluated in this study was manufactured by ECH_2O (model EC-5, Decagon Devices, Pullman, Wash.), and its structure is presented in figure 1. The sensor had dimensions of 0.09L × 0.02W × 0.01H m (0.30L × 0.07W × 0.03H ft), and its sensitive part consisted of two prongs made of 0.05 m (0.16 ft) long

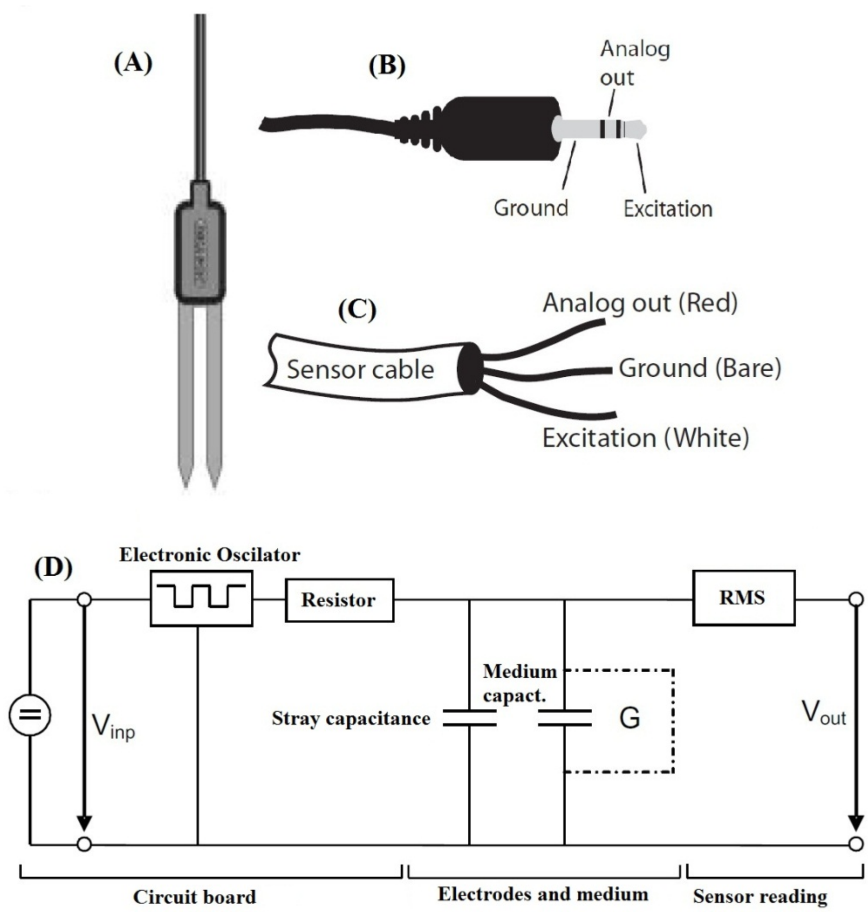

Figure 1. Sensor structure: (a) sensor; (b) connector; (c) cable; and (d) equivalent circuit diagram of a capacitance(Bogena et al., 2007); G is the energy loss due to relaxation and ionic conductivity; and V_{inp} (1200mV @ 10 mA for broiler and turkey litters and 2400mV @ 10 mA for laying hen manure) and V_{out} are the supply and sensor voltage output, respectively. The stray capacitance is 10 pF, and varies according to media moisture content, at an oscillation frequency of 75MHz with a 160 Ω resistance.

copper coated with acrylic. The sensor head consisted of a circuit board on silica with connection on copper covered with plastic (fig. 1). It had a response time of 0.2 ms and a Ψ measurement range of 0% to 100% (Decagon Devices, 2006).

A data acquisition system (CR10 with an AM416 multiplexer, Campbell Scientific, Inc., Logan, Utah) was used to collect the signal output of the EC-5 sensors at 10-s intervals. A PC was connected to the CR10 measurement module for programming and data retrieving.

Calibration of the EC-5 Sensor with Broiler and Turkey Litters

Broiler and turkey litters from a total house cleanout were obtained from production farms located in Kentucky and Iowa, respectively. The total cleanout of the broiler house was after 5 flocks over a 1-year period. The turkey litter was from a single flock of tom turkeys with 20-week growout. Rice hulls and oat hulls were used as the bedding materials for the broiler house and turkey house, respectively. Four plastic containers (0.45 L × 0.25 W × 0.15 D m, 1.48 L × 0.82 W × 0.49 D ft) were each loaded with 3.5 kg (7.7 lb) with broiler litter at an initial Ψ of 27.1 (±0.6)% and later with turkey litter at an initial Ψ of 22.8 (±0.5)% (wet weight basis, as brought back from the farm). The sample containers were first stored in a cold room (4°C, 39°F) for at least 12 h before being thermally equilibrated in an environmentally-controlled room at 21°C (70°F). After litter in a container had reached stabilized temperature, four sensors were vertically inserted 5 cm (2 in.) deep into it along with a type T (copper-constantan) thermocouple. Then the litter was sequentially subjected to five different density (ρ) levels of 318, 346, 379, 419, and 468 kg m^{-3} (20, 22, 24, 26, and 29 lb ft^{-3}) for about 5 min each. The ρ levels were achieved by pressing and thus changing the volume of the constant-weight litter sample.

An excitation voltage of 1200 mV was applied to all the sensors, and the first 2-min readings were discarded to ensure full stabilization. The same procedure was applied to the other three containers. Then Ψ level of all four containers (all with similar Ψ values) was raised by adding water to the relatively dry samples, and mV output of the sensors was taken at different ρ levels. After adding water to the samples, they were carefully mixed to ensure that moisture was evenly distributed through the litter sample. This protocol was repeated for four litter Ψ levels (as-is or wet basis) of 27.1 (±0.6)%, 36.6 (±0.2)%, 46.1 (±0.4)%, and 55.5 (±0.6)% for broiler litter and 22.8 (±0.5)%, 37.2 (±0.6)%, 46,6 (±0.1)%, and 56.1(±0.3)% for turkey litter. The Ψ levels in every manure container were determined gravimetrically by drying four 5 g (0.18 oz) samples at 105°C (221°F) for 24 h.

Hence, this part of the experiment with broiler and turkey litters at four Ψ and five ρ levels had a total of 20 treatment regimens. Each regimen was replicated four times. The average mV output of the four sub-sample sensors was taken as the output of each replicate.

The impacts of Ψ and ρ of the poultry litter on the sensor mV output were assessed through analysis of variance (ANOVA). The calibration equations obtained for the different litters were also compared. The empirical relationships of the sensor's mV output to Ψ and ρ of the litters were quantified through multivariable regression analysis.

Calibration of the Sensor with Laying-Hen Manure

To leave the manure pile undisturbed, an *in-situ* calibration of the sensor with laying-hen manure was conducted in a commercial high-rise layer house in central Iowa. Twenty spots at the top, middle, and bottom sections of the formed manure piles in the layer house were randomly selected and measured to cover the Ψ spectrum. Four EC-5 sensors were simultaneously inserted into each measurement area and the mV outputs were recorded with an EM-5 data logger (Decagon Devices, Pullman, Wash.). Manure samples of the measured area were taken and placed in sealed (Ziploc) plastic bags for subsequent oven-dry Ψ analysis.

In addition, manure samples from a manure-belt laying-hen house were collected to evaluate the sensor's response to higher Ψ levels of the same type of manure. These tests were performed in an environmentally-controlled laboratory at Iowa State University. Because of the higher Ψ of manure from the manure-belt houses, an excitation voltage of 2400 mV (instead of 1200 mV) was applied to the sensors in these trials to improve the measurement resolution.

The variable ρ was not included in the calibration for the laying-hen manure because sudden changes in ρ that might affect sensor readings are unlikely for this kind of substrate, as compared to the broiler/turkey litters, which are constantly prone to pressure changes due to direct contact with birds and their activity. For modelling purposes, however, the relationship of sensor output with manure Ψ was later developed and validated within a ρ range that was estimated from the data reported by Lorimor and Xin (1999) in their study with similar type of high-rise barns in the same region. The estimated range of ρ for the high-rise house was 151 to 581 kg m^{-3} (9 to 36 lb ft^{-3}). The manure ρ for the much wetter samples (Ψ ≈ 75%) from the manure-belt house was estimated to be 943 kg m^{-3} (55 lb ft^{-3}) based on the data reported by Li and Xin (2010) for manure from the same type of manure-belt houses.

Evaluation of the EC-5 Sensor's Sensitivity to Media Temperature

The previous generation of the EC-5 sensor had been found to be sensitive to media temperature. Hence, temperature sensitivity of the new sensor was evaluated. This evaluation was done with broiler and turkey litters each at two Ψ levels (35% and 55%, as-is basis). The litter samples were first stored in a 4°C (39°F) cold room for 12 h and allowed to warm up in the test room at 24°C (75°F) ambient temperature over 24 h. One EC-5 sensor was inserted into each of the four litter sample containers or replicates, all having similar litter Ψ and starting temperature. Measurements for all four containers were taken simultaneously and continuously during the warm-up period.

Temperature sensitivity (TS) of the sensor was calculated as follows,

$$TS = \frac{\Delta mV}{mV_{mean} \cdot \Delta T} \cdot 100 \quad (1)$$

where

TS = temperature sensitivity of the sensor,% measured mV per °C deviation from the mean temperature (14°C in this case)

ΔmV = change in sensor mV output with temperature deviation from the mean, $mV_{max} - mV_{min}$

mV_{mean} = mean of linear mV output for the temperature range, $(mV_{max} + mV_{min})/2$

ΔT = temperature change, $T_{max} - T_{min}$ (20°C in this case)

Uncertainty Estimatefor Ψ Measurements from the Calibrated EC-5 Sensors

In order to assess the magnitude of error associated with Ψ estimation from the calibrated EC-5 sensors, an uncertainty analysis was performed for the calibration equations obtained in this study. According to Currell and Dowman (2009), for a given linear calibration equation of the form $mV = m\ \Psi + k$, in which mV, Ψ, m, and k are response variable, explanatory variable, slope, and regression coefficient, respectively, the standard uncertainty u for a given value x_o can be calculated by the equation below,

$$u_{\Psi_o} = \frac{SE_{mV\ \Psi}}{m} \cdot \sqrt{\left[1 + \frac{1}{n} + \frac{\left(mV_o - \overline{mV}\right)^2}{m^2 \cdot s^2 \cdot (n-1)}\right]} \quad (2)$$

where

u_{Ψ_o} = estimated uncertainty of the calibration equation at a specific value Ψ_o,

$SE_{mV\ \Psi}$ = standard error of the regression,

m = slope of the regression line,

n = number of data points used in the calibration equation,

mV_o = mV value where the uncertainty is to be calculated,

$\overline{mV}$ = average calculated from all mV-values used in the regression,

s^2 = variance of the Ψ values used in the regression.

The estimate of the standard uncertainty associated with use of EC-5 sensor to determine laying-hen manure Ψ was done by applying equation 2 to the calibration equation obtained from the regression analysis. A similar procedure was applied to the turkey and broiler litter calibration equations. Additionally, the uncertainty analysis was used to assess the impact of including ρ in the calibration equation for poultry litters.

Results and Discussion

Calibration of the EC-5 Sensor with Broiler and Turkey Litters

The individual regression equations developed for each Ψ and ρ level are shown in table 1. Statistical analysis of the data revealed strong evidence of linear relationship between sensor mV output and either Ψ or ρ of the poultry litter ($P < 0.0001$). The results agreed with those of the study by Czarnomski et al. (2005) who reported positive linear relationship between the sensor mV output and soil Ψ for three different sensors used to measure soil water content: a capacitance instrument (ECH_2O sensor, model EC-20), a TDR cable tester, and a water content reflectometer. When calibrating EC-5 sensors *vs.* Ψ for different types of soil, Cobos (2009) also found that the sensor's response to Ψ followed a positive linear model. Fares et al. (2006) concluded that soil water content followed a positive linear relationship with soil ρ. Another recent study by Fares et al. (2011) again showed that the sensor mV output was sensitive to media ρ of tropical soil columns.

The coefficients of individual calibration equations resulting from multivariate regression analysis for broiler and turkey litters are presented in table 2, and the linear relationships are graphically represented in figure 2. Calibration equations in which Ψ was related to ρ and sensor output were also obtained through regression analysis and results are presented as equations 3 and 4, for ρ expressed in SI unit.

Table 2. Results from analysis of variance (ANOVA) for the EC-5 soil moisture sensor output (mV) vs. moisture content (Ψ,%) and bulk density (ρ, kg.m^{-3}) of broiler and turkey litters.

Parameter	A	B	C
Broiler Litter mV = A × Ψ + B × ρ + C	3.91 ± 0.11 (P<0.001)	0.54 ± 0.02 (P<0.001)	22.56 ± 9.49 (P=0.22)
Turkey Litter mV = A × Ψ + B × ρ + C	3.88 ± 0.16 (P<0.001)	0.63 ± 0.03 (P<0.001)	-10.16 ± 12.81 (P=0.27)

Unit conversion: 1 kg m^{-3} = 0.06 lb ft^{-3}

Table 1. Relationships of EC-5 soil moisture content sensor output to moisture content (Ψ) or bulk density (ρ) of broiler and turkey litters.

Property	Level	Broiler Litter	R^2	Turkey Litter	R^2
Model: mV =A × ρ + C					
Ψ%(w. b.)	Ψ1=27.1	mV = 0.367 ρ + 172.4	0.98	mV = 0.367 ρ + 193.2	0.98
	Ψ2=36.6	mV = 0.574 ρ + 127.2	0.99	mV = 0.574 ρ + 159.1	0.99
	Ψ3=46.1	mV = 0.663 ρ + 73.41	0.98	mV = 0.663 ρ + 159.8	0.99
	Ψ4=55.5	mV = 0.739 ρ + 161.6	0.99	mV = 0.570 ρ + 227.1	0.98
Model: mV = B × Ψ + C					
ρ (kg m^{-3})	ρ1=318	mV = 3.557 Ψ + 208.8	0.99	mV = 2.969 Ψ + 215.1	0.97
	ρ2=346	mV = 3.554 Ψ + 227.4	0.98	mV = 3.427 Ψ + 215.3	0.98
	ρ3=379	mV = 3.859 Ψ + 229.9	0.99	mV = 4.240 Ψ + 207.1	0.99
	ρ4=419	mV = 4.012 Ψ + 244.3	0.99	mV = 4.860 Ψ + 212.8	0.99
	ρ5=468	mV = 4.619 Ψ + 249.4	0.92	mV = 4.725 Ψ + 237.9	0.99

Unit conversion: 1 kg m^{-3} = 0.06 lb ft^{-3}

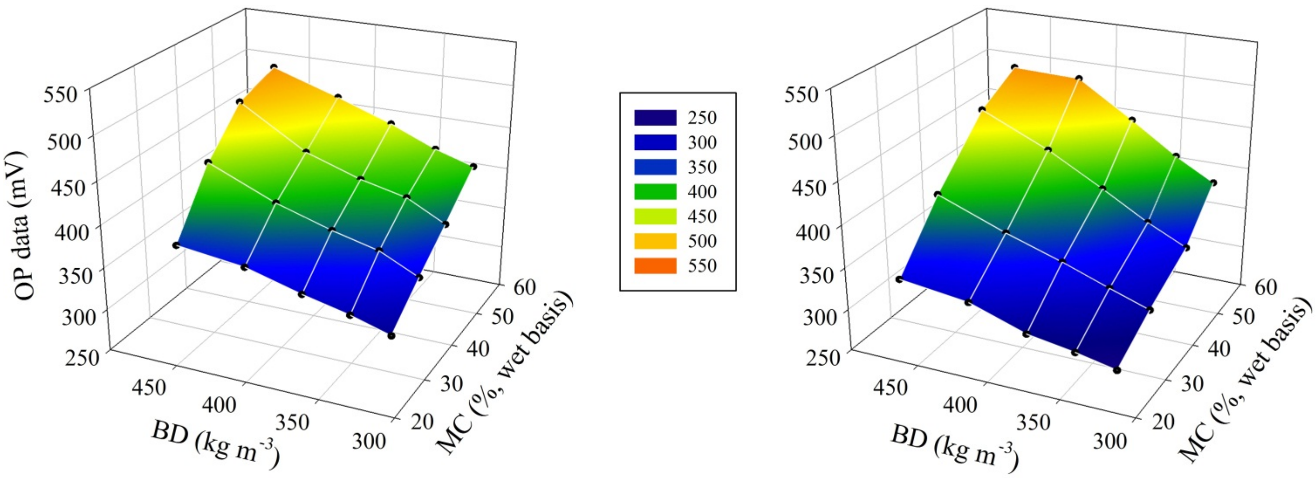

Figure 2. Response surfaces of the tested EC-5 sensor output (OP, mV) to moisture content (MC or Ψ,%, wet basis) and bulk density (BD or ρ, kg m^{-3}) of broiler (left) and turkey (right) litters (Unit conversion: 1 kg m^{-3} = 0.06 lb ft^{-3}).

For broiler litter, valid for the conditions of 27.1% < ψ < 55.5% and 318 kg m^{-3} < ρ < 468 kg m^{-3} (20 lb ft^{-3}< ρ < 29 lb ft^{-3}):

$$\Psi\ (\%) = (0.243 \pm 0.007)\ \text{mV} - (0.133 \pm 0.007)\ \rho - (2.928 \pm 2.591)\ (R^2 = 0.98) \quad (3)$$

For turkey litter, valid for the conditions of 22.8% < ψ < 56.1% and 318 kg m^{-3}< ρ < 468 kg m^{-3} (20 lb ft^{-3}< ρ < 29 lb ft^{-3}):

$$\Psi\ (\%) = (0.24 \pm 0.01)\ \text{mV} - (0.14 \pm 0.01)\ \rho + (3.85 \pm 3.15)\ (R^2 = 0.97) \quad (4)$$

Results of the ANOVA also indicated that equations 3 and 4 are significantly different from each other (p<0.0001). This outcome indicates that the type of bedding material (different between the broiler and turkey houses in this case) plays an important role on sensor output. Therefore we suggest that further calibration equations be developed for different substrates commonly used in littered barns, such as pine shavings, rice hulls, peanut hulls, etc.

In addition, since the mV output respond to ρ as well as to Ψ, this requires the user to determine ρ of the litter in order to get a reasonably accurate estimation. It should be pointed out that omission of ρ from the equation would lead to estimation errors up to 31% (refer to the uncertainty analysis section for more details). This performance characteristic represents a limitation of the sensor's application with poultry litters. Since continuous monitoring of litter ρ is not practical, there are a couple approaches that can be considered. One possible solution would be discrete monitoring of litter ρ, say, on a weekly basis, in which a representative number of litter samples for the barn area are collected to obtain an average *in situ* ρ value, followed by adjustments to the calibration equations. Discrete measurements of litter ρ can be easily estimated on site, for instance, with a 2 L (0.07 ft^3) bucket and a weighing scale of 2000 g (0.44 lb) range and ±1 g (0.002 lb) accuracy. Another approach could be relating litter ρ to average bird live weight that can be easily determined with step-on scales used in modern meat-bird production. Nonetheless, the determination of such relationship was not the objective of this study, and can be a motivation for future research on the applicability of moisture sensors in the field.

Calibration of the EC-5 Sensor for Laying-Hen Manure

Because laying-hen manure was obtained from two different sources (high-rise and belt houses), at two different ρ levels, regression analysis was performed separately to relate the EC-5 sensor mV and Ψ of the respective manure samples, and the results are presented in table 3. In figure 3 (left), the lines representing the respective relationships between mV and Ψ for the two sources of manure are quite similar, with slope being 16.6 (±0.8) mV/% Ψ and 19.5 (±0.4) mV/% Ψ for manure from high-rise and manure-belt houses, respectively (table 3). This outcome suggests that despite the large differences in manure ρ between high-rise and manure belt houses, they have little impact on sensor response to laying-hen manure Ψ. For this reason, the data sets from both types of laying-hen houses were pooled together, and a single linear calibration equation was obtained for the relationship between mV and Ψ (table 3).

The linear relation of the EC-5 sensor mV to Ψ of the laying-hen manure, obtained with the pooled data from both manure sources (high-rise and manure-belt houses), is shown in figure 3 (right) (R^2=0.97). The data gap between 40% and 65% of Ψ was due to the drastic differences in manure Ψ between the high-rise and belt houses, with the manure in the high-rise house being much drier than that of the belt house. Rearranging the regression equation for the measurements obtained from both housing systems yielded the following calibration equation for the laying-hen manure, for the conditions 151 kg m^{-3}< ρ < 943 kg m^{-3} (9 lb ft^{-3}< ρ <55 lb ft^{-3}).

$$\Psi\ (\%) = (0.065 \pm 0.003)\ \text{mV} - (8.32 \pm 2.48)\ (R^2 = 0.95) \quad (5)$$

Table 3. Relationships of moisture content (Ψ) with EC-5 sensor output (mV) of the form mV = A × Ψ + B for laying-hen manure obtained from two different sources (high-rise and manure belt houses) separately, thus different media bulk density (ρ), and for the combined data.

Layer Manure Source	N[a]	ρ (kg m^{-3})[b]	A	B	R^2
High-rise house	22	151-581	16.6 ± 0.8 (p<0.0001)	141 ± 28 (p<0.0001)	0.97
Manure-belt house	6	943	19.5 ± 0.4 (p<0.0001)	9 ± 5 (p=0.008)	0.99
Combined data	28	151-943	17.3 ± 0.6 (p<0.0001)	124 ± 24 (p<0.0001)	0.97

[a] Number of replicates.
[b] Unit conversion: 1 kg m^{-3} = 0.06 lb ft^{-3}.

Uncertainty on the Calibration Equations

The results of the uncertainty analysis performed on the EC-5 sensor calibration lines for poultry litters and manure are presented in table 4. For laying-hen manure, the average uncertainty in the estimate of Ψ was ±6.7% estimated value (as-is basis) over the range of 11.0% < Ψ < 75.0% (table 4).

The estimated average uncertainty when determining poultry litter Ψ with a calibration equation that did not include ρ was 31% and 30% (as-is basis) for broiler and turkey litters, respectively, over the range of 27.1% < Ψ < 55.5%. However, inclusion of ρ in the calibration equation for poultry litters led to much reduced uncertainty, ranging from ±1% to ±10% for broiler litter and from ±5% to ±12% for turkey litter over the range of 27.1% < Ψ < 55.5% and 318.3 kg m^{-3} < ρ < to 468.7 kg m^{-3} (table 4). These results validate the importance of including ρ as an input variable in the calibration procedure of EC-5 sensors for poultry litters.

The average uncertainty estimated on the calibration equations obtained from this study was ±7% for both poultry litters and laying hen manure, which is comparable to the value of ±5% reported by Cobos (2009) for potting soils, but considerably higher than the uncertainty reported by the same author for mineral soils of ± 3%. The higher uncertainty for the higher organic matter media such as litter and manure, as compared to mineral soils, presumably results from the higher variability in the properties of organic media as compared to mineral media.

Temperature Sensitivity of the EC-5 Sensor

Figure 4 shows the temperature sensitivity of the EC-5 sensor with broiler litter at Ψ of 35% or 55% over the litter temperature range of 4°C to 24°C (39°F to 75°F). It can be seen that the sensitivity follows a linear pattern. Using equation 1, the temperature sensitivity of the sensor was calculated to be 0.26% °C^{-1} and 0.37% °C^{-1} at Ψ of 35% and 55%, respectively. The sensor showed very similar temperature sensitivity with the turkey litters. The average temperature sensitivity for the broiler and turkey litters was 0.31% of the measured mV °C^{-1} deviation from the mean operating temperature over the 4°C to 24°C (39°F to 75°F) range. When checking the sensitivity of EC-20 soil sensors from the same manufacturer (previous version of the EC-5), Czarnomski et al. (2005) found that as temperature increased by 1°C (1.8°F), the soil moisture estimate decreased by only 0.1%. Ye et al. (2012), when testing the temperature sensitivity of EC-5 sensors inserted in soil at 40% of moisture in a temperature range of 9°C to 46°C (48°F to

Table 4. Results of the uncertainty (u) analysis for estimating moisture content (Ψ) of poultry litter or manure with the EC-5 sensor.

Media Type	Variables Included: Ψ (% w. b.)	Variables Included: ρ (kg m^{-3})[a]	Mean Uncertainty (%)
Calibration Equation of the Type: Ψ = A · mV + B			
Laying-hen manure	11.0< Ψ < 75.0	-	±6.7
Broiler litter	27.1 < Ψ < 55.5	-	±31.2
Turkey litter	27.1 < Ψ < 55.5	-	±30.4
Calibration Equation of the Type: Ψ = A · mV + B · ρ + C			
Broiler litter	27.1 < Ψ < 55.5	ρ = 318.3	±1.0
		ρ = 346.1	±8.3
		ρ = 379.1	±4.9
		ρ = 419.2	±5.1
		ρ = 468.7	±9.9
Turkey litter	27.1 < Ψ < 55.5	ρ = 318.3	±11.7
		ρ = 346.1	±9.1
		ρ = 379.1	±5.7
		ρ = 419.2	±5.0
		ρ = 468.7	±10.2

[a] Unit conversion: 1 kg m^{-3} = 0.06 lb ft^{-3}.

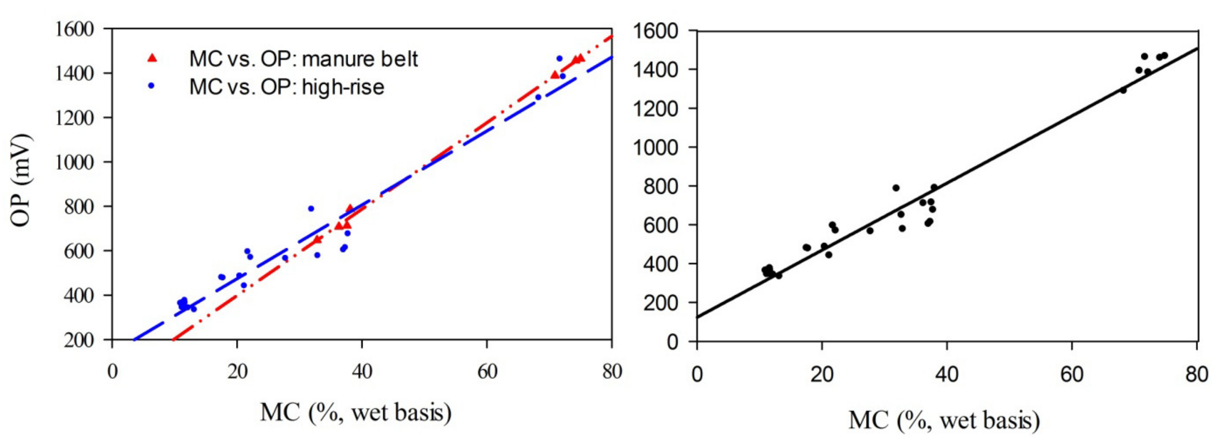

Figure 3. Linear relationships of the tested EC-5 sensor output (OP, mV) to moisture content (Ψ,%, wet basis) of laying-hen manure from high-rise and belt houses (left); and linear relationship of the sensor OP to Ψ for combined data (right).

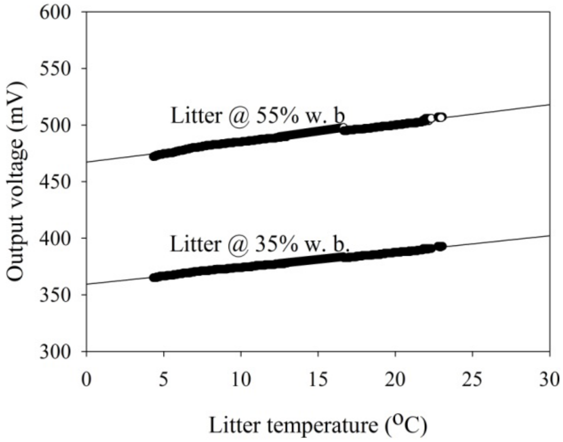

Figure 4. An example of the EC-5 sensor output response to temperature change in broiler litter at different moisture content (unit conversion: °F = 1.8 ×°C + 32).

115°F), verified that for every 1°C (1.8°F) increase in soil temperature, the sensor Ψ estimate decrease by 0.08%. In practice, for a given poultry house with reasonable environment control it would be unlikely to have such a large range of temperature fluctuation (20°C) as used in the evaluation of temperature sensitivity. Hence the interference of the litter temperature with the litter or manure Ψ measurement is expected to be rather insignificant.

It should be pointed out that while the study demonstrated the feasibility of the dielectric moisture sensor for real-time (as opposed to time-delayed) quantification of poultry litter/manure Ψ, it is advisable that a site-specific calibration equation be developed for each application. Such a practice will ensure that the litter or manure properties are properly reflected by the calibration equation.

CONCLUSIONS

A commercially available dielectric moisture content (Ψ) sensor (EC-5) was evaluated for use in real-time estimation of broiler litter, turkey litter or laying-hen manure Ψ. The following conclusions can be drawn:

1. Strong linear relationships exist between the litter or manure Ψ and voltage output of the sensor (R^2 = 0.95 - 0.98). Because the EC-5 sensor output is dependent on the characteristics of the measured material, media-specific models quantifying the relationship of the litter/manure Ψ vs. sensor voltage output were developed for broiler litter, turkey litter and laying-hen manure.
2. When using the EC-5 sensors to estimate poultry litter Ψ, bulk density should be included. The inclusion of litter bulk density as an input variable in the empirical equations, though cumbersome, reduces the uncertainty of the Ψ estimation from ±30.8% to ±7.1%.
3. The EC-5 sensor output showed a small, linear dependence on the poultry litter or manure temperature, which for practical purposes may be considered negligible.

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