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Designing a Cylindrical Capacitive Based Sensor for Monitoring the Table Salt's Moisture Content during Iodization

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ABSTRACT

Coaxial cylinder capacitive moisture sensor for determination of moisture content of table salts has been fabricated. The CMS method for determination of moisture content of table salts overcomes the effect of evaporation of iodine in table salt which results from heating in the oven drying method. The CMS overcomes the polarization effect result from the resistive methods of moisture content determination and it is non expensive to construct and it has high accuracy since measurements involves programming system in interpretation of the results. In this research, moisture content sensor based on capacitive principal created using two coaxial cylinders with height 5.207 cm, and different diameters of 4.303 cm and 1.198 cm embedded inside one another. The input signal of the CMS system was provided by the AC signal from the sensor capacitor, the capacitance of the sensor capacitor is directly proportional to the moisture content of the salt sample placed between the two coaxial cylinders of the sensor capacitor. The moisture content was obtained from the model $m=6.6145\times10^{-4}c+4.54044$ for calibration of the CMS by using the OVD as a reference method for determination of moisture content in the table salts. The model was then validated by constructing the comparison plot of OVD and CMS moisture contents. The comparison graph of OVD and CMS MC against test had conceding error bars between OVD and CMS MC. The coefficient of determination of 0.94 was obtained and the correlation plot was a linear relation expressed as $y=0.971x+0.773$. The model was then validated by solving for moisture content from measured values of capacitance.

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INTRODUCTION

The main energy source for extracting Table salt has for a long time been one of the most famous food additives used to either add food flavor or increase the shelf life of food substances. Even more significant, table salt is a great source of sodium and chlorine, the two important chemical elements required for proper functioning of various organs of the human body (Assey, 2009). Thus, salt is normally consumed by almost all human beings. Based on this fact, the World Health Organization (WHO), in its efforts to eliminate Iodine Deficiency Diseases (IDDs), designated salt as the carrier for iodine to human bodies (Lugendo, 2012). However, the natural iodine content in salt is very limited therefore table salts have to be fortified with iodine before being consumed.

While WHO has successfully enforced salt fortification with iodine all over the world, meeting the standards of iodization has remained to be a significant challenge. The challenge arises from loss of the added iodine after the salt has been iodized. Studies have revealed that, major factors that influence retention of added iodine in the iodized salt are the salt's elemental composition and moisture content ((Kamwaya and Akwilapo, 2005). Therefore, to make iodization successful, the salt's elemental composition as well as moisture content (MC) should meet the required standards. While the elemental composition can be maintained through salt purification, WHO recommends that the salt's moisture content should not exceed 3% in order to minimize evaporation of the added iodine (Lugendo, 2012).

Keeping the table salt's moisture content below 3% is challenging as salt is a hygroscopic compound which tends to absorb moisture from its surrounding (Eruola et al., 2012). Thus, to ensure successful salt iodization, measurement of the salt's moisture content before, during and after salt iodization process is necessary. Monitoring the moisture levels in the salt will help to minimize the loss of iodine by evaporation leading to successful use of table salt as the iodine vehicle. Nevertheless, successful monitoring of moisture content in table salts requires quick and reliable moisture measurement techniques. Again, this is a challenging task because various moisture measurement techniques have setbacks which hinder the accuracy of measurements.

In developing countries like Tanzania, moisture measurement relies on the conventional oven dry method (Assey, 2007). Despite its simplicity, this method is not very accurate since it uses the difference in salt's mass before and after oven drying to calculate the moisture content. However, the loss in mass may be affected by the volatile elements which also evaporate when the salt is heated (Punzalen et al., 2017). Thus, a more reliable technique is required to ensure accurate measurement of moisture content in table salts.

To circumvent the challenge of elemental evaporation as the sample is heated, several techniques have been developed. These techniques include the measurement of electrical conductivity and infrared spectroscopy (Barapatre and Patel, 2019). These methods do not require heating the sample in order to measure the moisture content. However, the challenge in electrical conductivity technique is polarization which may affect the moisture content reading leading to compromised accuracy. On the other hand, the infrared spectroscopy is very expensive and is not available in many laboratories (Punzalen et al., 2017). Thus, there is a need of developing another technique that will be fairly accurate but readily available for the salt producers.

This study proposed the use of capacitive sensor technique which operates on the principle of measuring the dielectric constant (Ogbu et. al., 2016; Chambela and Mushi, 2023). This technique has been used to measure moisture contents in soil (Ogbu et. al., 2016). Capacitive sensing method corrects the problem of polarization in electrical conductivity method and is cheaper compared to the infrared spectroscopy technique. However, despite their high accuracy in measuring moisture in soil, the technique is novel to measurement of salt's moisture. A capacitive sensing device can be easily designed and developed in the laboratory. Furthermore, the capacitive sensor can be made more accurate by linking it to special digital programs that can interpret the capacitance readings into moisture content (Rizi et al., 2016). Therefore, the aim of this study was to develop and test a capacitive moisture sensing device hereby referred to as the Capacitive Moisture Sensor (CMS). The performance of the designed CMS was validated based on the traditional oven dry method of measuring moisture content in salt.

METHODS AND MATERIALS

Operation of Capacitive Moisture Sensor

A capacitive moisture sensor consists of a pair of electrodes which form a capacitor with the sample whose moisture is measured placed between the electrodes to act as the dielectric material. Since the dielectric property of the sample is affected by its moisture content, the capacitance of the capacitor varies with the moisture content (Jafari et al., 2019). Generally, the higher the moisture content, the higher the capacitance. So by measuring the capacitance, one can infer the moisture content in salt.

Capacitance (*C*) is generally obtained by dividing the amount of charge (*Q*) required to increase the voltage (*V*) between the capacitor plates that are separated by a known distance containing the sample as the dielectric material. Generally, capacitance is calculated using Equation (1).

$$C = \frac{Q}{V} \tag{1}$$

Note that, *C* is measured in Farads, *Q* in Coulombs and *V* in volts.

However, capacitors are categorized in different forms depending on the material used in construction and the shape of conductors. One of the various forms of capacitors is the cylindrical capacitor. It consists of two symmetric cylinders with the same height but different diameters, embedded inside one another. The space between the cylinders is filled with a dielectric material. The capacitance of the cylindrical capacitor is determined by Equation (2) as in (Rizi et al. 2016; Jafari et al. 2019; Mushi et al., 2023).

$$C = \frac{2\pi\varepsilon_o \varepsilon L}{\ln\left(\frac{b}{a}\right)} \tag{2}$$

Note that, ε_0 is the dielectric constant of air (or vacuum), ε is the dielectric constant of the dielectric material, *L* is the length of the cylinder, *b* is the radius of the inner cylinder and *a* is the radius of the outer cylinder.

Experimentally, capacitance of a capacitor can be measured in various ways. The common methods include using the capacitor's reactance to form a voltage divider, creating an RC oscillator whose oscillating frequency is determined by the capacitance and detecting the capacitor charging time (Ogbu et al., 2016). In this work, the capacitance of the moisture sensor was designed by employing the RC oscillator. In this design, the CMS works with the RC oscillator to form a tuned circuit. Since the dielectric property of salt changes with the variation of its moisture content, any changes in the salt's moisture content can be detected by the changes in the operating frequency. Thus, the task of measuring moisture content in salt is reduced to studying the changes of oscillatory frequency of the RC circuit which is given by Equation (3), according to Jafari et al. (2019).

$$f = \frac{1}{RC} \tag{3}$$

where, *f* is the frequency of the signal, *R* is the total resistance in the RC circuit and *C* is the capacitance with salt as the dielectric material.

One should note that, the relationship between capacitance, and frequency (measured in Hz) is dependent on the

operating design. In the current design, the capacitive sensor detects charges stored into the capacitor as a signal with a known frequency. This signal is converted into a triangular wave and interpreted as analog input to the microcontroller. The microcontroller interprets the signal as the binary code that is further processed by a software to capacitance readings which are displayed through the computer monitor.
This work made use of several components including the Arduino circuit, oscillator circuit, ATMEGA microcontroller, the Liquid Crystal Display (LCD) as the displaying unit, computer and connecting wires.

Capacitive Moisture Sensor

The Capacitive Moisture Sensor (CMS) was constructed in the Physics laboratory at the Department of Physics of the University of Dar es Salaam. It is composed of three main parts: the sensor capacitor, the processing unit and the display unit as illustrated by Figure 1.

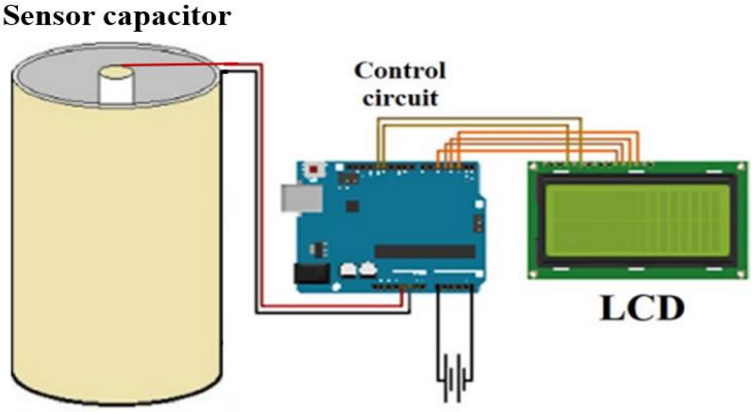

Figure 1: CMS system diagram.

Sensor Capacitor

The sensor capacitor is basically made of an aluminum cylinder and a rod arranged coaxially. The cylinder is 5.207 cm long with a diameter of 4.303 cm. The rod has a diameter of 1.198 cm and is positioned at the center of the cylinder whose bottom is sealed using plastic material to make a cylindrical co-axial capacitor. The walls of the sensor are varnished so as to avoid contact between the dielectric material and the air surrounding the sensor in order to minimize the effect of stray capacitance (Jafari et al., 2020).
The salt sample whose moisture content is under examination is put in the space between the rod and the cylinder to act as the dielectric material for the capacitor. Since the distance between the co-axial cylinders is fixed, the probe can measure salt's capacitance and feed it into the oscillator. This gives the oscillator a definite frequency that would vary directly proportional to the salt's moisture content. That is, the sensor's capacitance changes as the moisture content changes. This results to changes in frequency of the oscillator enabling the microcontroller to detect the amount of moisture in the salt sample.

Processing Unit

The processing unit picks the signal from the probe for interpreting the information carried. The unit is mainly composed of an oscillator and the micro controller. The signal is first picked by the oscillator which normally operates in astable mode switching low (negative) and high (positive) outputs rapidly and repeatedly. The frequency of the astable oscillator switching depends on resistance and capacitance connected to the oscillator. Since in our design, resistance is fixed, then only the capacitance probe determines the frequency of the oscillator. The oscillator frequency is then detected by the microcontroller in order to determine the salt's moisture content. Both the oscillator and the microcontroller were embedded to the Arduino circuit whose control software program was developed and installed in a personal computer.

Display Unit

The processing unit was connected to the Liquid Crystal Display (LCD). The LCD displays the capacitance and the amount of moisture in the salt as displayed in Figure 2.

Figure 2: Display of the capacitive moisture sensor.

Circuit of the designed CMS

The circuit of the designed CMS consist of a circuit board, Arduino Uno and liquid crystal displays (LCD) as shown in Figure 3. The Arduino Uno embedded with ATMEGA microcontroller, 14 digital input/output pins, 6 analog input pins, USB port, a 16 MHz crystal oscillator, a power jack and a reset button. The power jack connected to a 5V DC battery, a switch, a 3V voltage regulator and a light emitting diode. The 5 VDC battery connected to voltage regulator to regulate the voltage to steady 3 VDC. This is because the microcontroller and the liquid crystal displays (LCD) require 3 VDC supply.

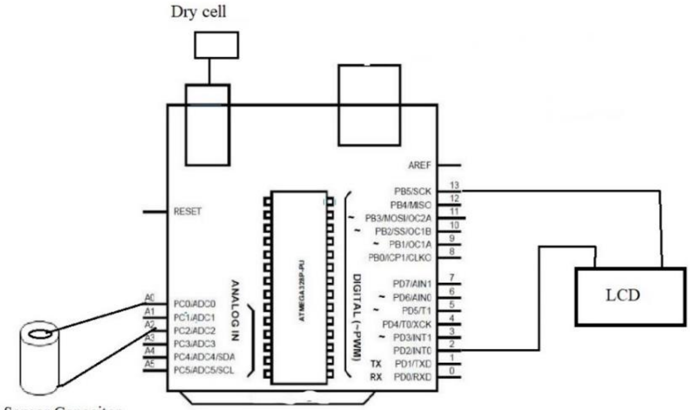

Figure 3: Circuit diagram of the designed CMS.

The central part of system consists of a microcontroller which is powered by 3 V from a voltage regulator. ATMEG microcontroller is favored because it allows directly interface of the microcontroller with the sensor digitally rather than constructing amplification and/or analog to digital conversion circuitry (Kumar et al., 2015). The Arduino program was installed in the Personal Computer (PC) for programming the microcontroller. The microcontroller was programmed for measurement of capacitance of the sensor capacitor. The Arduino circuit with the oscillator circuit and the microcontroller was connected to the display unit. The display unit is made of 12 by 2 Liquid Crystal Display (LCD) which display the capacitance readings obtained from the sensor to the screen. Figure 4 displays the prototype circuit of the CMS designed in this work.

Figure 4: Prototype circuit of the capacitive moisture sensor.

Principle of CMS

When a small amount of salt is inserted in the sensor capacitor, the moisture content present in the salt will affects the capacitance of the circuit. The resulting cycles of capacitor charging and discharging forms the periodic waveform signal. This signal is converted to dc voltage by the electronic circuit. When concentration of water content in the salt is changed, the dielectric constant of capacitor also changes. This results to the change in capacitance of the sensor capacitor, which in turns causes the change of the corresponding periodic waveform. This change of signal can be processed and finally be displayed by LCD. The Arduino platform is used to program a microcontroller to read the analog signal from the capacitive sensor and interprets the signal as the binary code that is further interpreted to readings of capacitance and displayed to the liquid crystal display as in Figure 2. However, in order to give correct measurement of moisture content in salt, the CMS should be calibrated so as to establish an empirical relationship between the salt moisture content and the capacitance reading on the LCD (Harris, 2018).

Calibration of the Designed Capacitive Moisture Sensor

In this work, the designed CMS was calibrated by determining the moisture content of 100 g of salt. The values of moisture content in the salt sample were varied by adding some fixed amount of water in the salt and the corresponding readings of the CMS were recorded. A total of 17 different readings were recorded. The addition of water and determination of moisture levels for the added volumes of water was done through the following procedures. 100 g of salt sample was spread on the backing paper placed on top of the aluminum foil and dried in an oven at a temperature of 110^0C overnight since at this temperature all the water content in the salt is expected evaporate. The sample was then removed from the oven and placed in plastic containers with desiccants to prevent further moisture absorption during the cooling process (Lugendo, 2012). The dry sample was then grinded into powder by using a blender in order to create uniformity in size of the particles of the dielectric material. The salt powder was again placed oven at a temperature of 110^0C overnight. Upon removal from the oven, the sample was left to cool in desiccators for 5 hours. Then, the mass and capacitance of an empty sensor capacitor were measured by an electronic balance and the CMS, respectively. The sensor capacitor was then filled with the dry powdered salt sample and the mass and capacitance of the sensor capacitor with the salt as a dielectric material was determined. The capacitance of sensor capacitor with dry salt was recorded in a table as the initial capacitance. The mass of the salt sample was determined as the difference between mass of empty sensor capacitor and its mass when it contains dry sample. The results were tabulated and the moisture content was calculated as the percentage ratio of the loss in mass (Barapatre and Patel, 2019). The procedure was then repeated by adding 1ml of water in the sensor capacitor containing salt sample and determining the corresponding moisture content and capacitance in order to complete the table. The moisture content in the salt sample was increased in steps of 1 ml of water until 17 values of moisture content and capacitance were obtained.

Calibration of the CMS was then validated by gravimetric or oven dry method (OVD) since it is generally acceptable to use the OVD method as the standard method for calibrating all moisture sensing devices (Ogwo et al., 2020). In this approach, the moisture content of salt was determined by calculating the percentage ratio of loss in mass. The mass of oven died salt sample was labeled as, M_d and the mass of an empty container was determined and labelled as M_e. Then, 1 ml of distilled water was added to the dry salt sample incrementally for until 17 different values were obtained. For each increment, the mass of the salt sample was measured and labelled as mass of wet sample, M_w. Further, for each increment, the OVD method was used to calculate the percentage of moisture content in the salt sample using Equation (4), according to Kilomklao et al. (2019),

$$MC_{OVD} = \frac{\left(W_{wet} - W_{dry}\right)}{w_{wet}} \times 100 \qquad (4)$$

where; W_{wet} is the weight of the salt sample when it is wet, W_{dry} is the weight of the dry salt sample and MC_{OVD} is the percentage moisture content of the salt sample measured by the OVD method. From this measurement, a calibration factor ($C.F$) which is the constant value that when multiplied with the capacitance reading from the sensor, gives the value of moisture content in the salt sample under measurement. This factor was obtained by taking the quotient of the moisture content value measured by using the OVD method and the value of the corresponding capacitance, read on the CMS display. Equation (5) was used for this purpose according to Ogwo et al. (2020).

$$C.F = \frac{MC_{OVD}}{C} \qquad (5)$$

The mean value of the calculated calibration factors was used to reprogram the microcontroller of the instrument through the assemble language code. Then the calibration graph was drawn, which is the graph of moisture content (MC_{OVD}) of salt sample obtained by OVD method versus capacitance values obtained from the developed CMS. The calibration graph was used to calibrate the developed CMS and validate its performance.

RESULTS AND DISCUSSION

Calibration of the Capacitive Moisture Sensor

Before the actual measurement of moisture content in salt samples using the developed CMS, the device was calibrated to establish the relationship between capacitance and moisture content. During calibration, the measured mass (*M*) and capacitance of the empty capacitor sensor were respectively 95.44 g and 5.7 pF while the mass of the dry salt sample was 49.42 g. Table 1 shows the capacitance readings of the CMS corresponding to the given values of moisture content. The standard deviation from mean value was used to determine the errors in measurement of moisture content and capacitance using Equation (6).

$$E = \frac{\sigma}{\bar{M}} \quad (6)$$

where *E* is error of the calculated moisture content (*MC*) and σ is the standard deviation from the mean value, $\bar{M}$.

Table 1: Capacitance against moisture content of table salts

S/N	Volume of added water (*ml*)	Mass of wet salt sample, (*g*)	Mass of moisture content (*g*)	Moisture content (%MC_{OVD})	Capacitance C (μ*F*)	Calibration factor (*C.F*)
1	0.00	49.42	0.00	0.00 ± 0.00	0.0005718	0.00
2	1.00	50.87	1.46	2.86 ± 2.55	0.0006712	2175.21
3	2.00	51.91	2.49	4.8 ± 1.52	0.0007121	3496.70
4	3.00	52.97	3.56	6.71 ± 1.09	0.002760	1289.86
5	4.00	53.80	4.38	8.15 ± 0.9	0.003540	1237.29
6	5.00	54.64	5.22	9.56 ± 0.76	0.005590	933.81
7	6.00	56.01	6.59	11.76 ± 0.62	0.007650	861.44
8	7.00	56.67	7.25	12.8 ± 0.57	0.009840	736.79
9	8.00	58.22	8.81	15.12 ± 0.48	0.013610	647.32
10	9.00	58.88	9.46	16.07 ± 0.45	0.015350	616.29
11	10.00	59.35	9.93	16.73 ± 0.44	0.019980	497.00
12	11.00	60.14	10.72	17.83 ± 0.41	0.018670	574.18
13	12.00	61.86	12.45	20.12 ± 0.36	0.022660	549.23
14	13.00	62.64	13.22	21.1 ± 0.35	0.024430	541.14
15	14.00	63.78	14.36	22.52 ± 0.32	0.029600	485.14
16	15.00	64.70	15.29	23.62 ± 0.31	0.029840	512.40
17	16.00	65.38	15.96	24.41 ± 0.3	0.031860	500.94
Average						**920.88**

Table 1 shows that the capacitance values increased in each increment of added volume of water. At first when the water was added to the dry salt sample the capacitance values was observed to increase rapidly due to the increasing of the dielectric constant of salt until the salt sample becomes saturated, then the values of capacitance was increased slowly. For each value of capacitance, the calibration factor was calculated and the average value of calibration factor was 920, this value was used to reprogram the capacitive moisture sensor.

The average calibration factor determined in this study was higher compared to the one calculated by Ogwo, et al. (2020) in the developed capacitive soil moisture sensor which had the average value of 219. This could be attributed to the fact that Ogwo, et al. (2020) developed a soil moisture meter in which soil has lower dielectric constant compared to the salt. To determine the relationship between moisture content and capacitance, a calibration curve of moisture content measured by the OVD method against the capacitance readings from the developed CMS was plotted by using Origin software and presented in Figure 5.

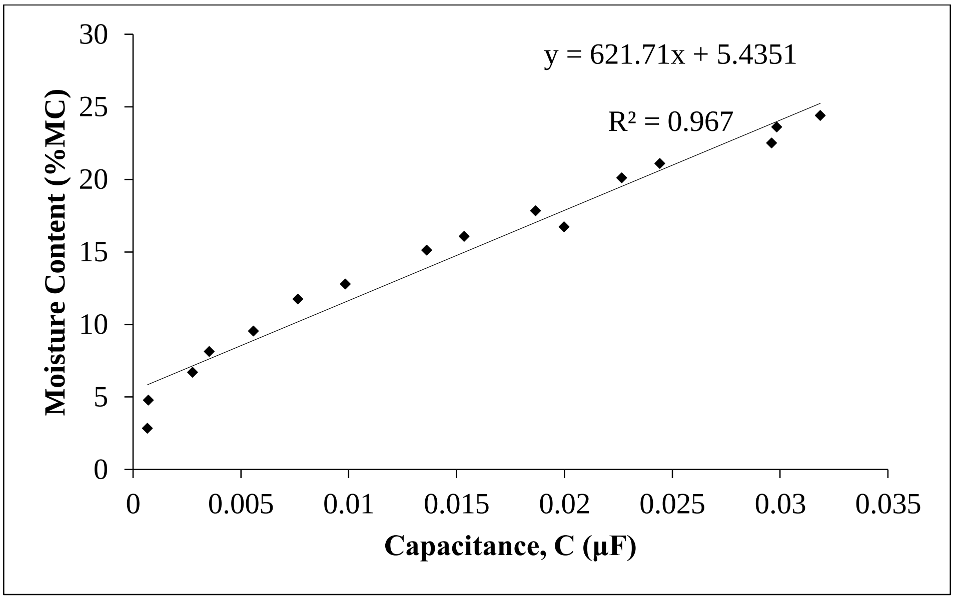

Figure 5: Calibration curve for the developed CMS.

As Figure 5 displays, the value of capacitance increases as moisture content increases. The relationship between moisture content and capacitance reading was established by using the fitted function which is given by the Equation (7).

$$MC = 6.2171\times10^{-2} C + 5.4351 \quad (7)$$

The calibration curve shown in Figure 5 reveals a high coefficient of regression which is 0.9677. This indicates that a high degree of accuracy for the CMS calibration. The model presented in Equation (7) was used for obtaining moisture content in table salt samples using the measured values of capacitance. A similar model was developed by Segundo et al. (2011), when they were designing a soil moisture sensor for controlling irrigation.

Validation of the Capacitive Moisture Sensor

In order to ensure the accuracy and reliability of the CMS developed in this work, the device was validated by comparing its measurements of moisture contents with the results of the OVD method for the same salt samples. Thus, the moisture contents of 17 salt samples read by the developed CMS were compared to the MC values measured by the OVD method. The difference of the moisture content (*MC*) between the two methods was obtained using Equation (8).

$$\%MC = |\%MC_{OVD} - \%MC_{CMS}| \quad (8)$$

The results of moisture content measurements using the OVD method and the CMS as well as the differences between the two methods are presented in Table 2.

From Table 2 it is observed that the deviation in the measurements of moisture contents measured by the OVD method and the CMS range from 0.21% to 2.16% with the average deviation of 1.38%. This implies very good performance of the developed CMS since literature shows that the average moisture content deviation is considered good enough if it is below 20% (Kilomklao et al., 2017; Ogwo et al., 2020). Therefore, the CMS developed in this study can be deployed in measuring the moisture content in salt samples.

To visualize the goodness of the developed CMS, a correlation plot of the moisture content values measured by the OVD method against those measured by the CMS was created. A high level of correlation with the correlation coefficient of 0.9678 was observed as shown in Figure 6.

Table 2: Moisture contents values as measured by the CMS and OVD methods and the corresponding deviation.

SN	Moisture Content Values (%)		Deviation of the Measurements (%)
	OVD Method	CMS Method	
1	0.00	4.92	0.00
2	2.86	4.98	2.12
3	4.80	5.01	0.21
4	6.71	6.34	0.37
5	8.15	6.88	1.27
6	9.56	8.24	1.32
7	11.76	9.60	2.16
8	12.80	11.05	1.75
9	15.12	13.54	1.58
10	16.07	14.69	1.38
11	16.73	17.76	1.03
12	17.83	16.90	0.93
13	20.12	19.53	0.59
14	21.10	20.70	0.4
15	22.52	24.12	1.6
16	23.62	24.28	0.66
17	24.41	25.61	1.2
Average deviation			**1.38**

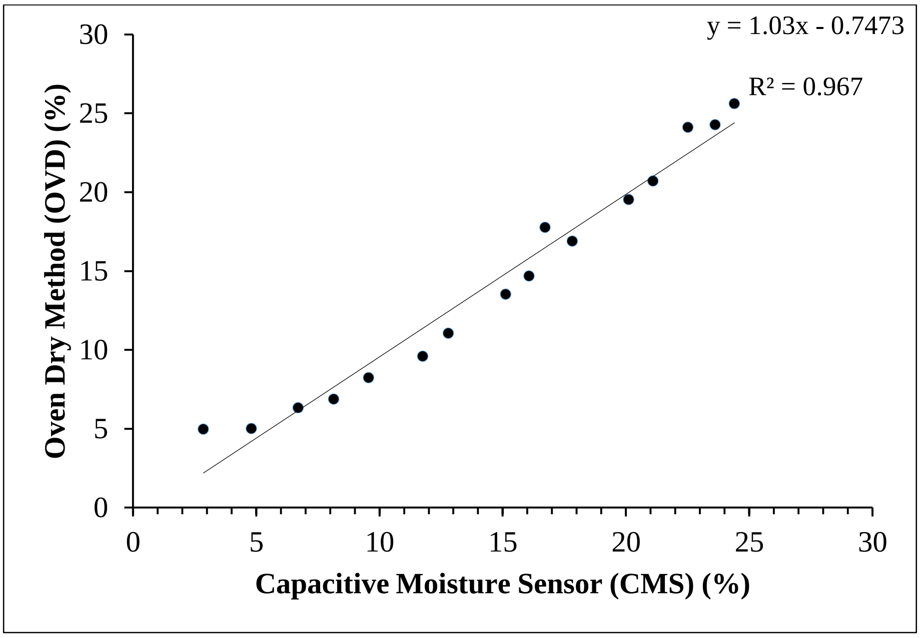

Figure 6: Correlation between moisture content values measured by the OVD method against CMS measurements.

Figure 6 also reveals that, the model given by Equation (6) can be used for determination of moisture content by taking the values of capacitance measured by the CMS as inputs.

The value of correlation coefficient also shows that the developed CMS can provide up to 96.78% accuracy in measuring the moisture content in the salt sample under measurement.

The accuracy of the CMS developed in this study is comparable to that of the soil moisture sensor developed by Ogbu et al. (2016) correlation coefficient of 0.964.

CONCLUSION AND RECOMMENDATION

The capacitive moisture sensor capable of measuring moisture content in table salt was designed and constructed by using the coaxial cylindrical capacitor interfaced with Arduino circuit and microcontroller. The experimental results demonstrated a relatively linear relationship between the capacitance measured by the developed sensor and the moisture content in table salt. The sensor was calibrated and validated by using standard oven drying method. The correlation of moisture content values measured by the CMS and the OVD method revealed a correlation coefficient (R^2) of 0.9678. The average value of percentage deviation between the moisture content values measured by the CMS and the OVD method was 1.38%, which shows a good agreement of the model used to convert the values of capacitance into moisture content. Compared to the traditional moisture sensors, the designed CMS has several advantage including low cost, portability because of its small size, reliability, sensitivity, precision and accuracy. Furthermore, the developed CMS can be easily fabricated and it is easy to use. This makes the developed CMS suitable for measuring moisture content in table salt. However, more optimization in the design and fabrication process can be made to create a coaxial capacitive moisture sensor capable of determine moisture content of different samples and display the value of moisture content directly in percentage.

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