DEVELOPMENT OF A POLYETHYLENE DIELECTRIC CAPACITANCE MOISTURE SENSOR METER TO SUSTAIN FOOD QUALITY

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ABSTRACT
Some available moisture meters come with a look-up table when measuring crop moisture content. In order to eliminate time-wasting in measuring crop moisture, a moisture meter was developed from two coaxial aluminium rods with different diameters and a polyethylene dielectric, which were suspended between parallel plates in a sensor meter. Salt solutions were prepared to allow for the simulation of varying relative humidity conditions according to standard values at different temperatures (25, 30, 35, and 40°C). The sensor meters (AD7746 and SHT71) were characterized at experimental temperatures and relative humidity and the trend equations were programmed into a microcontroller for output on a digital display board. The output of the AD7746 sensor meter was verified by comparing the values of moisture content of rice and corn obtained with the SHT71 control moisture meter and oven drying method. After calibration, the output of SHT71, and AD7746 moisture meters were compared and it was observed that the highest deviation of temperature and relative humidity was 1.57°C and 0.98% at 30°C and 25°C, correspondingly and the lowest deviation of Temperature and relative humidity was 0.00°C and 0.45% at 25°C and 40°C, respectively. The oven-drying method verification showed that the moisture content disparity was 0.13% for corn (v1). Therefore, the moisture meter developed was found suitable for on-farm and warehouse moisture content measurements in storage systems.

KEYWORDS: Sensor, Moisture sensitivity, Low-cost meter, Food quality, Precision agriculture

1. INTRODUCTION
Moisture content, among other attributes, is one of the primary quality parameters, which must be adequately determined during postharvest handling or bioprocessing because the improper evaluation of this factor could significantly affect stored agricultural products (Joaquin *et al*., 2019). However, the quality of these products depends on moisture content, density, and other composition properties that are determined following standard procedures. Conventional methods such as oven drying, distillation method, and drying with desiccants have different challenges. For instance, the standard gravimetric moisture determination method is time-consuming, destructive, and tedious (Zambrano *et al*., 2019). Nevertheless, the moisture determination methods are subject to a paradigm shift into quick analysis and display results on-premise. The new development spurred various research, including developing grain probe meters for paddy and other similar crops.

Joaquin *et al*. (2019) developed a frequency-based moisture meter for paddy only. The prototype unit has a grain capacity of a 100 g test chamber and detects moisture using a microcontroller-based processor with a three-digit LCD screen. However, the moisture probe cost US$ 100.00, which might not be competitive with the existing meters of popular brands. In another research, Gumma *et al*. (2018) proposed developing a grain moisture meter with moisture and price display using Arduino, moisture sensor, DHT sensor, and LCD. However, data on the performance of the device is scanty and hence its effectiveness and efficiency cannot be ascertained. . Another adaptable moisture meter was developed for ginger using a microwave sensor, directional coupler, and microcontroller (Nafis *et al*., 2018). The predictive model developed from the split test gave considerable accuracy of moisture content with an error of 2.9%.

The importance of a moisture meter in food and agro-allied industries cannot be overemphasized as it enables farmers and food processors to take quick and appropriate steps in safeguarding the deterioration of their stored products. The use of a moisture meter for moisture content measurement minimises handling of the products and prevents contamination. With the current Covid-19 pandemic embroidered with social distancing, it affords the opportunity of carrying out the exercise with minimal contact to prevent the spread of the disease while still achieving the objective of handling a large quantity of food items. This will prevent consequential eventual food losses after the pandemic. Most of the available moisture meters are crop-specific, so there arises the need to develop indigenous capable of handling more than one product and cost-effective bearing in mind the small scale farmers who occupy a major position in the agricultural sector of Nigeria. Given the above challenges, there is a need to develop a reliable, accurate, and cost-effective moisture meter to eliminate the destructive method of moisture content determination, minimize processing time, and optimize the accuracy of moisture content determined on-premise.

2. MATERIALS AND METHOD

2.1 Design Consideration

The characteristic of the sensor probe chosen was based upon the choice of optimum sensitivity for quick and effective means of data measurement. Based upon the capacitance formula which states that capacitance is directly proportional to the surface area exposed and inversely proportional to the distance between the two plate surfaces used, the sensor probes were designed to achieve this. These probes were designed to be long enough to increase the surface area and the distance between the plates was reduced to the barest minimum achievable. Details of the discussion of the sensors come along in the following sub-sections. Both were based upon the capacitive means of moisture sensitivity. The sensor probes transduce air moisture into capacitance measured read values accordingly, with capacitance being directly proportional to the surface area of the plates and inversely proportional to the distance between the plates, by the definition of capacitance. In the design, the surface area of the plates and the distance between them are fixed. The measured capacitance is also directly proportional to the permittivity of the dielectric which in turn varies directly accordingly to the volume of moisture present in the dielectric. Other features considered for the moisture meter are

(i) Calibrated directly in ° Celsius (Centigrade)
(ii) Linear + 10.0 mV/°C scale factor
(iii) 0.5°C accuracy guaranteeable (at +25°C)
(iv) Rated for full −55° to +150°C range
(v) Suitable for remote applications
(vi) Low cost due to wafer-level trimming
(vii) Operates from 4 to 30 volts (National Semiconductors, 1994).

2.2 Description of AD7746 meter

The block diagram of the AD7746 moisture meter shows the operation principle (Figure 1). It depicts the parallel plate capacitance sensor feeding capacitance raw measured values to the AD7746 IC, which passes it onto the microcontroller and then displays it on the LCD screen. The small scale AD7746 humidity meter communicates with the pre-programmed microcontroller (PIC16F877). The capacitance to the digital converter was connected in the single-ended capacitive configuration, and the output from the micro-controller was sent to the LCD board (HD44780U), which displays the relative humidity (percentage) and Temperature (degrees centigrade).

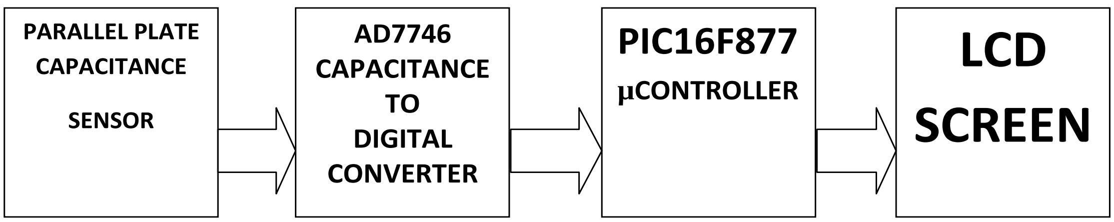


Figure 1: Block diagram of the AD7746 meter

2.3 Selection of the microcontroller

A PIC16F877 microcontroller was selected because of its sufficient number of ports (Figure 2), architecture RISC (Reduced Instruction Set Code), ability to handle I/O (input/output) and, ability to be programmed and reprogrammed a countless number of times (PIC16F87X Data Sheet 28/40-Pin 8-Bit CMOS FLASH Microcontrollers, 2001). The HD44780U dot-matrix liquid crystal display was chosen to display the measured values read from the meters for visual contact. The different saturated salt solutions were prepared to simulate varying relative humidity conditions according to standard values at different temperatures to verify the output read values from the SHT71 control meter and calibrate the small-scale, low-cost meter in particular. The salt solutions were prepared by putting a 20 ml quantity of distilled water into one litre plastic container, which was six in number chosen as desiccators having an incision made on its lid for an allowance to suspend the sensors to go through.

The two circuits developed in this study were powered from a 9V power source, employing an alkaline DC battery with fitted terminals. The output power from the battery was regulated to 5V by a 7805 IC power regular. The output power from the battery was regulated to 5V by a 7805 IC power regulator. The IC regulator has three points: the input, the ground and finally, the output which supplies the 5V output power. All ground points were connected with the ground output pin of the IC regulator. Also employed was the SHT71, which belongs to the Sensirion's relative humidity and temperature sensors with pins. The sensors (Temperature and relative humidity sensors) integrate sensor elements plus signal processing in a simple way that provides a digital output. A capacitive sensor element was used for measuring relative humidity, while the temperature was measured using a band-gap sensor. The two sensors (Temperature and relative humidity) were coupled to a 14-bit analogue to digital converter and a serial interface circuit.

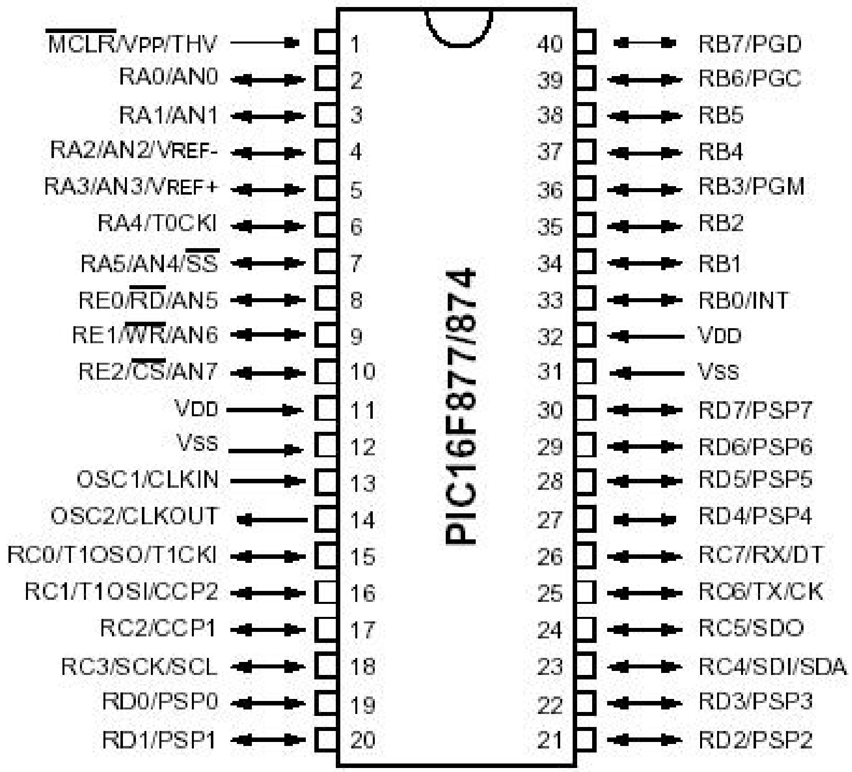


Figure 2: Block Diagram of the PIC16F877 Microcontroller

Capacitive values read by the sensor were transduced, measured, and outputted to the LCD display (HD44780U) with the help of the preprogrammed PIC16F877 microcontroller. Pins 35 to 40 of the microcontroller (Figure 3) were used for the output to drive the LCD screen, while Pins 18 and 23 were used for the input to feed and data signals from the AD7746 capacitance to the digital converter. With the help of two 10k resistors, the input line was maintained at an active high state, while pins 13 and 14 of the microcontroller were connected to an 8MHz oscillator for clocking LM35 IC was the temperature detector employed to detect temperature change. This was connected to the Pin 3 of the microcontroller to feed in the changing surrounding temperature of the air around grain strata.

2.4 Selection of digital converter

The LM 35 temperature sensor was used to convert temperature measurements of the stored grains to analogue voltage values. The LM35 series converts voltage output to temperature (Centigrade), and it does not require calibration before use. The accuracy of the LM35 is ±1⁄4°C at room temperature and ±3⁄4°C in a wide range of temperature (−55 to +150°C).

The AD7746 capacitance to digital converter converts the capacitance measured values read from the local parallel plate sensor to digital values. The AD7746 soldered on a breaker board converts capacitance values directly into the digital format affording the PIC16F877 employed in this research to read and directly process the read values for output. The AD7746 supports an I^2C-compatible 2-wire serial interface. The two wires on the I^2C bus are called SCL (clock) and SDA (data).

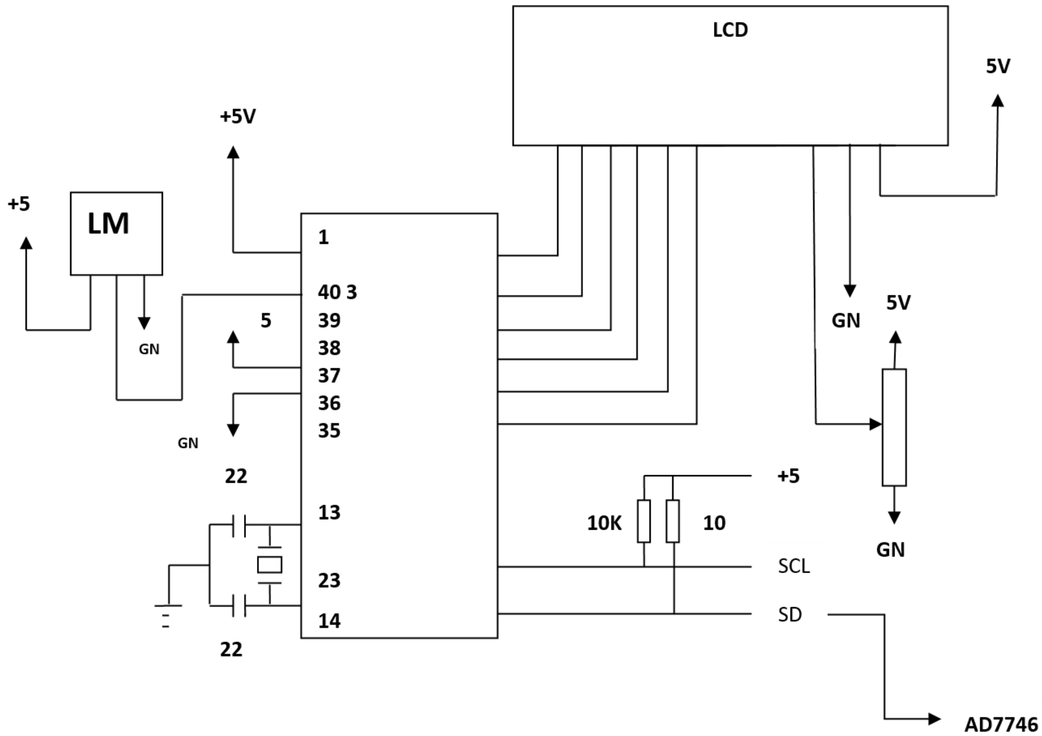


Figure 3: Schematics of Small-Scale AD7746 Moisture Sensor Meter

2.5 Sensor test

A 5 cm sample of coaxial rod and parallel plate sensor was suspended on a seven-day diluted acid solution. The sensors were now transferred afterwards alongside newly-designed sensor probes of the exact specifications (parallel plate and coaxial rod) and were suspended over saturated salt solution. Capacitance measurements were taken from all suspended sensors, and comparisons were made between sensor brands suspended over acid fumes and those never suspended on acid fumes. The procedure was executed to ascertain the characteristic behaviour of the sensors under varying harsh environmental conditions.

2.6 Characterization of the sensors (parallel plate and coaxial rod)

The two sensors used in this research work were characterized using the saturated salt solutions alongside the SHT71 control meter standing as the source control meter. The process established the more reliable sensors, linear at odd and extreme temperatures and relative humidity conditions, and the sensors' characteristic behavioural pattern. The sensors were left to dangle inside saturated salt solution alongside the SHT71 sensor control meter at stipulated temperatures (25, 30, 35, 40ºC) to achieve an environment of diverse equilibrium moisture content and relative humidity. The SHT71 meter present alongside in this experiment stood as the control source standard upon which the two sensors, parallel plate and coaxial rod, were characterized. The coaxial rod, parallel plate sensor, and SHT71 sensor meter were placed inside the saturated salt solution, having reached equilibration for 15 minutes in a salt solution at a particular temperature. The capacitance picofarads readings were recorded using a capacitance meter.

2.7 Calibration of the AD7746 sensor

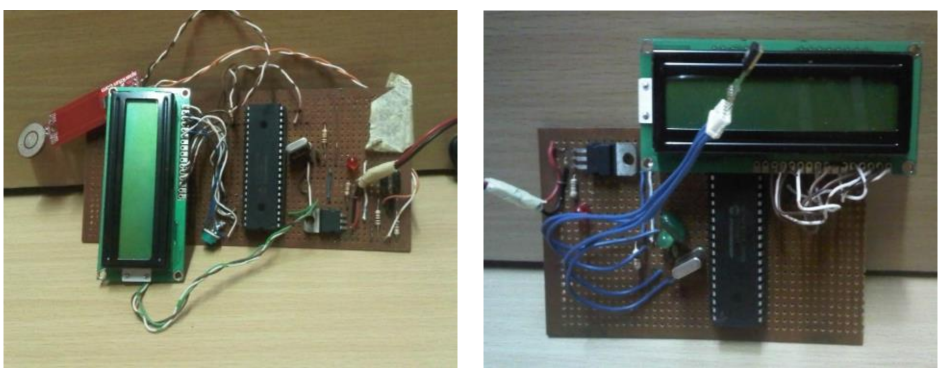
The parallel plate sensor was calibrated using a saturated salt solution environment with the finished built sensor meter, the SHT71 sensor meter, put together to stand as the control source, at which the standard relative humidity and temperature values were read. The output values read from the lowest sensors were measured in the unit of picofarads. These capacitive values were adopted at 25, 30, 35, and 40°C between the range of 0% to 100% relative humidity of the saturated salt solution environment in the stated formulae and then plotted into the linear graph. The equation obtained from the graph was programmed into the PIC16F877 microcontroller.

2.8 Validation of the moisture meter using the oven-dry method

Two varieties of rice and corn were selected to validate the results obtained with the AD7746 moisture meter. About 100 g of the samples were used as test samples. The moisture contents of the crops were compared to oven-dried samples following ASAE (2000) standards.

3. RESULTS AND DISCUSSION

Figure 4 shows the developed moisture meters (AD7746 and SHT71). The two sensors were tested with acid fumes to ascertain the sensors' stability in a harsh environment. Also, the calibration verification of the SHT71 sensor meter, which affirms the results with the ideal standard (saturated salt solution) as the standard control meter for this research, was investigated. Subsequently, the developed AD7746 moisture meter was calibrated to ascertain its accuracy and precision based on sensitivity to temperature and relative humidity.



(a) (b)

Figure 4: The pictorial representation of the (a) AD7746 moisture meter (b) SHT71 moisture meter

3.1 Sensor test with acid fumes

The results showed that the characteristic of the parallel plate suspended over diluted H_2SO_4 acid fumes did not change when compared with its counterpart sensor, which was not suspended over acid fumes. The acid fumes, on the other hand, affected the coaxial rod sensor characteristic significantly. The result shows that the parallel plate sensor is more reliable as it fits into the characteristics of an ideal sensor whose attributes were not affected when exposed to harsh environmental conditions (Soltani and Alimardani 2011).

It remains considerably sensitive only to the measured variable (air moisture) even when other parameters such as temperature are found unstable. Moreover, it was deduced that the parallel plate sensor was more linear, cohesive, and sensitive when compared with the coaxial rod sensor during the acid fume test. Hence, it was chosen for this research.

3.2 The calibration of the sensors

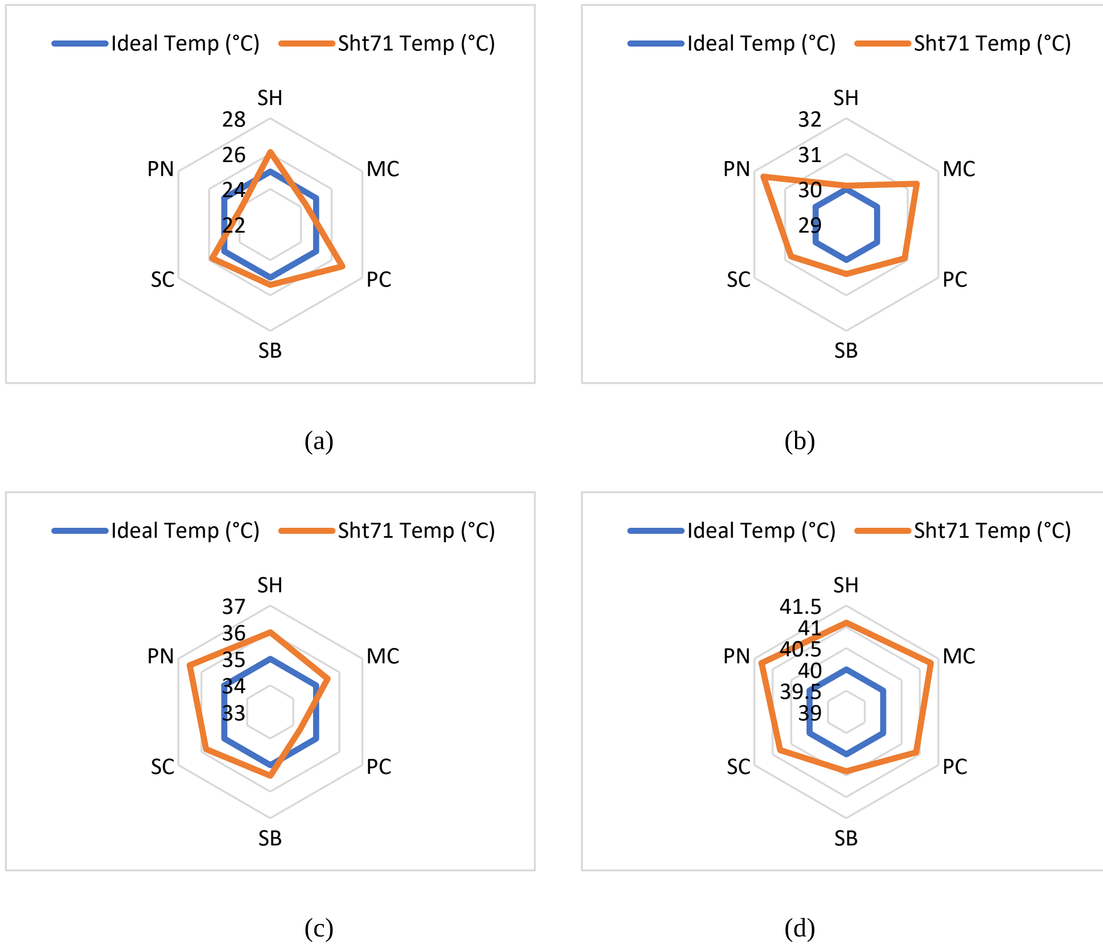
Table 1 shows the result of the calibration of the SHT71 sensor with some selected salts (Sodium Hydroxide, Magnesium Chloride, Potassium Carbonate, Sodium Bromide, Sodium Chloride, and Potassium Nitrate) at different temperatures (25, 30, 35, and 40°C). The moisture meter showed slightly different results when calibrated with different salt solutions. This may be due to the different water activity associated with the salts (Sharma *et al*., 2009) It was observed that the highest temperature deviation (1.70) occurred at 25 and 30°C with potassium carbonate and potassium nitrate salt, respectively (Figure 5). Similarly, the highest negative disparity (-1.10) was observed at 25°C with potassium nitrate salt, indicating that the moisture meter gave the highest sensitivity to the potassium-based saturated salts solution which may also be connected with the water activity of the salt (Sharma *et al*., 2009; Quincot *et al*., 2011)). Conversely, the optimal temperature performance of the moisture sensor was observed at 30°C with sodium hydroxide salt (Figure 5b). The difference between the values of temperature obtained (whether higher or lower) in comparison with the ideal temperature are however within the acceptable limits when matched with the findings of Fridh *et al*. (2018) on moisture meters for wood chips. The differences in RH observed in some points could also be linked to the water activity of the salts

Table 1: Calibration verification of the SHT71 meter at different Temperature

	Ideal Temperature							
	25°C		30°C		35°C		40°C	
Salt	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)
SH	26.10	9.40	30.10	8.50	36.00	7.20	41.10	7.50
MC	24.30	33.10	31.30	32.80	35.50	31.80	41.30	30.00
PC	26.70	44.00	30.90	43.90	34.30	43.50	40.90	42.10
SB	25.40	58.10	30.40	56.50	35.40	53.50	40.40	55.50
SC	25.80	71.60	30.80	71.20	35.80	70.50	40.80	69.60
PN	23.90	94.00	31.70	92.80	36.50	89.60	41.30	88.20

Temp – temperature, RH – relative humidity, SH - Sodium Hydroxide, MC - Magnesium Chloride, PC - Potassium Carbonate, SB - Sodium Bromide, SC - Sodium Chloride, PN - Potassium Nitrate

The ideal moisture meter must satisfy a significant condition because the differences between the SHT71 meter reading and AD7746 meter reading must be kept close enough to zero. The condition was necessary because the SHT71 meter was calibrated to develop a new moisture meter. Figure 6 shows the predicted response plotted against the actual response for the Temperature. It was observed that a significant part of the points (temperature) lies on the diagonal line, which shows a good fit with R^2 = 0.9920. The straight line depicts an apparent linear regression of the model; the vertical distance from the centre line to any given deviated point accounts for the loss function, which measures the degree of error in the measurement. This implies that data obtained by the temperature measured using SHT71 meter fits well well with the model developed as the ideal temperature



SH - Sodium Hydroxide, MC - Magnesium Chloride, PC - Potassium Carbonate, SB - Sodium Bromide, SC - Sodium Chloride, PN - Potassium Nitrate

Figure 5: Calibration verification of the SHT71 meter against ideal condition at Temperature (a) 25°C (b) 30°C (c) 35°C (d) 40°C

In addition, Table 2 represents the mean temperature and relative humidity of AD7746 and SHT71 meters. The deviation from the ideal temperature and relative humidity (0°C, 0%) revealed that the maximum temperature deviation occurred at 30°C with a negative disparity. The result implies that the low-cost moisture meter was more sensitive to the Temperature at this point. Based on the temperature accuracy of the developed moisture meter, the device performed well at 35°C.

However, the effect of relative humidity is likewise relevant. The highest disparity was observed at 25°C with a corresponding value of 0.98%. It shows that the relative humidity sensitivity of the meter increased with temperature from 25°C to 40°C with a minimum disparity of 0.45%. Hence, given the above observations, the tolerance for the low-cost small scale AD7746 meter was stated as ±1.57°C and ±0.98% for temperature and relative humidity measurements, respectively.

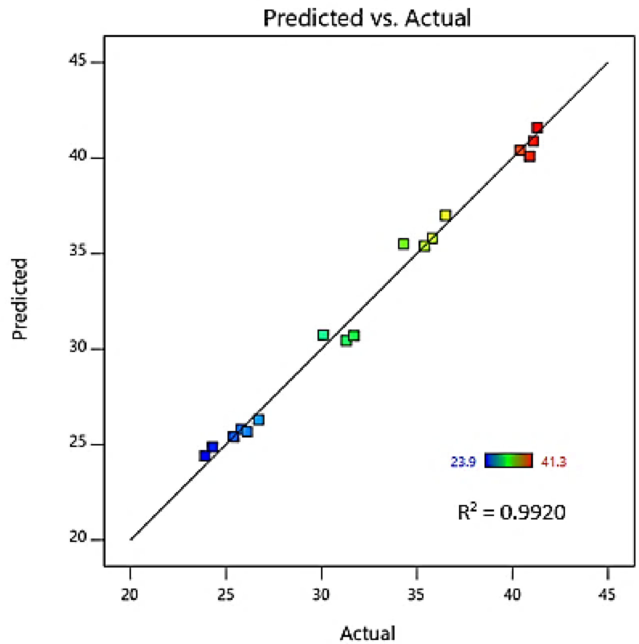


Figure 6: Performance of the SHT71 test data

The disparities experienced in the values of moisture contents obtained may be due to the response of dielectric property (which is the property sensed and converted to the moisture content in moisture meters) of the materials with some factors. Nelson (2015) reported that the dielectric properties of most materials vary with several influencing factors. Such factors include the amount of water in the material (particularly for agricultural materials) which is regarded as the dominant factor. Others include the frequency of the applied alternating electric field, the temperature of the material, the density, composition, and structure of the material (Nelson, 2015). These might have interplayed to induce the disparities observed.

Table 2: Calibration verification of low-cost AD7746 with the SHT71 control meter at different temperatures

Ideal Temp. (°C)	SHT71 Temp. (°C)	AD7746 Temp. (°C)	Disparity (°C)	SHT71 rel. humidity (%)	Ad7746 rel. humidity (%)	Disparity (%)
25.00	25.30	25.70	0.40	51.96	52.93	0.98
30.00	30.90	32.47	1.57	51.72	52.42	0.70
35.00	35.75	35.75	0.00	52.20	52.81	0.61
40.00	41.05	42.00	0.95	51.84	52.29	0.45

3.3 Validation of the AD7746 moisture meter

The results presented in Table 3 represent the validation values obtained for the low-cost moisture meter compared with an oven-dry method using corn and rice as test materials. At lower Temperature (26.40°C), the meter moisture content of corn (v1) was read as 7.70% using the developed low-cost moisture meter. The corresponding value of the moisture content using an oven-dry method was 8.00%. Furthermore, it was tested at a higher temperature (39.20°C), and the disparity between the results of the two methods was 0.50%. The meter performed well with corn, and it was also tested with rice at low and high temperatures. The result of the investigation (Figure 7) gave an accurate measurement as the disparity was negligible. The disparity observed between the readings of moisture content for corn is likely due to the difference in properties of the materials (physical and chemical) which influence the dielectric constant of the materials being measured as reported by Nelson (2015). The meter however compared well with other moisture meters developed for grains with accuracy between 0.3 and 0.5 % as reported by Forsėn and Tarvainen (2000), Quincot *et al*. (2011), and Nelson(2015)

Table 3: Validation results obtained for the low-cost moisture meter and oven-dry measurement.

Grain	AD7746 Temp. (°C)	AD7746 rel. humidity (%)	AD7746 moisture content (%)	Oven dry moisture content (%)	Disparity (%)
Corn (v1)	26.40	27.47	7.70	8.00	0.30
Corn (v2)	39.20	42.30	9.20	8.70	0.50
Rice (v1)	25.90	52.30	10.90	11.50	0.60
Rice (v2)	43.30	61.60	11.20	11.70	0.50

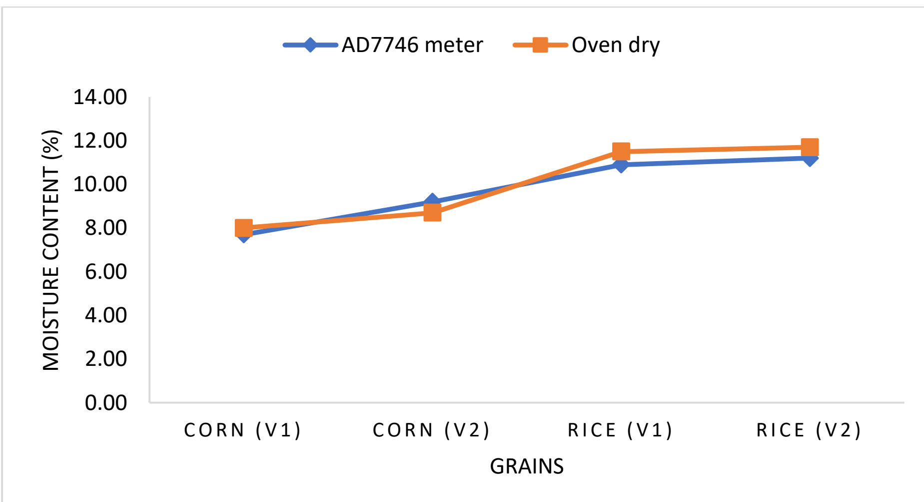


Figure 7: Validation graph for an AD7746 moisture meter

3.4 Economic analysis of the low-cost meter

The study developed a cost-effective, handheld, and accurate moisture meter. Table 4 shows the cost analysis of the low-cost, small-scale humidity sensor meter compared to the SHT71 control meter. The development cost ratio of the low-cost, small-scale AD7746 meter ranks in the ratio order of one to ten (1:10) approximately when compared with the SHT71 control meter. On the other hand, the average cost of a moisture meter in the present-day market is ₦ 40,000. Therefore, the development costs of AD7746 meter ranked on the average ratio of one to fifty-six (1:56) compared to the average moisture meter in the present-day market. Economic studies carried out on this meter in terms of cost compared with the SHT71 control meter or any existing moisture meter found in the market revealed that the objectives of this research were realized. Hence, it is an addition to precision agriculture and the manufacturing industry.

Table 4: Cost estimation of the developed meters

Parts	AD7746 Meter	SHT71 Meter
Screen	100.00	100.00
Microcontroller	300.00	300.00
AD7746 CAPDAC	200.00	---
Sensor	20.00	7,500.00
LED	20.00	20.00
Capacitor	10.00	10.00
Regulator	20.00	20.00
Oscillator	20.00	20.00
Resistors	15.00	15.00
TOTAL (₦)	705.00	7,985.00

4. CONCLUSION

The research successfully developed a low-cost AD7746 moisture meter, measuring the temperature and equilibrium moisture content, and relative humidity of stored grains constantly without hitches or hazards. The tolerance of the meter was observed to be ±1.57°C and ±0.98% for Temperature and relative humidity measurements, respectively. The development cost ratio of the small-scale, low-cost AD7746 meter ranks in the ratio order of 1:10 when compared with the SHT71 control meter and 1:56 when compared to an average moisture meter in the present-day market. Because of this, the development of the moisture meter could be a source of revenue for the manufacturing industry and precision agriculture, especially in areas where there is limited access to the laboratory. The solution was developed to enhance food quality checks and increase demand for food production to sustain lives during hardship.

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