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Research article

A simple low-cost method of determining whether it is safe to store maize

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Abstract: Reliable moisture measurement during drying is key to ensuring that grain is dried adequately to meet market requirements and be safe from spoilage by fungi in storage. While simple hand-held moisture meters are available for use by farmers in industrialized countries, smallholder farmers in developing countries cannot afford these devices and rely on subjective methods based on touch and feel to determine grain moisture. In this study, a simple, low-cost method to determine whether maize is dry enough for storage was developed based on the use of an affordable hygrometer and EMC/ERH relationship for maize. The Mini Digital hygrometer, the lowest cost hygrometer of 5 types tested, was the best based on its accuracy, device-to-device variability and ability to clearly distinguish various moistures of maize. A simple illustrated information-card was developed to guide farmers on using the device and for testing its accuracy.

Keywords: moisture content; hygrometer; maize; Zea mays; storage

1. Introduction

Maize is one of the major food staples of countries in sub-Saharan Africa and thus vital to their food security. One of the challenges in maize production in Sub Saharan African countries is drying for proper storage [1,2]. Estimated post-harvest losses vary greatly and was reported to be as high as 10 to 16% for just the harvesting and drying processes [2].

In sub-Saharan Africa, maize producers typically spread their shelled maize on a hard surface such as concrete pad or side of a tarred road or on tarps and rely on open-air solar radiation to dry [3]. Because the harvest period in the major growing season often coincides with the peak rainfall season, drying opportunities are delayed by rainy conditions, which increases the risks of grain spoilage by fungi and aflatoxin accumulation due to grain moisture remaining high for prolonged drying periods. Aflatoxins are toxic and carcinogenic metabolites produced by *Aspergillus flavus*, which affect both humans and livestock.

During drying, a key decision that needs to be made by the farmers is whether the grain is dry enough for storage. While portable handheld grain moisture meters are available in the market today, at a cost of 100 to 300 USD, they are out of reach to smallholder farmers in developing countries. For most maize farmers, the determination of grain moisture is a subjective process based on perceived weight or sound when shaken in hand [3]. Other methods that are used include breaking kernels with teeth to determine hardness, which increases with dryness, and by plunging one’s hand into bulk grain, which feels easier to penetrate when dry grain compared to wet grain [Ileleji, unpublished]. These methods are not always effective because of farmer differences in experience and perception. Determining whether grain is dry enough becomes even more difficult in moisture ranges from 14 to 16% (wet basis), when it is difficult to firmly discern dry maize at the moisture threshold of 13% from this range, that is 1 to 3 percentage points above 13%. The risk of incurring storage losses from spoilage due to fungi is high for maize stored at 14% moisture and above under warm tropical conditions. Therefore, simple and inexpensive technologies are needed to better assist in the decision-making process on whether maize is dry enough for storage.

Young [4] described the equilibrium relative humidity (ERH) technique, which correlates grain equilibrium moisture content (EMC), as the relative humidity (RH) in the pore spaces between grain kernels at equilibrium with the kernel moisture at a given temperature. Several factors need consideration in using ERH to determine grain moisture, which include the type of grain being measured, time to reach equilibrium, and the hysteresis effects, i.e., adsorption (rewetting) and desorption (drying) [4]. Research by Chen and Morey [5] demonstrated that maize in small, sealed containers shortened the time needed for the air in the pores between the kernels and the air in the head space to reach equilibrium with the maize kernels. Their observation has allowed experimentation with humidity sensors (hygrometers) to develop moisture sorption isotherm models for various species and varieties [6,7,8].

The ability to obtain grain moisture content derived from equilibrium relative humidity values has led to sensor development on temperature cables used in bulk storage silos, which use moisture sorption equations that automatically convert RH of the pore spaces between the kernels to EMC of the grain. An example of a moisture sensor cable is that manufactured by OPI Integris Advanced Grain Management Systems (OPI Systems, Calgary, Canada). Armstrong and Welting [9] developed a grain moisture sensor probe that uses the principle of ERH/EMC relationship to determine grain moisture. After insertion of the probe, a short period of time is needed for measuring equilibrium grain moisture, which is read off an LCD display at the handle-end of the probe [9,10].

The goal of this study was to utilize a low-cost hygrometer in helping the smallholder farmer make an objective decision when drying grain by determining: (1) whether to keep drying, (2) stop drying and store, (3) take to the market for sale if desired. We tested five hygrometers, sold by retail outlets, for their accuracy based on the expected %RH from saturated salt solutions (NaBr, NaCl and KCl) at three temperatures (20, 25 and 30 °C), to select one based on cost, sufficiency of accuracy, variability of readings between devices and ease of calibration. We provide a simple protocol for using the hygrometer for the potentially less educated farmers in developing countries, including those in sub-Saharan Africa.

2. Materials and Method

2.1. Hygrometers

The five digital temperature and humidity hygrometers tested in this study are shown on Table1. As the basis of our selection, we compared the accuracy of the digital hygrometers using saturated salt solutions (NaBr, NaCl and KCl) at three temperatures (20, 25 and 30 °C). The use of a saturated salt solution has been determined as a fairly accurate and convenient method for producing known relative humidities and for calibrating humidity sensors (hygrometers) at temperatures above 0 °C [11]. Five individual devices of each hygrometer-type were placed in a 500 mL airtight sealable plastic bag (15 cm × 23 cm) with a plastic container holding 5 mL of the saturated salt solution. These were incubated for 24 h at the three temperatures and the relative humidity was recorded.

Table 1. Technical details of digital hygrometers tested.

Hygrometer (Make/Model)	Company	RH Range (%)	RH Accuracy	Temperature Range, °C (°F)	Temperature accuracy, °C (°F)	%RH Resolution	Price (USD)
Mini Digital	Neewer®, Shenzhen, China	10 to 99	±5	−50 to 70 (−58 to 158)	±1.1 (±2)	1	4.00
Xikar Round Digital Hygrometer 832xi	Xikar, Kansas City, MO, USA	20 to 95	±2	0 to 50 (32 to 122)	±1.1 (±2)	1	25.00
AccuRite 00613	Chaney Instrument, Lake Geneva, WI, USA	16 to 98	±3 21–80%	0 to 50 (32 to 122)	±1.1 (±2)	NA	12.00
Calibar IV	Cigar Oasis, Farmingdale, NY, USA	20 to 99	±1 & 3 40–80%	0 to 50 (32 to 122)	±1.1 (±2)	1	22.00
Inkbird DC3V	Inkbird Technology, Shenzhen, China	30 to 90	NA	−5 to 50 (23 to 122)	±1.1 (±2)	NA	12.00

NA: Data was not available.

2.2. Grain conditioning

Maize (2015 season) was obtained from Purdue Agronomy Center for Research and Education, ACRE (Purdue University, West Lafayette, In) where it was grown, mechanically harvested with a combine harvester, and dried in a commercial high-temperature continuous flow dryer. The moisture content (wet basis) of the grain was determined according to the ASABE standard air-oven method [11].

Maize was conditioned to desired moistures as described by Williams et al. [12] with the following modifications. The maize and water were placed in a 19 L drum with a tight-fitting lid, mixed on a stationary drum roller (Morse Manufacturing Co., East Syracuse, NY) for 1 h and incubated for five days in a cold room at 4 °C. The final moisture contents (MC) wet basis of the conditioned grain were 11.87 ± 0.04, 14.03 ± 0.03, 15.21 ± 0.02, 16.31 ± 0.02 and 17.79 ± 0.03.

2.3. Grain moisture determination with hygrometer

Conditioned maize (50 g) was placed in a 250 mL sealable plastic bag (7.5 cm × 15 cm). Each digital hygrometer/thermometer model was imbedded in the maize of a given MC and excess air was pushed out of the bags before sealing. The bags were incubated at 20, 25 and 30 °C, and temperature and humidity were recorded at 0, 15, 30, 45, 60, 75 and 90 min. Data points of RH from 0 to 90 min for a given MC and temperature was recorded using 5 different digital hygrometer/temperature units per model (n = 5 replications, i.e. one unit per experimental run).

In order to evaluate how close two of the selected digital hygrometers predicted maize MC, two analyses were conducted: (1) the equilibrium relative humidity was computed from the maize moisture content using the Chung-Pfost equation [8] with the isotherm constant for dent maize [13] and (2) the MC of maize sealed in plastic bag with the digital hygrometers was derived from the Chung-Pfost equation using RH and temperature readings as inputs stabilized after 30 min. The former provided values of the ERH in the maize micro-climate in the sealed bag, while the latter provided values of how the digital hygrometers predicted MC based on their RH readings. Moisture content after equilibration was also measured with a Dickey-John mini-GAC (Dickey-John Corporation, Auburn, IL).

2.4. Analyses for selection of digital hygrometers

SAS 9.4 (SAS Institute, Chicago, IL) was used to determine means and standard errors. The ability of the digital hygrometer types to accurately measure the RH produced in a micro-environment using the three saturated salt solutions were evaluated using 5 units per type (n = 5) based on the absolute error, percent accuracy and percent coefficient of variation (%CV). Accuracy of a sensor can be expressed in "absolute error" as the difference between the RH value given by the sensor and the expected true RH value of the saturated salt solution or also expressed in percentage of absolute error of the true RH value. The %CV explains the relative variability of the RH measured by the replicate digital hygrometer units, which provides an indication of how RH readings varied from one unit to the other.

Of the five hygrometers, the two with comparative high accuracy (low absolute error and % accuracy), low %CV and low price were first selected. Percentage accuracy less than or equal to 13.3% or an absolute error of −10 was the threshold used with reference to humidity levels produced by NaCl. This threshold is based on two criteria: (1) a failsafe approach, should the hygrometer under predict a high RH value, that results in a determination of "wet", requiring further drying; (2) the use of RH value produced by the saturated NaCl solution, the primary component of common table salt, as the preferred calibration salt, which is available for use by low-resourced smallholder farmers everywhere compared to the availability of NaBr and KCl. In selecting between the top two hygrometer choices, in addition to hygrometer price, we used how close to the true MC value of maize did the hygrometers predict MC based on the RH readings and equilibration temperature. Lastly, the ease of calibrating the device was considered, with priority given to calibration simplicity using saturated NaCl solution.

3. Results

3.1. Determination of choice of hygrometer applicable to low-resourced farmers

The first selection was based on testing the accuracy and variability of the five digital hygrometers under three temperature conditions with three different saturated salt solutions (NaBr, NaCl, KCl) (Table 2). Accuracy is the measure of closeness of the measured RH reading by the hygrometers to the expected value of RH by the salt solution at equilibrium, as expressed by the absolute error and percentage accuracy, and the percent coefficient of variation measures the degree of variability among the different sensor units for the same model used.

Table 2. Evaluation of low-cost digital hygrometers at equilibrium with saturated salt solutions at various temperatures[a].

			Digital Hygrometers: Mini Digital			Xikar			AcuRite			Caliber			InkBird		
Salt	Temperature (°C)	Expected RH	Absolute Error	% Accuracy	%CV	Absolute Error	% Accuracy	%CV	Absolute Error	% Accuracy	%CV	Absolute Error	% Accuracy	%CV	Absolute Error	% Accuracy	%CV
NaBr	20	59.1	−5.1	8.6	3.52	3.1	5.2	0.32	−9.9	16.8	1.83	3.4	5.8	3.49	−4.1	6.9	2.51
	25	57.6	−5.6	9.7	3.65	3.2	5.6	0.33	−9.2	16	1.86	2.4	4.2	1.67	−3.2	5.6	2.65
	30	56	−4.7	8.4	3.12	3.8	6.8	0.33	−8	14.3	2.08	3.2	5.7	1.6	−2.8	5	2.18
NaCl	20	75.5	−4.9	6.5	0.71	−2.5	3.3	0.41	−19.3	25.6	2.85	−5.5	7.3	1.57	−14.1	18.7	2.65
	25	75.3	−5.9	7.8	1.73	−2.1	2.8	0.55	−20.1	26.7	3.08	−3.3	4.4	1.81	−12.7	16.9	3.26
	30	75.1	−2	2.7	1.51	0.4	0.5	0.27	−18	24	7.19	−0.6	0.8	1.45	−5.8	7.7	4.83
KCl	20	85.1	−8.1	9.5	0.78	3.9	4.6	0.79	−17.1	20.1	2.5	0.9	1.1	2.42	0.9	1.1	3.33
	25	84.3	−6	7.1	0.89	5.5	6.5	0.45	−16.1	19.1	2.05	0.2	0.2	2.44	1.2	1.4	2.46
	30	83.6	−4.9	5.9	0.89	4.6	5.5	0.23	−13	15.6	1.7	−1.8	2.2	1.96	−3.1	3.7	1.08

[a] A unit device of each hygrometer-type was placed in a 500 mL airtight sealable plastic bag (15 cm × 23 cm) with 5 mL of a saturated salt solution, incubated for 24 h.

Absolute Error = RH by digital hygrometer – Expected true value with saturated salt solution.

% Accuracy = (Absolute Error/Expected true value) × 100.

% Coefficient of Variation (%CV) = (Standard Deviation/Mean) × 100.

N = 5 digital hygrometer units per measurement.

Of the five low-cost hygrometers compared, none of the devices provided humidity readings consistent with that expected at equilibrium conditions of each salt solution (Table 2). All the hygrometers under-predicted RH reproduced by the saturated NaCl solution. While the Xikar and Caliber over predicted RH produced by the saturated NaBr solution, the Mini Digital, AcuRite and InkBird hygrometers under-predicted RH produced by the saturated NaBr solution. The results of the KCl produced RH were very similar for Mini Digital and AcuRite hygrometers (under-predictions), and over-predictions for Xikar, Caliber and InkBird, except for Caliber and InkBird, which RH under-predicted at 30 °C (expected RH = 83.6%).

The AcuRite and InkBird devices were eliminated from consideration because they exceeded the 10% accuracy threshold for under-predicting RH reproduced by the saturated NaCl solution. The %CV for these devices were also quite high for RH produced by the saturated NaCl solution (above 2% and up to 7% for AcuRite). The Caliber was one of the more accurate devices, and comparable in price (22 USD) to the Xikar (25 USD). Although the Caliber has a self-calibration function, the adjustment process was considered too complicated for potential users (less educated smallholder farmers) of the grain moisture device. The Xikar device had the best accuracy and %CV of all five devices, but was also the most expensive of the five digital hygrometers. Its self-calibration is achieved by incubating the device in a plastic bag with the NaCl solution, and pressing a set button once equilibrium is established. As a result, variation between the individual Xikar devices was low by using this simple procedure. The Mini Digital device was the least expensive. The hygrometer readings were consistently lower than the expected values for all the salt solutions (consistent under-prediction and negative bias). Additionally, the %CV for the saturated NaCl and KCl solutions were quite low as well. However, the Mini Digital hygrometer cannot be calibrated, rather the extent to which its calibration has deviated can be checked by a simple calibration procedure using saturated NaCl solution.

3.2. Maize equilibrium relative humidity

The Mini Digital and Xikar hygrometers were selected for further testing based on their percentage accuracy to known relative humidity of the NaCl solution, low absolute error, low %CV between devices, ease of use/calibration and cost. Maize conditioned to 11.9, 14.0, 15.2, 16.3 and 17.8% MC was placed in a plastic bag with either the Mini Digital or Xikar hygrometers. In order to enable a more accurate automatic continuous logging of temperature and RH data, a Lascar EL-USB-2 digital hygrometer/temperature sensor and data logger (Whiteparish, England) was also included in the plastic bag with the digital hygrometers. The Lascar EL-USB-2 digital hygrometer/temperature sensor had a reported accuracy of 2.25% RH (20 to 80% RH) and 0.55 °C (5 to 60 °C), a measurement range of −35 to 80 °C temperature and 0 to 100% RH and logging rate of 10 s to 12 h. Based on predicted RH calculated with the Chung-Pfost equation [8], the RH values for each MC over the three temperatures (20, 25 and 30 °C) should not overlap with the values obtain from maize at the other moistures (Table 3). Reading from the Lascar data loggers indicated the RH within the bags of maize was steady after 15 min regardless of temperature or grain moisture (Figures 1B and 2B). Both the Mini Digital or Xikar hygrometers took between 30 and 45 min to reached a discernible equilibrium reading (Figures 1A and 2A). At all three temperatures, the Mini Digital hygrometer showed a clear separation of each maize MC (Figure 1A). In contrast, the Xikar (Figure 2A) exhibited extensive overlap between the RH readings at the different maize moistures.

The Lascar data logger (Figures 1B and 2B) only exhibited a slight overlap between the RH readings with the different maize moistures. The clear distinguishing of the RH curves for the Mini Digital hygrometer and its cost favored the Mini Digital hygrometer as a low-cost decision making tool for determining whether it is safe to store maize.

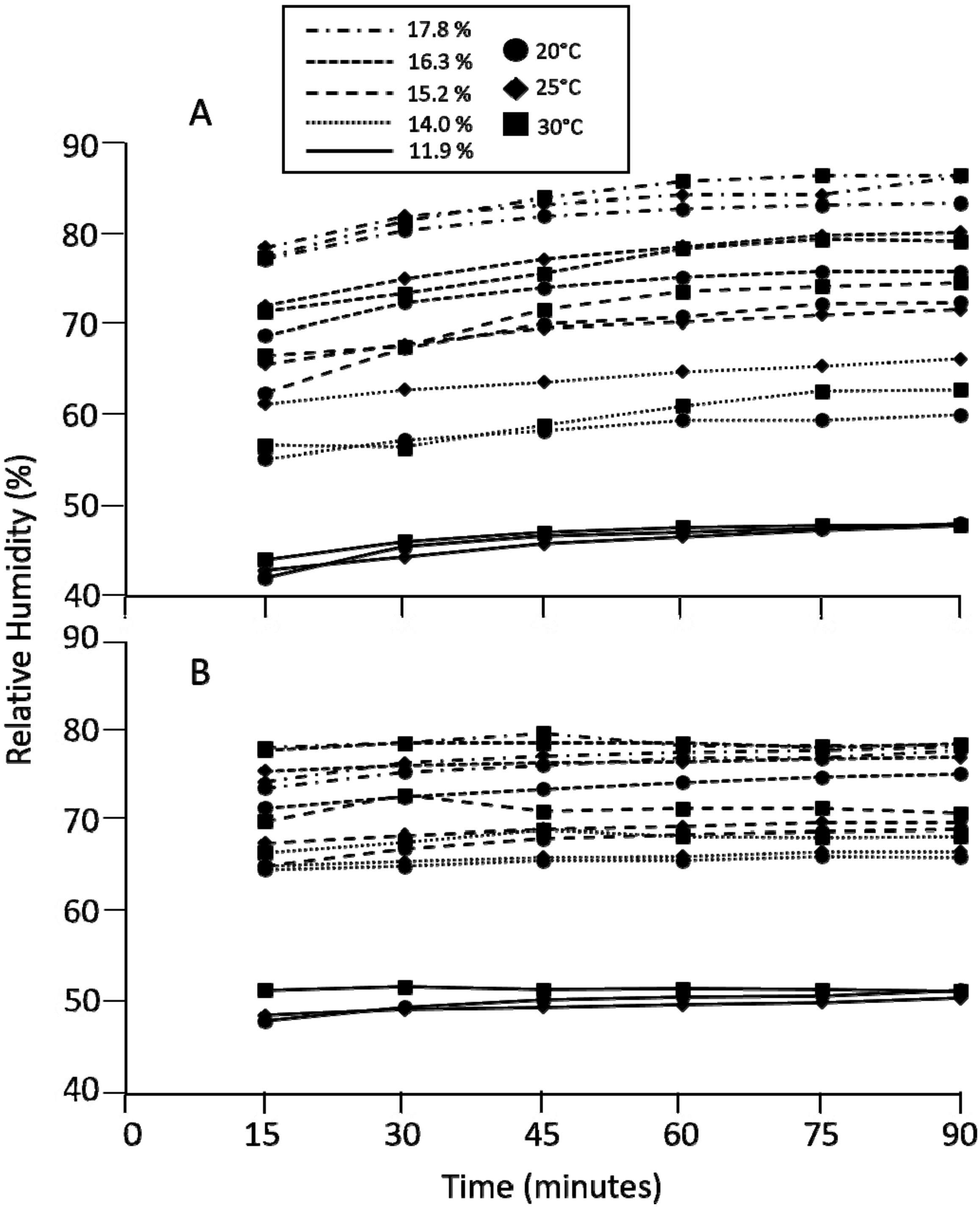

Figure 1. Changes in relative humidity (RH) readings for maize at different MC and temperatures sealed in plastic bags. Data represent the mean RH values from five (A) Mini Digital devices and three (B) Lascar data loggers.

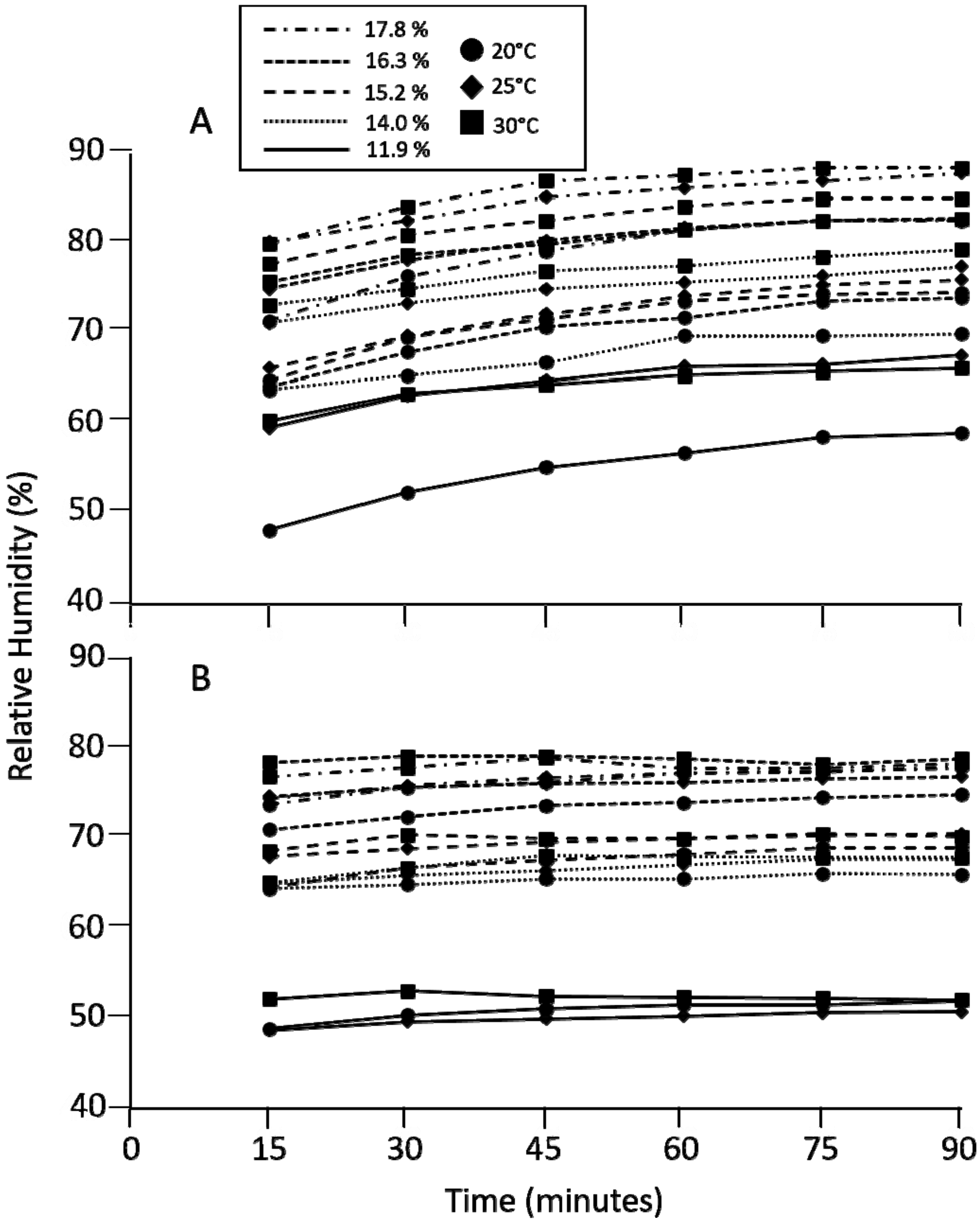

Figure 2. Changes in relative humidity (RH) readings for maize at different MC and temperatures sealed in plastic bags. Data represent the mean RH values from five (A) Xikar devices and three (B) Lascar data loggers.

3.3. Maize moisture calculations

A target for maize storage was an RH value of 65% for the temperature range of 20–30 °C, which would be a maximum MC of about 13.5%. As a test scenario, we determined how closely the Mini Digital and Xikar hygrometer predicted grain ERH in 30 min. Both the Mini Digital and Xikar devices indicated that maize at 16.3 and 17.8% MC were not ready for storage (Figure 3). However, the reading of the Xikar at 20 °C was too close to 65% RH. Mini Digital readings with the maize at 11.9 and 14.0% MC indicated RH values below the 65% RH, indicating the grain was sufficiently dried for storage (Figure 3A). In contrast, the Xikar device indicated that the 14.0% MC grain was still above the 65% RH limit (Figure 3B). At the 15.2% MC, the Mini Digital indicated that the grain was near the 65% RH (Figure 3A). With Xikar device, the RH reading of this grain MC at 20 °C was well above 65%.

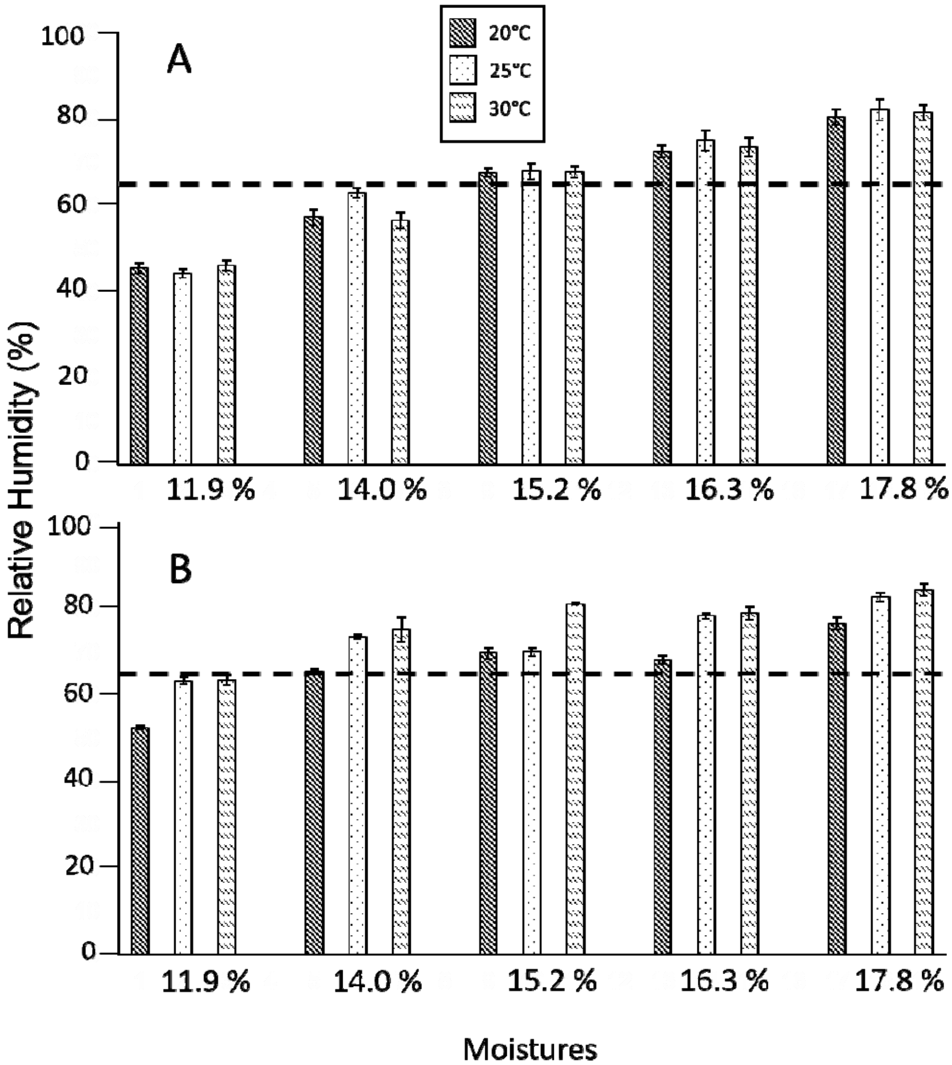

Figure 3. Comparison of the relative humidity (RH) readings from five (A) Mini Digital devices and Five (B) Xikar devices after 30 min. Bars are the mean values with standard errors represented as brackets.

We calculated the predicted grain moisture based on the Chung-Pfost equation [13] with the RH and temperature readings after 30 min (Table 4). When the grain moisture was measured with a commercial moisture meter (Dickey-John) at room temperature, the values obtained were 12.68 ± 0.19, 15.05 ± 0.11, 15.32 ± 0.38, 16.37 ± 0.17 and 17.48 ± 0.12. At 12.68, 15.05, and 15.32% MC range, the calculations of EMC based on the Mini Digital device were less than one percentage point off the MC from oven-dried method. At 16.37 and 17.48%, the device read just over one percentage point higher. In contrast, the Xikar device read consistently well above the actual grain MC.

Table 3. Predicted equilibrium relative humidity (ERH) of maize of various moisture contents (MC) and temperatures.

	Temperatures °C		
MC (%)	20	25	30
11.9	53.1[a]	56.2	59.0
14.0	67.6	70.1	72.2
15.2	74.3	76.3	78.1
16.3	79.6	81.2	82.7
17.8	85.3	86.6	87.6

[a] ERH (%) was determined with the Chung-Pfost (ASAE D245.6) equation for maize.

Table 4. Calculation of maize moisture content (MC) with the Mini Digital and Xikar hygrometers[a].

		Moisture Content (%)				
Measurement Method	Temperature (°C)	11.9 (0.0)[b]	14.0 (0.0)	15.2 (0.0)	16.3 (0.0)	17.8 (0.0)
Mini Digital[a]	20	12.2 (0.2)	14.2 (0.4)	16.3 (0.2)	17.5 (0.4)	19.9 (0.6)
	25	11.4 (0.2)	14.7 (0.2)	15.8 (0.4)	17.7 (0.7)	19.9 (0.8)
	30	11.2 (0.2)	13.0 (0.3)	15.2 (0.3)	16.7 (0.6)	19.2 (0.6)
Xikar[a]	20	13.4 (0.1)	15.8 (0.1)	16.8 (0.3)	16.4 (0.2)	18.6 (0.4)
	25	14.8 (0.2)	17.2 (0.2)	16.3 (0.2)	18.5 (0.2)	20.0 (0.4)
	30	14.4 (0.2)	17.2 (0.8)	18.9 (0.1)	18.2 (0.5)	20.1 (0.4)

[a] Moisture content (MC) of maize sealed in plastic bag with the hygrometers was derived from the Chung-Pfost equation using RH and temperature readings as inputs stabilized after 30 min. Value for all data points are the means of 5 replicates of maize MC for the oven method, and the means of RH from 5 Mini Digital and Xikar devices. The standard error values are in parentheses.

[b] MC of maize used obtain from standard oven method ASAE S352.2.

4. Discussion

We tested five inexpensive hygrometers with retail prices in the range of 4 to 25 USD. Results obtained under different RH modified using saturated salt solutions revealed that the cost of the device did not correlate with accuracy (absolute error) or variation between individual devices. The percentage accuracy less than or equal to 13.3% or an absolute error of −10 was the threshold used with reference to humidity levels produced by NaCl to first eliminate non-applicable devices. Because the ultimate goal is to make these simple hygrometers affordable, easy to use and accessible to large numbers of low-resourced smallholder farmers in developing countries, applying calibration measures to individual devices similar to Chen [8] was not practical. Therefore, the three hygrometers (AcuRite, Caliber, and InkBird) with the least accuracy and most variability were rejected. The Mini Digital and Xikar devices, which represent the least (4 USD) and most expensive (25 USD), respectively, were further tested.

Two aspects for a successful moisture device are its ability to distinguish different moisture levels over a range of temperatures and its ability to reach equilibrium in a reasonably short time. The target moisture often recommended for storage of maize in sub-Saharan African countries is 13% and below [2]. At this moisture, *A. flavus* and storage fungi will not grow [14]. When maize of different moisture was placed in a small sealable plastic bag, both the Mini Digital and Xikar devices recorded ERH in about 30–45 min. Our results indicated that the Mini Digital device was superior to the Xikar because it exhibited clear separation of the various moistures regardless of temperature. The overlapping ERH readings from the Xikar device could cause confusion and result in unacceptable error in deciding whether maize is dry enough to put in storage.

Based on this study, we have developed a protocol for use of the Mini Digital device by low-resourced smallholder farmers to determine if their maize is sufficiently dry for proper storage. Farmers can place a hand full of their maize into a small plastic bag with the hygrometer. After 15 to 30 min, a RH reading above 65% would indicate that further drying is necessary. RH values below 65% would indicate that the maize is dry enough for storage. We would further advise that if the maize is to be marketed, drying should continue until 60% RH is reached. For the Mini Digital hygrometer, there is an expected standard error for the temperatures tested. For the moisture range of 11.87–17.79% there can be an error range of 1.03–2.48% RH that is expected.

Although the Mini Digital hygrometer cannot be recalibrated if the device has drifted, the user can easily verify it accuracy using a simple calibration procedure with saturated NaCl solution. The procedure involves placing a capful of saturated table salt (NaCl) solution in a sealed environment (bag) with the device. Depending on the room temperature, the hygrometer should read between 70–74%.

5. Conclusion

A simple low-cost method to determine whether maize is dry enough for storage using an affordable hygrometer was developed based on EMC/ERH relationship for maize. Five commercially available low-cost hygrometers ranging from a retail price of 4 to 25 USD were tested to determine their ability to distinctly measure ERH of maize at various moistures, and in particular determine whether 65% threshold has been exceeded for samples of maize being tested. The lowest cost device, the Mini Digital hygrometer was selected as the best of 5 units tested based on its accuracy, device-to-device variability, cost and ability to clearly distinguish various moistures of maize.

Initial Extension workshops and surveys conducted in Senegal and Kenya suggest that farmers are willing to purchase and use this low-cost moisture measurement approach. However, questions about the durability of the Mini Digital device, whether it would be widely adopted, and if indeed its adoption would result in a reduction in storage losses from spoilage by fungi and aflatoxin contamination remain to be answered. Additionally, the authors acknowledge the fact that the low cost hygrometers tested lack any published manual indicating technical data and limited replications on the variability of these devices was conducted. However, despite these lapses, the results and conclusions herein was based on good scientific procedures addressing a pressing need of finding a low-cost method for determining whether it is safe to store maize.

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Conflicts of interest

All authors declare no conflicts of interest in this paper.

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