The longevity of seeds in storage is highly sensitive to their moisture content (MC) and temperature (Ellis and Roberts, 1981). In general, the duration of seed viability (germination capacity) in storage is reduced by half for every 1% increase in MC (fresh weight basis) or 6°C increase in temperature (Ellis and Roberts, 1980; Harrington, 1972). Controlling storage temperature on a large scale is costly, particularly in tropical climates, and often is not economically feasible in developing countries; however, drying (and hermetic packaging) is a low-cost approach to extend seed longevity (Ellis, 1988; IIVR, 2016). Maintaining viability is not an issue for stored dry commodities (e.g., grains, pulses, dried fruits or herbs), but storage at low MC is still critical for the preservation of quality and prevention of spoilage. Elevated MC in dried products enables the growth of both microorganisms associated with spoilage and insects that damage stored commodities (Fontana, 2007; Murdock et al., 2012; Roberts, 1972). In addition, sufficient drying prevents the growth of fungi that produce mycotoxins (e.g., aflatoxin) in stored commodities, particularly maize (Zea mays L.) and peanuts or groundnuts (Arachis hypogaea L.) (Wu, 2014; Wu et al., 2014). Thus, the ability to measure and therefore manage MC of seeds and dry commodities is critical to maintaining their postharvest quality.

Seeds and commodities are hygroscopic, and their MC will change in response to the relative humidity (RH) of the air to which they are exposed. The MC of a commodity at a given RH decreases as the temperature or the oil content of the commodity increases. Thus, while the MC of commodities will differ at a given RH and temperature due primarily to differences in oil content (Cromarty et al., 1982), MC and equilibrium RH are related uniquely for a given commodity at a constant temperature, a relationship known as an isotherm (Fig. 1). The growth of both fungal and insect storage pests is prevented at RH percentages less than 70% (fungi) or 35% (insects) using relative humidity.
methods to estimate MC from RH have been described (Probert et al., 2003; Sutcliffe and Adams, 2014). We expand on that approach here to enable more widespread use of a RH-based method for measuring seed and commodity MC and encouraging adoption of improved post-harvest storage conditions.

**Procedures**

Once an isotherm (RH/MC relationship) is known for a commodity (Fig. 1), it is only necessary to measure the RH of air in equilibrium with the commodity to estimate MC (Probert et al., 2003). Electronic temperature and RH meters are now widely available and relatively inexpensive (as little as US$3.00) (Fig. 2A). Various indirect indicators of RH are also available and have been described for use with seeds (Sutcliffe and Adams, 2014). In particular, humidity indicator strips (e.g., Humidicator paper [Micro Essential Laboratory; www.microessentiallab.com]) that change color in response to RH similar to pH paper are particularly inexpensive and convenient (Fig. 2B). For a few cents apiece, a small strip of such paper can quickly indicate the RH inside a container containing a seed or commodity sample (Fig. 2C). Thus, all that is required to estimate seed or commodity MC is to insert an indicator strip several centimeters into the bulk commodity or enclose an indicator strip with a subsample inside a waterproof container (e.g., a clean, dry plastic water bottle), allow it to equilibrate (generally within 30 min), and compare the color to the chart. For larger volumes, representative sampling is important, so taking multiple subsamples and enclosing them in a container with the indicator strip may give the best estimate of average MC.

We prepared a spreadsheet that can convert RH values to MC values for many seeds/grains (Fig. 3; Supplemental...
Material, also available at www.dryingbeads.org/tools) based on the equation developed by Cromarty et al. (1982) that predicts the relationship between $a_w$ and seed MC based on the temperature and seed oil content:

$$M_e = \frac{(1 - D_0) \times \sqrt{-440 \times \ln (1 - a_w)}}{1.1 + (T/90)}$$

where $M_e$ is the equilibrium MC (dry weight basis), $D_0$ is the seed oil content (fraction of dry weight), and $T$ is the temperature ($^\circ$C). The equation is quite accurate between approximately 20 and 70% RH, also the most sensitive range for the Humidicator strips. The spreadsheet allows entry of the temperature to adjust for temperature effects on the isotherms. Any product not listed in the spreadsheet could be calibrated for use with the indicator paper by equilibrating samples at a range of known MC values (determined by an oven test) and observing the corresponding indicator strip color when incubated with each sample.

Note that the Humidicator indicator paper contains cobalt chloride, which can present a health hazard if significant quantities are inhaled or ingested. We believe that the risk is very small for the intended use, as exposure by contact would be low due to the small size of the strip used. But for maximum safety, food samples that have been in contact with the strips should be discarded. Contact could also be avoided by placing the strips inside of a porous container (e.g., a plastic tube with holes for air movement or a cloth or mesh bag) when used with foods.

**Results and Discussion**

Particularly in humid climates, proper storage of seeds and commodities requires initial drying to safe MC and the use of waterproof packaging to prevent rehydration from the atmosphere. The use of RH meters or indicator strips makes it convenient to determine whether the commodity has been sufficiently dried and to monitor the RH inside moisture-proof packaging (e.g., Fig. 2C). For simply monitoring storage suitability, no conversion of RH to MC is necessary, as the color of the indicator paper (RH) can be related directly to the potential storability of the commodity (Fig. 3). Although the color scale can distinguish only differences of 10 to 20% in RH, this is sufficient to estimate grain MC to within approximately 1% in the range from 40 to 60% RH (Fig. 3). At the extremes (<20% or >80% RH), the conditions are clearly very good or very poor for storage, so precision in conversion to MC is less important in those RH regions. We have incubated the strips over a series of saturated salt solutions creating specific RHs, and the colors of the strips accurately reflect those known values. If greater accuracy is desired, electronic RH meters can be used, and the exact values can be entered into the spreadsheet for conversion to MC.

There are numerous additional applications for this inexpensive and readily available method for estimating commodity MC. For example, harvest times are generally determined by grain MC, but this is often based on experience, visual appearance, or texture (e.g., by biting). Enclosing a small sample of grain in a container with an indicator strip would give a more accurate estimate of MC and therefore of maturity. Easy measurement of MC will make traditional air- or sun-drying of commodities more effective by knowing when maximum drying in a given environment has been achieved. The ability to convert the indicator readings to MC would allow calculation of a standard MC for a given commodity for sales by weight. It could also enable a premium to be paid for dry commodities to compensate the grower for the weight loss, as...
such incentives are needed to make adoption of on-farm drying systems economical for the grower (Ann, 1996). In addition, drying to low MC and storage in waterproof containers enables community seed banks and breeding organizations to store seeds and germplasm for long periods (up to years) without refrigeration, resulting in low energy use and independence from unreliable power supplies (Dadlani et al., 2016; IIVR, 2016). Electronic RH meters and particularly RH indicator strips provide simple and inexpensive methods to monitor such storage conditions and assure maintenance of low MC conditions.

**Supplemental Material**

A Moisture Content Calculator, v. 1.2, is available online as a supplemental file (https://dl.sciencesocieties.org/publications/ael/tocs/1/1).

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**References**


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