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Review

Assessment of moisture content measurement methods of dried food products in small-scale operations in developing countries: A review

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ABSTRACT

Background: Moisture-related microbial growth is a key factor contributing to food spoilage in developing countries. Dehydration or drying of food reduces the moisture content supporting this microbial growth, thereby addressing this problem. Hence the moisture content of food materials is a key factor influencing the quality of storage thereby reducing post-harvest loss and is thus very important for the farmers.

Scope and approach: Current moisture measurement techniques (both destructive and non-destructive) available do not take into account the inherent difficulties in the context of developing countries including the relatively high instrumentation cost, unreliable power supply, specificity of the measurement method to food type, and training and maintenance requirements, among others. This paper includes a review of the existing moisture content measurement methods followed by an evaluation of their applicability for this proposed application in developing countries.

Key Findings and Conclusions: A few recently developed instruments show promise but there is little research on how small-scale farms and co-operatives in developing countries can achieve a safe standard for their dried foods. Of these, two potential methods, equilibrium relative humidity and infrared imaging, were identified as promising techniques, but further research and development would be needed to make them suitable for use in small-scale operations in developing countries.

1. Introduction

In developing countries more than 30 percent of fresh food may be lost post-harvest (Gustavsson, Cederberg, Sonesson, van Otterdijk, & Meybeck, 2011). Post-harvest losses in turn, results in quantitative, qualitative and economic losses (Hailu & Derbew, 2015; Hodges, Buzby, & Bennett, 2011). Further, the reported food waste is responsible for an equivalent to 6–10% of anthropogenic greenhouse gas emissions (Gustavsson et al., 2011). These post-harvest losses are primarily due to moisture-related microbial growth, which can make food unfit for human consumption, leading to illness or death. Microbial growth rate depends on a variety of factors, such as pH, temperature, and water activity (a_w). Water activity is a measurement of the availability of water for biological reactions and mathematically relates to the ratio of the vapour pressure of water in a food to the vapour pressure of pure water (Government of Manitoba, 2017). It is considered to be the most critical factor for microbial growth (Prior, 1979). Moisture or water content is a measurement of the total water contained in a food product, usually expressed as a percentage by weight on a wet basis. Although water activity is related to moisture content through the moisture sorption isotherm at a given temperature and humidity, this relationship is complex and is specific to the food product (Mathlouthi, 2001). To avoid microbial growth, the moisture content and water activity must be kept below approximately 10% and 0.60–0.65, respectively (Mercer, 2008), depending on the type of food. Fresh foods, which are high in moisture content often have a water activity close to 0.99 and are particularly prone to microbial growth (Jay, Loessner, & Golden, 2005).

In developing countries, safe storage of food with a high moisture content is made more challenging by high outdoor temperatures and often inadequate refrigeration and storage facilities. Therefore, it is common to dry food products to reduce food spoilage. Drying the food

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reduces the amount of moisture available to support microbial growth, thereby increasing the product shelf life, which is an ideal solution when appropriate storage is not available (Jayaraman & Das Gupta, 1992; Mercer, 2008; Ogawa & Adachi, 2014). But, how dry is dry enough? In the pharmaceutical, agricultural, and food industries, among others, numerous measurement methods are used to ensure target moisture contents are reached. Yet, operations in developing countries, particularly those on a small scale such as co-operatives or small farms, often lack the regulatory, technical, and financial means to establish quality control systems similar to these other industries.

Assessment of moisture content in food materials in developing countries, particularly in small scale operations, generally falls into one of three categories. The categories have been created to distinguish between methods which are quantitative, semi-quantitative and qualitative, and are presented here in decreasing level of accuracy:

a) The first category comprises standard test methods, which are highly quantitative in nature. For example, an adaptation of the American Society for Testing and Materials standard method (ASTM D2974-14) is commonly used for product moisture analysis or calibration of moisture monitoring devices in large-scale food production facilities (ASTM, 2014). This technique usually requires the use of specialized, costly equipment, as detailed in Table 1 (Appendix). Such tests are time-consuming (taking from a few hours to over 24 h), and routinely done by trained technicians in a laboratory environment (Park, 2008).
b) The second category includes semi-quantitative approaches such as low-cost moisture meters (Opit et al., 2014), as well as new approaches for assessing food dryness. Developments in the electronics field have led to relatively low-cost and easy-to-use electronic meters. While these methods lack the official recognition of the ASTM procedures, they tend to be relatively accurate and can be used for field measurements, even in developing countries (FAO, 2011). One on-line source describes the use of a commercially available “pen-like” battery-powered moisture meter to measure the approximate water content of dried fruit in India (Indiamart, 2017). The material's moisture content is measured in these machines by means of a DC resistance circuit, which measures the total current that moisture causes to flow between the needle electrodes. The auto ranging display shows direct moisture content percent. Unfortunately, its high resolution (0.1%) and measurement accuracy (± 0.2%) are accompanied by a $600 USD cost. An example of a new approach is the Drycard, which was developed by the University of California Davis (UC Davis, 2017b). The Drycard is a low-cost tool that provides a colorimetric indicator of the equilibrium relative humidity (ERH) of a dried food or seed sample placed in a tightly sealed glass jar or other suitable container. Additional information about the Drycard is provided in Section 2.1.1.
c) The third category includes qualitative methods – the most common of which is the “flex test”. A “jar test” may also be used in small farming operations. The “flex test” consists of bending the dried, or partially dried, material between your fingers. The surface should feel dry and leathery to the touch, while the sample has a degree of flexibility to it. A degree of brittleness may indicate that the sample has been over-dried. In some instances, excessively rapid drying may create a dry, leathery surface due to case hardening. For this reason, samples should also be torn apart to check their interior for signs of moisture. An example of a "jar test" used in some settings is as follows. Moisture measurement of maize is done by placing dry non-iodized salt and maize kernels in a tightly-sealed jar. The moisture content is considered to be less than 15% if the salt does not adhere to the sides of the jar after shaking and rolling it gently for 2–3 min (FAO, 2011). As can be seen, these tests lack any degree of rigor and may be subject to a wide range of interpretation.

In many developing countries, particularly in the context of small-scale operations, unregulated trading/selling of dried food products takes place. Often the inspection of these products is done by sight and feel, with no formal method of grading the produce. Given the concerns of postharvest losses for farmers and food safety for consumers in developing countries, it is essential for the moisture measurement technology to be low cost, easy to transport, employing a relatively accurate method, and broadly applicable for different food materials. However, existing low-cost methods suffer from low accuracy, while the higher accuracy methods are expensive to adapt to a small-scale scope and require specialized equipment. Thus, an investigation of quick, inexpensive, relatively accurate, and portable moisture measurement methods is needed with the aim of informing broader adoption of these quality control methods for field use.

While scientific literature on moisture content measurement methods in solids (not limited to foods) is abundant, to our knowledge the most comprehensive review was published over three decades ago (Pyper, 1985). While there are several moisture measurement reviews specific to the food industry (Cauvain & Young, 2009; Srikiatden & Roberts, 2007; Zhang, Sun, & Zhang, 2017); most are focussed on laboratory methods, e.g., non-invasive where the sample is not destroyed during measurement (Nath, Das, Ramasamy, & Ramanathan, 2015; Spitzlei, 2000), relevant to specific food types (e.g., grains) (Bennett & Hudson, 1954; Kandasamy, Varadharaju, Kalemullah, & Maladhi, 2012; Ling, Lyng, & Wang, 2018; Pixton, 1967) or specific techniques (e.g., microwave oven drying) (Ahn, Kil, Kong, & Kim, 2014; Bouraoui, Richard, & Fichtali, 1993). Current literature also consists of resources detailing principles of moisture measurement across a variety of industries, which are generally method or application specific, and most often relevant to a laboratory setting. Details of these resources are provided in Table 2 (Appendix).

Most of the moisture measurement related papers (e.g., Eren, Brusic, & Goh, 1997; Isaksson, Tøgersen, Iversen, & Hildrum, 1995) focus on non-invasive techniques but only a few exceptions (e.g. Nath and Ramanathan (2017) have examined the suitability or adaptation of the methods for use in agricultural co-operatives or other small-scale operations in developing countries. This review paper fills a gap in the literature by summarizing various moisture measurement principles and providing an analysis of their suitability for application in small-scale co-operative and farming operations in developing countries. Furthermore, the findings presented here can also serve as a resource for those doing home food dehydration who lack the equipment required for accurate final moisture content determination.

Given the currently available literature on moisture measurement methods and the need for new, low-cost techniques, the objectives of this paper are:

A. To summarize common moisture content measurement methods for dried food products with respect to the measurement principle, typical applications, and the advantages and limitations in the food industry so that the suitability of each method to the small-scale farming and co-operative context can be assessed.
B. To determine which methods are most applicable for use in small-scale farms and co-operatives in developing countries, or which methods are most likely to be adaptable to this context, based on a set of criteria developed to examine each method and a hypothetical case study of a co-operative in a developing country.

The first part of the paper summarizes the moisture content measurement methods which are then assessed in the second part for their applicability or adaptability to the proposed context.

2. Review of literature on moisture content measurement methods

A literature review of existing moisture content measurement methods was conducted. This was followed by development of a set of

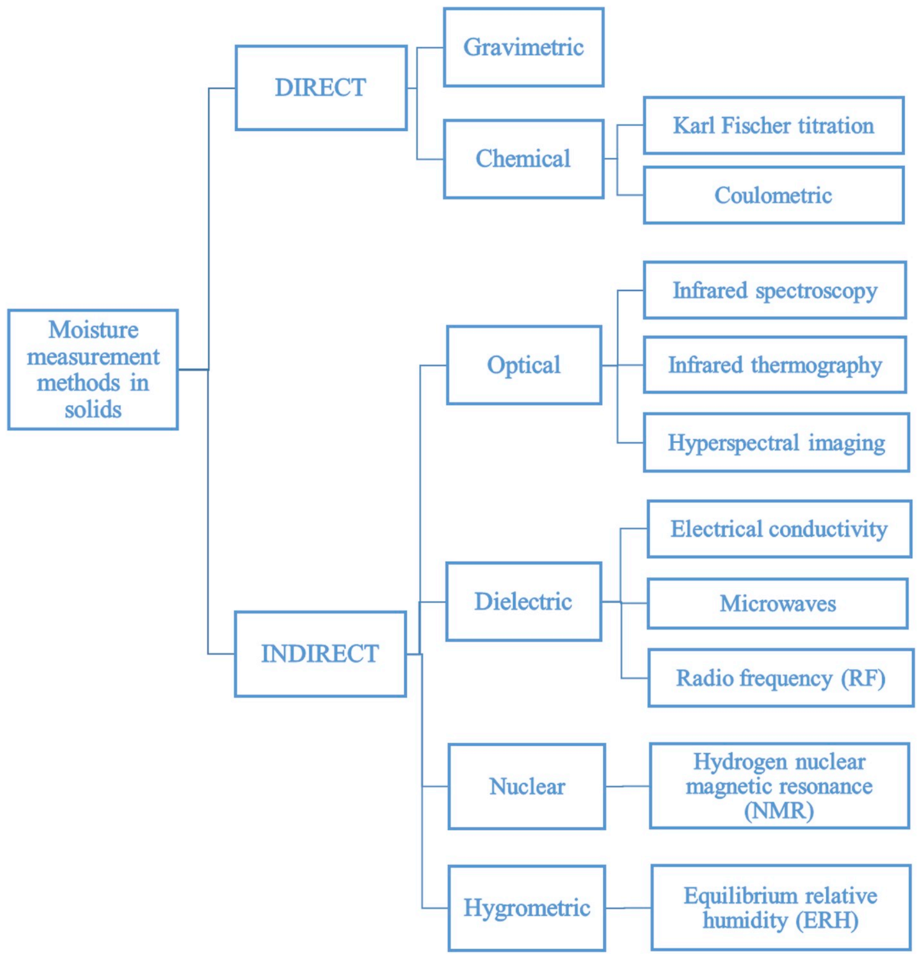

Fig. 1. Classification of moisture content measurement methods for solids.

criteria against which to assess these methods for their applicability, or adaptability to small-scale farming operations or cooperatives in developing countries and an assessment of each method against said criteria.

A literature search on moisture content measurement methods in agricultural food products, in particular high moisture content fruits and vegetables grown in developing countries, showed a limited number of review papers addressing all existing methods (most of them addressed particular ones), and none that addressed moisture measurement in developing countries. Additional searches focussing on food dryness monitoring techniques in developing countries were conducted to determine if any drying assessment was currently being conducted and by which means. For each moisture measurement method found, the measurement principle, contact method, testing techniques, advantages, disadvantages, and typical applications were noted. While the focus of this paper is agricultural food products, some of the measurement methods reviewed are also applied in industries other than the food industry and this is noted in the sections below to provide context. The methods were grouped into two categories: direct and indirect measurement (See Fig. 1).

Direct methods measure moisture content without an intermediate variable, including measuring the moisture content by weighing or titration before and after drying, and/or distillation (Nath & Ramanathan, 2017; Pyper, 1985). Indirect measurement methods are classified as such because they determine the moisture content by measuring the variation of a physical property (e.g., temperature, refractive index, pressure) relative to a baseline or over time. This property, transformed into a signal (e.g., wavelength shift, electric current), is then correlated to moisture content (Nath & Ramanathan, 2017; Wernecke & Wernecke, 2014). Both direct and indirect moisture measurement methods can be used in a variety of applications including laboratories, processing lines, and in the field (Kupfer, 2005). However, only indirect methods can be used for automation and continuous measurement (Karmas, 1980).

2.1. Direct methods

Direct methods are typically conducted in a laboratory setting as they generally require specific environmental conditions and specialized equipment. The high level of accuracy of these methods makes them a useful reference for indirect methods. Their reproducibility also makes them useful for standardization and characterization of specific sample types or equipment (Wernecke & Wernecke, 2014). However, direct methods are often time consuming, destructive, and require extensive sample preparation (Pande, 1975). The direct methods described here are the gravimetric method and a chemical method: Karl Fischer titration, which are categorized under “quantitative” methods.

2.1.1. Gravimetric method

The gravimetric method is a standard laboratory technique that is widely used in a variety of industries (e.g., food, construction, textiles, agriculture, and chemical) (Behari, 2005; Wernecke & Wernecke, 2014). The sample is weighed, then dried (usually for a prescribed period of time under specific conditions of temperature and often under vacuum) and weighed again. The moisture content is calculated based on the initial and final weights of the sample, which assumes that all weight loss is due to the removal of water and ignores the loss of other volatiles (Bonner, 1981; Wrolstad et al., 2005 pp. 1–71). The sample preparation and drying conditions (e.g. time, temperature, type of oven, humidity, and pressure) influence the efficiency of moisture removal and the resulting drying time required to complete a test can vary from hours to days (Bradley, 2010).

2.1.2. Chemical methods

2.1.2.1. Karl Fischer titration method. The Karl Fischer titration method is a standard laboratory technique used to measure moisture content in liquids and solids in construction, textile, and agriculture materials, among others (Bonner, 1981; Jones, 1981; Wernecke & Wernecke, 2014). Moisture content is determined with a calibration curve correlated to the volume of reagent used to titrate the water of a sample. The sample is completely dissolved in a solution consisting of a primary alcohol (methanol) as the solvent, and a base (pyridine) as a buffering agent. Next, a brown titrant solution of sulfur dioxide (SO_2) and iodine (I_2) is added drop-wise to the sample solution. The iodine reacts with water and the titrant solution loses its color. Further titrant solution is added until the reaction between the water and the iodine is completed, as indicated by the titrant solution recovering its color again because of iodine availability. The amount of water in the original sample solution is determined based on the amount of titrant solution added before re-coloration occurs (Bradley, 2010).

2.1.2.2. Colorimetric titration method. Colorimetric methods have been used in moisture monitoring for many years. A common example of this is the incorporation of cobalt chloride ($CoCl_2$) into desiccant materials as an indicator for their degree of water pick-up. In its un-hydrated form, cobalt chloride ($CoCl_2$) is light blue in color. As a dihydrate, cobalt chloride ($CoCl_2{\cdot}2H_2O$) takes on a purple coloration which turns to pink when the compound is hydrated even further to give a hexahydrate ($CoCl_2{\cdot}6H_2O$).

As mentioned in Section 1.1, the United States Agency for International Development (USAID) and the University of California Davis have developed an easy-to-use, low-cost device called the "DryCard" (UC Davis, 2017a). It leverages the color changes of cobalt chloride to gauge the moisture content of food materials after drying. The DryCard is placed in a sealed air-tight container along with a representative sample of the material being tested. As an equilibrium relative humidity begins to be established in the closed system, the cobalt chloride impregnated paper will turn to a color indicative of its degree of hydration. Color changes are typically noticed within 20–30 min, with a reliably stable reading being obtained after 2 h. If the sample material is sufficiently dry, the cobalt chloride strip will be blue. A blue color would indicate an equilibrium relative humidity value below 65% (i.e., a water activity of 0.65) which is generally considered to be the threshold level below which mold growth cannot occur. In a case such as this, the product should undergo additional drying or be used immediately. However, when a sample has a higher moisture content, the DryCard turns pink indicating that the water activity is above 0.65 as the pink color means the cobalt chloride is present in its hexahydrate state. A feature of the DryCard is that it can be used repeatedly because the cobalt chloride hydration process is reversible. Should the indicator paper become soaked in water, the cobalt chloride may be leached out, causing the device to become difficult to read. The DryCard provides a key improvement over a flex test. The DryCard provides a 'yes/no' (semi-quantitative) response, but there is still a need to accurately quantify moisture content. This will help ensure that sufficiently low moisture levels are being achieved to eliminate the risks of microbial growth in the final product. It is also unclear what the uptake of methods like the DryCard will be.

2.2. Indirect methods

Indirect methods can be used to determine various material properties including moisture content. However, these indirect methods need to be calibrated against a direct method. Indirect methods can be faster than direct methods and non-destructive, but can be sensitive to environmental conditions (e.g., temperature) and material properties (e.g. density) (Kupfer, 2005; Sun, 2009). Indirect methods include optical, dielectric, nuclear, and hygrometric approaches, which are considered to be quantitative methods.

Most indirect methods, with the exception of hygrometric methods, use electromagnetic radiation to determine moisture content by exploiting the strong influence of water in a material on the electromagnetic field (Pyper, 1985). If a known electromagnetic field is applied to a sample before and after drying, the moisture content can be determined by comparing the changes in physical properties, such as refractive index (e.g., optical methods), caused by the alternating electromagnetic field in the presence of water (Kupfer, 2005; Sun, 2009). The manner in which the waves propagate and interact with an applied electromagnetic field is influenced by the electrical, magnetic, physicochemical (e.g., homogeneity, texture, size, shape) properties of a material, and the distance at which the sensor is placed (Behari, 2005). Material characteristic calibration curves are needed to convert the radiation signal into moisture content (Wernecke & Wernecke, 2014). The choice of spectrum range depends on the absorption, reflectance, and transmittance of the targeted material, the expected moisture content in the sample, the type of water bonds, and on the contrast in optical properties between the targeted material and water (Erba, Daniotti, Rosina, Sansonetti, & Paolini, 2016).

2.2.1. Optical methods

Optical measurement methods are most useful for measuring samples with a homogenous surface, whereas rough surfaces or variations in color can result in errors. Another limitation is the penetration depth of the electromagnetic radiation, which is influenced by material absorption and reflection characteristics. Both the material and moisture content influence the radiation path length, making calibration of these methods material-specific (Wernecke & Wernecke, 2014). Optical methods have been used in the food industry for color sorting and detection of surface defects primarily in large processing plants (Huang, Yu, Xu, & Ying, 2008; Sun, 2009).

2.2.1.1. Infrared spectroscopy. Infrared (IR) spectroscopy is one of the most common methods for remote sensing of moisture content in soils (Behari, 2005; Schmugge, 2011) and for moisture measurement in a variety of biological samples, including food (Bradley, 2010). The popularity of this approach is due to a short measurement time (e.g., analytical result in 15 s for moisture measurement in cereal products via Near IR) (Osborne, 2000, pp. 1–14), that little or no sample preparation (e.g. extraction, grinding, and weighing) is required, the ability to conduct non-destructive testing, the sensitivity of the test method, and that it does not require a reagent (Liu, Zeng, & Sun, 2015).

The measurement principle is based on the capacity of molecules and atoms to be excited by light absorption at different wavelengths (Fraden, 2016; Huang et al., 2008). IR electromagnetic radiation can be used to quantify moisture content based on the reflection and absorption of this radiation by water molecules especially prominent at around 3300 cm^{-1} (Boyes, 2010; Sun, 2009). Near infrared (NIR) (780 nm–2500 nm) (Osborne, 2000, pp. 1–14) and mid-infrared (MIR) (2500 nm to 25,000 nm) (Lawson-Wood & Robertson, 2016) are used most commonly. NIR penetrates deeper into the sample but is less intense and therefore less sensitive compared to MIR (Behari, 2005; Scotter, 1997; Sun, 2009).

One widely used variation of IR spectroscopy is Fourier Transform Infrared (FTIR) spectroscopy, which uses a mathematical procedure (Fourier transform – FT) to transform raw data into the actual spectrum. FTIR spectrometers have been developed for specific applications, such as production lines where quick moisture content measurements are required (Sun, 2009).

2.2.1.2. Infrared (IR) thermography. IR detectors can be used to generate thermographic images or as photon-sensitive sensors (photodiodes) in NIR systems (Maroy, Van Den Bossche, Steeman, & Van De Vijver, 2016; Sun, 2009).

The measurement principle is based on detecting the difference in IR emitted from a dry sample and a wet sample. An IR camera detects thermal energy (primarily in the 3–20 µm range) emitted by the surface of an object and transforms this into a visible "temperature map" of the surface. The amount of radiation emitted depends on the surface characteristics and temperature of the object. As water has a higher specific heat capacity than most materials, if a wet sample were heated or cooled, it would take longer to return to equilibrium with the surrounding environment than a dry sample. (Bauer, Pavón, Pereira, & Nascimento, 2016; Fraden, 2016; Maroy et al., 2016).

2.2.1.3. Hyperspectral imaging (HSI). Hyperspectral imaging has emerged as a useful method for non-destructive measurement and visualisation of moisture content in food materials. It provides a basis to evaluate the drying kinetics of the drying method. HSI is one of a class of techniques, produced in imaging spectrometers, commonly referred to as spectral imaging or spectral analysis that combines both conventional imaging and spectroscopy (Dutta, Raghavan, Orsat, & Ngadi, 2015). The data in hyperspectral imaging is presented in the spatial direction, which is useful for extracting information with minimum loss. Reflectance is the most common mode for hyperspectral imaging and is usually carried out in the Vis - NIR (400–1000 nm) or NIR (1000–1700 nm) range. Hyperspectral imaging has been used to detect defects, contaminants and quality attributes of fruits, vegetables and meat products (ElMasry, Wang, ElSayed, & Ngadi, 2007; Lu & Peng, 2006; Qiao, Ngadi, Wang, Gariepy, & Prasher, 2007). Several studies have used this technology for moisture content determination (Amjad, Crichton, Munir, Hensel, & Sturm, 2018; Huang, Wang, Zhang, & Zhu, 2014; Wu et al., 2012). Amjad et al. (2018) determined the moisture content of potato slices of variable thicknesses and at varying drying temperatures during convective drying in a laboratory hot air dryer. Hyperspectral imaging was used by Huang et al. (2014) to evaluate dried soybean quality, while Wu et al. (2012) used it to determine the moisture content of prawns at different levels of dehydration. Generally, partial least squares regression or multiple linear regression calibration models have been used to analyse the spectral data. A key advantage of HSI is its ability to carry out non-destructive measurements of irregular shaped objects during the "on-line" drying process.

2.2.2. Ditctric methods

Water molecules have a high dielectric constant, or relative permittivity, due to their permanent dipole. The dielectric constant is "the ability of a material to store electromagnetic energy" (Kim et al., 2006, p. p.1196). Water molecules rotate and align their electric dipole moments in response to an applied electromagnetic field (Behari, 2005; Schmugge, 2011) and this reorientation produces an *electrical polarization noise* that can be used to measure the dielectric properties (dielectric constant and dielectric loss) of a material and thus determine its moisture content (Venkatesh & Raghavan, 2004). This is possible because the dielectric constant of water (approximately 80) is much higher than that of most substances (e.g. air at 25 °C is 1, and most organic materials are in the range of 2–5). Therefore, small variations in the water content of a material produce considerable changes in its dielectric constant (Bradley, 2010; Pyper, 1985).

Dielectric properties of a material depend on its composition, moisture content, ionic conductivity, temperature, scattering due to nature of heterogenous materials (food samples), density variations, and properties of the frequency used (McKeown, Trabelsi, Tollner, & Nelson, 2012; Venkatesh & Raghavan, 2004) as well as the geometry of the particle and the orientation in relation to the applied electrical field (Kupfer, 2005). Therefore, calibrations of dielectric constant to moisture content are usually material specific (Cataldo, Tarricone, Vallone, Cannazza, & Cipressa, 2010).

2.2.2.1. Electrical conductivity. Measurement of direct current conductance is the basic principle for many types of moisture content measurement methods. Capacitance and resistive methods are widely used in pharmaceutical applications, soils, and grains (Kupfer, 2005). Moisture content is determined based on the variation in capacitance or resistivity of the dielectric properties of a material before and after drying (Pixton, 1967). Widely available moisture meters operate applying principles of capacitance and resistance, wherein, a small electrical current is passed using a contact method with the sample. The amount of resistance correlates to the amount of moisture in the material (Ezeike, 1987). Certain low-cost hand-held moisture meters (discussed in 1.1) that are based on measuring electrical conductivity (or resistance) would fall under semi-quantitative methods of evaluating moisture content.

2.2.2.2. Microwave method. The microwave method is widely used to determine moisture content in the agriculture, textile, building, and food industries, among others (Boyes, 2010; Kurik, Kalamees, & Kallavus, 2016; Proietti et al., 2015; Schmugge, 2011). Similar to IR waves, moisture content can be determined based on transmitted, absorbed, or reflected microwaves, or by using resonance techniques (Boyes, 2010; Kim et al., 2006; Venkatesh & Raghavan, 2004). The moisture content can be correlated with the attenuation the wave suffers in the presence of a wet material. To use this method effectively there should be no other substances with high relative permittivity, such as titanium dioxide and other metal oxides in the microwave field (Kupfer, 2005). An example of the use of the microwave method is a moisture content meter developed by the United States Department of Agriculture, which was integrated into a convection drying system for peanuts. This allows real-time moisture determination of a peanut kernel without shelling the peanuts (Lewis, Trabelsi, Nelson, Tollner, & Haidekker, 2013).

2.2.2.3. Radio frequency (RF) method. The RF method is most often used to measure moisture content in materials with a homogenous composition, making them suitable for gas humidity measurements (Wernecke & Wernecke, 2014). However, the technique has been also applied to food products, for example, in moisture measurement of wheat (Dunlap & Makower, 1945; Lawrence & Nelson, 1993). This method determines the moisture content by measuring the propagation delays of the electromagnetic waves in a material using a single frequency or various frequencies to simultaneously measure one or two electrical parameters (Kupfer, 2005).

2.2.3. Nuclear methods

2.2.3.1. Hydrogen nuclear magnetic resonance (NMR). The NMR method is a versatile standard laboratory method widely used in the food, pharmaceutical, and cosmetic industries (Wernecke & Wernecke, 2014). Moisture content is determined based on the effect of electromagnetic radiation on the angular momentum or spin of atomic nuclei (hydrogen proton being the most commonly used) with odd numbers of protons and neutrons. As water molecules become charged by an external magnetic field, a magnetic dipole is created in the direction of the spin axis, producing a nuclear magnetic moment with a magnitude that is equal to the magnitude of the created dipole. This magnitude is excited by a low RF alternating field, producing a detectable high frequency resonance pulse, often between MHz and GHz. The moisture content of the material is directly proportional to the intensity of the detected signal (Fraden, 2016; Patel, Khan, & Kar, 2015; Proietti et al., 2015; Scotter, 1997).

2.2.4. Hygrometric methods

Hygrometric methods are based on equilibrium relative humidity (ERH) instead of moisture content. ERH is numerically equal to water activity but expressed as a percentage of the actual amount of water in the air versus the amount of water the air could hold at saturation (Prior, 1979).

2.2.4.1. Equilibrium relative humidity (ERH). Relative humidity (RH) sensors are reasonably easy to use as a means of assessing the water activity of food products. Sensors are typically based on capacitance or resistance and operate over a sufficiently wide temperature range (e.g., 0 °C–50 °C) that is suitable for most applications. Their measurement range is most often from approximately 20%–90% RH, with an accuracy of ± 2%–5% at mid-range, with potentially greater variability at the extreme ends of the RH range. Temperature can be routinely measured with an accuracy of ± 1.0–1.5 °C. Due to the high level of dependence of vapour pressure on temperature, this is an important consideration in selecting a relative humidity meter.

A survey of RH meters available through a number of scientific supply companies in North America provided some insight into their cost, accuracy, and resolution. A pocket-sized, pen-like device costing approximately $40 USD had a RH range of 20%–90%, with an accuracy of ± 5% RH and a resolution of 1%. Other meters costing up to $80 USD or higher had similar design and response features. A RH meter costing approximately $350 USD had a RH range of 10%–95% with a mid-range accuracy of ± 2.5% RH and ± 5% elsewhere. Its resolution was reported to be 0.1% RH. This accuracy range and associated high cost, as well as a physical configuration designed strictly for measurements of ambient air conditions, seriously restricts their application to measurements of RH within closed containers.

RH sensors can be calibrated using saturated salt solutions such as lithium chloride and sodium chloride. Unfortunately, routine calibrations may prove challenging to untrained users of these devices. Additionally, calibration samples must be selected within the operating range of the sensors, and calibration should take place within a controlled laboratory environment.

For actual ERH measurements, samples must be placed in an airtight container and maintained at a constant temperature until the ERH reading is taken. Times to achieve ERH in these containers can be up to several hours in some instances, depending on the size of the container and the amount of sample present, as well as the moisture content of the sample. Such procedures create the need for temperature-controlled storage and maintenance of an inventory of appropriate sample containers.

Additional complications can result from samples which are case hardened due to improper drying. The leathery, dry outer layer may slow the diffusion of moisture from the interior of the sample. This can substantially lengthen the time required to achieve a relative humidity equilibrium or result in an erroneously low reading if sufficient time is not allowed for the sample to equilibrate with the surrounding headspace air in the sample container.

2.3. Limitations and advantages of the moisture content measurement methods

The methods discussed above have numerous permutations that can be used in a variety of industries and applications, including moisture measurement in the food industry. Overall, direct methods are more time consuming than indirect methods and are better suited for laboratory applications. Indirect methods generally require less sample preparation and can be used in the field and processing line applications, but some require material-specific calibration curves. Only some of these methods are suitable for measuring samples with low moisture content including dried foods, which have an ideal moisture content of around 10%, but this varies depending on the type of food.

3. Comparative analysis of moisture content measurement methods suitable for small-scale co-operatives and farms in developing countries

The moisture content measurement methods described in Section 2 were assessed to determine their potential applicability or adaptability for use in small farms and co-operatives in developing countries. A set of criteria was developed through the literature review, discussions with experts, and acknowledging the challenges that the agri-food sector faces in developing countries as reported in Mercer (2011). A hypothetical case study was developed to guide the assessment of each of the methods and its applicability in the proposed context.

The methods described in Section 2.1.1 include those designed for use in laboratories, processing plants, and/or in the field. They can be expensive, time consuming to use and/or may require specialized expertise to conduct the test and interpret the results. This section examines the applicability of these methods in the proposed context: measurement of moisture content in dried foods and vegetables processed in small-scale farms and co-operatives in developing countries. To review their applicability, each method is compared with the characteristics of an “ideal” method. This ideal method should be easy to operate and maintain, portable, durable, as versatile and accurate as possible and with a rapid response time. It should also require little or intermittent energy so that it can be powered from batteries or solar photovoltaic panels and it should be inexpensive and safe to use in the field with minimal training. Therefore, each method was assessed in each of the following seven categories in Table 3.

Ideally, the moisture measurement method should also be applicable for quality control applications at the various stages of production (US EPA, 1995) including: i) fresh sample, ii) pre-drying treatments (size selection, peeling, and color preservation), iii) drying or dehydration, iv) using natural or artificial methods, v) post dehydration treatments (quality testing and inspection, packaging) and vi) storage. However, for this review, the assessment will focus only on the stage after the food has been dried and prior to storage. Evaluation of the moisture content of the finished product is also important and allows for verification before storage as it is essential that the moisture content of a food product be known when it is accepted for storage (Botswana Agricultural Marketing Board (BAMB), 2018).

Five of the methods (Karl Fischer titration, dielectric using microwaves and radio frequency, NMR, and HSI) are not examined in detail as the criteria above make them inappropriate for the proposed context. The Karl Fischer titration method is primarily used in a laboratory setting and requires specialized training. The equipment is delicate, costly, and not suitable for field use and the required chemicals may be difficult and expensive to obtain in developing countries. The equipment required for the dielectric, NMR, and HSI methods is too costly to consider implementing in the proposed context. Additionally, significant expertise, training, and maintenance (regular calibration) is required for NMR devices.

Four methods (gravimetric, optical, dielectric/electrical, and hygrometric) that have the potential to be used in a variety of contexts are examined further and evaluated for their applicability for use in a hypothetical case study co-operative.

3.1. Case study to examine the suitability of moisture content measurement methods in foods based on a hypothetical co-operative in a developing country

To assess each of the methods against the established criteria, a case study of a hypothetical small-scale co-operative in a developing country is employed. This case study is an assemblage of the characteristics of various co-operatives with which the authors have experience. The case study is not intended to represent a particular setting, but to provide a general high-level context for an initial ‘screening’ evaluation of the moisture content measurement methods. The co-operative model was

Table 3
Evaluation criteria for moisture content measurement methods and their applicability for use in small scale operations in developing countries.

Category	Description
1. Ease of operation and maintenance, portability	Indicates whether a method can be a sustainable solution in the proposed context in the long term
2. Training needs	Indicates how simple or complex the measurement method is and the relative difficulty of providing training in the proposed context
3. Versatility	Indicates whether a method can be used for measuring moisture contents of different types of foods
4. Accuracy	Indicates method accuracy and what range of values would be acceptable to ensure sufficient dryness is achieved
5. Response time	Indicates how long the measurement method will take, with preference for a rapid response time to give farmers/ cooperatives the opportunity to store products promptly and continue with drying of other batches
6. Power supply	Indicates what type and how much power is needed for operation (e.g. batteries, electricity).
7. Cost	Indicates the magnitude of the initial and operating costs as well as maintenance cost

chosen for this assessment because, for decades, co-operatives in developing countries have been seen as essential for social and economic development. Very often, agricultural and post-harvest activities only function reasonably because of formal or informal associations like these.

The case study is a small co-operative on a farm in a developing country comprised of 20 women. The setting of the co-operative is a country with temperatures typically above 25 °C and high relative humidity values around 80%. The co-operative has access to electricity from the grid, but supply is intermittent and costly. The per capita Gross Domestic Product (GDP) of the country in which the co-operative is situated is assumed to be approximately $5000 USD. This was based on the threshold levels of the analytical group considered to be “Emerging market and developing economies” according to the (International Monetary Fund (IMF), 2018). The annual per capita household energy use in a household in is assumed to be in the range of 5–30 GJ/year. Despite the challenging economic conditions, mobile phone and internet access are both common.

The co-operative currently dries mangoes and is considering adding tomatoes to their dried product line. Tomato production, particularly in developing countries, has increased in recent years due to the economic and nutritional importance of the crop (Arah, Amaglo, Kumah, & Ofori, 2015). The three largest producers of tomatoes currently are China, USA, and India (FAOSTAT, 2018).

The initial moisture content of mangoes is in the range of 80%–85%. Tomatoes have a moisture content of approximately 94% (Mercer, 2008). To be microbiologically safe for storage and transportation to market, these foods should be dried to achieve moisture contents of approximately 10%.

Prior to drying, the mangoes are sliced into pieces 5–6 mm thick and tomatoes are cut into thin wedges. Typically, 10–12 h at 50 °C would be sufficient to achieve a safe moisture content in mangoes of these dimensions. The tomatoes are dried with the skin facing downwards to increase drying efficiency. For tomatoes under optimal conditions, 20–24 h of exposure to 50 °C would be required, because of the higher initial moisture content (MacKenzie, Nutt, & Mercer, 2009).

Drying and storage methods vary across different regions. Some of the most common drying techniques in a developing country setting are solar, convective, infrared, fluidized or spouted bed, desiccant drying technologies (Chua & Chou, 2003). Solar drying has often been considered the most appropriate, given its advantages of being a faster, hygienic, and cheaper technology (Mercer, 2008). For the purposes of this case study, given the economic and technical requirements, solar drying was assumed. Solar-heated air (at approx. 50 °C) flows through the drying chamber where wire-mesh drying racks are located that allow air to reach all sides of the food. The moisture-laden exhaust air is vented through an outlet port. Fresh, heated air is drawn into the drying chamber either by natural convection or by fans (Chua & Chou, 2003). Active solar methods, such as the method described here, are considered to be suitable for drying high moisture content food.

After the mango slices have been removed from the dryer, they are tested for dryness using the “flexibility test”. As mentioned previously, this is a rather subjective qualitative test where the sample is bent between a person's fingers. Unfortunately, this is often the only test that is available to those doing the drying. If the sample feels leathery and is somewhat flexible, there is a reasonable expectation that the material has been sufficiently dried. Samples that are brittle and break apart would be considered as being over-dried.

It is recommended that material removed from a dryer be allowed to temper for a short period of time. Samples from the dryer that are still warm tend to still be soft and flexible until they have cooled to ambient temperatures. Generally, 10–15 min are sufficient for this cooling to take place. In cases where the ambient air is excessively humid, there can be an uptake of moisture from the air by the material leaving the dryer. Care must be taken to avoid this problem.

Cooling after removal from the dryer also helps reduce sweating in storage. Product that is sealed in a container while it is still warm may continue to lose small amounts of moisture from its surface. This water vapour may condense on the inner surface of the packaging material where it produces localized areas of high moisture. This readily available moisture can support mold growth and result in product spoilage, even though the bulk of the material has a moisture content that is considered as being “safe”.

Case hardening could also occur, where the sample appears to be sufficiently dried from the outside but remains moist on the inside. For tomatoes, the co-operative is planning to use a similar visual test to what is done with mangoes. If tomatoes have been properly dried, they would be dark in color and feel tough and leathery and there would be no signs of moisture when the samples are bent (Mercer, 2014). However, with the co-operative's goal to expand production, they are considering more reliable, less subjective alternatives to the flexibility test to improve their quality control process. With this production context at the co-operative in mind, each of the moisture content measurement methods were analysed based on the criteria in Table 3.

3.2. Gravimetric method

For the gravimetric method, the test procedure and operation of the balance are relatively simple compared to procedures for the other methods. However, it requires the user to have numerical literacy and basic math skills. The balance also requires occasional recalibration. This method is versatile and can be used for a variety of different food products. The accuracy of the gravimetric method is dependent on the precision of the balance - more precise balances are typically more expensive and low-cost balances do not have the precision required to accurately determine the moisture contents of the food products. For the mango or tomato slices, generally a balance that can confirm the weight to the nearest ± 1 mg is considered to be ideal.

One significant limitation of the gravimetric method is the response time given that the testing time is on the order of hours or days. Likewise, intermittent power supply is problematic, as after each power outage the drying needs to be reinitiated and the sample could have absorbed moisture from the environment, which changes the drying conditions. The main advantages of the gravimetric method in the proposed context are that it is relatively simple to use and versatile but testing times are long and the accuracy of this method is directly tied to the precision, and therefore the cost of the balance.

3.3. Optical: spectroscopy

Spectroscopy may be relatively simple to use as long as measurement conditions, including the distance between the sample and instrument, remain constant. However, the spectrometer requires regular calibration by personnel with specialized training (e.g., in multiple linear regression), which may present a challenge in the proposed context. Spectroscopy is also dependent on sample properties (e.g., water content) therefore it is critical that the spectrometer have calibration curves/calibration library for the various products that will be tested. While spectrometers can be highly accurate for moisture content measurement when accurate calibration curves have been developed (± 0.2% of moisture content of full scale) (Huang et al., 2008; van de Voort, 1992; Wang & Paliwal, 2007), the results can be impacted by the drying process. For example, if material is improperly dried and case hardening occurs or the samples are too thick, the light waves may only penetrate the dried surface and not into the moist interior of the sample. In particular, variations at the edges of the product samples (e.g., whole cereals), as well as other physical factors such as the sample height, shape or surface texture and some influence of the seed coat (or hull) texture could also affect moisture measurement readings (Caporaso, Whitworth, & Fisk, 2018). The cost of a spectrometer is also relatively high considering the context of the case study (starting around $1000 USD). Even though spectroscopy has quick response times, can be highly accurate, and may come with an easy-to-use interface, the main limitations of this approach are the lack of versatility between sample types and the initial capital cost.

3.4. Dielectric: electrical conductivity

Dielectric methods (e.g., moisture meters) based on electrical conductivity are widely used in portable devices for field measurements due to their low cost and ease of use (Nath & Ramanathan, 2017; Trabelsi & Nelson, 2010). Electrical methods are easy to use and would require minimal training. However, a disadvantage of electrical methods is the dependence on physical and chemical characteristics of foods, such as surface and color or moisture loss, protein denaturation (Halden, De Alwis, & Fryer, 1990), respectively, which usually change from harvest to harvest even when it is the same food variety. Electrical methods are material specific, which means that each material of interest needs its own calibration curve of conductivity versus moisture content. If a co-operative is looking to measure moisture content in different types of dried food, in the case of optical methods, a device would need to have the capability to measure multiple calibration curves, for example, one for mango and another for tomato. This, in turn, would require certain expertise or training related to the calibration process. An advantage over optical methods is that slight variations in the food's characteristics do not affect measurement.

Dielectric methods can be highly accurate, ranging from ± 0.5–1% of moisture content and short response times (on the order of minutes) (Rotronic Canada, 2016). However, dust and high temperature and humidity affect measurements. For example, high humidity may lead to condensation on the electrical sensor, leading to measurement errors. Electrical devices may also be affected by orientation of the sample in relation to the applied electrical field. This is something that would need to be taken into consideration if using this method to measure moisture content in dried mangoes and tomatoes.

The advantages of dielectric methods include a short response time and the minimal training requirement however the results are sensitive to measurement conditions and sample geometry.

3.5. Hygrometric

While hygrometric methods are typically used in the lab, two approaches can be adapted for field use: the dew point method and the RH measurement method.

3.5.1. Dew point method

Measurement using these devices is relatively straightforward and requires minimal training, however, specialized training would be needed for the calibration process. The dew point method is versatile and also highly accurate, capable of measuring water activity to ± 0.003–0.005 a_w (Prior, 1979; Yu, Schmidt, & Schmidt, 2009). However, the conversion of water activity to moisture content is not linear and so moisture-sorption isotherms are required to translate water activity into a moisture content value to assess whether the sample has reached target dryness. Also, the accuracy of the device may be reduced if the surface is exposed to dust, which presents a challenge in the proposed case study context where roads are generally not paved. The response time is on the order of minutes but there is a high equipment cost, on the order of thousands of dollars.

3.5.2. ERH method

RH or water activity sensors are relatively easy to use in the context of foods. The measurement approach is relatively simple but regular calibration using desiccant salts (e.g., sulphuric acid, NaCl) is required, which may be challenging in this context. Sensors based on capacitance and resistivity may be used, but their measurement may be affected by high temperatures and humidity. The method is versatile and can be used on a variety of different crops but it is difficult to assess a sample representative of the whole dried batch.

Accuracy will depend on the type of device used to measure RH. Hygrometers can reach accuracies of ± 0.003–0.005 a_w (Yu et al., 2009) depending on the device but colorimetric indicators may be temperature dependant. To reduce measurement error, the sample must be placed into an airtight container and maintained at a constant temperature throughout the measurement period. The latter might be difficult to achieve without climate control. The test time depends on the moisture content of the dried food, the size of the container, and the empty space in it. As a consequence, equilibration can be on the order of days. If the sample is case hardened, it could take up to a week or more to reach ERH because of the leathery coat. Most hygrometers use batteries which may be difficult to obtain. Hygrometers cost less than dew point equipment but may still be too expensive in the current context.

3.6. Summary of case study analysis

The suitability of moisture content measurement methods for small-scale food drying operations, such as within a cooperative in a developing country, was examined. However, each developing country operation is unique and the analysis presented is a high level screening. A detailed analysis of a particular setting is beyond the scope of the current study but will be the focus of future work. The most commonly used methods are simple visual observations and a flexibility test. While this is a highly subjective means of assessment, it does not depend on any expensive equipment or access to electricity, etc., and can be accomplished with minimal training. However, there are significant opportunities for error (e.g., considering that a case-hardened product is sufficiently dry), which could lead to food safety and human health implications.

Table 4 provides a summary of the applicability of moisture content measurement methods for small-scale farms and cooperatives in developing countries based on the previous analyses. It should be noted that this assessment could also provide insights for measurement of moisture content of foods dried using in-home food dehydrators in developed countries.

Table 4
Applicability of moisture content measurement methods in small farms and co-operatives in developing countries.

Method	Measurement technique	Operation & Maintenance	Versatility	Accuracy	Response Time	Power Supply Accessibility	Training	Cost
Gravimetric	Thermo - gravimetric analysis		✓			✓	✓	✓*
Optical	Infrared spectroscopy	✓		✓	✓	✓	✓	
Dielectric	Electrical conductivity	✓		✓	✓	✓	✓	
Hygrometric	Equilibrium relative humidity		✓	✓		✓	✓	

Notes.
✓ Indicates method satisfies the requirements for the proposed context.
* Cost is lower than for other methods but still may be prohibitive if high precision balance is required.

Overall, the methods assessed in the case study do not appear suitable in their present forms for small-scale operations in developing countries. This is due to a variety of factors that differ across the different methods. These include: high equipment costs; requirements for operation (including portability) and, maintenance, and other associated costs; a lack of versatility and the need for calibration curves for use with different materials; required user training; and the need for external power supplies or batteries. Of these factors, cost appears to be the most common limitation in applying any of the existing approaches in the proposed context.

Given that experts in the field agree on the need to develop a low-cost moisture content measurement method (Kupfer, 2005; Nath & Ramanathan, 2017), and based on our evaluation, we recommend that equilibrium relative humidity (ERH) and infrared (IR) techniques deserve further examination related to their potential to be adapted to meet the target users' needs.

3.6.1. ERH method

A low-cost RH sensor inserted into a small jar with a tight - fitting lid could be used to assess equilibrium RH of a sample following drying. Unfortunately, such sensors present operational challenges and those devices that are low in cost suffer from reduced accuracy at low relative humidity levels. There is also a problem in correlating water activity with overall moisture content in certain food systems. Relating water activity or ERH to actual water content on a percent-by-weight basis requires moisture sorption isotherms which are not readily available. This also introduces an added layer of complexity to the measurement process.

While the Dry Card offers a semi-quantitative approach to evaluation of a material's degree of dryness, some applications may require a more accurate quantitative approach. Such measurements can only be achieved through more sophisticated means such as electronic sensors. An example that may meet this criterion is a battery-powered palm-sized water activity meter called the "Pawkit" developed by Topac Inc., which is designed for quick checks and inspections. It is portable and its accuracy is lower ($\pm 0.02a_w$) than those of calibrated laboratory equipment, however it provides a quick check of whether the moisture content measurements are staying on track (Topac, 2002). Hence the application of this equipment would require further evaluation, particularly in terms of the requirements with respect to accuracy and costs within the context of use on small farms and cooperatives in developing countries.

3.6.2. Infrared methods

The second method that could be adapted for the proposed applications is the use of IR imaging. While many IR measuring devices currently available tend to be expensive, it may be possible to modify a mobile phone for this purpose. Even though they are costly and require power to operate, mobile phones are widely used in all parts of the world and are readily available. One company recently introduced a chip-sized spectral sensor for a variety of applications in food safety, soils, oil and gas and pharmaceuticals that is small enough to be incorporated into a mobile phone device (Si-Ware, 2017). A potential limitation of this approach could be the small differences in low NIR wavelengths at certain moisture contents, making it difficult to obtain an accurate result.

Another infrared-related technique of potential merit is IR thermography, which has been used for measurement of moisture in the construction industry. It is already available on mobile phones (FLIR Systems Inc., 2017). By heating the sample in the sun and then placing it in the shade, one could use an IR camera to determine how long it takes to reach thermal equilibrium with its surroundings. This thermal response, once calibrated to thermal mass, could be used to determine the sample moisture content.

Response times for both IR methods would be on the order of seconds or minutes, which would be ideal for the intended end use. These methods warrant further investigation and testing within the context of use on small farms and cooperatives in developing countries.

4. Conclusion

There are numerous direct and indirect methods for determining moisture contents in solids, which have been used extensively in many industries, including chemical, pharmaceutical, food, glass, concrete industries. However, application of these moisture content measurement techniques by small-scale farmers and cooperatives in developing countries differs considerably from these industrial contexts. Many of the methods are complex, time-consuming, and expensive, making them inappropriate for use in small-scale operations in developing countries. Further, methods that are routinely used on processing lines or for field applications in more developed countries are often unsuitable where electricity supply is unreliable or ease of portability is a requirement.

A detailed literature review of the current moisture measurement technologies generally used in food industries was carried out and characteristics of an appropriate technology that can be realistically applied in the context of small-scale farmers and cooperatives in developing countries were identified. As determined from the review as well as discussions with experts, an "ideal" moisture meter for use in developing countries should be suitable for field use, portable, inexpensive, electricity-independent, versatile, durable, accurate, and have a rapid response time.

An evaluation of the current moisture measurement methods was completed based on these identified criteria. Although none of the methods are likely feasible in their present form, equilibrium relative humidity and infrared spectroscopy-based techniques were identified as having promise for this context. Finally, recommendations were made for future studies focussing on developments of these two methods for their use in making rapid and economical assessments of food moisture content in developing countries.

Declaration of interest

Declarations of interest: none.

Appendix

Table 1
Summary of various moisture analysers in the market

Method	Measurement technique	Application context	Power supply requirement*	Cost*	Sample devices currently available in the market*	Company
Gravimetric	Thermogravimetric analysis	Laboratory, production floor, field Food applications	Electricity, batteries	$400–6000	BL-MS-70, BL-MX-50, BL-MF-50, BL-ML-50, BL-934010, PCE-MA 110, FS-1, FS-2, FS-3, Cenco 26900EMB, 26900, KERN MLS-D, EM 120-HR Precisa, IL-50, KERN MLB-50	(A)
Chemical	Karl Fischer titration	Mostly laboratory Food applications	Electricity	$6000-11000	TitroLine 7500 KF 05 Titrator, TitroLine 7500 KF trace M1 Titrator**	(B)
	Coulometric	Laboratory	N/A	N/A	N/A	N/A
Optical	Infrared spectroscopy	Laboratory, on-line processes, field Food applications	Electricity, batteries	$4500-17000	PCE-MWM 240A, PCE-A-315-WD, MoisTech NIR IR-3000R	(C)
	Infrared thermography	Field	N/A	N/A	N/A	N/A
Dielectric	Electrical conductivity	Laboratory, on-line processes, field Food applications	Electricity, batteries	$100 - 3500	PCE-PMI 1, PCE-SMM 1, HP23 AW set	(D)
	Microwaves	On-line processes, field Food applications	Electricity	$6500	PCE-A-315, PCE-MWM 400**	(E)
	Radio frequency	Field Food applications	Electricity, batteries	$600	LB 350, GE Protimeter Surveymaster**	(F)
Nuclear	Nuclear magnetic resonance	Laboratory, on-line processes, field Food applications	Electricity	N/A	NMR Spectrometer - Pulsar, NMR Analyser - MQC, MicroPolar LB 567/LB 568**	(G)
	Neutron and γ-ray scattering	Field	N/A	N/A	N/A	N/A
Hygrometric	Equilibrium relative humidity	Laboratory, field Food applications	Electricity, batteries	$50-3000	Aqualab 4 TE	(H)

Notes:
The inclusion or omission of instruments in this list and their manufacturers does not indicate support for a specific instrument nor prejudice against a company; they are only examples to demonstrate what exists and their costs.
* Information was retrieved from the web or from customer service representatives of companies that sell moisture analysers (December 2016).
** Information was retrieved from the web or from customer service representatives of companies that sell moisture analysers (May 2017).
N/A - unable to find information.

Table 2
Catalog of several existing scientific literature on moisture content measurement methods
Sources: (A) CSC Scientific Company Inc., Tovatech LLC, Gardco, PCE Instruments, Tester.co.uk (B) Clarkson Laboratory and Supply Inc. (C) MoistTech Corp., PCE Instruments (D) PCE Instruments, Rotronic Canada (E) PCE Instruments (F) Berthold Technologies (G) Berthold Technologies, Oxford Instruments (H) Meter Group Inc.

Publication type	Author(s), year	Various industries (including food)		Particular industry (other than food)	Food industry only		Methods	
		Measurement of different components, including moisture	General moisture measurement, not only solids	Moisture measurement in solids	Food quality, including moisture measurement	Moisture measurement only	Particular methods	All methods or most common
BOOKS	Pande (1975)		X					X
	Mitchell & Smith, 1977		X					X
	Boyes (2010)	X						X
	Fraden (2016)	X						X
	Wernecke & Wernecke (2014)		X					X
	Kupfer (2005)		X				X	
	Behari, 2011			X			X	
	Shukla, 2011			X				X
	Sun (2009)				X		X	
	Ruan & Chen, 1998					X	X	
BOOK SECTIONS	Erba et al. (2016)			X				X
	Kurik et al. (2016)			X				X
	Maierhofer et al., 2015			X				X
	Proietti et al. (2015)			X				X
	IEEE, 2013			X				X
	van Duynhoven, Voda, Witek, & Van As, 2010				X		X	
	Bradley (2010)				X			X
	Fontana Jr., 2007					X	X	
	Park & Bell, 2004					X		X
	Wrolstad et al. (2005)					X	X	
REVIEW PAPERS	Chen & Lu, 2005		X					X
	Černý, 2009	X					X	
	Federici, 2012	X					X	
	Karmas (1980)					X		X
	Pixton (1967)					X		X
	Huang et al. (2008)				X		X	
	Pyper (1985)	X						X
	Nicolaï et al., 2007				X		X	
	Scott, 1991				X		X	
	Jimaré Benito, Bosch Ojeda, & Sanchez Rojas, 2008	X					X	
	Cen & He, 2007				X		X	
	Venkatesh and Raghavan (2004)				X		X	
	Jha et al., 2011				X		X	
	Venkatesh & Raghavan, 2005				X		X	
	Liu et al. (2015)				X		X	
	Patel et al. (2015)				X		X	
	Zettel et al., 2016				X		X	
	Scotter (1997)				X		X	
	Pettinati, 1980				X		X	
	Nath and Ramanathan (2017)					X	X	
	Kropf, 1984					X	X	
	Bouraoui et al. (1993)					X	X	

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