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Authors
Bradford, Kent J
Dahal, Peetambar
Van Asbrouck, Johan
et al.

Publication Date
2018

DOI
10.1016/j.tifs.2017.11.002

Trends in Food Science & Technology 71 (2018) 84–93

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

The dry chain: Reducing postharvest losses and improving food safety in humid climates

Kent J. Bradford[a,*], Peetambar Dahal[a], Johan Van Asbrouck[b], Keshavulu Kunusoth[c], Pedro Bello[a], James Thompson[d], Felicia Wu[e]

[a] Department of Plant Sciences, Seed Biotechnology Center, University of California, Davis, CA 95616, USA
[b] Rhino Research, Moo Baan Sai Samphan 66/17, 66000 Phichit, Thailand
[c] Department of Seed Science & Technology, Professor Jayashankar Telangana State Agriculture University, Rajendra Nagar, Hyderabad 500030, India
[d] Department of Biological and Agricultural Engineering, University of California, Davis, CA 95616, USA
[e] Department of Food Science and Human Nutrition, Department of Agricultural, Food, and Resource Economics, Michigan State University, East Lansing, MI 48824, USA

ARTICLE INFO

Keywords:
Dry chain
Aflatoxin
Drying
Food waste
Postharvest storage

ABSTRACT

Background: Even as increasing populations put pressure on food supplies, about one-third of the total food produced for human consumption is wasted, with the majority of loss in developing countries occurring between harvest and the consumer. Controlling product dryness is the most critical factor for maintaining quality in stored non-perishable foods. The high relative humidity prevalent in humid climates elevates the moisture content of dried commodities stored in porous woven bags, enabling fungal and insect infestations. Mycotoxins (e.g., aflatoxin) produced by fungi in insufficiently dried food commodities affect 4.5 billion people worldwide.
Scope and approach: We introduce the term “dry chain” to describe initial dehydration of durable commodities to levels preventing fungal growth followed by storage in moisture-proof containers. This is analogous to the “cold chain” in which continuous refrigeration is used to preserve quality in the fresh produce industry. However, in the case of the dry chain, no further equipment or energy input is required to maintain product quality after initial drying as long as the integrity of the storage container is preserved. In some locations/seasons, only packaging is required to implement a “climate smart” dry chain, while in humid conditions, additional drying is required and desiccant-based drying methods have unique advantages.
Key findings and conclusions: We propose both climate-based and drying-based approaches to implement the dry chain to minimize mycotoxin accumulation and insect infestations in dry products, reduce food loss, improve food quality, safety and security, and protect public health.

1. The problem of postharvest food waste and toxicity

A central issue for the 21st century is to continue to feed the growing human population in a sustainable manner, while accommodating the effects of climate change and limiting expansion of agricultural land and water use. Although predictions vary, there is little doubt that the human population will increase to 9 to 10 billion from the present 7.6 billion during this century (United Nations, 2015). The Food and Agriculture Organization of the United Nations has estimated that due to this increasing population and changing demand accompanying economic development (e.g., more meat in the diet), food production will need to increase by 60% in 2050 compared to 2005 (Alexandratos & Bruinsma, 2012). Agronomists have responded by focusing on increasing crop yields using a variety of input management practices and high-yielding nutrient-rich cultivars, as occurred during the Green Revolution (Burney, Davis, & Lobell, 2010; Godfray et al., 2010). However, increasing yields to the extent required may be difficult in many climates and locations, particularly in the face of strained economic and environmental resources (Lobell, Cassman, & Field, 2009).

A complementary approach is to reduce postharvest food losses. Although estimates of loss vary depending on location and handling system (Parfitt, Barthel, & Macnaughton, 2010), about one-third of food produced for human consumption is spoiled or wasted (Gustavsson, Cederberg, Sonesson, Van Otterdijk, & Meybeck, 2011; Rockefeller Foundation, 2013). In developing countries, most losses occur between the farm and the consumer, while in developed countries a similar percentage of food is wasted by the final purchaser (Dou et al., 2016). For dry products (e.g., cereals, which provide 70% of all calories consumed and 53% of total caloric losses), the majority of losses are due to

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[*] Corresponding author.
E-mail address: kjbradford@ucdavis.edu (K.J. Bradford).

https://doi.org/10.1016/j.tifs.2017.11.002
Received 22 July 2017; Received in revised form 4 November 2017; Accepted 7 November 2017

microorganisms (molds, bacteria), insects and rodents resulting from poor postharvest storage management (Kumar & Kalita, 2017; Lipinski et al., 2013; Mendoza, Sabillón et al., 2017; World Bank, 2011).

The problem is exacerbated, particularly in humid climates, by the production of toxic and carcinogenic secondary metabolites, called mycotoxins, by phytopathogenic and food spoilage fungi (molds) such as *Aspergillus, Penicillium, Fusarium, Cladosporium* and *Alternaria* species (Mendoza, Kok, Stratton, Bianchini, & Hallen-Adams, 2017; USDA, 2006). *Fusarium, Cladosporium,* and *Alternaria* species infect grains during their maturation, whereas *Aspergillus* and *Penicillium* species can infect crops in fields but mainly propagate in stored grains (Kabak, Dobson, & Var, 2006). Mycotoxins are the most important non-infectious, chronic dietary risk factors, greater than plant toxins, synthetic contaminants, food additives or pesticide residues (Kuiper-Goodman, 1998). The most common mycotoxins in agriculture are aflatoxin, deoxynivalenol, zearalenone, fumonisin and T-2 toxin (USDA, 2006). The International Agency for Research on Cancer (IARC) has classified "naturally occurring mixes of aflatoxins" as a Group 1 human carcinogen (IARC, 2012). Aflatoxin is a potent liver carcinogen, causing hepatocellular carcinoma in humans and animals. About 4.5 billion people are affected by mycotoxins that have been linked to tumors of the liver, kidneys, lungs, urinary and digestive tracts, to birth defects and to nervous system problems (Kensler, Roebuck, Wogan, & Groopman, 2011; J. H. Williams et al., 2004). Aflatoxin also acts synergistically with hepatitis infection, which is often prevalent in regions where mycotoxins are present in food supplies (Chen et al., 2013). As a result, up to 28% of liver cancer cases worldwide are directly associated with consumption of foods containing aflatoxin (Liu & Wu, 2010). In combination with poor nutrition, aflatoxins can also contribute to stunted growth and adverse effects on the immune systems in children (Khlangwiset, Shephard, & Wu, 2011; Wild, Miller, & Groopman, 2015). Stunted children will never achieve their full physical or mental potential, with enormous social and economic costs. Methods to decontaminate mycotoxins present in foods are known, but are not as yet widely deployed (Alberts et al., 2017; Temba et al., 2016).

Elevated moisture content (MC) of stored foods is the primary cause of storage mold growth. To be more exact, it is the thermodynamic water activity (a_w) that actually limits biological metabolic activity. The water availability can also be described in terms of the associated equilibrium relative humidity (ERH), which is equivalent to a_w multiplied by 100. Products in contact with an atmosphere of a given relative humidity (RH) or a_w will come to (near) equilibrium at a MC that is dependent upon the products' composition (Chen, 2000). Generally, toxigenic molds can only grow and produce toxins at an ERH above 85% (Abdel-Hadi, Schmidt-Heydt, Parra, Geisen, & Magan, 2011; Fontana, 2007). Thus, drying foods sufficiently to be in equilibrium with atmospheres below 85% RH prevents further accumulation of mycotoxins during storage. Lack of management of the dryness of food stores is responsible for wide distribution of mycotoxins in the African food and feed system (Darwish, Ikenaka, Nakayama, & Ishizuka, 2014), and in general, poor postharvest storage conditions are a major cause of mycotoxin contamination of the human diet (Chulze, 2010; Magan & Aldred, 2007; Unnevehr & Grace, 2013). While mycotoxins can also be produced in the field prior to harvest, research has "firmly established that … immediate drying is the only cost effective way of controlling aflatoxin build-up in maize in the humid tropics" (De Padua, 1996). Such postharvest handling and storage interventions can reduce human aflatoxin exposure (Turner et al., 2005).

Storage insects account for up to 40% of the total physical and nutritional loss of grain and dry food products in the developing world (Chomchalow, 2003; FAO., 1994; Kumar & Kalita, 2017). Pesticides are used to control insects in stored food commodities, but their use risks accidental poisoning of consumers (FAO, 1989b). Oxygen-proof packaging has been utilized to control insects and fungi in stored products without pesticides (Baoua, Amadou, Ousmane, Baributsa, & Murdock, 2014; De Bruin, Villers, Wagh, & Narvarro, 2012; Ng'ang'a, Mutungi, Imathiu, & Affognon, 2016a, b; S. B. Williams, Baributsa, & Woloshuk, 2014). This method relies on having commodity ERH high enough for product, microbial or insect respiration to consume the oxygen present in sealed storage containers (Abalone, Gastón, Bartosik, Cardoso, & Rodríguez, 2011), which can also entail some degree of damage to the stored commodity (Lacey, Hamer, & Magan, 1994; White, Sinha, & Muir, 1982). Hermetic bags have also been shown to reduce aflatoxin accumulation during storage (S.B. Williams et al., 2014), although this was less effective for maize stored above 14% MC (Ng'ang'a et al., 2016a). Drying products to levels low enough to reduce or prevent insect activity (~35% ERH) and maintaining dryness using hermetic packaging is a complementary strategy for controlling storage insects when adequate drying is possible (Kunusoth, Dahal, Van Asbrouck, & Bradford, 2012). Both low oxygen and low MC storage approaches require packaging to prevent oxygen or moisture from reaching the commodity (Hayma, 2003; IRRI, 2016).

Fig. 1. Improper food storage leads to loss of quality. An example of large stores in India in which porous jute bags of grain are stacked and inadequately protected from rain, leading to high moisture content and even to sprouting (inset) (Photo: Altaf Qadri, Associated Press https://www.thestar.com/news/world/2012/05/10/indias_wheat_left_to_rot_due_to_lack_of_storage.html).

Although poor storage, primarily high MC, is a key cause of postharvest commodity damage and contamination (Fig. 1), relatively less attention has been directed at addressing this fundamental issue (García & Heredia, 2014; Rockefeller Foundation, 2013; Wild et al., 2015). Most research has focused on increasing crop plant resistance to microorganism growth, on modifying the fungal organisms to prevent toxin biosynthesis, or on eliminating them from the production environment, while research on improved drying and storage conditions has been largely bypassed (Alberts et al., 2017; PACA, 2016; Schmidt, 2013; Unnevehr & Grace, 2013; Wild et al., 2015). Philanthropic funding by U.S. donors explicitly directed towards reducing food wastage in developing countries from 2008 to 2012 amounted to only $14 million, only 5% of the ~$260 million directed towards increasing agricultural productivity (Rockefeller Foundation, 2013). Significantly, the Bill and Melinda Gates Foundation has supported the Purdue Improved Crop Storage program (PICS, 2015) and the Rockefeller Foundation recently has targeted the issue of food storage and waste in its YieldWise initiative (Rockefeller Foundation, 2017).

Our purpose here is to describe a coherent and achievable strategy for improving postharvest commodity storage to reduce both food loss and mycotoxin accumulation. It begins with recognition that excessive product moisture due to high atmospheric RH is the primary cause of damage to dried commodities. It follows that proper initial drying and moisture-proof packaging are practical and effective interventions for reducing product loss and improving food safety. This "dry chain" approach is analogous to the "cold chain" commonly employed for the postharvest preservation of perishable commodities (Kader, 2002). The cold chain is the process of cooling fresh vegetables and fruits quickly after harvest and then maintaining an unbroken chain of low temperature conditions throughout storage, transport and marketing to the consumer. However, the majority of stored food commodities are dry products, primarily grains and seeds, whose preservation simply requires maintenance of dryness without investment in refrigerated trucks and storage facilities.

2. High humidity is the enemy

Drying was the primary method for long-term food preservation until the relatively recent introduction of canning or freezing. Meat, fish, fruits, berries, herbs and other plant foods were dried for storage and consumption during less abundant seasons by virtually all human cultures. A major application of drying was for preservation of grains following the invention of agriculture and increasing human dependence on cereals. The Biblical (Genesis 41:19–36) story of the seven fat years followed by seven lean years and of the stockpiling and storage of grain for the latter indicates knowledge and use of the ability of dry grains to be stored for long periods of time in an edible state. This story is set in Egypt, whose arid climate is naturally conducive to grain dehydration and low moisture content storage, as is also evident in the remarkable preservation of mummified remains there after several thousand years.

As the ERH of food products decreases, the metabolic activity of spoilage bacteria, fungi and insects is slowed because they require water to function. When sufficient water is removed from the system, they are unable to remain metabolically active and either develop desiccation-resistant structures (e.g., fungal spores) or perish (Crowe, Hoekstra, & Crowe, 1992). The ERH at which this occurs is consistent across all products, but the product MC at that ERH varies according to the composition of the product. For example, products with a higher oil content will have a lower MC at any ERH than products with a lower oil content (Fig. 2). This is because water is excluded from the hydrophobic oil bodies in the products' cells, reducing the water content relative to the total product weight. However, the relationship between MC and ERH at a given temperature (termed an "isotherm") is consistent for a given product (Fig. 2). We can therefore use either ERH or MC interchangeably to refer to the water activity or content of the product (Chen, 2001). With respect to storage biology, it is preferable to use ERH rather than MC because the effect of ERH on spoilage organisms is consistent across products regardless of their composition.

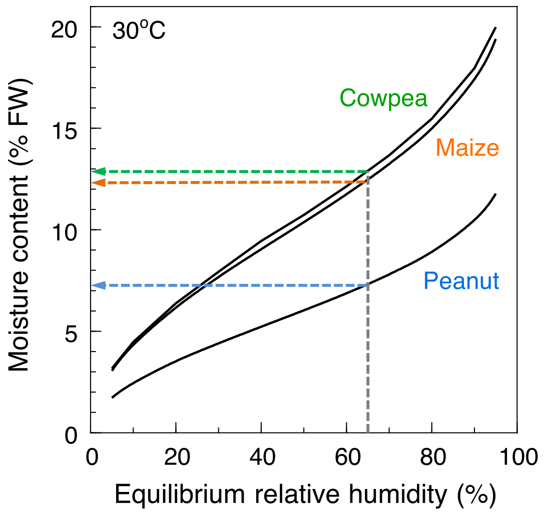

Fig. 2. Isotherms, or equilibrium relative humidity (ERH) versus moisture content (MC) relationships at a given temperature, for cowpeas, maize and peanuts at 30 °C. Isotherms for rice and wheat are similar to those for maize. These isotherms illustrate the higher MC at a given ERH of starchy grains and pulses (maize, cowpea) compared to oily commodities (peanut). As illustrated by the arrows, the MC at the maximum ERH (65%) for storage without fungal growth is 12–13% for pulses and grains but only 7–9% for oily seeds such as peanuts or rapeseed. Isotherms for many seeds and grains and calculator for conversion between ERH and MC are available from Bradford et al. (2016).

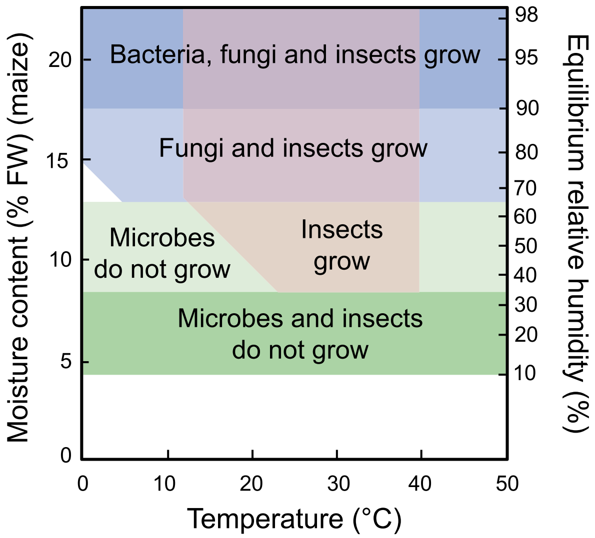

Fig. 3. Diagram illustrating the combinations of temperature and MC (or ERH) at which different organisms can grow in storage. Moisture contents at corresponding ERH values approximate those for cereal grains. Below 65% ERH, products are safe from fungal growth, and below 35% ERH, neither microbes nor insects can grow. Storage life will increase exponentially as ERH and temperature decrease, but even at 65% ERH, dry food products can maintain quality for up to a year at ambient temperatures. Modified from Roberts (1972) and Bewley, Bradford, Hilhorst, and Nonogaki (2013).

The ranges of activity of different organisms can be plotted in relation to the ERH (or MC) and temperature (T) ranges at which they can grow (Fig. 3). Respiration of seeds stops below about 95% ERH and bacteria do not grow below about 90% ERH (Bello & Bradford, 2016; Walters, Farrant, Pammenter, & Berjak, 2002). At ERH values below 65%, fungi also are unable to be metabolically active or grow (Fig. 3). This ERH corresponds closely with the recommended maximum MC for storage of cereals (12–14%), pulses (13–15%) and oil crops (6–9%) (Fig. 2) (FAO, 2014). Grain storage insects are able to be active below 65% ERH due to their ability to limit water loss and to generate water metabolically from their food (Murdock, Margam, Baoua, Balfe, & Shade, 2012). However, storage insects are unable to survive at ERH values less than about 35% (Kunusoth et al., 2012; Roberts, 1972). Thus, drying to less than 35% ERH will prevent activity of both fungal and insect pests. However, depending upon the drying method, the additional cost of drying to this level may not be economical. Also, rice is susceptible to cracking if milled at low MC, and some commodities (e.g., beans) are subject to mechanical damage if handled when too dry. Very low ERH/MC levels are likely appropriate only for long-term storage of seeds where preservation of vigor and viability is important (R.H. Ellis & Hong, 2007; Hong et al., 2005). Seed longevity can also be increased by reducing storage temperature. A 5 °C reduction in T approximately doubles seed lifetime, but this is equal to the effect of a 1% reduction in seed MC (Harrington, 1972; Roberts & Ellis, 1989). Thus, small reductions in ERH can equal the effect of reduced temperature without the infrastructural investment or energy input required for refrigerated storage (Dadlani, Mathur, & Gupta, 2016; IIVR, 2016; Pérez-García, González-Benito, & Gómez-Campo, 2007). For both seeds and dry commodities, **high humidity is the enemy**. In their study of maize storage in various containers in Nigeria, Omobowale, Armstrong, Mijinyawa, Igbeka, and Maghirang (2016) noted, "Relative humidity was of greater significance than temperature in affecting all maize quality parameters considered."

3. The dry chain is the solution

Safe storage conditions for food products can be described with a set of axes representing wet versus dry in the vertical direction and warm versus cold in the horizontal direction (Fig. 4). Food products are

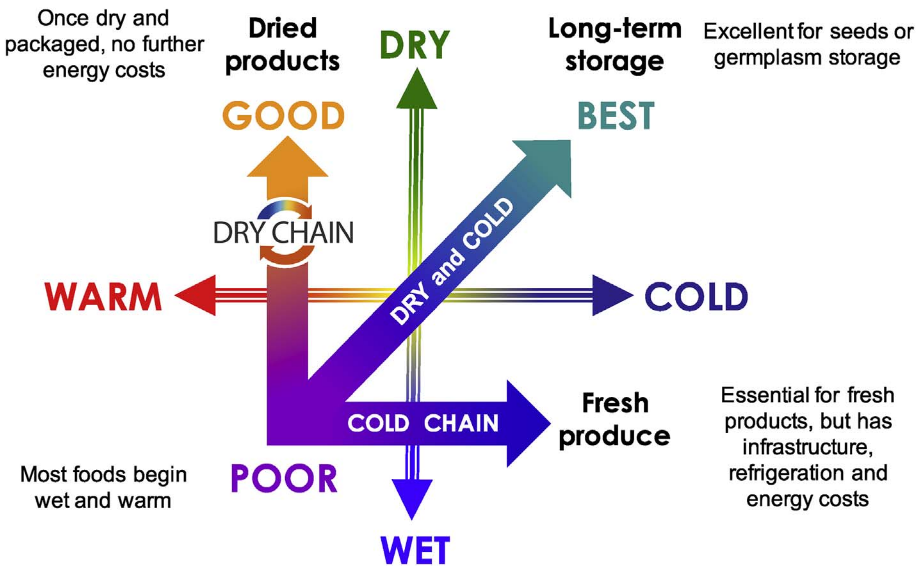

Fig. 4. Illustration of the cold chain and the dry chain for commodity storage. The storage conditions are characterized by combinations of temperature (warm, cold) and moisture (wet, dry). Most food products store very poorly when they are wet and warm (lower left quadrant). For fresh horticultural produce, which cannot be dried, the only option is to cool the product quickly and keep it refrigerated throughout transport and storage, known as the cold chain (lower right quadrant). For products that can be dried, medium-term storage can be attained by drying alone even without cooling, which we term the dry chain (upper left quadrant). For the longest-term storage, such as for seed preservation in germplasm banks, both drying and cold storage are best (upper right quadrant).

generally relatively warm and wet when harvested (lower left quadrant in Fig. 4), but have very short storage lives in that state. Fresh produce that cannot be dried is handled in a cold chain to maintain low T and high RH continuously through transport, storage and marketing to the consumer (lower right quadrant in Fig. 4, wet and cold). Similarly, the dry chain entails drying products as soon as possible after harvest and maintaining continuous dryness until their final use. After initial drying, simply maintaining low MC using moisture-proof packaging will be sufficient for medium-term storage without the need for refrigeration (upper left quadrant in Fig. 4, dry and warm). In large-scale commodity storage, T within the product mass must be kept fairly uniform to prevent high humidity developing in cooler areas. In temperate climates, this is usually accomplished by controlled ventilation with outside air. In warm, humid environments, temperature variation across seasons is less pronounced, and ventilation with humid outside air would be counterproductive. For very long-term storage, such as for seeds in germplasm banks, reduction in both MC and T is the best practice (upper right quadrant in Fig. 4, dry and cold).

4. Drying of food commodities

4.1. Air drying

Drying large quantities of grains and other food products and protecting them from rehydration has been a challenging problem in practice, particularly in humid climates. As the product MC at harvest is generally higher than is optimal for storage, sun drying or heated-air drying is almost universally employed (Lantin, Paita, & Manaligod, 1996).

Sun drying is accomplished by spreading thin layers of grain on the ground, on tarps, on drying tables or on floors. Grain can be dried to a MC in equilibrium with the average daily RH, although drying in the sun and covering with a tarp at night can reduce grain ERH closer to the minimum daily RH. For example, maize is often harvested at 28–32% MC, and should be dried to 12–14% MC for safe storage. Based on ERH/MC isotherms, this corresponds to an ERH of 65% (Fig. 2), the highest ERH that prevents fungal growth (Fig. 3). In many locations and seasons in the tropics, the ambient RH is not low enough to dry commodities to safe levels using sun drying alone (Fig. 5A). While sun or ambient air drying is the most widespread drying method and should be used to the extent possible, it is least effective exactly in the locations and at the times at which postharvest drying is most needed (Mendoza, Sabillón, et al., 2017).

On the other hand, many tropical climates have dry seasons that can enable implementation of the dry chain. For example, in northwestern India, eastern Pakistan and southern Nepal, the daily maximum temperature during April to June exceeds 40 °C with minimum RH of ~10% (Fig. 5B). Wheat harvested during this period can be sun dried to levels that prevent both insect and fungal growth. In south Nepal during May, 2014, repeated sun drying reduced wheat grain MC to 5% (~15% ERH) (our unpublished data). However, local practice is to put grain into porous jute bags after drying and stack them in poorly covered outdoor stockpiles (Fig. 1). When the rainfall and high humidity of the monsoon season subsequently arrives in July to September (Fig. 5B), the porous packaging allows the grain MC to increase, enabling insect damage and fungal growth (NDTV, 2013). In climates where atmospheric conditions enable sun drying to safe storage ERHs (R. H. Ellis, 1988), only storage in moisture-proof containers or plastic bags is needed to maintain the dry chain, a system that we term the "climate-smart dry chain." Tropical regions in which dry periods coincide with major grain harvests include breadbasket regions of India, Pakistan, north Thailand, Egypt, inland western Africa, and western China.

Plastic bags may be subject to rodent damage, which would compromise their ability to prevent moisture uptake, but hermetic packaging apparently reduces attraction of rodents by preventing odors from escaping (FAO, 1989a).

4.2. Heated-air drying

Heated-air driers are used for drying grains and commodities and are standard practice in developed countries, particularly in temperate climates. However, heated-air drying becomes less effective as the ambient T and RH increase. For example, incoming air at 20 °C and 50% RH would have an RH of 12% when heated to 45 °C, but when the incoming air is at 35 °C and 80% RH, elevating the temperature to 45 °C would reduce the RH only to 45%. While this would be adequate for foods, seeds for planting must be kept below 35–43 °C during drying to prevent loss of viability, limiting the effectiveness of heated-air drying (Mrema, 2011, pp. 368–411). For food commodities, higher temperatures can cause scorching or require tempering between repeated drying to achieve desired final dryness levels (Mutters & Thompson, 2009). In warm, humid climates, while substantially better than ambient-air drying, heated-air drying is less effective for drying than it is in temperate climates.

Heated-air grain drying facilities are of limited availability in developing countries, particularly in rural regions where commodities are produced, and are primarily operated by millers who need to adjust commodity MC for processing (Ann, 1996). Efforts have been directed

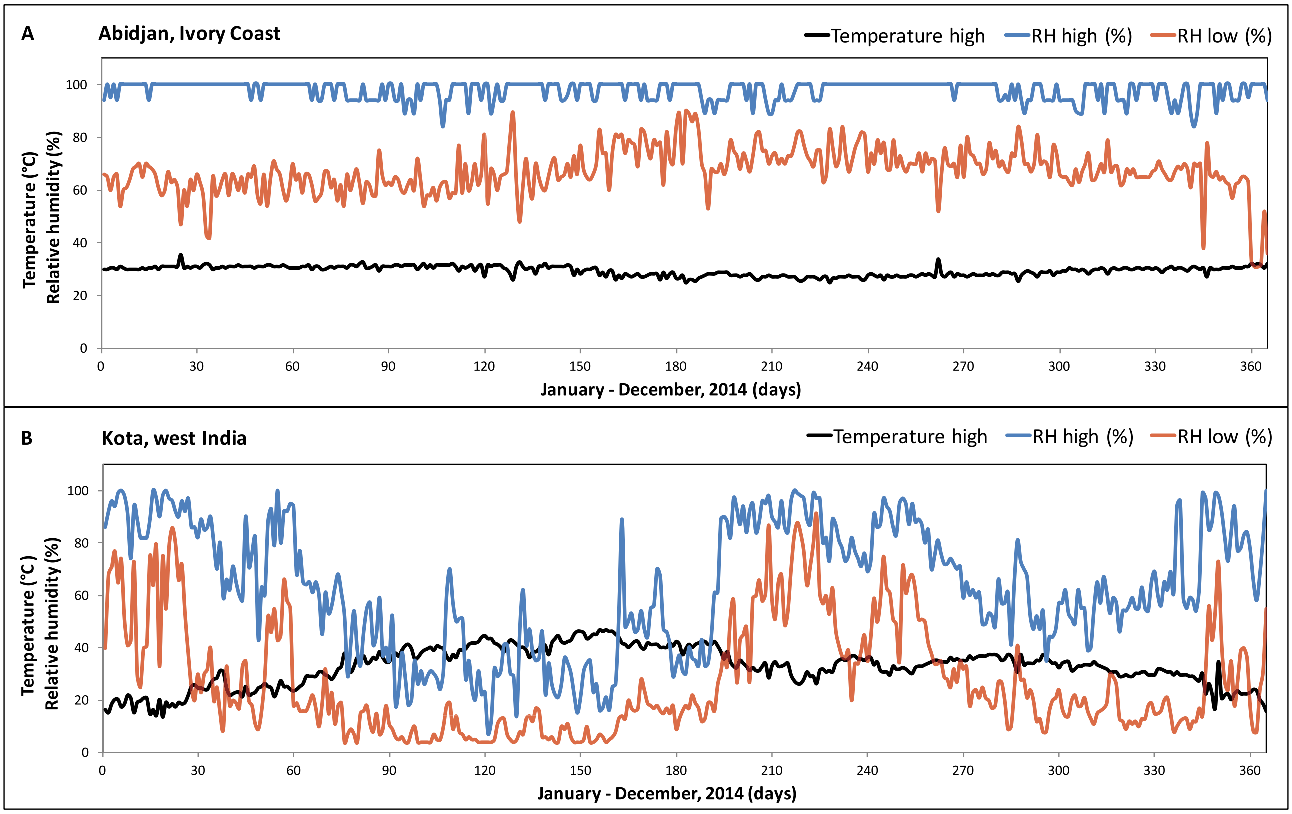

Fig. 5. Daily high temperatures and low and high relative humidities (RH) at two tropical locations, Abidjan, Ivory Coast (A) and Kota, west India (B). The constant high humidity in Abidjan would prevent use of open-air drying to reduce commodity moisture contents to safe storage levels and would promote spoilage in open stores. In contrast, the low RH and warm temperatures in Kota from late March (day 75) through June (day 180) would enable drying to very low moisture contents. However, the subsequent monsoon season (July to September; days 190–270) would not be conducive to air drying of harvested products and would enable rehydration of commodities stored in porous containers to unsafe levels. Data from Weather Underground (www.weatherunderground.com).

toward making heated-air drying more available to small farmers, such as by providing mobile driers that can be fueled by gas or by burning locally produced materials (e.g., corn cobs) (Champ, Highley, & Johnson, 1996; Iqbal & Ahmad, 2014). Solar driers provide another option for heated-air drying of commodities in rural areas (Chua & Chou, 2003; Horticulture Innovation Lab, 2017; Ileleji, 2016; Iqbal & Ahmad, 2014; Salvatierra-Rojas, Nagle, Gummert, de Bruin, & Muller, 2017).

4.3. Desiccant-based drying

Another option for seed and commodity drying in humid climates is the use of desiccants that can absorb water and bind it strongly. Forced-air driers based on silica gel as a desiccant are widely used in the seed industry and germplasm storage facilities to dry seeds and dehumidify seed storage rooms (Chua & Chou, 2003). A more effective desiccant for drying to low ERH is produced from zeolite clays, which can form a microcrystalline pore structure that specifically and tightly binds water (Hay & Timple, 2013; Hay, Thavong, Taridno, & Timple, 2012; Van Asbrouck & Taridno, 2009). When Drying Beads™ made from these zeolites are enclosed in a moisture-proof container with the products to be dried, they absorb water from the air and quickly lower the RH within the container to near zero. Consequently, and without the need for heat, water evaporates from the product and is bound to the beads. Drying Beads can absorb 20–25% of their dry weight in water, and when saturated, can be fully reactivated for reuse by heating.

The efficacy of desiccant-based seed drying has been demonstrated in India, Nepal, Bangladesh, Kenya, Tanzania, Thailand and other countries with support from the United States Agency for International Development (USAID) Horticulture Innovation Lab (Bradford et al., 2014; Kunusoth et al., 2012). This simple "manual" system of enclosing a commodity in a sealed container with a quantity of desiccant is quite cost-effective on quantities up to approximately 100 L volume at a time, which is sufficient for vegetable or foundation seeds or for small farmer grain quantities (Timsina et al., 2018). Bioversity International in Delhi, India, is implementing this system to establish community seed banks to preserve local crop varieties and planting seeds (Dadlani et al., 2016). The Indian government has established a low-energy seed bank based on desiccant-based drying and hermetic storage (IIVR, 2016). A scale-up project supported by USAID resulted in installation of Drying Bead-based drying systems in several large seed/food companies in Bangladesh (Van Asbrouck & Kunusoth, 2015). For larger-scale commercial seed lots or food commodities, a forced-air system based on the Drying Beads is under development. A mobile version of such a system could deliver drying services to farmers or community centers. Combining desiccant drying with on-farm plastic or metal crop storage bins could increase their efficacy in preserving quality, as recommendations for their use include sufficient drying prior to storage, which is often not achieved (Mendoza, Sabillón, et al., 2017; Taruvinga, Mejia, & Alvarez, 2014).

5. Requirements for the dry chain

5.1. Awareness of the problem

A key impediment to improving commodity storage in tropical developing countries is limited appreciation of the importance of controlling RH in the storage environment, as illustrated by the use of open storage in porous bags (Fig. 1). Following failures of ambient storage conditions, it is often thought that cold storage facilities must be the answer (e.g., Nagpal & Kumar, 2012). However, for dry commodities, this can be a potentially disastrous option, particularly when power supplies are unreliable. For example, refrigeration systems for typical cold storages produce RH in the range of 75–85%. Products stored in these conditions will equilibrate with that RH, resulting in high MC. When these products are removed from the cold store, they are at high ERH and susceptible to pest growth at ambient temperatures. Thus, cold stores for dry commodities must be specially designed to lower the RH at the low T and prevent increases in commodity MC. This is usually done by cooling the air below storage temperature to lower its dew point temperature and then reheating the air to the desired storage temperature. Our experience in tropical south Asia indicates that such cold storage facilities consistently under-size or omit the dehumidification capacity, resulting in high RH in the stores. In addition, power failures can result in RH and commodity MC rising to damaging levels. A less risky and more sustainable approach is to focus on reducing commodity ERH and utilizing water-proof packaging to prevent reabsorption of moisture from the atmosphere. Once dry and inside moisture-proof containers, cooling is advantageous to extend product life. However, cold storage of dry commodities in porous packaging in humid climates with unreliable power infrastructure can be counterproductive. Funds intended for improving dry commodity storage would be better targeted toward enabling the dry chain rather than toward building cold-storage facilities.

5.2. Measuring and monitoring moisture content and humidity

Once the importance of controlling RH for safe storage is recognized, a significant difficulty in implementing improved drying and storage systems is the limited ability to measure and monitor either MC or RH in the locations where it is needed. In the cold chain, it is evident that thermometers to measure and monitor the temperature of storage facilities are essential for quality assurance. Similarly, in developed countries, it is routine for grain elevators and warehouses to have calibrated electronic meters that can quickly measure MC of the commodities delivered and stored (Grabe, 1989). This enables dry commodities to be marketed by weight based on correction to a standard MC. Otherwise, the monetary value of a given dry weight of product varies as it either hydrates or dries. In contrast, in developing countries commodities are generally sold by volume rather than by weight in rural areas (World Bank, 2011). The actual seed or grain MC is seldom known, although it may be estimated by indirect methods such as biting the grain, which may nonetheless provide a reasonable pragmatic guide for an experienced farmer. Smallholder farmers generally air dry their produce according to tradition and as weather patterns allow, for example by covering or moving under shelter when possible during rains, but have little means to know the actual product MC or the RH of the environment.

The standard method for determining seed/grain MC is by the oven test, in which a sample is weighed, dried in an oven for a period of time (depending on the seed type), and reweighed (ASAE Standards, 1991; ISTA, 2004). The loss in weight is attributed to water, and the MC percentage is calculated on a fresh weight basis as the initial weight minus the final weight times 100, divided by the initial weight. While simple, many factors can affect the accuracy of oven tests, including the temperature and duration of drying and composition of the product (Grabe, 1989). In addition, neither sufficiently accurate scales nor ovens are available for small farmers or in their communities, preventing the application of this method.

Similarly, meters to measure and monitor RH have seldom been available in the developing world except after aggregation of commodities into larger storage or milling facilities. However, electronic T and RH meters are now widely available and inexpensive (as little as US $3.00) (Fig. 6) (Tubbs, Woloshuk, & Ileleji, 2017). Far less expensive are humidity indicator strips (similar to pH paper) that change color in response to RH (Fig. 6). For a few cents apiece, a small piece of such reusable indicator paper can measure the RH of ambient air or of the inside of a container, which can be converted to product MC if needed (e.g., Fig. 2) (Bradford, Dahal, & Bello, 2016). However, for simply monitoring storage suitability, no conversion is necessary, as the color of the indicator paper can be related directly to the potential storability of the commodity, as shown on the DryCard™ (Thompson et al., 2017) (Fig. 6). Enclosing such indicator paper or a DryCard inside of a moisture-proof container containing a sample of the commodity or embedding it in the commodity mass quickly estimates the ERH and therefore the risk for mycotoxin accumulation or insect damage. This is a very inexpensive and convenient way to estimate the ERH of the product in the field, during drying or in storage. As has been noted, "What gets measured gets managed" (Lipinski et al., 2013), so the ready availability of inexpensive methods to measure and monitor RH is game-changing for increasing awareness that humidity is the key factor to control during dry commodity storage.

5.3. Strategies for initial drying

The starting point in the dry chain requires lowering the product MC to the desired level. The first step in this process will generally be air drying, as is widely practiced (Lantin et al., 1996), and the drying capacity of the atmosphere should be utilized to the extent possible (Fig. 7). When this is sufficient, the product can simply be packaged for storage (i.e., the climate-smart dry chain). However, air drying is often insufficient in humid climates, and additional drying methods must be employed. It would be optimal if these methods could be broadly distributed to the farm level to initiate the dry chain prior to aggregation of commodities, which exacerbates the opportunities for microbial and insect infestation, and at higher MC, can result in damage due to microbial heating. Mobile drying units that can be brought to farms, as is done with mobile threshers, are an attractive option (Iqbal & Ahmad, 2014; Rockefeller Foundation, 2017). The combination of a mobile thresher along with a mobile drier and water-proof packaging would be sufficient to implement the dry chain at the farm level.

Access to and affordability of such mobile drying services may still be out of reach for many small farmers. However, desiccant-based drying methods are potentially suitable for individual farm use, as they require only moisture-proof containers and access to the desiccant. One feasible approach would be for community-based drying centers to provide such access on a rental basis. A farmer could use Drying Beads to dry seeds or commodities in metal or plastic storage bins or in hermetic bags, then return them to the drying center for reactivation and use by other stakeholders. The community seed banks using Drying Beads being established by Bioversity International (Dadlani et al., 2016) provide a model that could evolve into full-service drying centers for a diversity of grains and horticultural crops, including fruits and vegetables.

5.4. Packaging and storage to preserve dryness

In a humid climate, it is not enough to just dry a commodity; it must also be packaged to prevent rehydration from rain or the ambient air. This is in part the principle behind large hermetic cocoons such as GrainPro Superbags (www.grainpro.com) developed initially at the International Rice Research Institute (De Bruin et al., 2012; IRRI, 2016) and the Purdue Improved Crop Storage (PICS) bags distributed with the support of the Bill and Melinda Gates Foundation (Murdock & Baoua, 2014; PICS, 2015). These cocoons and bags are both moisture-proof and impermeable to oxygen. In addition to offering protection from rain and humidity, oxygen cannot enter the sealed bags. As microorganisms and insects present inside the bags consume oxygen through respiration, they eventually reduce oxygen levels to the point where their own metabolism cannot be supported and their growth and reproduction cease. These bags and larger scale cocoons can greatly improve commodity storage when properly utilized (Afzal, Bakhtavar, Ishfaq,

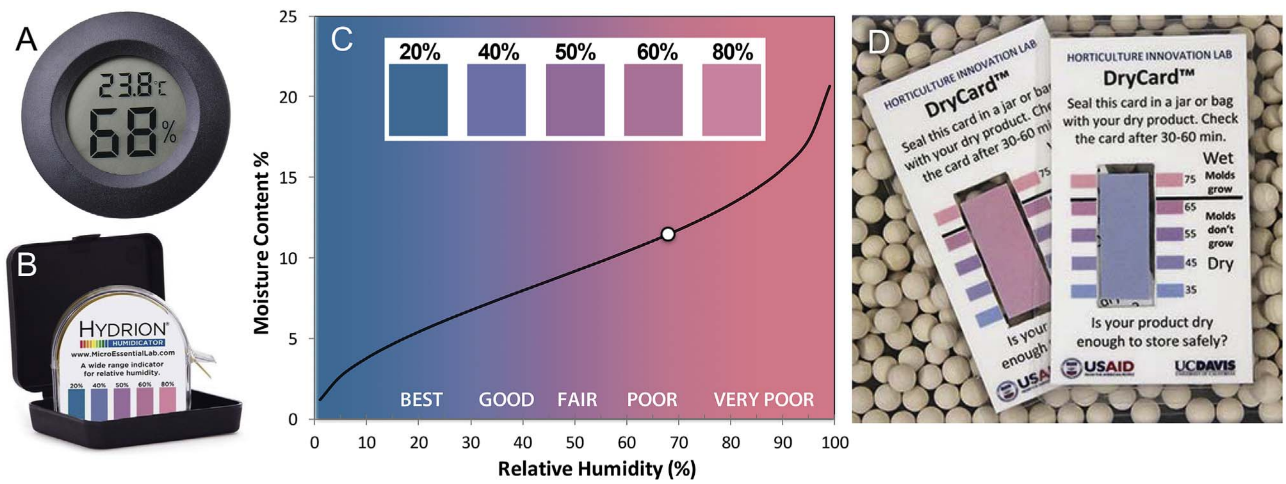

Fig. 6. Measurement of relative humidity (RH) and its relationship to product moisture content (MC) and storage potential. (**A**) Inexpensive electronic meters can conveniently measure temperature and RH. (**B**) RH indicator (Humidicator) paper that changes color in response to the ambient RH (www.microessentiallab.com). (**C**) Graph showing an example of an ERH versus MC isotherm with the Humidicator indicator strip scale superimposed on it. While not as accurate as an electronic meter, this scale is sufficient for determining the adequacy of storage conditions over the range of ERH commonly encountered (Bradford et al., 2016). The storage potential for maintaining seed viability is indicated for different RH ranges. Storage potential for food products is somewhat better than indicated below 65% RH, as maintenance of viability is not a concern. (**D**) The DryCard™ has a laminated RH indicator strip with an adjacent RH scale for durability and convenience. The back of the strip is exposed to allow equilibration with the ambient air (Thompson et al., 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

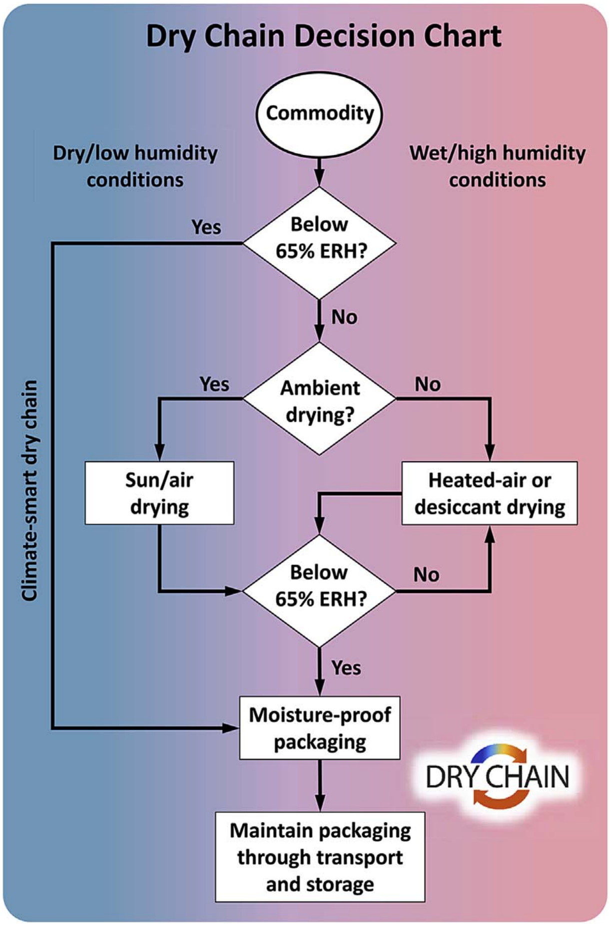

Fig. 7. A decision chart for implementation of the dry chain for postharvest storage of dried food commodities. The paths indicate when different drying interventions are required.

Sagheer, & Baributsa, 2017; Ng'ang'a et al., 2016a, b; S.B. Williams et al., 2014).

The mode of action of PICS bags requires that the commodity be at an ERH high enough to initially support the metabolism of enclosed organisms in order to reduce the oxygen levels rapidly and prevent damage (Murdock & Baoua, 2014). However, wheat grain at 14% MC (~78% ERH) exhibited negligible respiration at 10, 20 or 30 °C and only a slow rate at 40 °C, but respiration rose dramatically as MC increased, attributed primarily to microorganisms rather than to the grain (White et al., 1982). Experimental and modeling studies confirmed that wheat grain at 13% MC (~72% ERH) or less would only slowly reduce oxygen levels in the airspace of closed hermetic cocoons (Abalone et al., 2011). Thus, reduced MC as well as low oxygen were needed to fully prevent production of mycotoxins in PICS bags (Ng'ang'a et al., 2016a). Storage of products in such hermetic containers at ERH < 65% is still beneficial, as insects can be active down to 35% ERH (Fig. 3) and can be controlled by the oxygen impermeability. As such bags and cocoons are moisture-proof, they are fully complementary for use in implementing the dry chain (S.B. Williams, Murdock, & Baributsa, 2017).

6. Social and economic constraints on and benefits of the dry chain

While the effectiveness of both drying and hermetic storage in reducing postharvest loss has been demonstrated, there are social and economic constraints on their implementation (Ann, 1996). Enabling smallholder farmers to dry and store their own harvests in safe conditions would benefit them in numerous ways. Lacking such ability, smallholders generally must sell their products immediately after harvest, when supplies are greatest and prices are lowest. Safe, on-farm storage would allow them to market their products at a time when prices are higher. In addition, the portion of their produce used for their own consumption would not suffer losses due to spoilage or accumulation of mycotoxins resulting from poor storage conditions. As pesticides would not be required to prevent insect damage, poisoning due to inadvertent consumption of contaminated grain would be avoided (FAO, 1989b). It has been noted that for the poorest farm households, “decisions about development of production and livelihood are often geared as much as to cutting risk and vulnerability as to enhancing incomes” (Memedovic & Shepherd, 2009). Improved capacity for on-farm storage of dried products would increase smallholders' food security and reduce vulnerability to market forces. Drier products also reduce the weight of water transported to warehouses or markets. Commodities would enter the marketing chain at lower ERH, reducing the potential for heating and spoilage that comes with large stacks of high-moisture grains. Distributing the drying and packaging processes locally would reduce the need to build large centralized drying facilities. Funds saved from not building such facilities could be invested instead in providing local drying and packaging services to initiate the dry chain.

A number of changes in marketing chains are needed to encourage broad adoption of the dry chain system in developing countries. Smallholder farmers currently have limited access to drying or storage facilities, so their choices are to sell their products to traders immediately after harvest or to store them for consumption or later sale and risk spoilage. Although they would benefit from drying, there are disincentives for farmer investment in commodity drying. If sold by volume, low MC is not rewarded, and if sold by weight, the farmer loses money on every kilogram of water that is removed. The availability of humidity meters, indicator strips and DryCards (Bradford et al., 2016; Thompson et al., 2017; Tubbs et al., 2017) could enable price compensation according to product dryness even in rural markets and incentivize on-farm drying.

With respect to packaging, the model employed by the PICS program is based on farmers purchasing the storage bags and reusing them for several years to recoup their initial investment (Baributsa, Djibo, Lowenberg-DeBoer, Moussa, & Baoua, 2014). That is, the commodity is stored on-farm in the PICS bags but is marketed in bulk with the farmer retaining the bags for reuse. However, this makes the product susceptible to rehydration and pests downstream in the marketing chain due to high ambient RH in open storage. In the dry chain model, commodities in humid environments would remain continuously in moisture-proof containers throughout the storage, transport and marketing chain. A recycling system could collect bags or packaging at the processing plant or end use point (generally near urban areas or transport centers) and return them to farmers for reuse. This would create additional entrepreneurial opportunities for providing mobile drying services, bags and containers in agricultural areas and recycling containers back to farmers.

Alternatively, the intermediate traders or end users (e.g., millers and food processors) in the value chain could own the bags or containers, provide them to contracted farmers and recycle them, with costs recouped from the reduced losses and higher product quality obtained. Approximately two-thirds of the value of farm commodities in developing countries accrues to the traders between the farmers and the end users, but they also suffer the most losses from spoilage (Ann, 1996; Lee, Gereffi, & Beauvais, 2012; Rockefeller Foundation, 2013). Food processors at the end of the supply chain (particularly those exporting to developed countries) currently reject high percentages of purchased commodities due to quality standards and mycotoxin contamination. The financial costs of these losses could be better invested in providing drying services and packaging free or at low cost to farmers. The latter model has been successfully implemented by some seed companies in Bangladesh, with the companies providing containers and Drying Beads to their contracted seed producers to efficiently dry their seeds (Van Asbrouck & Kunusoth, 2015). Containers and beads are returned to the company for reuse along with the higher quality dried seeds.

The most important social incentive for and potential benefit from implementation of the dry chain is to prevent the tragic consequences of mycotoxins in the food supply. While biological and technological solutions to prevent fungal growth in the field and in storage may someday come to fruition (Alberts et al., 2017), the primary cause of mycotoxin contamination is the storage of food commodities at high ERH (Wild et al., 2015). Rather than consider this an intractable problem and focus on downstream mitigation, the cause can be addressed directly with methods that are appropriate for the most-affected climates. It is difficult to remove aflatoxin from the food chain once it is present, and its toxic effects have enormous social, economic and humanitarian costs. Investment in and promotion of the dry chain is the most rational immediate approach to alleviate these consequences until other solutions become available.

7. Conclusions: implementing the dry chain

The essential components for implementation of the dry chain are available: (1) convenient and inexpensive methods to measure and monitor product ERH from the farm to the consumer; (2) methods to dry food commodities even in humid climates; and (3) moisture-proof containers or packaging to maintain low commodity MC regardless of external RH (Fig. 7). Broader awareness of the importance of controlling RH throughout the value chain is critical. By identifying humidity as the primary enemy of quality for dried products, the importance both of initial drying and of maintaining dryness through the value chain is emphasized. The "Make it Dry—Keep it Dry" slogan of the dry chain (www.drychain.org) must become the mantra for dry food supply systems in humid regions. Awareness that RH, not T, is the critical factor for storage of dry products focuses attention on the fundamental problem rather than on building refrigerated facilities that are expensive and energy consuming, and exacerbate the problem in locations where power supplies are not reliable.

Implementation of the dry chain should take advantage of climate-based drying to the extent possible. It is economical to use ambient air or solar drying to remove as much water from the product as possible. By measuring the ambient RH and product ERH, it is easy to determine whether further drying is possible or equilibrium has been reached. Heated-air drying or desiccants enable further drying to safe levels even when ambient RH is high, followed by maintenance of low MC via moisture-proof packaging. In many cases, it will be to the economic advantage of downstream purchasers to facilitate distributed, on-farm implementation of the dry chain. As for the cold chain, cooperation is required throughout the supply system to maintain product quality. A value chain-based approach, with those benefitting most from the cost savings or value created providing funding for implementation, makes the most sense for reducing food loss and contamination (Rockefeller Foundation, 2013). A comprehensive policy of establishing community-based drying service centers and supporting the implementation of the dry chain by governments, NGOs and private companies would empower smallholders, increase productivity, provide jobs and improve public health.

Acknowledgements

The research and development activities on which much of this article is based were made possible in part by the generous support of the American people through the United States Agency for International Development (USAID) under Award No. EPP-A-00-09-00004 (Horticulture Collaborative Research Support Program Awards #09-002945-03, #09-002945-50 and #09-002945-104). The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. K.J.B. thanks the Rockefeller Center in Bellagio, Italy for the opportunity to be a Fellow there during April 2016 when this paper was drafted.

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