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Adel Kader Review

Postharvest technologies for small-scale farmers in low- and middle-income countries: A call to action

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ABSTRACT

The benefits of agricultural innovations in increasing productivity and reducing postharvest losses have not been shared universally. Postharvest losses of horticultural crops are high in low- and middle-income countries (LMICs) where small-scale farms play a critical role in production. A number of innovations in application of the cold chain and the dry chain to address postharvest losses are appropriate for small-scale enterprises. Case studies offer additional insights about some of these technologies, including how they made an impact for small-scale farms. Increasing global food insecurity demands could be mitigated by rapid and sustainable changes in postharvest management in LMICs. Relatively recent attention on food loss and waste (FLW) among key global organizations offers an opportunity for greater levels of resources being dedicated to this urgent issue. Major production-side global initiatives have achieved systemic impacts across LMICs. A more coordinated effort among researchers and other stakeholders working to reduce postharvest losses is needed to achieve significant reductions in LMICs.

1. Introduction

In the past century, steady adoption of research-driven technological innovations by the produce industry in high income economies has reduced postharvest losses due to product deterioration causes and improved the quality of perishable products marketed from these regions (Kader, 2006). Pre-cooling, refrigerated storage and transportation, drying and dry storage, controlled atmosphere storage, improved packaging and unitization, regulated ripening, growth-regulating chemicals and other technologies provide high quality fruit and vegetables for consumers on a year-round basis, and reduce postharvest losses during marketing. In contrast, losses of harvested perishable products before consumption have been estimated at nearly 40% in low- and middle-income countries (LMICs) (Kader, 2005; Spang et al., 2019), while worldwide losses of fruits and vegetables between harvest and retail were estimated at 22% (FAO, 2019). However, it is clear that losses vary widely, depending on the specific crop, season and growing location. These losses are not just economic and nutritional - they also reduce sustainability of horticultural production and make a significant contribution to global climate change (Buzby et al., 2011; Foresight, 2011).

Advanced postharvest technologies are employed in LMICs, but chiefly by large-scale or high-value export enterprises seeking to minimize losses and provide high-quality products for consumers to the upper- and middle-income countries (bananas from Ecuador to the US, green beans and ornamentals from Kenya to Europe). Smallholder farmers, usually women, who provide horticultural products for the local market or even to those export-oriented industries, do not have access to technologies that would reduce the devastating losses they experience between harvest and market.

Recent reviews related to this topic have focused on specific types of technologies, such as cooling and cold storage (Behdani et al., 2019; Makule et al., 2022), solar dryers (Devan et al., 2020), and hermetic grain storage (Baributsa and Njoroge, 2020). We highlight the principal sources of loss, and consider opportunities for development of innovative technologies to reduce them, with an emphasis on cooling and drying technologies. In particular, we point to the dramatic reductions in costs and increased capability of information dissemination and renewable power sources as drivers for technological innovation that might change the postharvest dilemma for smallholder farmers without requiring them to replicate the large-scale and high-cost postharvest systems that have been so successful in high-income economies

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(mechanical refrigeration systems, vacuum coolers, convection dryers). We emphasize technologies that have been demonstrated as effective in LMICs and discuss potential improvements to these technologies. Case studies are included to emphasize these points. This review is also intended as a call to action for the postharvest biology and technology community to focus on the needs of smallholder horticulturists in LMICs (Behdani et al., 2019).

1.1. *Postharvest losses – magnitude and impact*

In LMICs postharvest losses of perishable horticultural crops average about 38% (Spang et al., 2019), but can be as high as 80% (Kitinoja and Kader, 2015). Postharvest losses have been estimated to contribute eight percent of global annual greenhouse gas emissions (FAO, 2019; Project Drawdown, 2023). On a weight basis, horticultural crop losses exceed all other types of food loss (Lipinski et al., 2013). Because of unpredictable weather and losses of arable land, anthropogenic climate change has decreased productivity of global agriculture by 21% since 1961. Reduction of postharvest losses could offset this decrease, increase food availability, and reduce greenhouse gas emissions (Ortiz-Bobea et al., 2021).

In LMICs, most postharvest losses occur early in the value chain (Gustavsson et al., 2011; Kader, 2005). Factors responsible for these losses include poor temperature management, physical damage, inadequate packaging, poor storage, poor transportation and marketing infrastructure, adverse policy decisions, and lack of access to postharvest information and technology.

1.2. *Importance of losses at the smallholder farmer level*

The United States Agency for International Development (USAID) defines a smallholder producer or farmer as one who has less than 5 ha of arable land (Feed the Future, 2019). Small-scale farms are critical for the production and supply of horticulture crops in many LMICs (FAO, 2021), and fruit and vegetables are often more profitable than staple crops (corn, rice, beans, etc.) (Rahiel et al., 2018). Horticulture production by smallholder farmers builds resiliency, mitigates climate-risk, and can be an important source of income and nutrients (Schreinemachers et al., 2018).

Excessive postharvest losses detrimentally impact the potential benefits of horticulture, often forcing smallholder producers to be 'price-takers' (Ambuko et al., 2018). Lacking on-farm postharvest storage, growers may need to accept whatever price is offered (Yeshiwas and Tadele, 2021), and are obliged to sell produce immediately after harvest, even when the market is oversupplied and profit margins are low (Rutta, 2022; Rahiel et al., 2018). For example, the cost of tomato production in Uganda is estimated at $625 per hectare (Omia Agribuisness Development Group, 2023). Production ranges from 10.1 to 20.2 tons per hectare. If losses after harvest are 50% (Aidoo et al., 2014), this represents a loss of $3.13 per kg of production or $312 per hectare. There is also the lost opportunity cost. If tomatoes sell for $0.50 per kg, for example, at the low end of production (10 tons per hectare) income potential is $5000. A 50% loss not only costs the $312 of production costs, but also the lost potential income of $2500.

Discouragingly, over a twenty-year period between 1994 and 2014, there was no significant decrease in the level of postharvest losses of horticultural crops in LMICs (Singh et al., 2014). Vegetable and fruit production can improve the health and economic vitality of smallholder farmers; and recognition of the significance of postharvest horticultural losses has led to a focus on this issue by FAO, the World Bank, the United Nations Environmental Program, the United States Department of Agriculture, the World Food Program, and USAID. The United Nations' Sustainable Development Goal (SDG) 12.3 targets reductions in losses throughout the supply chain, and the African Union Member states have pledged to cut postharvest losses in half by 2025 (Stathers et al., 2020).

However, investments in agriculture are still predominantly focused on staple crops (Haddad et al., 2016), and horticulture generally has not received the research investment it deserves, there is on average only one horticulture researcher per 1 million of population, while cereal crops have 4–5 (Schreinemachers et al., 2018). Moreover, postharvest research capacity is only a small fraction of horticultural research (Kitinoja et al., 2011). Furthermore, there has been a general lack of interdisciplinary cooperation to address postharvest losses in horticulture (Kitinoja et al., 2011).

Factors limiting the impact of investments to decrease postharvest losses in horticulture crops have included inappropriate scale of interventions, lack of focus on improving knowledge and practices, continued deficiencies in coordination, lack of market connections, and short time frames for research projects (Stathers et al., 2020). As production and efficiency has increased in fruits and vegetables, the growth in losses has also increased (Abbade, 2020).

1.3. *Causes of postharvest loss*

The causes of food losses after harvest differ between fresh and dried commodities. For fresh fruits and vegetables, poor management of temperature and relative humidity (generally temperatures above optimum and relative humidities below optimum), poor packaging, inadequate storage facilities, transportation and roads, and poor planning and policies are responsible for the high percentage losses of fruits and vegetables (Kader, 2005). High temperatures increase the speed of ripening and softening, decay development, and water loss (Kader, 2013). Low relative humidity in the environment around the commodity also increases water loss, and many packages that are commonly used in LMICs are not able to maintain high relative humidity. Poor packaging, transportation and roads lead to physical damage, which generally increases water loss, ethylene production (accelerating ripening and senescence), and decay (Kader, 2010). Inadequate sanitation of workers and water systems can lead to contamination by human pathogens that may interfere with market opportunities, especially for export markets. All of these issues are exacerbated by poor production planning and coordination, and lack of access to markets, which leads to gluts of harvested product with inadequate means of preservation.

For dried products, inadequate drying and poor storage conditions are the main drivers of postharvest insect and fungal contamination (Kumar and Kalita, 2017). Fungal contamination of dried foods reduces the value of the commodity for market and frequently renders the product inedible, and even toxic. Drying after harvest is an excellent way to stabilize products and allow storage without refrigeration. However, to be successful, it is critical that the product is dried to, and stored hermetically at, a water activity (A_W) of less than 0.65 (65% equilibrium relative humidity (ERH)) (Bradford et al., 2018). Equilibrium relative humidity is the relative humidity that develops in the air around a dried commodity after it is sealed in a container for a period of time. An A_W below 0.65 prevents the growth of microorganisms and, in combination with low oxygen atmospheres that develop in hermetic bags, reduces insect growth. Storage in a hermetic package (GrainPro, PICS Network, Vestergarrd's ZeroFly Bag) also prevents moisture absorption from the air, and is particularly important in humid climates. In LMICs, it is very common to observe dried products stored in jute sacks and other types of porous packaging that do not protect the product from re-absorbing moisture, resulting in product deterioration (Bradford et al. 2018).

2. Opportunities to reduce losses

2.1. *Cold chain*

Temperature management is critical for limiting postharvest losses in fresh fruits and vegetables. High temperatures during harvest, storage, and transport accelerate metabolic activity, increase water loss, can stimulate production of ethylene, and promote decay of fruits and vegetables, thereby shortening their shelf-life and reducing their quality and nutritional content (Yahia and Elansari, 2011). Ideally, products should be pre-cooled immediately after harvest to remove field heat (Elansari et al., 2019), then maintained at the optimal cool temperatures in a 'cold chain' from harvest to consumption (Islam et al., 2022). Limited resource smallholder farmers can apply simple practices such as harvesting during cooler periods of the day and placing products in the shade, and couple these with low-cost technologies to reduce temperature-related losses (Amwoka et al., 2021). However, the lack of refrigeration during the "first mile" of rural horticulture value chains can result in major postharvest losses (Lipinski et al., 2013). Access to cooling and cold storage facilities, as well as cold transport, is a critical need for farmers in LMICs.

2.1.1. Evaporative cooling

In evaporative cooling, dry air absorbs water, cooling itself and the water in the process. Cooling capacity is highest when the ambient air is at low humidity, and temperatures are moderate (Kumar et al., 2018); therefore, it works best in the dry tropics and sub-tropics. For postharvest management, evaporative cooling systems in which external air passes through wetted material into a storage chamber are most common (Manuwa and Odey, 2012). In passive evaporative cooling systems, evaporation occurs at a wetted surface and heat is transferred by conduction and convection; while active systems use an external device to force air through the wetted material, thereby increasing cooling efficiency (Ndukwu and Manuwa, 2014).

Evaporative coolers are attractive to smallholder farmers in LMICs because they are affordable, can be made with locally available materials, generate high relative humidity (thereby reducing water loss), and, under ideal conditions, can provide the correct temperature (10 – 12 °C) for storing chilling-sensitive commodities (lal Basediya et al., 2013). In the right climates, evaporative cooling is suitable for short-term storage of fruits and vegetables and can also be used to precool products (Amwoka et al., 2021). The limitations of evaporative cooling include the use of water, which may not be readily available, and the physical limitations on cooling potential in high humidity conditions (Verploegen et al., 2019).

2.1.1.1. Passive evaporative coolers. The Zero Energy Cooling Chamber (ZECC) (Fig. 1), a common passive evaporative cooling chamber invented in the early 1980s in India, comprises a rectangular chamber enclosed by a double wall of bricks with sand filling the gap between the two brick walls (Roy and Khurdiya, 1982). Product is placed inside the chamber and a cover is placed over the top. Water is trickled into the sand, and the chamber is cooled by evaporation from the surface of the bricks. Pot-in-Pot coolers (also known as Zeer Pots) (Fig. 2) are low-cost passive evaporative cooling units constructed of two unglazed pots (one large, one slightly smaller) with sand filling the void between the two pots (Verploegen et al., 2019), much as in the ZECC. Water is applied to the sand and a damp cloth is placed on top of the pot opening to generate evaporative cooling effects (Kader, 2005). The volume of such pots is quite limited, but they can be useful for home storage. The Charcoal Cooler is a passive, evaporatively cooled room that can be as simple as a wood frame wrapped with interior and exterior mesh or chicken wire, with the void between the layers of mesh filled with charcoal that is wetted by dripline or by hand (Ndukwu and Manuwa, 2014). Ambuko et al. (2017) noted the ability to maintain high humidity levels, thereby reducing weight loss, and consistent temperatures as two of the key benefits of using ZECCs. In a trial evaluating the ZECC with amaranth, these ZECC attributes reduced water loss by nearly 50% in ZECC-stored product compared to ambient room control, and maintained significantly higher levels of vitamin C.

In the humid tropics, the value of the ZECC is solely in reducing water loss, since cooling potential is very limited in those environments. An important consideration for postharvest researchers exploring alternative cooling systems is choosing the comparisons that they make. In the examples cited above, the evaporative cooling system is typically compared with standard practice (no cooling, or simple shade). While

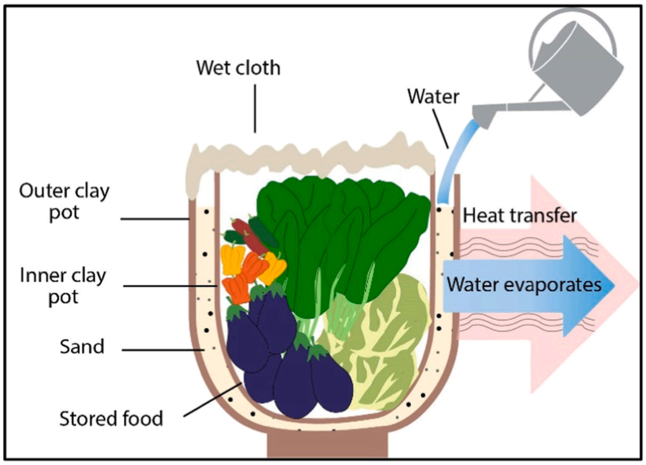

Fig. 2. Pot-in-Pot evaporative cooler. Courtesy of MIT D-Lab: A Guide to Assembling, Using, and Maintaining Clay Pot Coolers. Sourced from: https://d-lab.mit.edu/resources/publications/guide-assembling-using-and-maintaining-clay-pot-coolers.

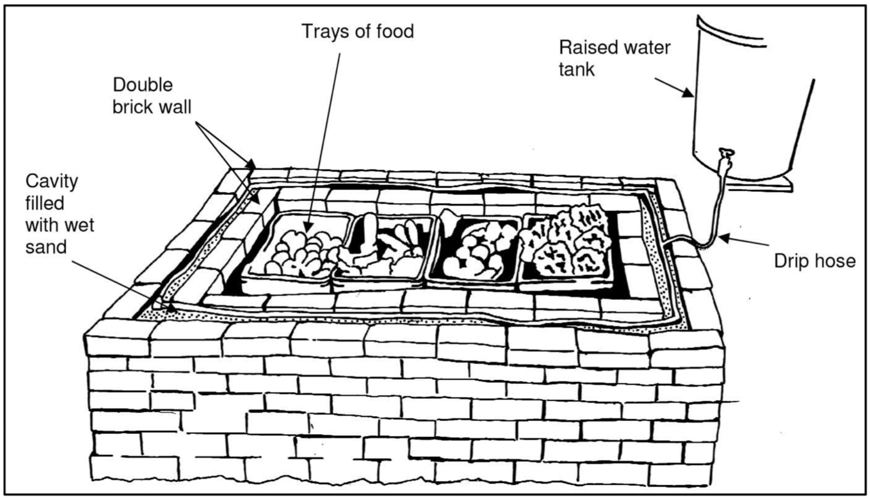

Fig. 1. Zero Energy Cooling Chamber (ZECC). Courtesy of Practical Action, Neil Noble. Sourced from: https://srrweb.cc.lehigh.edu/app/ZECC.

this may indicate some benefit, it does not provide a comparison with the effectiveness of proper refrigeration.

2.1.1.2. Case study - Not always low-cost. *Wheeler and Kitinoja (2014) found the price of a ZECC to be highly variable depending on local material costs, with prices for a 100 kg capacity unit ranging from $280 ($2.80 per kg) in Ghana for the ZECC unit alone – with no shade structure, no raised tank or irrigation lines – to $615 in Thailand. Verploegen et al. (2019) determined that a larger pot-in-pot capable of holding 70 kg of product, and sitting in a plastic bowl with wetted sand in the space between, was a highly cost-effective evaporative cooling option at $17 ($0.24 per kg) in Burkina Faso, where clay pot production is common. Working within the constraints of local materials is important for providing technology options that provide fairly rapid return on investment.*

2.1.1.3. Active evaporative coolers. Active evaporative coolers incorporate fans to move air through the wetted cooling medium, and can achieve lower temperatures than passive coolers (lal Basediya et al., 2013). Workneh (2010) designed an active, direct, 800 kg capacity unit that incorporated a fan, for a total cost of approximately $440 ($0.54 per kg), and determined that reduction in losses in a smallholder farming community in Ethiopia would cover this cost in as little as 1.2 years. Active evaporative cooling units can also incorporate pumps to recirculate water. For example, a small 0.4 m^3 solar-powered unit in Nigeria described by Olosunde et al. (2015), utilized a pump recirculating water through a wetted jute fiber pad. Storage in this unit extended the shelf life of tomatoes, mangos, bananas and carrots by 15, 9, 12, and 20 days, respectively, compared to ambient storage.

In the 'Pusa' evaporative cooler developed and tested in India (Chopra and Beaudry, 2018a), nylon felt fabric covers the cooler walls. The fabric retains and spreads water that is continuously applied using a pump, thereby improving system efficiency. Chopra and Beaudry (2018b) compared a ZECC to the Pusa evaporative cooler, and over a 5-day period the temperature of product stored in the fabric evaporative cooler was 3.5 °C lower than that in the ZECC. The Pusa unit, costing about $4000, can hold 2000 kg of fruit and vegetables, and provided significant air temperature reductions (up to 14 °C) during the day; but high humidity levels at night limited air temperature reductions to only 4.7 °C below ambient temperature.

2.1.2. Mechanical/Traditional cooling

Proper implementation of the cold chain for most horticulture products still depends on mechanical refrigeration. Despite the negative environmental impact of older refrigerants, the high efficiency of the Carnot cycle makes standard compressor/evaporator refrigeration the most sustainable means of achieving low temperatures (Oxtoby et al., 2011). The need for cooling and cold storage underscores the need for access to reliable and affordable energy through an electric grid or through standalone systems such as solar, solar with batteries, or generators. Solar powered cold storage is now being recommended as part of essential infrastructure to reduce postharvest losses for smallholder farmers (UNIDO and REEEP, 2020). Unfortunately, the high costs of standard refrigeration equipment, insulated rooms, and solar power supply make this key technology inaccessible for smallholder farmers in LMICs.

2.1.2.1. The CoolBot™. One approach to providing affordable cooling is to minimize the cost of the refrigeration equipment. StoreItCold's CoolBot™ is a controller that overrides the temperature control on a standard home air conditioning (AC) unit, allowing the unit to cool a room to as low as 2 °C while also preventing the AC unit's fins from freezing (StoreItCold, 2023). The CoolBot™ controller costs $374, and an off-the-shelf split unit 12,000 BTU/h AC costs $800, a combined cost much lower than commercial refrigeration systems. However, an approximately 8 m^3 turnkey unit (insulating panels, AC unit and CoolBot™) in the United States costs $5250, highlighting the fact that insulated panels and room construction are still a major cost. Despite the substantial capital cost of a CoolBot™ equipped cold room, the system is an effective solution to LMICs' critical need for cold storage. In comparison to even the best evaporative coolers, a CoolBot™-equipped cold room provides wider temperature control, higher cooling capacity, works in all climates, and allows for longer storage periods, when desirable.

Although CoolBot™ rooms are considerably less expensive than traditional refrigerated cold rooms, the upfront cost remains a barrier for smallholder farmers (Kitinoja and Barrett, 2015), although a positive return on investment could be achieved in as little as two to three years in certain markets (Reid and Kornbluth, 2011; Saran et al., 2012). Controlling capital costs, either by reducing the cost of materials (room construction, insulation) or providing subsidies; increasing utilization of the room with high value crops, implementing a space rental model, or coordinating the purchase of units by farming cooperatives, are critical steps to give smallholder farmers access to effective cold chain technologies.

2.1.3. Coldroom construction

As noted above, the cost of proper cooling is largely the cost of building a well-insulated structure. The effectiveness of a refrigerated room is absolutely dependent on the quality of its insulation and the use of a good vapor barrier. Small commercial coldrooms use insulated panels (typically polystyrene or polyurethane) and large rooms are often insulated with spray-on polyurethane foam, which provides both high quality insulation and a vapor barrier. Polyurethane foam also has structural properties; and very large insulated rooms have been constructed by spraying polyurethane foam on the inside of an inflated balloon, followed by a layer of concrete sprayed over reinforcing steel (Bomberg and Kumaran, 1999). The high cost of the insulated panels used to construct CoolBot™ coldrooms in Bangladesh by the Feed the Future Innovation Lab for Horticulture suggested an examination of locally-sourced insulation materials, such as feathers (produced in large volumes at poultry operations), rice hulls, or chopped straw. Any of these materials (or other finely divided dry organic waste material) could serve as insulation in a double-walled room, provided that the outer wall included an adequate vapor barrier. An alternative strategy that warrants testing is to spray polyurethane foam on an existing structure, providing insulation and vapor barrier at the same time. Additional research and development are needed in this area.

2.1.4. Case study - The role of government in advancing cold chains

*In Nepal, government subsidies allowed R&D Innovative Solutions, Inc. to provide 150 CoolBot™ cold rooms to horticulture producers that otherwise could not afford the unit. For smallholder kiwi fruit growers, access to cold storage reduced losses. Some of these rooms used minimal insulation, but the improvement in quality of stored product was still significant enough to create positive returns. In another example of government support, an Uzbek government preferential lending program for cold storage, implemented with the support of international financial institutions, led to more than a 1000-fold increase in the country's cold storage capacity in 2011 (*Tracy and Taylor, 2017*). Government support can be critical for the growth of a cold chain. But for sustainability, reliable market demand for produce from improved cold storage facilities is essential (*Amwoka et al., 2021*).*

2.1.5. Case study - Know your market

Lewis et al. (2017) *conducted an analysis of the CoolBot™'s economic feasibility in Bangladesh using field data sourced from a Feed the Future Innovation Lab Horticulture project in collaboration with the Feed the Future*

Innovation Lab for Nutrition. Primarily due to the high import tariffs levied on aluminum-sided insulated panels, the capital cost of the CoolBot^{TM} powered cold room was extremely high in Bangladesh – $12808. Additionally, the farming cooperatives utilizing the cold rooms only used, on average, less than 1% of the available roughly 36 m^3 storage capacity. The research showed that if a CoolBot^{TM} powered coldroom's space is used efficiently, if high-value commodities are stored, if subsidies are provided for capital costs, and if low-cost but effective insulation is used, a CoolBot^{TM} coldroom in this LMIC scenario could be very profitable for users.

2.1.6. Case study - Rental model

Several technologies and financing approaches have been demonstrated to overcome the accessibility issues for smallholder farmers in LMICs resulting from the high capital costs of cold storage units and required energy access. The ColdHubs organization provides solar-powered, battery-supported, cold storage units at markets and farms in Nigeria (Fagundes, 2019). *The high capital cost of the unit (*ca. *$45,000) is amortized by farmers and traders renting space in the cold room on a crate per day basis* (Makule et al., 2022). *This rental model is also used by FreshBox in Kenya (farmers pay $0.70 per crate per day to store horticulture products in solar-powered coldrooms)* (FreshBox, 2022)*, and SokoFresh in Kenya (farmers pay SokoFresh $0.02 per kg and SokoFresh also provides training in postharvest management practices to customers)* (SokoFresh, 2023).

2.1.7. Cost benefit of cooling technologies

It is important to consider the costs benefits when comparing cooling and cold storage technologies. Direct, passive evaporative systems, such as the ZECC, alone are not adequate components of a fully-implemented, longer-term storage, cold chain for reducing food losses in LMICs. Mechanical refrigeration in all its manifestations, and evaporative cooling systems that incorporate fans to increase airflow through wetted material, are more effective solutions in suitable locations. Mechanical cooling units, such as the CoolBot™ or evaporative coolers with fans, despite their high up-front costs, are either cheaper or very competitive on a volumetric basis with the direct evaporative cooling units, and have the significant advantage of being able to reach optimal storage temperatures for fruits and vegetables in many locations (Table 1). A key constraining factor, of course, is access to energy; solar panels and batteries are emerging as affordable options in certain LMICs.

Table 1

Cost-benefit analysis of cooling technologies; costs adjusted for inflation to reflect current values.

Technology	Source	Cost	kg capacity[z]	Cost/ kg
ZECC at lowest cost found	Verploegen et al., 2019	$61	100	$0.6
ZECC at low range	Wheeler & Kitinoja, 2014	$365	100	$3.65
ZECC at highest cost	Wheeler & Kitinoja, 2014	$802	100	$8.02
Large Capacity Pot in Pot	Verploegen et al., 2019	$21	70	$0.3
ZECC with shade structure, irrigation, average cost across six sites	Wheeler & Kitinoja, 2014	$946	100	$9.46
Evaporative cooler using felt nylon – the Pusa	Chopra and Beaudry, 2018b	$4340	2000	$2.17
Evaporative cooler with fan	Workneh, 2010	$620	819	$0.75
Turnkey CoolBot™ from StoreItCold (current)	StoreItCold LLC, 2023	$4925	1282	$3.84
CoolBot™ Bangladesh	Lewis et al., 2017	$16,902	5667	$2.98

[z] Capacity for CoolBot™ units was based on 340 crates being the approximate capacity of a 36 m^3 cold room (Lewis et al., 2017). Capacity for evaporative cooler was 6 crates (Wheeler and Kitinoja, 2014).

2.1.8. 'Novel' cooling technologies

2.1.8.1. Liquid nitrogen. Liquid nitrogen has been suggested as a refrigeration system for use during storage and transport (Linde, 2023; Yun et al., 2018). However, since the boiling point of liquid nitrogen is − 196 °C, the evaporation rate must be carefully controlled to prevent the stored products from freezing (Valeriu et al., 2010). Liquid nitrogen cooling has a few advantages compared to mechanical cooling, including reduced need for mechanical parts, no need for refrigerants that may contribute to ozone depletion, and quiet operation. However, in the context of LMICs with variable infrastructure, it is questionable whether sufficient production of liquid nitrogen and transport of the liquid nitrogen, is viable or affordable. Liquid nitrogen may be more appropriate for expensive horticultural products for medium or large enterprises in LMICs until the technology has been adapted to become more affordable and reliable in variable conditions.

2.1.8.2. Peltier or thermoelectric cooling. Thermoelectric cooling uses the Peltier effect to create a temperature difference between two junctions of dissimilar materials, for example different metals like copper or zinc (OEERE, 2023). A Peltier cooler is a solid-state active heat pump comprising many parallel junctions between two ceramic plates, and transfers heat from one side of the device to the other when a DC voltage is applied. Peltier coolers are widely used in small-scale cooling applications, cooling high speed computers, microscope stages, portable beer coolers and the like. These devices have relatively low efficiency compared to heat-pumps, but they are inexpensive (current prices are around $50 per kW of cooling), and extremely simple. To provide the equivalent of a small air conditioner, a bank of Peltier devices would be fitted with heat exchangers and fans (interior and exterior) and an appropriately-sized power supply (grid, solar, or generator).

2.1.8.3. Ice. The use of ice for cooling has a long history. The success of California's fresh horticultural exports to the Eastern U.S. depended on rail cars cooled by ice 'bunkers' at each end of the car, and fans that circulated room air through the melting ice. The system provided high humidity air, close to the freezing point, but without any danger of freezing high freezing point commodities like lettuce. In LMICs, ice is commonly used for handling fish, and large block ice production and crushing equipment can be found at fishing ports and fish markets. Technologies that allow smallholder farmers to use ice for pre-cooling and transporting their products merit consideration. However, it will be critical to use potable water to make ice and prevent contact of melted ice with the commodity due to risks of cross-contamination.

2.1.9. Cool transport

Refrigerated transport is infrequently used in many LMICs, even for very perishable products. Even accessing non-refrigerated transportation can be a challenge for producers in LMICs. These countries typically have limited high quality road systems and few vehicles designed to transport fresh horticulture crops (Kader, 2005), and the transportation is generally not under the control of the producer. Whether on rickshaws, trucks, trailers, or on top of buses, products are exposed to ambient temperatures, inclement weather, sun, dust (Faqeerzada et al., 2018), and physical damage. Ineffective transport from farm to market can be the most consequential driver of postharvest losses in LMICs (Rubagumya et al., 2023). Precooling and packaging are important steps prior to transport (Behdani et al., 2019), but as highlighted earlier, these postharvest interventions can be lacking in LMICs. Lack of cool transport can isolate smallholder farmers from markets; especially markets that offer a premium such as in urban centers (Filmer et al., 2021). Aggregation centers, equipped with cold storage and supported by national policy, can help smallholder farmers' access markets and reduce transport costs (Cooper et al., 2021).

Cool transport in LMICs for fruits and vegetables receives relatively little attention as a postharvest intervention (Tapsoba et al., 2022). There are efficient cold transport systems in LMICs that can deliver horticulture products thousands of miles away, like the export of floriculture crops from Kenya and Ethiopia to Europe (Button, 2020); but the technological advancements in these markets do not always spread to smaller-scale domestic farmers. For all aspects of transportation for the postharvest sector in LMICs, there needs to be better transfer of technology from high-value, export-oriented operations to smallholder operations. In the case of cool transport, adaptation of mobile reefer units to vehicles such as tuk tuks, rickshaws, and trailers is needed to curb losses during transport.

2.2. *Dry chain*

Implementation of the dry chain for staples (grains, pulses and nuts) and for dried high-value products (fruit, vegetables), extends storage life and reduces insect attack and development of fungal toxins (Mahuku et al., 2019; Bradford et al., 2018). Drying can be a solution to the losses associated with production peaks in horticultural crops, when high quality product is often discarded, or sold at a loss because supply of fresh product exceeds demand in the market and cold storage is not accessible. Drying is a ubiquitous step in staple crops; but also 20% of perishable, horticulture crops are dried for preservation (Grabowski et al., 2003). While drying reduces the nutritional content of horticultural crops, a significant portion of nutrients remains and is available in the now-preserved product (Smith et al., 2018).

2.2.1. *Solar drying*

Open air sun drying is the most widespread method of drying agricultural products in LMICs, and can be effective under warm, dry conditions; however, those conditions are infrequently available during the harvest season or in humid climates (Mendoza et al., 2017; Bradford et al., 2018). In addition, traditional open air drying, whether on the ground, on trays, in baskets, on paper or plastic sheets, or on roofs, leaves products exposed to pests, predation, theft, and contamination (Nagwekar et al., 2020). Solar dryers not only dry products faster than open air drying, but are more hygienic, can better preserve nutritional value of a dried commodity, and can be inexpensive (Chua and Chou, 2003). The flow of low-humidity heated air over the product in solar dryers increases the efficiency of evaporation of water from the product to the air (Fuller, 2010). The many solar dryers that have been developed are either direct dryers (drying product is heated by solar radiation), indirect dryers (solar heated air is passed over drying product), or mixed (combination of both solar radiation and externally heated air) (Devan et al., 2020). Additionally, active solar dryers use fans to improve airflow, while passive solar dryers rely on convective movement of air (Matavel et al., 2021). Upfront costs for solar dryers can be a significant barrier for smallholder farmers (Nagwekar et al., 2020); relatively low-cost options that could be purchased by an individual or cooperative are discussed below.

2.2.1.1. Indirect, active solar dryers. The Pallet Dryer (Figs. 3 and 4) is an indirect, active solar dryer that can be used to dry product in a bulk bin (Reid et al., 2022). The dryer is built with a bottom black sheet of plastic or fabric on the ground. A pallet or other such platform is placed at one end of the black substrate and a sheet of clear plastic over the pallet acts as a solar collector. Holes cut in the clear plastic over the slots in the pallet allow hot air to rise into a bin with a perforated base placed on the pallet. The air under the clear plastic is heated by the sun's radiant energy on the black substrate (the solar collector), and the heated air flows through the pallet opening and the bin. A lid placed on the bin is fitted with a 60-watt solar panel and a 60-watt, 12 V fan (rated at 300 cfm) that pulls warm air from the solar collector through the product being dried. The Pallet Dryer is low-cost (ca. $150) and can hold approximately 150 kg of bulk product. In a trial drying 50 kg of coffee beans, the moisture content of the beans reached the 12% target after 30 h in the Pallet Dryer, less than half the 72 h required for beans on a raised bed in a direct, passive greenhouse dryer. Etim et al. (2020) also had success with an indirect, active solar dryer in Nigeria that dried ca 5 kg of bananas to desired moisture content 40% faster than open air drying.

2.2.1.2. Chimney solar dryer. The Chimney Solar Dryer is a low-cost (ca. $150) mixed, passive drying unit that was designed to be a better drying alternative to cabinet dryers using stacked trays of product (Fig. 5). By laying trays of product on a long table, the Chimney Solar Dryer design allows for heated air to travel around and over the trays of product rather than through them. Constructed with materials that can be sourced locally in LMICs, the dryer includes a drying table covered in black or dark material that is connected to a chimney. Products to be dried are placed on trays on the table and covered with greenhouse polyethylene to create a solar collection tunnel and the heated air is drawn through the tunnel by convection up the chimney. Research has shown the value of the Chimney Solar Dryer for smallholder farmers, as it is capable of drying twice as much product in roughly half the time compared to an FAO-type cabinet dryer (Deltsidis et al., 2018); is significantly faster than open-air drying (Mithun et al., 2021; Kumi et al., 2020); and has a short return on investment period if the product being dried fetches a premium price in the market (Lewis et al., 2017).

2.2.1.3. Tunnel dryers. Tunnel dryers can use passive airflow with venting or incorporate fans to generate airflow, and are typically mixed solar dryers consisting of a rounded frame covered in polyethylene plastic (Devan et al., 2020). Getahun et al. (2021) developed an indirect tunnel dryer in Ethiopia with solar powered fans forcing heated air across the product in a two-stage solar dryer that transfers heated air from the first tunnel to a second tunnel. The unit dried 65 kg of chilies 30–54 h faster

Fig. 3. The Horticulture Innovation Lab's Pallet Dryer.

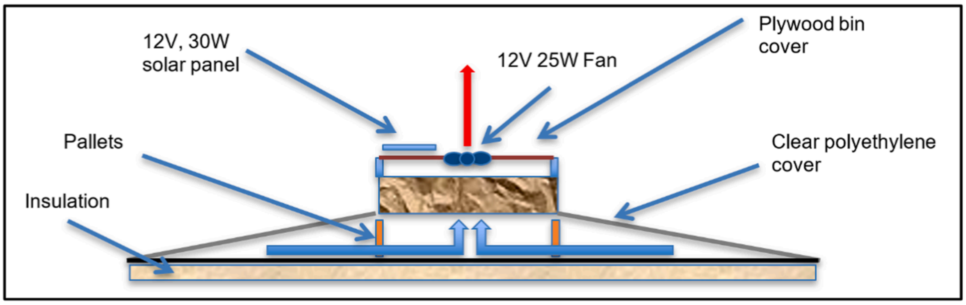

Fig. 4. Cut away view of the Pallet Dryer demonstrating airflow of heated air through bin with drying product inside.

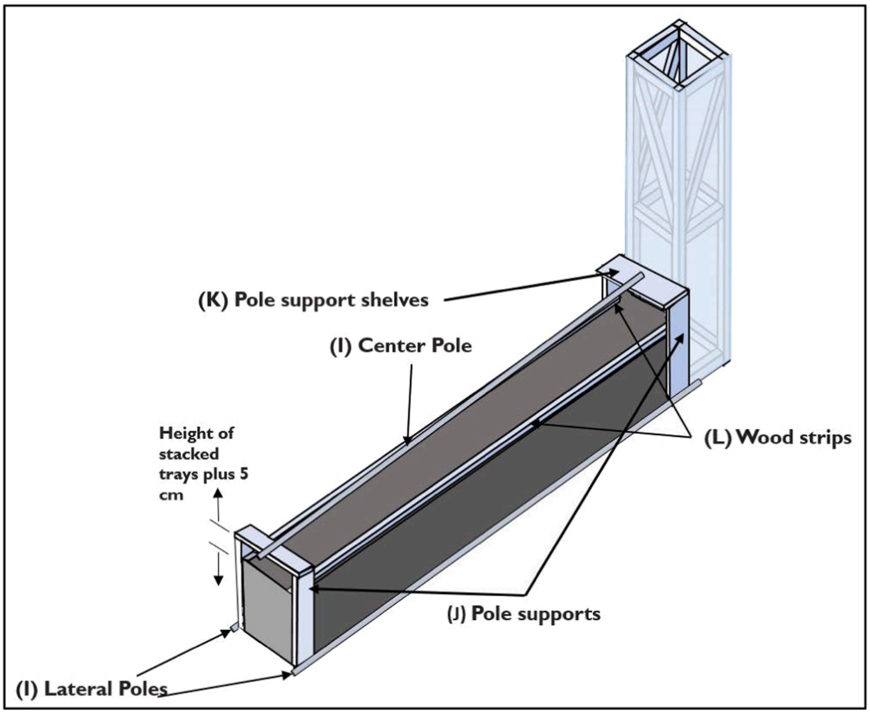

Fig. 5. Horticulture Innovation Lab's Chimney Solar Dryer - In this image the plastic covering the table is not pictured.

than open air drying. An 8.5 m long, mixed active solar tunnel dryer with two axial fans and a large solar collection area dried 8.5 kg of ginger 40% faster than open air drying (Tesfaye and Habtu, 2022).

2.2.1.4. Cabinet dryers. Cabinet dryers are small units meant primarily for household use (Ekechukwu and Norton, 1999). These smaller dryers can be direct, indirect, or mixed dryers using passive or active airflow. A mixed, passive cabinet dryer promoted by FAO (Fig. 6) has a solar collector at the entrance to the dryer box (Dauthy, 1995). Purdue University's Dehytray (ca. $120) is a compact cabinet, direct solar dryer that is a vented black tray with a clear, tight fitting lid to generate higher temperatures compared to ambient, and has been utilized by smallholder farmers (Mobolaji et al., 2021). Limitations of cabinet dryers include their small capacity and the stacked arrangement of the product in some of the units' drying boxes which impedes airflow (Precoppe et al., 2015).

2.2.1.5. Greenhouse solar dryers. Greenhouse solar dryers have been used in LMICs to dry relatively large quantities of commodities. A direct, passive greenhouse dryer is simply a frame with a transparent covering – glass, greenhouse plastic or polycarbonate sheets. The product is placed on the ground or on raised trays within the structure to dry in the heated air (Matavel et al., 2021). Direct, active greenhouse dryers incorporating exhaust fans to improve air flow can dry horticulture products up to 50% faster than open air drying (Shahi et al., 2011). Mixed active greenhouse solar dryers can also add an external heat source and fans to increase drying efficiency (Matavel et al., 2021). In an effort to develop a highly efficient greenhouse dryer for large quantities of chili, Kumar et al. (2020) incorporated both fans and a chimney to remove moist air.

2.2.2. *Hermetic storage for dried horticulture products*

Hermetic storage is critical in the postharvest preservation of dried commodities, as it prevents moisture intrusion, preventing fungal growth and reducing insect activity, and can also create a low-oxygen environment (Murdock et al., 2012; Alemayehu et al., 2023). Hermetic storage can also preserve the visual and organoleptic quality of dried horticulture crops (Villers et al., 2008). The Purdue Improved Crop Storage (PICS) hermetic storage bags have been used by thousands of farmers and traders in LMICs and cost between $2 to $4 each (Baributsa & Njoroge, 2020; Purdue Education Store, 2022). GrainPro Inc. offers a low-cost hermetic storage bag specifically for smallholder farmers and ZeroFly's hermetic bag includes an outer woven storage bag treated with an insecticide (GrainPro Company, 2022;Vestergaard, 2022). It is worth noting that, even with a documented high return on investment, the price point of the bags can be too high for some smallholder farmers (Masters and Guevara Alvarez, 2018; Villers et al., 2008).

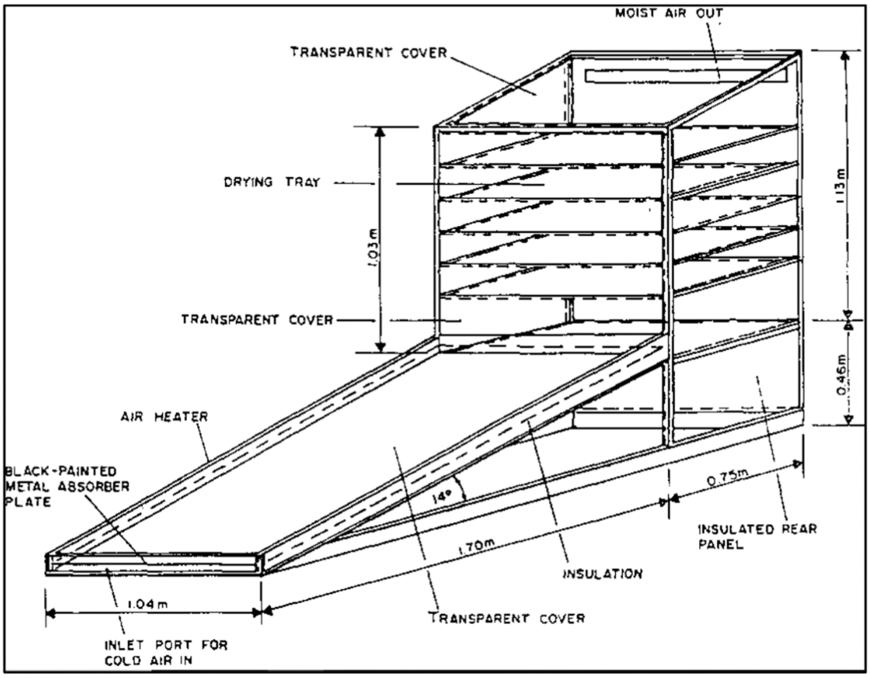

Fig. 6. Solar cabinet dryer with separate air heater featured by FAO. Courtesy of FAO.
Source: https://www.fao.org/3/v5030e/V5030E0c.html.

2.2.2.1. DryCard and other moisture meters. For hermetic storage to be effective, it is important that the product be properly dried (Tubbs et al., 2016); but accurate, affordable, and accessible methods to test moisture content are lacking in LMICs. Electronic moisture meters can be too expensive for small-scale producers and traders, who rely on inaccurate subjective tests, such as chewing or handling the product, to determine dryness (Vera Zambrano et al., 2019). Measuring moisture content requires meters with specific calibration curves for each product (Vera Zambrano et al., 2019). A better approach is the use of hygrometers, which measure equilibrium relative humidity (ERH) which is directly related to the product's A_w. An A_w of 0.65 (ERH of 65%) is the threshold for fungal growth in all dried products, and therefore provides a universal standard for determining the safe dryness threshold of dried products.

New sensors have permitted the development of inexpensive electronic hygrometers. Feed the Future's Food Processing Innovation Lab calibrated an off-the-shelf hygrometer costing $2 to $4 (Feed the Future Food Processing Innovation Lab, 2019). The Feed the Future Innovation Lab for the Reduction of Post-Harvest Loss is promoting the GrainMate moisture meter for traders and aggregators. This device costs approximately $75 and can provide an accurate moisture content reading within six minutes (Lloyd, 2017).

The Horticulture Innovation Lab's DryCard™ is a low-cost, accurate dryness indicator (Fig. 7). The DryCard is a business card-sized tool incorporating a strip of $CoCl_2$ humidity indicator paper (Hydrion Humidicator Paper, Micro Essentials Laboratory, New York, NY) and a relative humidity color scale. The color of the humidity paper reflects the relative humidity in the headspace (ERH), which is directly correlated to the moisture content of the commodity. The DryCard includes a demarcation at the mauve color that corresponds to a relative humidity of 65%, the critical threshold for preventing fungal growth during storage. The $CoCl_2$ strip's color changes perceptibly from blue at 33% relative humidity to pink at 75%. Relative humidity can be determined, with the scale printed on the card, to an accuracy of 2% relative humidity (Thompson et al., 2017). If stored dry between uses, the DryCard can be reused many times. With the exception of the $CoCl_2$ humidity paper, DryCards can be made with materials available in LMICs, and sold for sufficient profit ($1 to $1.50) to sustain a small business.

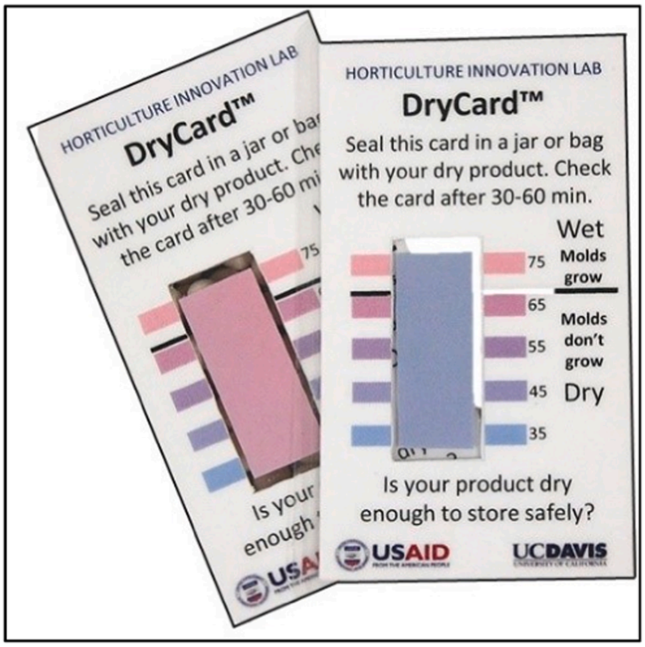

Fig. 7. The Horticulture Innovation Lab's DryCard. Pink means wet, not pink means dry.

2.2.2.2. Case study - The dry chain in action. A young female entrepreneur in Guinea began a successful pineapple drying business using the Chimney Dryer, the DryCard, and hermetic containers for storage, that employs 15 people who process and package dried pineapple. The dried pineapples are sold at local gas stations for 20 mil Guinean francs (GNF) (~$2) (CORAF, 2021)*. This is a significant value addition considering one package consists of just a few pineapple slices and an entire pineapple can sell for 5–10 mil GNF ($0.50 – 1.00) during the peak of the pineapple season.*

2.3. *Packaging for water loss and physical protection*

2.3.1. *Packaging to prevent water loss*

Among the most perishable of horticultural crops are the leafy vegetables. Their high surface to volume ratio and the low resistance of their epidermis to water movement means that they quickly lose enough water to wilt, resulting not only in significant loss of saleable weight, but also loss of visual, textural, and nutritional quality. While high humidity refrigeration is the ideal technology for reducing water loss in these and other less perishable horticultural commodities, a practical method to maintain high relative humidity for many smallholder farmers and traders has been the use of perforated or non-perforated polyethylene bags. The negative environmental consequences of using these bags has led to prohibition of their use in the marketing of foodstuffs in several places. In Rwanda, as an example, single use polyethylene bags are outlawed (Nielsen et al., 2019).

Compostable and biodegradable polymers have been used to manufacture alternatives to high density polyethylene (HDPE) bags, but the present polymers have higher water vapor transmission rates than HDPE, and are thus less effective in preventing water loss, in addition to being significantly more expensive.

Shogren (1997) evaluated the water vapor transmission rates (WVTR) of several biodegradable polymers to determine their suitability as water-resistant membranes. Values of WVTR at 25 °C ranged from 13 to 2900 g/m^2/day. Polyester and polylactic acid films (which are among those commonly used for compostable bags) had WVTRs of 172 and 680, respectively. The WVTR of HDPE is ca. 1 g/m^2/day (Combellick, 1987), so water loss from produce stored in bags made from alternative polymers would be much higher than would be expected in HDPE bags.

There is a clear opportunity for polymer chemists to develop an affordable biodegradable membrane that is tailored to the needs of perishable horticultural products, with good physical properties, a low water vapor transmission rate, and preferably oxygen and CO_2 transmission rates that would facilitate the establishment of modified atmospheres at ambient temperatures. Promising results from compostable, microperforated polyester films have recently been reported by Rodov et al. (2022) with ripening bananas and Owoyemi et al. (2021) with red bell peppers; both demonstrated improved shelf life and quality maintenance in bags made from these compostable polymers.

2.3.2. *Improved packaging for reducing damage of fresh produce*

Sacks, baskets, or rough wood crates are most commonly used for packing fresh commodities in LMICs, and can cause significant mechanical damage during storage and transport due to their rough surfaces, oversized dimensions, and inability to protect the product from weight stacked on top (Kitinoja and AlHassan, 2012; Faqeerzada et al., 2018). Plastic crates or improved baskets can significantly reduce losses (Stathers et al., 2020), but have difficulty competing with low cost baskets or sacks (Yeshiwas and Tadele, 2021) or are not accessible for smallholder farmers.

Integrating plastic crates into value chains can be complicated in LMICs. Determining which entity or individual should own the crates, establishing a return system for crates, ensuring that the market provides a premium for the higher-quality product in the crates, and negotiating with transporters to load product in crates all factor into the feasibility of crates being integrated into a value chain, along with the smallholder farmer's level of risk aversion and social norms (van Wagenberg et al., 2019).

2.3.3. *Case study - Adoption of plastic crates*

Traditional handling of tomatoes in Rwanda results in an average loss of 35% of the product after harvest, largely as a result of physical damage (Gill, 2019). *A plastic crate capable of holding 25 kg of tomatoes costs ca $7.00 in Rwanda, and good quality tomatoes sell at wholesale for* ca. *$1 per kg. One trip with a returnable plastic crate would result in an increased income of $8.75 per crate, (assuming that it eliminates the postharvest losses) more than covering the cost of the crate, which can be used multiple times. A farmer with a small-scale vegetable farm recorded postharvest losses of 50 kg a week until he adopted improved grading and sorting practices, purchased 10 crates and stored product in cooler temperatures. These postharvest improvements resulted in his produce being first quality rather than "second-grade"; profit from just his eggplant production increased by $150 in one growing season. The Rwandan Standards Board certifies organizations that meet certain food handling standards including the use of plastic crates, and there are several examples of higher end retailers integrating plastic crates into value chains* (Dijkxhoorn et al., 2016). E*ven within an enabling environment, capital costs for the crates are universally considered a barrier in LMICs that could be lowered through government interventions to encourage low-interest rate loans, reduce tariffs on imported crates, or subsidize local manufacture of crates* (Hosking et al., 2021).

2.4. *Edible coatings*

Edible coatings for fresh horticulture products have been used for many years to enhance product shelf life (James and Zikankuba, 2017). Edible coatings provide a barrier against gas and moisture exchange on the surface of produce, slowing respiration, senescence, and enzymatic oxidation (Cofelice et al., 2019). Enhanced interest in reducing food loss and waste, as well as in reducing the use of single-use plastic packaging, have fueled a resurgence of interest in edible coatings. Edible organic coatings typically consist of lipids, proteins, and/or polysaccharides (Flores-López et al., 2016). Edible coatings based on *Aloe vera*, mineral oils, polyvinyl acetate, chitosan, cellulose, and protein have shown desirable effects on fresh produce, including reduced decay, without negative impacts on taste (Dhall, 2013); but much of this work remains at the research stage and has not translated into commercial products. For example, bananas coated in 1% chitosan (sourced from shrimp shells) in Bangladesh had a 4-day extension in shelf-life (Hossain and Iqbal, 2016). Papaya coated with 1.5% *Aloe vera* gel, a coating derived from Aloe plants grown in arid locations in many parts of the world, lost 10% less water compared to uncoated papayas, and more effectively preserved quality and key nutrients (Sharmin et al., 2015).

The use of nanotechnology to develop coatings with improved barrier, mechanical, optical, and thermal properties, and improved active properties (antimicrobial), is a new emphasis in coating research (De Oliveira Filho et al., 2022). In recent years, a number of companies have introduced new edible coating products for fresh fruits and vegetables including Apeel™, Mori™ and Sufresca®, among others. The impact of these new products won't be known for a few years as there is little independent research, but it is clear that there is a lot of interest in the produce sector in use of coatings.

There is some question as to the accessibility and feasibility of coating technologies for smallholder farmers in LMICs. Will they have access to purchase coatings locally, and can they afford them? Do they have the means to effectively apply coatings? Will the coatings be as effective or perhaps more effective with poor temperature management?

Most edible coatings can be applied directly onto the surfaces of fresh produce by dipping or spraying, followed by air drying (Tahir et al., 2019); therefore, simple washing and packaging equipment is sufficient for effective use. However, in LMICs, most smallholder farmers do not utilize washing and packing equipment for produce. Investment in washing and coating application equipment, availability and affordability of coating materials, and the regulatory status for different coating materials are currently limitations to commercialization of this technology. In addition, to maximize the potential of these coatings, other foundational postharvest practices and technologies to manage temperature and prevent physical damage, among others, need to also be in place at the smallholder level.

2.5. Genetic modification

Molecular and cell biology approaches have provided important information on factors affecting the postharvest life of perishable crops, and early research demonstrated the power of these technologies in extending postharvest life of perishable products. Oeller et al. (1991) demonstrated that ripening in tomatoes could be inhibited by antisense silencing of genes encoding ACC synthase, and Ayub et al. (1996) demonstrated the same effect in melons by silencing ACC oxidase. Concern about the safety of genetically modified organisms meant that these exciting results remained just research curiosities, but new techniques that eliminate the need for foreign genetic material have led to regulatory approval and release of engineered crops with improved postharvest performance or quality in high income economies. Examples include the Arctic® (non-browning) apple, produced using a sense post-transcriptional silencing approach (Stowe and Dhingra, 2021), potatoes with reduced browning and acrylamide production using 'all native DNA' transformation (Rommens et al., 2008), and mushrooms engineered to reduce browning using the CRISPR-Cas9 gene editing technology (Waltz, 2016).

So far, these powerful tools for improving postharvest life using molecular or genetic approaches have not been applied to the benefit of smallholder farmers in LMICs. Genetic modification of important ethylene-responsive crops such as mango could provide cultivars with extended postharvest life. Many of the important crops for smallholder farmers in LMICs are chilling sensitive, responding negatively to low but non-freezing temperatures. Their potential postharvest life is relatively short because they cannot be stored at temperatures below 10–12 °C. Molecular-genetic approaches to cold response in plants have identified many avenues for investigating and possibly preventing chilling injury. Some researchers have explored transcription factors that appear to be involved in plant responses to low temperature. For example, Yang et al. (2020) found that over-expression of the cold-response C-repeat binding transcription factors from longan fruit improved cold-tolerance of Arabidopsis. Future studies in LMICs could apply such basic research findings to improving the postharvest performance of many important and indigenous crops.

3. Adoption and scale up experiences with solar dryers

The scaling of technologies can be thought of as a series of processes to disseminate technologies and practices through a structured approach, with the goal of equitably increasing the impact of the technologies (Willis et al., 2016). Scaling of solar dryers can be challenging (Boroze et al., 2014), and research examining the efficiency of postharvest technologies has at times failed to capture the potential return on investment for the smallholder farmer (Kitinoja, 2013); a key metric for successful uptake.

Solar drying is competing with open air drying, a traditional method that is cost free. Therefore, researchers need to address the end-users' unique needs, available resources, and potential motivations for adopting a new drying approach. Preservation of fruits and vegetables is not always the overriding factor. For example, Howe (2019) determined that the improved product hygiene that solar dryers offer was a major consideration for smallholder farmers in Nepal. In Guinea, female farmers appreciated the reduction in labor the Chimney Solar Dryer provided, since they found it was much easier to rotate trays than to carry heavy drying tables in and out of a storage area on a daily basis.

An advantage of greenhouse solar dryers is that the units can be used for other purposes when not drying. The disadvantage is that the hot air rises, so these dryers can be inefficient. Active solar drying units that incorporate solar panels and fans provide access to a source of energy for alternative uses (charging cell phones, powering lights) or can be incorporated into evaporative cooling systems. With the cost of these components decreasing and accessibility increasing, active solar drying units could provide unique advantages. Research approaches should consider models for how solar drying units that are not multi-purpose can be more fully utilized throughout the year, rather than based on the seasonality of one commodity. This could be through cooperative ownership models, which lowers capital costs; but the success of a cooperatively owned unit can depend as much on social, organizational, and institutional issues as on the effectiveness of the technology itself (Glover et al., 2019*)*. Additionally, reflecting the complexity of agricultural and food systems, research teams should collaborate across fields, including physical sciences with social sciences, to improve scaling outcomes and sustainability.

Understanding local markets and local consumption patterns for dried horticulture products is essential. Depending on the cost of the solar drying unit being distributed, markets that offer a premium for high-quality, food-safe, dried fruits and vegetables could be crucial for positive return on investment. An analysis of the chimney solar dryer in Bangladesh found that the profitability of the dryer was dependent on the products being dried (Lewis et al., 2017). Even if a minimal local market exists, it is possible for farmers to export their dried goods to larger cities or other countries where the demand is higher; but this depends on the components of market access (market information, trading contacts, transportation systems) being available to the farmer. If dried fruits and vegetables are not part of the typical diets, researchers need to pair technologies with guidance on how the products can be incorporated into meals and are a source of nutrition.

In order to deliver an end-product to market, the scaling of solar dryers demands that technologies are bundled with effective storage methods, tools to determine dryness, and knowledge-strengthening on implementing the dry chain. All components of the dry chain are necessary to produce high quality products and meet users' outcome expectations. Farmers in LMICs often rely on open-air drying, but, particularly in humid climates, this practice is often ineffective (Bradford et al., 2018). Improperly dried products are often also stored in non-hermetic storage, allowing them to reabsorb moisture from the air. The lack of dry chain technology bundles leads to excess moisture content, which drives quality degradation and also increased levels of mycotoxin contamination (De Beuchat, 1983). Aflatoxin, a type of mycotoxin, is considered one of the most toxic natural substances in the world (Ortega-Beltran and Bandyopadhyay, 2021).

As with any technology, the broader enabling environment for uptake of a technology needs to be comprehensively understood. Agricultural systems are complex (Ostrom, 2009), and when components of those systems, such as policies, institutions, and financing, are aligned toward reducing postharvest losses, this would enhance an enabling environment to support technology adoption (Díaz-Bonilla et al., 2014).

4. Postharvest extension and new forms of information dissemination

In many LMICs, the agricultural extension services are underfunded and poorly coordinated (Davis et al., 2020). Specifically, postharvest extension programs and knowledge sharing systems are often lacking in LMICs (Kitinoja et al., 2011; Hewett, 2012). Postharvest training and service centers (PTSCs) are a proven effective extension approach in LMICs, with one program at the World Vegetable Center facility in Tanzania reaching over 22,000 growers in sub-Saharan Africa through a master trainer, train-the-trainer type program (Kitinoja and Barrett, 2015). These centers are strategically located hubs where producers and traders can receive training on proper postharvest practices, access cold storage and drying units, and purchase supplies.

Digital platforms for agricultural extension can be further leveraged to close knowledge gaps in postharvest management. Mobile phones, specifically, can be used as conduits for agricultural extension (FAO, 2017). Mobile phones are becoming more common in smallholder farming communities as noted in a recent survey of smallholder farmers in Kenya which found that 98% of the respondents owned a mobile phone (Krell et al., 2020). Videos, information, and market data provided through mobile phones can close knowledge gaps in postharvest management of horticultural crops and help farmers make informed decisions (Ali and Kumar, 2011). The effectiveness of the extension information provided in digital media is dependent on its quality and applicability to the end-user (Asasira et al., 2019); but initiatives such as Scientific Animation Without Borders (SAWBO) have noted improved practices when participants are shown animations in local languages of scientifically-based postharvest technologies or practices (Bello-Bravo et al., 2018). There are also locally-driven initiatives such as a smart-phone app being developed by R&D Innovative Solutions in Nepal that will provide commodity- specific maturity indices, ideal storage temperatures, and typical storage times.

Although mobile phones are becoming more and more ubiquitous, scaling or sharing postharvest practices or technologies through the platform needs to be done responsibly, as is the case with all innovations (Wigboldus and Leeuwis, 2013, McGuire et al., 2022). A household in a smallholder farming community may own a mobile phone, but access to the phone may be inequitable between men and women. Inequitable access to information could reinforce inequitable gender roles. An approach used by an organization in Northern Africa to avoid reinforcing inequities was to build a network consisting of women controlling the postharvest information digital platform while exchanging information with interconnected women farmers (El-Neshawy, 2018).

5. Conclusion

The world is facing a confluence of challenges impacting global food security, including climate change, increased input costs, and disruptions to supply chains due both to the pandemic and to the war in Ukraine (Rice et al., 2022). It is critical that postharvest losses and waste in agriculture are rapidly minimized at all levels (small-scale to industrial) and in all geographies to increase access to food. Major achievements have been made in postharvest management, but these advances have not been universally translated across global agricultural systems. To achieve a significant reduction, interdisciplinary expertise is critical in translating postharvest research into agricultural impact. Furthermore, experts in LMICs should play a central role in the development of technological solutions as in-country expertise can be critical in adapting and developing innovations to meet local constraints and opportunities.

This paper presents several innovations in postharvest management introduced in LMICs that have made impacts; however, more comprehensive and systemic impacts are required. For example, we focused on smallholder farmers, but medium-sized operations in LMICs, along with the formation of cooperatives or associations among smallholder farmers, can be conduits for adopting technologies with higher capital costs. Ultimately, greater cohesion and urgency is needed among policymakers, researchers, private industry, sociologists, agro-economists, public sector, local-leaders, among others, to meet this call to action to finally make significant reductions in postharvest losses in LMICs.

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Declaration of Competing Interest

All authors are in some capacity affiliated with the Feed the Future Innovation Lab for Horticulture at UC Davis, either as staff or as voluntary contributors. Furthermore, the authors have all had involvement in the development of several technologies highlighted in this review paper, including the DryCard, the Chimney Solar Dryer, and the Pallet Dryer.

Data Availability

No data was used for the research described in the article.

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