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Understanding barriers impeding the deployment of solar-powered cold storage technologies for post-harvest tomato losses reduction: Insights from small-scale farmers in Tanzania

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Postharvest food loss remains one of the major food security challenges in Sub-Saharan Africa (Africa). In Tanzania, it is estimated that about 50 percent of fresh tomatoes perish before reaching consumers due to poor post-harvest management. The lack of cold storage facilities is one of the leading causes of massive post-harvest tomato losses, negatively affecting farmers' livelihoods and the sector's economic contribution. For small-scale farmers in off-grid locations, the adoption of solar-powered cold storage technologies has been found to be a potential solution for reducing losses of highly perishable crops such as tomatoes. However, in Tanzania, the deployment of Solar-powered Cold Storage Technologies (SPCSTs) is limited, leaving the vast majority of rural small-scale farmers without access to such facilities. This study examined barriers impeding the deployment and uptake of Solar-powered Cold Storage Technologies in Tanzania. Farmers' perceptions about SPCSTs and constraints limiting their deployment were examined through semi-structured interviews and Focus Group Discussions (FGD) held between April and June 2021 in Kilolo district, Southeast Tanzania. Participants involved fifty-two ($n = 52$) small-scale tomato farmers and twenty-three ($n = 23$) experts and key informants from government and non-profit organizations that were purposively selected. The results show that the deployment of solar-powered cold storage technologies is constrained by limited awareness, high investment costs, low-paying capacity among farmers, and consumer preference for non-refrigerated foods. Addressing these barriers demand promoting policies and programs that attract and retain investment in cold storage technologies and improve SPCSTs affordability through flexible payment arrangements.

KEYWORDS

post-harvest, food loss, cold storage, tomato, Tanzania

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Introduction

Over the last few years, countries around the world have recorded high levels of food loss and waste. Despite efforts by governments and development agencies, food loss and waste remain serious food security problem in developing and more developed countries (FAO, 2019; Stathers et al., 2020). A recent report from the Food and Agriculture Organization (FAO) reveals that about 30 percent of global food is lost or wasted due to several factors, including poor post-harvest management (FAO, 2019). Within Africa, studies conclude that the causes of food loss are many and largely depend on the crop type (Affognon et al., 2015; Kitinoja, 2016; Betsy and Kitinoja, 2019; Spang et al., 2019). The African Postharvest Losses Information System (APHLIS) indicates that a large proportion of post-harvest losses in maize and rice value chains is largely caused by poor post-harvest management and limited access to efficient storage facilities (World Bank, 2011). For example, the World Food Program (WFP) reports that between 2012 and 2014, maize farmers in East and West African countries lost 40 percent of maize produced due to poor storage conditions [World Food Programme (WFP), 2014]. For perishable crops, especially fresh vegetables, post-harvest losses have been found to be driven by a lack of cold storage infrastructure and mishandling of fresh produce during harvesting, storage, and transportation (Dome and Prusty, 2017; Kasso and Bekele, 2018; Ridolfi et al., 2018). In several parts of Africa, the lack of cold storage facilities is responsible for up to 60 percent of post-harvest tomato losses experienced by most small-scale farmers (Wakholi et al., 2015; Sibomana et al., 2016; Ridolfi et al., 2018).

Like elsewhere in Africa, in Tanzania, limited access to cold storage facilities is one of the leading causes of the rapid spoilage of freshly harvested tomatoes. Studies indicate that post-harvest tomato losses could be between 20% to 50% due to inefficient storage practices employed by most small-scale farmers [United Republic of Tanzania (URT), 2016; FAO and URT, 2018; World Bank, 2018]. To navigate post-harvest storage challenges, farmers in Tanzania often resort to traditional storage practices, such as storing fresh vegetables under the shade and covering harvested produce with dry grasses while waiting for buyers (Groenbech et al., 2016; James and Zikankuba, 2017; MatchMaker, 2017). However, such practices are unreliable and inefficient, leading to rapid spoilage due to significant exposure of freshly harvested produce to heat and unhygienic conditions (Kitinoja, 2013; Stathers et al., 2013). Given the lack of proper storage infrastructure, small-scale farmers in Tanzania and several parts of Sub-Saharan Africa are often forced to sell their fresh tomatoes at low-profit margins, negatively affecting their incomes and livelihoods (Sibomana et al., 2016; James and Zikankuba, 2017; Ridolfi et al., 2018). As such, improving access to proper storage facilities is vital in helping farmers avoid food loss, increase their income, and boost the supply of nutritious foods to the continent's growing number of consumers (Delloite, 2015).

FIGURE 1
Solar-powered cold storage facility in Nigeria. Source: www.coldhubs.com.

In recent years, Solar-Powered Cold Storage Technologies (SPCSTs) have been widely recognized as an essential infrastructure to prevent post-harvest losses on fresh produce, particularly for small-scale farmers residing in off-grid locations [Abrahamse, 2019; Kitinoja et al., 2019; United Nations Industrial Development Organization (UNIDO) and The Renewable Energy and Energy Efficiency Partnership (REEEP), 2020]. SPCSTs are mobile or walk-in cold rooms (chambers) made from insulated materials and used shipping containers installed with solar panels on the roof (Figure 1). Energy from solar panels is then stored in batteries that feed the entire cold storage system, providing maximum cooling temperature to keep produce, including fruits, vegetables, and dairy products, fresh for more than three weeks [German Agency for International Cooperation (GIZ)., 2016; Betsy and Kitinoja, 2019]. For highly perishable produce such as tomatoes, SPCSTs offer multiple benefits, including extending produce shelf-life and quality while also preventing post-harvest losses hence higher incomes and profits (Kitinoja, 2014, 2019; Abrahamse, 2019). For example, in Nigeria, following the introduction of SPCSTs by ColdHubs, since 2018, more than 5,000 tons of vegetables and fruits have been saved from storage losses, leading to an income increase among small-scale farmers and traders accessing the facilities (Ikegwuonu, 2018; Betsy and Kitinoja, 2019). Depending on size and storage capacity, the unit cost for SPCSTs varies considerably.

While significant progress has been made in the research and development of SPCSTs for small-scale farmers in India and some parts of Southeast Asia, in Tanzania, and across Sub-Saharan Africa, very little has been researched about SPCSTs, and little is known about how these facilities can be deployed to small-scale farmers (Kitinoja, 2014; Puri, 2016; NCCD, 2015). Only a small fraction of small-scale farmers in Nigeria and, very recently, in Kenya and Rwanda are reported to have access to

SPCSTs, leaving the vast majority of small-scale farmers with no access to efficient storage facilities to avoid food loss and waste [German Agency for International Cooperation (GIZ)., 2016; United Nations Industrial Development Organization (UNIDO) and The Renewable Energy and Energy Efficiency Partnership (REEEP), 2020]. This lack of research about SPCSTs has constrained government interventions and the future adoption of SPCSTs in Tanzania. This study addresses this knowledge gap by examining barriers impeding the deployment of SPCSTs in Tanzania. Considering the lack of research about SPCSTs across Sub-Saharan Africa, Tanzania provides a good case study to understand underlying barriers impeding the deployment and adoption of SPCSTs in Africa and how governments and non-government actors can intervene to improve their access to farming communities. The aim of this study is, therefore, to understand farmers' perceptions regarding SPCSTs and existing barriers constraining the deployment of SPCSTs to farming communities. A better understanding of the barriers impeding the deployment and uptake of SPCTs will help governments, development agencies, and the private sector implement practical programs and interventions to improve access to clean cooling technologies for low-income African farmers.

Materials and methods

Study area

The study was conducted in the Kilolo district in the Iringa region in the South-Eastern part of Tanzania. The district is the largest producer and supplier of fresh tomatoes consumed in Dar es Salaam (Tanzania's commercial capital) and those exported to neighboring countries such as Kenya and Rwanda (Mwagike and Mdoe, 2015; World Bank, 2018). In the Kilolo district, various tomato varieties are grown however it was reported that Tanya, Roma, and hybrid tomato seed variety, locally known as Money-maker, were the most preferred tomato seeds by the majority of small-scale tomato farmers due to their high yield potential. For this study, data collection was carried out in Ilula Ward, located about 40 km east of the Iringa region. The ward, with a population of 26,415, has six villages, namely Ilula Itunda, Igunga, Madizini, Image, Ikokoto, and Masukanzi, in which tomato farming is a primary source of income [United Republic of Tanzania (URT), 2016]. In 2006, following the booming of the fresh tomato sector, Ilula ward was officially recognized as a township under Tanzania's Local Government Act No.

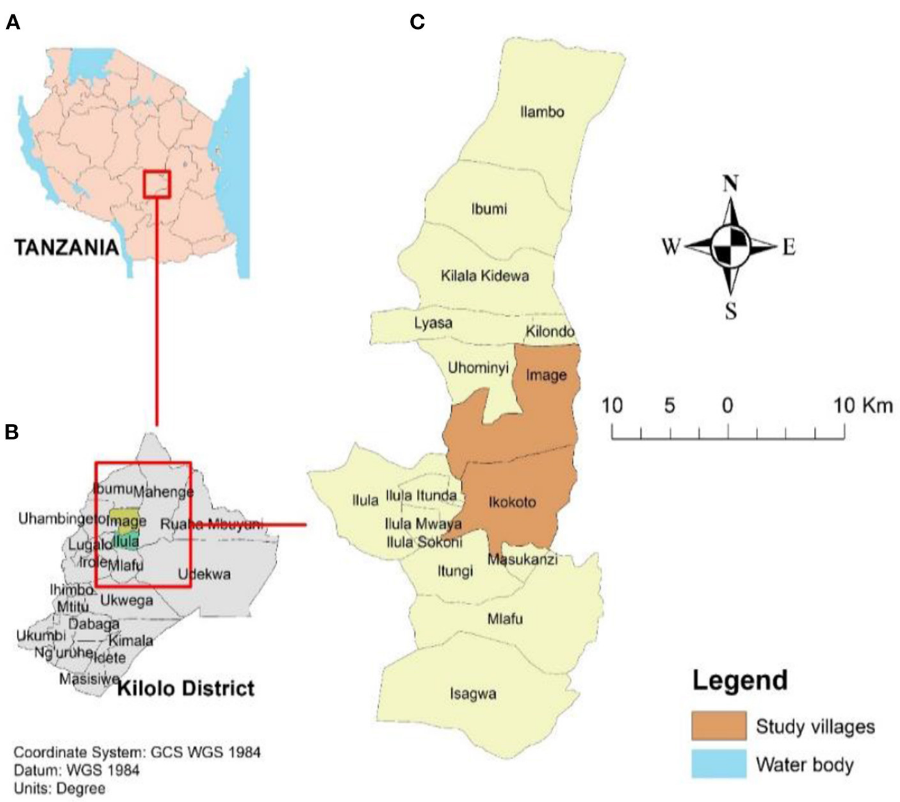

FIGURE 2
Map of study areas. **(A)** Map of Tanzania. **(B)** Map of Kilolo District. **(C)** Expanded Map of Kilolo District showing Study Villages.

8 of 1982 (Lazaro and Thomsen, 2013). This recognition led to the establishment of Ilula Tomato Trading Centre in 2010 (Saga, 2012). To understand postharvest management challenges confronting small-scale farmers, Image and Ikokoto villages (Figure 2) were purposively selected for this study. The two villages are the leading producers of tomatoes in the Kilolo district; hence are more appropriate and relevant to examine constraints affecting the deployment of Solar-Powered Cold Storage Technologies and explore farmers' perspectives about SPCSTs.

Study participants

Participants for the study were recruited using two sampling techniques (Purposive and Snowballing) to ensure a better representation of the study population. In purposive sampling, a researcher selects participants that represent the phenomenon being investigated (Neuman and Robson, 2009). Considering the focus of this study, criteria such as age, gender, land size (acres), and farmer's experience in postharvest (handling, storage, packaging) and in trading fresh tomatoes were used to select suitable participants for Interviews and Focus Group Discussions (FGDs). Using these criteria and with the guidance of leaders from farmers' associations in Ikokoto and Image villages, a simple random sampling strategy was employed to recruit participants from each village. From the list of farmers provided by leaders of farmers' associations, 40 farmers were purposely sampled for face-face interviews and Focus Groups Discussions (FGDs).

Data collection procedures

Primary data collection was conducted from March to June 2021. The first phase of primary data collection involved conducting semi-structured interviews with selected participants. Interviews were conducted in farmers' preferred locations, mostly on their farms and outside their residences. A semi-structured questionnaire was used to facilitate face-to-face interviews with selected farmers. The questionnaire covered a wide range of issues, including post-harvest management practices currently in use, drivers of post-harvest tomato losses, post-harvest handling (marketing and transportation of tomatoes), and farmers' access to storage facilities. A Swahili-translated consent form was given to each participant for signing before the interview to confirm their willingness to participate in the study. The interviews were audio-recorded to allow better analysis and post-interviews transcription. After the interviews, FGDs were held in both villages, with each FGD comprising six (6) male and female adult tomato farmers. The FGDs focused on understanding farmers' perceptions and their views regarding SPCSTs. Fifty-two ($n = 52$) farmers were interviewed (40 from face-to-face semi-structured interviews and 12 from FGDs).

The second phase of primary data collection involved semi-structured in-person and telephone interviews with experts and key informants knowledgeable about the research topic. Similar to interviews with farmers, purposive and snowballing techniques were also used to recruit experts and key informants. The majority of expert interviews were face-to-face, while only a few of the interviews were *via* telephone. Experts interviewed included senior officials from the government agencies such as the Ministry of Agriculture, representatives from solar companies with active business in Tanzania, donor community, and Non-Governmental Organizations (NGOs). Experts interviews were guided by a list of open-ended questions that focused on understanding experts' views on barriers to deploying SPCSTs and what and how such barriers can be addressed. Twenty-three ($n = 23$) experts and key informants were interviewed (Table 1).

Data processing and analysis

For data analysis, a thematic analytical approach was adopted to identify data generated from the interview transcripts. In thematic analysis, collected data from interviews are classified and analyzed based on patterns of issues (themes) reported or brought up by the interviewees (Braun and Clarke, 2006). This approach allows the researcher to identify and understand patterns of different meanings of data collected and therefore generate evidence based on participants' experiences and perspectives (Braun and Clarke, 2006; Percy et al., 2015). In this study, the first step of data analysis involved organization and reducing data collected in a manner that can be used to address research questions. First, all audio interview transcripts were listened several times to capture participants' responses and identify responses with similar patterns. The interview transcripts were later uploaded into QSR NVivo software for coding and analysis. The NVIVO software was used to organize a large set of data from the interview transcripts allowing easy generation of themes and sub-themes that respond to study research questions. Common themes reported by most participants were then put in order of significance and given unique codes that provide insights into important findings of the study. To increase the study's validity, direct quotes and major statements reported by participants are also presented to echo participants' voices, discuss and report the major findings of this study. Frequencies, percentages, and summaries of data analysis presented in the Tables and Figures were generated using 2016 Microsoft Excel software.

TABLE 1 List of experts and key informants interviewed ($n = 23$).

No	Experts category	Description	Number of participants	Reason for selection for interviews
1.	Government agencies	Ministry of Agriculture (Departments of Postharvest, Horticultural Sector Crop Development)	3	Oversee Policy regulation, enforcement, and coordinate Agriculture/Post-harvest programs in Tanzania
2.	Donors/International development agencies	USAID- Feed the Future, UN-Food, and Agriculture Organization (FAO), UN-World Food Programme (WFP), and HELVETAS- Swiss Agency for Development and Cooperation (SDC Tanzania Office)	4	Provides technical and financial support for horticulture/agriculture sector development programs in Tanzania
3.	NGOs/Civil society	Tanzania Horticulture Association (TAHA), MVIWATA, Agriculture Non-State Actors Forum (ANSAF), and FINTRAC	3	Engaged in horticulture sector development and post-harvest programs implementation, farmers training, and extension support.
4.	Research/academia	Sokoine University of Agriculture (SUA)., World Vegetable Centre (IVRDC), and International Institute of Tropical Agriculture (IITA)	5	Carries out research and development of post-harvest technologies for small-scale farmers in Tanzania
5.	Solar companies (private actors)	ENSOL, AG Energies, Mobisol, and Chloride SOLAR	4	Key Players in the Solar/Renewable Energy Sector, Promote and deploy solar technologies, services, and products in Tanzania.
6.	Extension officers	Village Extension Officer	1	Works directly with farmers/study population
7.	Tomato traders	Tomato Traders in Study Areas	3	Key non-state actor and part of the post-harvest tomato value chain
	Total		23	

Results and discussions

Farmers' socio-economic characteristics

The socio-economic characteristics of interviewed farmers are presented in Table 2. The results reveal that more than half (55%) of the participants were tomato farmers between the ages of 20 and 39, about 43% were between 40 and 59 years, and only a small portion (2.5%) were farmers of 60 years and above. The increased youth participation in tomato farming suggests that younger adults are becoming more involved in tomato production than older adults. This may also imply that older farmers who traditionally dominate small-scale farming in Tanzania fail to adapt and cope with production and post-harvest challenges associated with growing tomatoes. In Tanzania, factors such as low land-use requirements, higher chances for short-term profits, and horticulture sector growth potential have been identified as key drivers to increased youth engagement in horticultural farming (Groenbech et al., 2016; Ng'atigwa et al., 2020).

On a gender basis, the findings reveal that of the 40 farmers interviewed, most tomato producers were male farmers (85%). Though efforts were made to ensure equal representation of both female and male tomato farmers for the interviews. It was later discovered that the number of female tomato farmers in both villages was very low. Low female farmers' participation in tomato production was found to be attributed to increasing costs for tomato production and post-harvest activities. While in both villages, tomato production is a primary source of income, female tomato farmers were noted to be financially constrained and hence unable to fully participate and benefit from tomato farming. According to female farmers interviewed, production costs to control pests and diseases and postharvest activities like hiring casual laborers for picking, sorting, and transporting harvested tomatoes are often beyond their financial means, making it difficult for most female farmers to venture into tomato production. During FGD, it was reported that, on average, a farmer would need about 2 million Tanzanian shillings (TZS), equivalent to the United States of America (USA) $1,100, to be profitable at the end of the growing season. Due to high production costs, most female farmers end up becoming laborers on other people's farms, while others ventured into petty trading for survival. In Tanzania, due to poor farming conditions and a limited supply of production inputs, tomato yields per acre are among the lowest in Africa, which has serious implications for small-scale farmers' earnings per growing season (FAOSTAT, 2016; Mutayoba and Ngaruko, 2018; Mwatawala et al., 2019). The lack of financing for female small-scale tomato farmers, therefore, makes it difficult for most female farmers to engage in tomato production. Male

TABLE 2 Socio-demographic characteristics of participants ($n = 40$).

Category	Percent of farmers interviewed
Age	
20–39	55%
40–59	42.5%
60+	2.5%
Gender	
Male	85%
Female	15%
Education level	
No formal education	15%
Primary education	67.5%
Secondary education	17.5%
Other	0.0%
Years involved in tomato farming	
1–3 years	20%
3–7 years	7.5%
>7 years	72.5%
Land size (ownership)	
0–2 acres	67.5%
3–4 acres	22.5%
More than 4 acres	10.0%
Received training on postharvest management	
Yes	10%
No	90%

Source: Author's analysis.

FIGURE 3
Overpacked Fresh tomatoes in wooden boxes and bamboo baskets "Tenga" in image village (source: author).

dominance in tomato farming in this study suggests that male farmers have better access to the financial resources needed to prosper in tomato production. This observation was later confirmed during the FGD with farmers in Image village, where participants revealed that, unlike women, men were getting financial and logistical support from local tomato traders, commonly known as "middlemen," in exchange for harvested tomatoes at the end of the production season.

Further, due to gender biases, most middlemen were noted to be more comfortable investing their resources to male farmers than female tomato farmers. The results of this study provide vital evidence of how gender-based inequalities hamper rural women's valuable contribution to the horticultural sector in Tanzania. These findings are in line with the findings from studies by Mwatawala et al. (2019) and Ng'atigwa et al. (2020), which concluded that gender-based constraints paired with an increased cost of tomato production in Tanzania were major reasons for the significant decline of female farmers participation in tomato farming. Additionally, nearly all interviewed (90%, Table 1) were found to have never received post-harvest management training. The lack of training on post-harvest management was noted to contribute to unnecessary post-harvest tomato losses that could be avoided. For proper storage and to avoid physical damage, tomato farmers are advised to use appropriate packaging materials, such as plastic crates with a smooth surface inside, limiting any potential injury to harvested tomatoes (Sibomana et al., 2016; Njume et al., 2020). However, in the study villages, most farmers were observed to use inappropriate packaging facilities, mainly wooden crates, and bamboo baskets *"Tenga"* that were observed to be overpacked, causing significant damage and spoilage of tomatoes during storage, transportation, and delivery (Figure 3). Poor post-harvest management practices employed by most farmers were also noted to affect the quality of tomatoes delivered in wholesale and retail markets in Ilula and beyond. These findings underscore the need for deploying proper packing materials, particularly plastic crates, that should be paired with efficient storage facilities to help farmers minimize post-harvest tomato losses and ensure delivery of quality tomatoes to wholesale markets and consumers.

Post-harvest storage practices

Access to proper storage facilities was found to be a serious challenge. The vast majority of farmers were found to have no access to reliable and efficient storage facilities but instead rely on traditional post-harvest storage practices that fail to prevent storage losses. More than a third (35%, Figure 4) of farmers interviewed mentioned to have no specific method of preventing post-harvest tomato losses. This group of farmers employed "harvest and sell," a post-harvest strategy whereby freshly harvested tomatoes are delivered to buyers or wholesale markets immediately after harvest (Figure 4). A similar number of farmers (30%) reported to control post-harvest losses using chemicals whereby matured tomatoes are treated with a chemical product that delays tomato ripening before harvesting. According to these farmers, this strategy helps extend the shelf life of tomatoes as they search and wait for potential buyers to show up. Another group of farmers (17.5%) mentioned covering harvested tomatoes with dry grass and

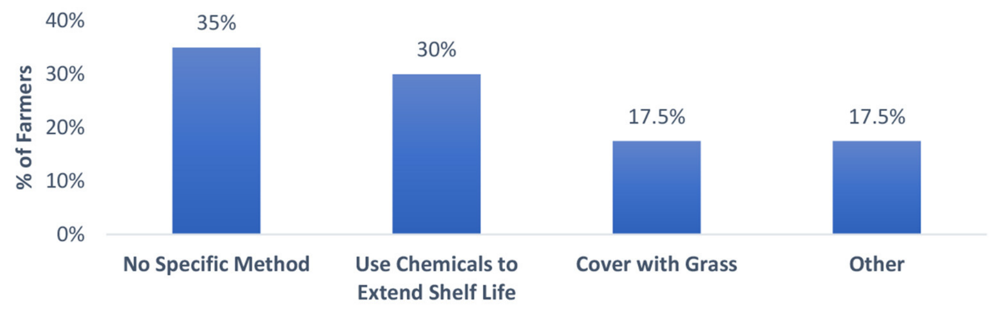

FIGURE 4
Storage practices employed by farmers. Source: author's analysis.

keeping freshly harvested tomatoes under the indoor shade for a few days while waiting and searching for clients. The last group of farmers (17.5%) reported that since they do not have a storage facility, they would normally delay harvesting tomatoes until they receive orders from buyers (Figure 4). As a result of heavy reliance on traditional storage practices, a large volume of fresh tomatoes was found to perish before being delivered to markets, particularly when farmers fail to secure clients (buyers) on time.

Since tomatoes have higher water content and are highly perishable, keeping them at an ideal temperature that limits moisture loss and extends shelf life is very important (Kitinoja and Thompson, 2010). Access to cold storage facilities is more efficient and an ideal infrastructure than traditional storage practices commonly practiced and used by the majority of small-scale tomato farmers in Tanzania and across Sub-Saharan Africa (Sibomana et al., 2016; Betsy and Kitinoja, 2019; Njume et al., 2020). For perishable food products such as tomatoes, cold storage facilities such as SPCSTs extend their shelf life and prevent rapid water loss, limiting spoilage caused by poor storage conditions [German Agency for International Cooperation (GIZ)., 2016; Abrahamse, 2019; Kitinoja et al., 2019]. Studies also show that in places such as Tanzania, where daily temperatures could be very high, the availability of cold storage facilities such as SPCSTs is critical to minimize fresh produce exposure to the sun, pathogens, and other weather-related challenges that could damage the fresh produce (Yadav et al., 2014; FAO and URT, 2018; World Bank, 2018). The need for SPCSTs and its significance to farmers were later raised during FGD as farmers reported losing a significant amount of tomatoes during heavy rains.

Illustrating this concern, one FGD participant in Ikokoto village had this remark:

> *"When it is the rainy season, tomato buyers from places like Dar es Salaam and other cities fail to come to collect tomatoes in Ilula. Unfortunately, this is when we have huge volumes of tomatoes; almost everywhere you go in this village, every farmer will have tomatoes. But, because we can't predict the rains and have no place to store them until the rains slow down, we end up wasting our tomatoes in large quantities"* (Male FGD Participant, Ikokoto village).

The lack of proper storage infrastructure and its impact on farmers' livelihoods was also mentioned by another tomato farmer who expressed his frustration stating, *"It is very sad to see almost all the tomatoes you have grown will have to be wasted because you have nowhere to keep them while you wait for a buyer"* (Male Farmer, Image Village).

High rates of post-harvest tomato losses linked to poor storage conditions is a major challenge confronting the vast majority of small-scale farmers in Tanzania and has been documented by several studies (FAO and URT, 2018; World Bank, 2018; Mwatawala et al., 2019). Improving access to cold storage facilities, therefore, helps farmers avoid unnecessary storage losses and sell their harvested produce at a convenient time, boosting farmers' income and supply of tomatoes to consumers (Mashindano et al., 2013; Kitinoja, 2014).

Barriers impeding deployment and uptake of solar-powered cold storage technologies

In this section of this paper, I discuss and highlight barriers hindering the deployment and uptake of solar-powered cold storage technologies in Tanzania. Barriers identified were extracted from consultation with experts and farmers through direct interviews and focus group discussions. During experts' interviews, the interview questions were centered on understanding their knowledge and views about SPCSTs and how they can be deployed to off-grid communities in Tanzania.

Limited knowledge and awareness of SPCSTs

Limited awareness about solar-powered cold storage technologies was found to be a major barrier to the future adoption of solar-powered cooling technologies in Tanzania. When asked about SPCSTs, an overwhelming majority of farmers in both villages mentioned to lack knowledge about SPCSTs, and only a few of interviewed farmers stated to be familiar with or had seen walk-in solar-powered cooling facilities. While during interviews, some farmers were observed to have household appliances powered by solar, and in some cases, some homes could be seen with solar panels on the roof. Even those with solar devices in their households reported to have never seen solar-powered cooling facilities. It was later noted that farmers that mentioned to have seen a walk-in solar-powered cooling facility were referring to a solar fridge (solar-refrigeration facility) that they happen to see outside their community.

Though most farmers lacked knowledge of solar-powered cold storage facilities, when asked about their view of the technology's potential, most were positive about SPCSTs and felt that the availability of solar-powered cold storage facilities could be an ideal solution to minimize the spoilage of tomatoes they experience during peak harvest seasons. In one discussion with FGD participants, farmers shared their optimism about SPCSTs stating that walk-in cold storage facilities powered by solar are what they need to prevent postharvest tomato losses during heavy rains. According to this group of farmers, access to SPCSTs in the village could also help them store and sell their tomatoes when prices for fresh tomatoes are profitable.

> *"Not Sure, but I think they may be good for a specific period, especially when the weather is bad and prices for tomatoes are low" (Male Farmer, Image village)*

According to experts, the lack of exposure to solar-powered cold storage technologies reported by farmers in the study communities is not surprising and was common across Tanzania. Experts claimed that limited consumer knowledge about cold storage technologies stems from the fact that solar-powered cold storage technologies are a new technology in Tanzania. As such, they are rare to find and not known to the public in Tanzania, which confirms the views expressed by farmers. Additionally, experts note that the lack of knowledge of SPCSTs is a barrier itself to future uptake because many people, including farmers, have barely seen them on markets or farms. Other experts believed limited farmers' knowledge about SPCSTs is also because most solar companies focus largely on advancing markets and promoting fast-moving solar products such as lighting appliances, mobile phone chargers, TVs, and others in high demand in Tanzania. As a result, very few solar companies have shown interest in promoting or venturing into deploying cold storage technologies to farmers and other market groups. This concern raised by several experts was also shared by another solar expert who argued:

> *"I think the problem is from us, the solar companies in Tanzania; no solar company has stepped out to promote or showcase solar-powered cold storage. If people in the hotel industry have cold rooms or heaters powered by electricity, that means there is a market for solar once such customers are aware of these technologies. I think farmers, small-scale food processors and exporters, and people in the hotel industry can afford them and will eventually adopt solar-powered cold storage technologies. So, awareness is a big problem from the consumers' side. In our case, our company has started to do a market assessment to understand how big the market is, and once that is done, we are targeting dairy suppliers and vegetable farmers*" (Interview with Solar Expert, Dar es Salaam, Tanzania)

Furthermore, according to experts, unlike smaller solar devices such as household appliances that are widely adopted in Tanzania, the market for cold storage technologies is different, and since they are also expensive to the end-users, the target market needs to be well informed on the benefits of having such facilities in their business operations. Awareness-raising, in this case, is important because they are already perceived to be expensive, so prospective users may be hesitant and would not feel the need to have them unless educated on the benefits of adopting such technologies. Experts further emphasized that even for commercial farmers who may afford such technology, the lack of knowledge and awareness of the financial benefits of investing in a cold storage facility could affect their decision to invest in such facilities. From these findings, it is clear that inadequate consumer knowledge about cold storage technologies powered by solar poses a significant barrier to the future uptake of SPCSTs in Tanzania, particularly in farming communities where such technologies are needed. The study results demonstrate the urgent need to raise awareness, promote and educate prospective users about the economic benefits of using solar-powered cold storage technologies. Before deployment, increased public awareness and consumer education about SPCSTs will be critical toward increasing demand and uptake for such technologies to different market segments besides farmers.

High investment costs

Discussions with experts revealed that the high investment cost for deploying SPCSTs was a serious barrier to the future adoption of SPCSTs in Tanzania. According to solar experts interviewed in this study, unlike other smaller size solar devices that have much fewer energy requirements, the investment for cold storage technologies is much higher because, to attain efficient cooling; the cold storage facility has more material needs such as more batteries, solar panels, and several other logistical or installation procedures that are costly. These system requirements are costly to solar service providers; hence only a few can venture into deploying SPCSTs. One expert noted that deploying a medium-size solar-powered cold storage facility would need an investment of about US $20,000 and above, which is a huge business investment given the current market size for solar-powered cooling technologies in Tanzania. The high cost of SPCSTs has serious implications for potential users of SPCSTs, especially small-scale farmers whose earnings and income are low hence limiting their ability and financial capacity to adopt SPCSTs.

> *"We were thinking of entering the market of cold storage service, but the initial cost for solar panels, batteries other materials became a problem. For a just single cold room facility, it was going to cost more than the USA $20,000 in capital investment which is a lot. One thing that we realized to be profitable in solar solar-powered storage technologies, you need a low energy consumption system in terms of solar batteries and panels"* (Interview with Senior Solar Expert, Dar es Salaam, Tanzania)

The study also noted that high installation and deployment costs concerns raised by solar experts are also worsened by other market challenges, including low purchasing power from potential users and limited financing on renewable energy projects for local solar service providers. Solar experts consulted on this matter stated that most solar products on the market are purchased through credits or facility loans where solar customers pay a small initial deposit to acquire the devices, and further payment is made in smaller installments for a certain period. In Tanzania and several parts of Africa, *Credit Payments* and *Pay as You Go* are popular payment arrangements practiced by most solar service providers. Despite the success of these payment arrangements in Africa, experts warned that such payment arrangements may not work for SPCSTs. According to experts, cold storage technologies powered by solar are meant to be used for commercial operations and, therefore, can only be profitable if there is a big market for such facilities, something that many experts believe is currently missing in Tanzania. Experts claimed that a large market share for SPCSTs would minimize costs for installation and deployment and after-sale services that are very common when deploying large-scale solar technologies.

> *"At the moment, there is an option to use solar refrigerators that are more affordable than a cold storage facility. But for cold storage, you need to have enough clients, such as big hotels or large farmer associations, to be profitable. These kinds of clients may need cold storage for cooling huge volumes of food products. For now, the market is still very, very small"* (Interview with Solar Expert, Dar es Salaam, Tanzania)

Conversations with solar experts also revealed that local solar firms lack sufficient capital because they have no access to private financing hence unable to embark on deploying large-scale solar technologies such as SPCSTs that demand more capital upfront. According to experts, despite the government of Tanzania efforts to attract foreign investment in solar technologies with policies such as tax incentives for local and foreign solar firms and removing import duties for most solar materials (e.g., solar panels, batteries, etc.), more needs to be done. Limited government commitment to renewable energy programs has been reported to affect the growth of private financing for local solar firms limiting their ability to take on large-scale solar projects that require much more capital (Garcia et al., 2017). Studies also show that in several parts of Africa, insufficient foreign direct investment in solar energy projects remains one of the major obstacles to market growth and deployment of large-scale solar technologies, including cold storage facilities [Ulsrud et al., 2018; German Agency for International Cooperation (GIZ) and International Renewable Energy Agency (IRENA), 2020].

Affordability concerns

Though most farmers were positive about SPCSTs, however, during FGDs, the issue of cost was frequently mentioned as a serious constraint for farmers' ability to adopt and use solar-powered cold storage technologies when such facilities are deployed to their community. Most farmers believed cold storage facilities powered by solar would be very costly and beyond their financial means despite the benefits. Citing past experiences with solar technologies, some FGD participants shared stories of how they failed to pay on time for solar devices they acquired through loans from local service providers. According to these participants, though devices, such as solar lamps, were less expensive and issued on credit, they still could not afford and pay on time. Since most of their peers lack steady and regular income, acquiring or paying for SPCSTs either individually or as a group may be difficult, and most of their peers may not afford it.

> *"Our way of earning income is we sell tomatoes and get money, once we have the money is when we pay for expenses like transportation and Vibarua (tomato pickers). So, I can't pay for storage before selling my tomatoes, and sometimes there are market delays as we always wait for people who can buy the tomatoes before we harvest them" (FGD participant, Image village).*

Experts also concurred with the affordability concern raised by farmers. According to experts, most solar products, including cold storage systems, are unaffordable for regular consumers in Tanzania. An Expert from Tanzania Renewable Energy Association (TAREA) shared his view on the fear of cost raised by farmers, stating: *"In solar systems, the most expensive item is an energy storage system, which is the BATTERY, and to have an efficient cooling system, you need several batteries to store energy that will offer long-term cooling for your products, which is expensive."*

However, another expert from an established solar company believed there is a solution for farmers. According to this expert, a good business model that matches t needs and what consumers can afford can tackle the affordability challenge. This expert believed that putting in place appropriate payment plans can encourage many low-income users to adopt solar products they perceive to be very expensive.

> *"YES, affordability is and will continue to be a challenge in the solar business because the upfront cost for solar products is often very high. But there are financing arrangements such as "PAY AS YOU GO" that have been used in the solar business and seem to be profitable and working well in Tanzania. These kinds of payment plans have been a success and contributed to the massive adoption of solar products in Tanzania. This is why, today, if you visit villages in Tanzania, you will find people using solar products in their homes for household use or commercial use" (Interview with Solar Expert, Dar es Salaam).*

Despite the fear of cost expressed by farmers, the study shows that with regular consumer education on the financial benefits of why using SPCSTs increases profit margins, farmers would be convinced to invest their financial resources in SPCSTs they perceive to be unaffordable. This should be paired with appropriate financing arrangements that make it easier for low-income users to afford and adopt SPCSTs.

Socio-cultural barriers

The social-cultural settings and market conditions in Tanzania were also found to be a potential constrain to the future uptake of solar-powered cold storage technologies in Tanzania. According to experts and farmers, consumer preference for fresh tomatoes (non-refrigerated vegetables) could be a serious obstacle to the wider uptake of cold storage in Tanzania. Experts claimed that while the availability of SPCSTs will be financially beneficial to farmers and traders, helping them prevent postharvest tomato losses, however, such benefit could be of less significance to buyers and consumers who prefer fresh tomatoes to refrigerated vegetables. Before deployment, technology developers should explore how tomato consumers would react to refrigerated vegetables that are less popular to locals in Tanzania, argued one expert from the World Vegetable Centre (AVRDC) Office in Arusha, Tanzania. For many experts, the market response to chilled tomatoes from cold storage facilities is something that needs to be seriously examined before deploying SPCSTs to wholesale markets and farming communities. On a similar note, another expert from Sokoine University of Agriculture (SUA) mentioned that "the market for tomatoes is still dominated by fresh tomatoes, which is more appealing to the consumers in Tanzania. As such, consumers may be reluctant to buy chilled tomatoes, which may discourage traders, farmers, and other potential users from using SPCSTs because such decision may affect their business. Echoing this concern, this expert had this remark.

> *"In the Tanzanian setting, how many Tanzanian consumers would buy a chilled tomato? That means getting the buyers or consumers to buy chilled tomatoes; you need to change consumers' mindset regarding chilled tomatoes before introducing cold storage facilities. Another challenge would be the cold chain infrastructure needed; as you know, if you keep tomatoes refrigerated, you need to keep the tomatoes refrigerated until it gets to the end-user or consumer. Once you keep the tomatoes chilled, you need to sell them chilled. If you sell them fresh once they were chilled, chances are they will spoil" (Interview with Expert, Dar es Salaam).*

Similar to experts, farmers were also worried about how their clients and regular buyers would react to chilled tomatoes from SPCSTs. During FGDs, farmers in both villages stated that distant buyers who are their major clients may be unwilling to buy chilled tomatoes because of a cultural preference for freshly harvested tomatoes.

> *"Distant buyers from Dar es Salaam, Tanga, or Dodoma sometimes opt to come straight to the farm and pick the tomatoes they want; usually, they want you to harvest those that are in the "green stage" so that they don't spoil during transportation. These kinds of buyers will not buy tomatoes that have been stored in cold storage facility" (Male FGD participant, Image village).*

In Tanzania, due to a strong cultural preference for fresh fruits and vegetables, the majority of consumers tend to be reluctant and unwilling to purchase processed foods including dried, chilled, or frozen food products. Studies have suggested that the negative perception of processed foods could be attributed to a lack of exposure to quality processed foods, pricing concerns, underdevelopment of food processing industries, and cultural reasons (Mmari et al., 2015; Alphonce et al., 2020; Chacha and Laswai, 2020). This means that proper education and consumer sensitization will be needed to address public concerns over chilled and other forms of processed tomatoes. This finding regarding consumer preferences for fresh tomatoes over chilled tomatoes underscores the critical need to incorporate and consider social-cultural aspects when designing and implementing solar energy projects. It highlights other important factors that need to be examined and prioritized before deploying SPCSTs in Tanzania. This is important because, traditionally, the deployment of solar technologies tends to largely focus on assessing technical and logistical challenges while the socio-cultural settings of the target population are often overlooked (Bauner et al., 2012; Ulsrud et al., 2018).

Discussion

The study results show that in both study communities, farmers experience massive post-harvest tomato losses due to poor storage conditions. Amid a lack of proper storage facilities, the vast majority of farmers employ traditional storage practices; however, most of these practices are inefficient; hence farmers continue to experience postharvest tomato losses. These findings are consistent with the results from previous studies (James and Zikankuba, 2017; FAO and URT, 2018; World Bank, 2018) that revealed that the lack of cold storage facilities near production areas intensifies the post-harvest food loss problem in the fresh tomato value chain in Tanzania. For example, recent studies by FAO and URT (2018) and World Bank (2018) conclude that poor storage conditions were responsible significant volume of post-harvest tomato losses that most small-scale farmers experience in Tanzania. It can therefore be argued that deploying cold storage facilities to these farming communities could substantially reduce post-harvest tomato losses that farmers experience regularly. More importantly, since the vast majority of farmers in the study villages and across Tanzania reside in rural areas where access to electricity is limited, solar-powered cold storage technologies will be more appropriate to prevent unnecessary losses of freshly harvested tomatoes. On the other hand, the study found that several barriers impede the deployment of solar-powered cold storage technologies in off-grid farming communities in Tanzania. Specifically, limited knowledge and awareness about SPCSTs, high upfront investment costs, affordability concerns, and socio-cultural market constraints were found to be major barriers constraining the deployment of SPCSTs in Tanzania. Limited awareness of solar-powered cold storage technologies was attributed to the low development of solar-powered cooling technologies in Tanzania. The study findings that low consumer knowledge of SPCSTs could be due to the fact that solar-powered cold storage technologies are emerging technologies not only in Tanzania but across Africa; hence the vast majority of consumers are unaware of such technologies. Despite limited knowledge about SPCSTs, the study shows that most farmers interviewed were positive about SPCSTs and believed the availability of such facilities could be an ideal solution to prevent unnecessary post-harvest tomato losses and spoilage they experience. This suggests that with proper market sensitization and regular consumer education programs on the financial, health, and environmental benefits of using SPCSTs, such technologies would be widely accepted and adopted by farming communities vulnerable to food loss and waste.

The importance of consumer education for solar technologies such as SPCSTs has been widely emphasized by several other studies about solar energy (Power for All, 2017; Global Off-Grid Lighting Association (GOGLA) and Altai Consulting, 2018). Evidence from these studies indicates that since several factors may hinder or influence adoption decisions, consumer education serves as a tool to empower end-users and address their concerns about the viability of solar technologies in their lives (Scott, 2017). For example, a study by Global Off-Grid Lighting Association (GOGLA) and Altai Consulting (2018) observed that despite the financial constraints, low-income consumers in East and Central Africa were more convinced to invest their cash in solar devices after being educated, exposed, and informed about the many benefits of using such devices. For Tanzania, investment in consumer education is critical because current policy and program interventions have been directed toward advancing the adoption of home solar energy systems mainly for household appliances (e.g., lighting devices, radio, TV, etc.) while very little attention has been given on cooling technologies (Garcia et al., 2017; Kitinoja, 2019). The lack of visibility and public knowledge about solar-powered cold storage technologies implies that any future deployment efforts for SPCSTs must prioritize consumer education and increase public awareness about SPCSTs. The results in this study corroborate with the findings of the most recent studies about solar-powered cooling technologies in Africa [Abrahamse, 2019; United Nations Industrial Development Organization (UNIDO) and The Renewable Energy and Energy Efficiency Partnership (REEEP), 2020] that also call for massive public education and awareness-raising campaigns for solar-powered cold storage technologies in the region.

The findings in the study also show that given the high capital costs, the vast majority of local solar companies in Tanzania are unable to supply and deploy solar-powered cold storage technologies because they lack sufficient capital. The lack of capital to deploy SPCSTs was found to be linked to limited access to external private capital and donor support for SPCSTs. Currently, in Tanzania, and based on the feedback from interviews with solar experts, no solar company is involved in deploying solar-powered cooling technologies. When asked, solar experts cited insufficient capital as a major reason for their low interest in venturing into solar-powered cooling technologies. This suggests that deliberate efforts from both the government and private sector are needed to improve access to private financing and donor support for solar-powered cooling technologies in Tanzania. Available studies show that while financing for renewable energy has steadily increased globally, countries in Africa have not adequately benefited from the global financial boom in the renewable energy sector (African Development Bank Group (ADB), 2019; Quansah and Ramdé, 2011; International Renewable Energy Agency, 2014). Likewise, the reduction of donor funding in renewable energy programs that have played a very crucial role in lowering installation and customer acquisition costs of solar energy technologies in Sub-Saharan Africa (SSA) has affected several key players in SSA countries, including Tanzania (Harrison and Adams, 2017; Power for All, 2017). For example, in Tanzania, since 2013, programs such as the Lighting Africa Program of the World Bank and International Finance Cooperation (IFC) have been very instrumental in advancing market development and off-grid installations of solar energy technologies in low-income communities (Sergi et al., 2018; Aly et al., 2019). However, due to a decrease in donor funding to pave the way for private-led market growth for renewable energy programs, the majority of local solar firms in Tanzania are failing to venture into large-scale solar projects such as SPCSTs. This financial barrier identified in this study has also been reported by previous studies [Abrahamse, 2019; United Nations Industrial Development Organization (UNIDO) and The Renewable Energy and Energy Efficiency Partnership (REEEP), 2020], which also conclude that high-upfront costs remain a serious challenge for the deployment of solar-powered cooling technologies in Africa [Abrahamse, 2019; United Nations Industrial Development Organization (UNIDO) and The Renewable Energy and Energy Efficiency Partnership (REEEP), 2020]. The results in this study underscore the critical importance of increasing access to financial resources and private investment for African-based solar firms to enhance their capacity to deploy and supply large-scale solar projects that are capital intensive

Findings in this study also reveal that most small-scale tomato farmers may not afford to use or acquire SPCSTS because they lack regular and steady income. Addressing this financial barrier demands developing locally appropriate and flexible financing arrangements as well as policy incentives that will reduce installation and acquisition costs for prospective end-users of SPCSTs. Though the study notes that popular payment arrangements such as *Pay As You Go* may not work for SPCSTs, however, recent developments of SPCSTs and progress made by SPCSTs start-ups like Cold Hubs in Nigeria, Solar Freeze in Kenya and Inspira Farms in Rwanda offer solid evidence that innovative financing arrangements can address the financial barriers facing prospective users of SPCSTs in low-income markets (Abrahamse, 2019; Betsy and Kitinoja, 2019). Likewise, since SPCSTs are new and emerging in Tanzania and across Africa, it can be argued that prior to deployment, a comprehensive market assessment for SPCSTs will be necessary to investigate market conditions and establish effective financing arrangements that match consumers' financial and social-cultural settings.

Even though financial barriers and limited awareness are undeniably critical challenges to the deployment of solar-powered cold-storage technologies in Tanzania, the study also demonstrates that consumer preference for fresh foods compared to refrigerated foods could also negatively affect SPCSTs acceptance in Tanzania. Unlike previous studies, about solar-powered cooling technologies (Kitinoja, 2014, 2019; Abrahamse, 2019; United Nations Industrial Development Organization (UNIDO) and The Renewable Energy and Energy Efficiency Partnership (REEEP), 2020), where much more emphasis was on assessing the technical and commercial viability of SPCSTs in Africa. Findings in this study also demonstrate that failing to recognize socio-cultural aspects before deployment may potentially affect the uptake of SPCSTs in Tanzania and across Africa, where a large proportion of consumers are not accustomed to chilled and frozen foods. This indicates that understanding and addressing perceived socio-cultural constraints before the deployment of SPCSTs is as important as tackling technical and financial barriers, especially in new markets such as Tanzania.

Conclusion

The findings of this study reveal that the deployment of solar-powered cold storage technologies is constrained by several factors, including low technology awareness, high investment costs, and low paying capacity among prospective users of SPCSTs. Despite these barriers, farmers interviewed were very positive about SPCSTs potential to prevent storage losses they experience regularly. Overcoming barriers identified demands enforcement of policy incentives that will attract investment for SPCSTs, consumer education, and developing flexible payment plans that match farmers' financial and social-economic status. For SPCTs to be affordable, their acquisition costs need to be subsidized to match the financial profiles of small-scale tomato farmers who suffer the most from a lack of cold storage. Thus, promoting policies such as removing import duties for solar technology materials specifically for SPCSTs will be vital for opening the market and attracting more solar service providers to venture into supplying and deploying SPCSTs in Tanzania. Similarly, consumer education on the environmental and financial benefits of using SPCSTs would also address the concern over consumer preference for fresh tomatoes that may negatively affect SPCSTs acceptance in communities that are not accustomed to refrigerated food products. Finally, given the lack of research about SPCSTs in Tanzania and across Africa, this study also makes an important policy and scholarly contribution. The assessment of these barriers provides valuable insights for decision-makers engaged in postharvest agriculture and renewable energy programs in Africa on a number of issues that need to be considered to ensure the successful deployment and uptake of solar-powered cold storage technologies that are currently unknown and inaccessible to many in Tanzania and across Africa.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This study involved interactions with human participants therefore research ethics clearances were obtained through relevant authorities in Canada and Tanzania. In Canada, ethics approval was reviewed and approved by Queen's University's General Research Ethics Board (GREB). And, in Tanzania, ethics approval and clearance were reviewed and approved by the Commission for Science and Technology (COSTECH). To ensure participants' privacy and confidentiality, an informed consent sheet outlining the purpose of the study was given to all participants of this research and written informed consent to participate in this study was obtained from all participants prior to the start of the interviews and Focus Group Discussion (FGD).

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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