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Nature-inspired solutions for food loss prevention: exploring smallholder farmers' willingness to adopt solar-powered cold storage

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At COP27, the United Nations made a clarion call for addressing food system inefficiencies, specifically highlighting the need for innovative research into sustainable cold storage technologies for postharvest loss reduction. Consistent with this call, we explore smallholder farmers' willingness to adopt off-grid solar-powered cold storage in Ghana using surveys with small scale vegetable growers ($n = 1{,}001$). We put in conversation with one another multiple adoption theories—economic constraints, innovation diffusion, adopter perception—in framing our analysis, enabling us to test a broad list of theoretically relevant variables. Descriptive analysis show more than two-thirds of smallholder farmers were willing to adopt solar-powered cold storage for food loss reduction. Findings from logistic regression analysis reveal farmers' willingness to adopt solar-powered cold storage mirrors a blend of drivers that cut across theoretical fronts including economic constraints (i.e., wealth and profit); innovation diffusion factors including training on postharvest management and timely access to extension services; perception variables (i.e., the extent to which farmers view food loss as a major issue and prior exposure and use of similar agricultural innovations); and contextual agricultural conditions (i.e., farm size and yield). Our findings demonstrate the complexity of technology adoption in smallholder agricultural systems and the need for agricultural policy on adoption to move beyond the predominant emphasis on economic factors to include attention to adopter perception and contextual factors. It is critical for agricultural policy to address these multifaceted drivers simultaneously to enhance the uptake of sustainable modern agricultural solutions like solar-powered coolers.

KEYWORDS

nature-inspired solutions, solar-powered cold storage, adoption, smallholder farmers, food loss

Introduction

At COP27, the United Nations (UN) recognized addressing food system inefficiencies as pivotal to achieving the Sustainable Development Goals, particularly goals on hunger and climate change. This clarion call to address food loss and other food system inefficiencies stems from the fact that a third of food produced globally is lost postharvest (World Resources Institute, 2021), while food loss is responsible for nearly 8% of total greenhouse gas emissions (GHGs) (UNEP, 2022). The *Sustainable Food Cold Chains* initiative is a key outcome of COP27, which targets increasing investment in sustainable cold chain technologies globally to address food loss at various stages of the agricultural production chain. To catalyze this agenda, the UN particularly called for collaborative research to co-produce innovative and low-cost postharvest management technologies for farmers and other food system actors in off-grid environments.

Innovative low-cost PHL technologies are crucial in disproportionately food insecure regions like sub-Saharan Africa (SSA), where about half of the population are undernourished (FAO, 2024), yet 40% of the annual yield is lost postharvest (Rutten and Mhlanga, 2015; Totobesola et al., 2022). The rate of food loss is higher for vegetables, with evidence showing farmers lose about 50% of the annual harvest, with women farmers bearing the brunt of these losses (FAO, 2020; Totobesola et al., 2022). In SSA, the lack of PHL reduction technologies is a key determinant of the price of perishables (Melomey et al., 2022; Sugri et al., 2021). In the peak harvesting season, farmers are compelled to accept low prices or risk losing the entire harvest due to the lack of affordable cold chain technologies (Addo et al., 2015; Attoh et al., 2014; Osei et al., 2022; Sugri et al., 2021; Tsiboe et al., 2019). Farmers are even reported to be committing suicide because of their inability to repay loans due to heavy postharvest losses (Attoh et al., 2014; Britwum, 2013).

Nature-inspired solutions such as solar-powered cooling offer a timely opportunity to make cold chain technologies available for food loss prevention in resource-poor off-grid environments across the world (Amjad et al., 2023; Olosunde et al., 2016). In tropical environments with abundant insolation, solar-powered cooling has emerged as an opportunity to enhance cold chain services to smallholder farmers, especially those cultivating perishables such as fruits and vegetables. Green cooling is considered a breakthrough technology for several reasons. Apart from the potential to serve farmers in remote off-grid locations, solar-based cold storage technologies are relatively environmentally friendly due to their greenhouse gas emission avoidance potential (Amjad et al., 2023). Despite the recent recognition of this potential of solar-powered cold storage solutions in SSA (Olosunde et al., 2016), very little is known about farmers' willingness to invest in these technologies. Understanding the factors that shape willingness to adopt is necessary for identifying policy entry points for targeting to ensure traction and adoption.

Drawing on data from a survey of smallholder vegetable farmers in Ghana, where solar-based cold storage technologies have been actively promoted, we examine the determinants of farmers' willingness to invest in these technologies for postharvest management. This line of research is crucial as development practitioners and researchers aim to scale sustainable and low-cost solar-powered postharvest management techniques in the Global South. Our findings will be timely in identifying key drawbacks and entry points for improved targeting in future scaling efforts.

Theoretical background

Social scientists have long theorized technology adoption seeking to explain why some farmers are willing to adopt new technologies while others are not. The theoretical literature on adoption tends to fall into 3 paradigms: the innovation-diffusion, the economic constraints, and the adopter-perception (Adesina and Zinnah, 1993; Ruzzante et al., 2021). In the rest of the section, we discuss these theoretical strands and highlight how they shaped the choice of relevant variables for this analysis.

The innovation-diffusion model

The innovation-diffusion paradigm is largely based on Rogers' seminal work, and is structured around the foundational assumption that specific attributes of an innovation are the key drivers of its spread. Rogers (1993) identified five adopter categories: innovators, early adopters, early majority, late majority, and laggards. Framing these categories of adopters sequentially in order of likelihood to adopt, Rogers argues that knowledge of specific attributes of the technology including its relative advantage, compatibility, complexity, trialability, and observability is crucial in shaping adoption.

Relative advantage refers to the degree of perception that the newer technology is/may be better than existing ones. Rogers contend that farmers are slower to adopt preventative technologies because relative advantages are based on a perception of superiority. Since prevention is based on a non-event, it is difficult for consumers to perceive the relative advantage of a non-event. Thus, farmers with prior experience of food loss and adequate access to information or knowledge of the effectiveness of given technologies may be more willing to adopt it (Ainembabazi and Mugisha, 2014; Mohammed et al., 2023). Compatibility is based on the degree to which an innovation is perceived as consistent with existing values, past experiences, and the needs of potential adopters. Some groups may be averse to trying new innovations, if the technology or its use contradicts the values of the group, a situation Rogers framed as *innovation negativism*. For instance, smallholder farmers with a history of adopting similar sustainable agricultural practices/innovations may be more likely to try new eco-friendly technologies in other farm operations/domains such as postharvest management. Complexity refers to the degree to which an innovation is difficult to understand or use. According to Rogers (1995), the more complex a technology is, the slower people will adopt it. For example, with home computers generally, the first to adopt were those with highly technical backgrounds, such as engineers, partly because of their technical ability. Trialability refers to the degree to which an innovation may be experimented with. Innovations that can be experimented with before adoption are more likely to be adopted faster than those that lack trial/demonstration opportunities. Finally, observability underscores the degree to which the innovation is visible to the consumers and the underlying assumption is that technologies that are more visible will have a higher degree of adoption than abstract technologies.

Rogers (1995) also highlights other variables that influence the rate of adoption, including the type of innovation decision, the nature of communication channels, the nature of the social system, and the extent of the change agent's promotion efforts. According to Rogers, the more people involved in an innovation decision, the slower the innovation decision. Communication channels also influence the diffusion of innovations. The general hypothesis is that interpersonal communication channels, such as radio or neighbor-neighbor communications, are associated with relatively lower rates of adoption, although there is some complexity to this. For example, mass media communication channels were better for less complex innovations, but personal contact such as extension services were found to be more important for technologies that were perceived as complex (Rogers, 1995). The channel of communication hypothesis as Rogers postulates, is supported by earlier work of Ryan and Gross (1943) which examined the diffusion of hybrid seed corn throughout the Midwest US from 1936 to1939. Salesmen were the first to diffuse the information, but as years went by, most people heard about the technology from their neighbors. In other words, while early adopters' decision to adopt was shaped by salesmen, neighbors influenced the adoption decisions of late adopters the most. In this sense, access to information through extension could be a broad key determinant of willingness to adopt solar cooling in the early stages (Adesina and Zinnah, 1993; Amrullah et al., 2023).

Economic constraints models

The economic constraints school emphasizes that resource endowments is the key determinant of adoption (Negatu and Parikh, 1999). This argument is based on the underlying assumption that farmers will aim to maximize profits hence their adoption decisions are likely to be primarily based on rational choice shaped by the ability to afford and cost-benefit considerations (Ruzzante et al., 2021). Consistent with this thinking, economic limitations including a lack of access to credit facilities, assets and capital can constrain adoption especially for technologies with significant upfront costs (Adesina and Zinnah, 1993). Havens and Flinn (1975) deployed this model to study the diffusion of Green Revolution technologies and found that new technologies tend to be adopted by those who control productive resources like land and capital, as well as those with adequate access to credit. Moreover, larger farmers—based on farm size, a proxy of economic capacity—are also able to take the risks of innovation because they tend to be ideal loan candidates (Havens and Flinn, 1975). These farmers may also have enough space to experiment with technologies that are space demanding.

Similarly, Yapa and Mayfield contend that non-adoption of technologies is not a passive action taken by farmers, as the innovation-diffusion paradigm would assume (Yapa and Mayfield, 1978). Rather, non-adoption is an active state that is determined by the prevailing economic conditions farmers operate within. In exploring non-adoption of agricultural technologies in the Karnataka State of India, Yapa and Mayfield (1978) agree that awareness and accurate information as emphasized in the innovation-diffusion paradigm are necessary conditions for adoption but cannot alone explain non-adoption. The most important factor to them is economic power as expressed in control over productive resources including land, credit, and inputs (Awotide et al., 2012; Sui and Gao, 2023).

The economic constraints paradigm, although foundational, is not the only economic model for theorizing adoption. Fadeyi et al. (2022) advanced a broader grouping of economic theories on adoption into what they call "Decision-Making Theories." Moving beyond adoption capacity, decision-making theories emphasize the role of anticipated economic returns as shaped by risk and profitability. Examples of these theories include Utility Maximization and Expected Utility (Karbo et al., 2024). Expected Utility theory assumes that adoption is determined by the perceived risk and uncertainty levels of a technology. In other words, a person is more likely to adopt a technology if the expected utility surpasses the utility from the current technology in use, by weighing their expected utility values. In contrast, utility maximization theory says that an individual will choose the technology that maximizes their utility (Karbo et al., 2024). Danso-Abbeam et al. (2019) demonstrated the value of utility in their work on the adoption of Zai technology in Ghana.

Adopter-perception paradigm

This model asserts that the perceived need to innovate and the perceived attributes of the innovations determine willingness to adopt. While mirroring some aspects of economic theory, such as perceived cost, risk and returns on investment, this model extends theoretical thinking on adoption to include potential adopters' perception of the degree of communicability and congruence of the technology (Kivlin and Fliegel, 1967; Liu and Liu, 2024). Since farmers perceive these factors differently, adoption decisions can differ. Adesina and Zinnah (1993) deployed these constructs in studying the adoption of modern mangrove rice varieties in Sierra Leone and argued that farm and farmer specific factors highlighted in the economic constraints and innovation-diffusion models, did not wholly explain the adoption decisions of modern mangrove rice varieties. Rather, perceptions of the technology's specific traits significantly shaped adoption behavior. Building off the argument that specific attributes of a technology drives willingness to adopt, Meijer et al. (2015) further emphasize how perception of such attributes is shaped by both extrinsic factors, such as the characteristics of the farmer and external environment, as well as intrinsic factors including communication and access to extension services.

Culture and contextual factors

Other scholars have emphasized the role of cultural and other contextual factors in shaping technology adoption (Ruzzante et al., 2021). While this body of literature is broad and loosely defined, underlying physical factors such as distance to the market, access to information, and geographical variables, like droughts and flooding have been emphasized (Adam et al., 2014; Flarian et al., 2018; Palis, 2006). Other than physical variables, sociocultural dynamics including gender and social networks have been identified as important determinants of willingness to adopt technologies. Larsen (2019) found that network effects through the spread of information and inputs can have a significant effect on adoption—in Tanzania, a farmer is 39 percentage points more likely to adopt a banana seed cultivation if there is at least one banana grower in the network. Studies on gender and adoption of agricultural technologies have rather shown mixed outcomes in sub-Saharan Africa—a situation that requires further research. For instance, while Gebre et al. (2019) report no significant gender gap in adoption of modern maize technologies in Ethiopia, a more recent analysis of modern technology adoption by Neway and Zegeye (2022) reveal a statistically significant gender gap in adoption, with female-headed households having lower likelihoods of adoption. Recent studies in other countries have reported a statistically significant gender gap in technology adoption (Mishra et al., 2020; Tufa et al., 2022). These mixed findings underscore the underlying role of varying sociocultural conditions in shaping gender outcomes and the need for more context-specific research on adoption in general. The explanations provided for gender differences further point to how sociocultural constructs like gender are intricately connected to economic and perception variables in shaping adoption decisions. Other contextual factors such as farm size and the broader agricultural policy environment, particularly policies on incentives have been highlighted as important (Adam et al., 2014).

Each of the above discussed theoretical paradigms cover a range of relevant factors that can potentially influence willingness to adopt agricultural technologies. While each paradigm projects a set of unique factors to be the most important to adoption, they are reinforcing when deployed together in understanding willingness to adopt solar-powered cold storage. Putting these isolated paradigms in conversation with one another, our theoretical framing reflects underlying economic conditions, adopter perception, information flow and contextual factors. Specifically, we hypothesize that economic factors including wealth/assets, access to credit etc. as well as adopter perception factors such as perceived burden of postharvest loss, perceived ability to handle food loss through personal strategies and information access dynamics, including access to timely extension services and postharvest loss training will be positively associated with adoption of solar-powered cold storage by smallholder farmers. The list of variables we included in our models for each theoretical front is not exhaustive of the number of factors reviewed here in this section. Based on the literature and experience working with smallholder farmers in the study context, in our data collection, we focused on those predictors that are congruent with contextual conditions.

Study context

The study was conducted in the Upper West Region of Ghana. The region is located within the northern savannah ecological zone of Ghana bordered to the north and west by Burkina Faso, and the Upper East and North East regions to the East and Savannah region to the South (see Figure 1). With a land area of about 18,476 km^2, the region is primarily underlain by savannah ochrosol and lithosol soil types known for their suitability and centrality to the production of cereals, legumes, vegetables, and pasture crops (Asiamah, 2008). The northern savannah ecological zone experiences a single maxima rainfall regime, which yields a single annual growing season from May to September (Asravor, 2018; Batung et al., 2021; Kansanga et al., 2019a,b,c). Agriculture is the primary livelihood among the 702,110 people in the region, practiced by up to 80% of households (Mohammed et al., 2023; Pienaah et al., 2024).

Smallholder farming is the dominant mode of agriculture with landholdings typically less than 2.5 hectares (Kansanga et al., 2018; Nyantakyi-Frimpong, 2019). While women dominate smallholder agriculture in the savannah ecological zone, particularly vegetable cultivation, they have weaker control over land and other productive resources (Kansanga et al., 2019a,b,c; Nyantakyi-Frimpong and Bezner Kerr, 2017; Vercillo, 2020). Under the patrilineal customary land tenure system of the region, men have automatic user rights to agricultural commons through inheritance from fathers, while women may only use unengaged portions of the family commons under the purview of their sons or husbands (Kansanga et al., 2018; Kuusaana and Eledi, 2015; Yaro, 2010). Since land is the most important collateral in accessing loans and agricultural subsidies, women's weaker control of land has a rippling effect on their access to other productive resources. Despite agriculture being the dominant livelihood in the Upper West, the region is one of the most food insecure in Ghana, with about 64% of the population being severely food insecure in the country, with about nine in every 10 people living on less than a dollar a day (Ghana Statistical Service, 2015).

Agriculture in the savannah ecological zone is primarily rain-fed and with climate variability, farmers are compelled to cultivate timely to avoid crop failure (Abdul-Razak and Kruse, 2017; Dapilah and Nielsen, 2019). With the limited growing window of between 4 and 5 months, some farmers have historically undertaken dry season vegetable gardening in valley floors by constructing hand-dug wells (Kansanga et al., 2023; Yiridomoh et al., 2020). Livestock rearing and shea processing are other key livelihood diversification strategies among households in the region (Nyantakyi-Frimpong et al., 2018). In recent decades, however, successive governments have amplified these efforts and promoted vegetable cultivation as an agricultural diversification to improve livelihoods. These policies include the recent one-village-one dam policy targeted at creating dug outs across communities to promote the cultivation of vegetables for domestic and international markets (Owusu and Obour, 2023). Commonly cultivated vegetables in the region include fruits vegetables comprising tomatoes, pepper, onions, and a collection of green leaves. Despite vegetable production gaining traction in the northern savannah of Ghana, postharvest storage technologies are limited (Sugri et al., 2021; Wongnaa et al., 2023).

Methods

Data collection

The study is based on a cross-sectional survey of smallholder vegetable farmers (n = 1,001). Data collection took place from June to August 2023. The survey was conducted primarily to assess vegetable production and food loss dynamics with emphasis on food loss rates, access to postharvest management services and willingness to adopt new technologies. The survey also included information on other relevant demographic, socioeconomic and agricultural related variables including gender, age, wealth, access

10.3389/fsufs.2025.1525148

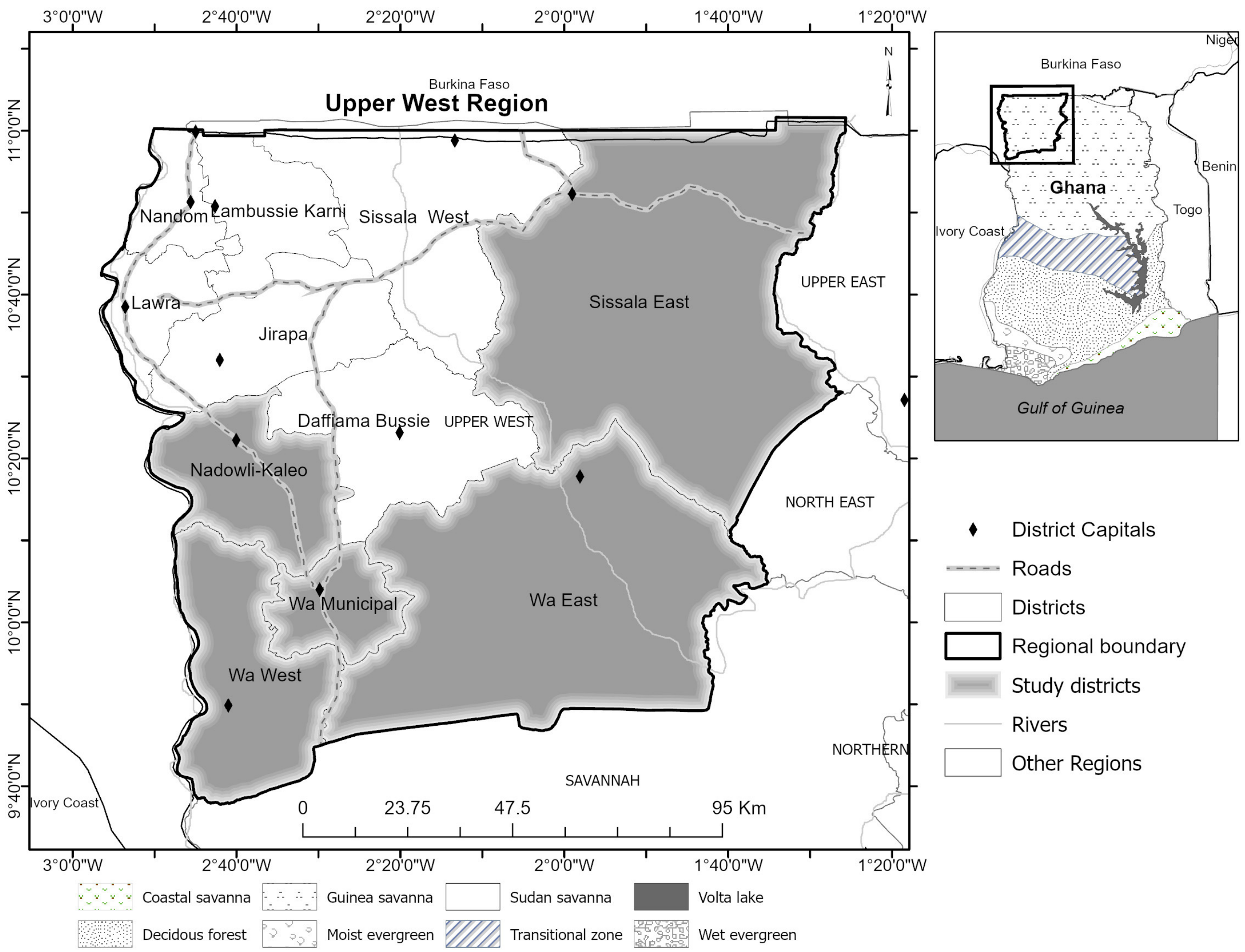

FIGURE 1
Map of study context.

to extension services, credit access, climate resilience and physical and mental wellbeing.

A multistage sampling technique was employed. First, a non-probability purposive sampling technique was used to select five study districts where vegetable production was dominant. Since vegetable cultivation is concentrated in specific communities in each district, major vegetable farming communities in each district were subsequently purposively selected using secondary information from the regional offices of the Ministry of Food and Agriculture and initial field visits. Using a list of vegetable farmers at the community level, we systematically sampled every third vegetable farmer to participate in the survey subject to participant availability at the time of survey administration until the desired sample was reached. Prior to administering surveys in each community, the research team made a community entry visit to seek the consent of local leaders and deliberate with farmers on a suitable date. Evening announcements were made by the community announcer a day before actual data collection to remind sampled participants about the survey the next day. Using the list of sampled farmers, the research team moved from house to house to administer the survey with the help of a community gatekeeper. Ethical clearance for the study was granted by the Non-Ethical Research Board of George Washington University.

Measures

The key dependent variable for this research is “willingness to adopt solar-powered cold storage for postharvest food loss reduction.” This variable was derived from a question asked to smallholder farmers to indicate if they were willing to adopt a solar powered cooling innovation for their postharvest management needs. We asked this question in the context of an ongoing pilot of solar-powered cooling by a consortium of partners in the middle and northern savannah of Ghana to address the lack of engineered solutions for postharvest loss. This question generated a binary measure on willingness to adopt (0 = no, 1 = yes).

Based on the review of theoretical literature on technology adoption, we included several relevant covariates that mirror farmer demographic characteristics, household economic capacity, access to agricultural services and farmer perception. In terms of demographic characteristics, we included the age and education of the farmer (0 = no education, 1 = primary school and 2 = secondary school and above). We also collected data on the number of years the farmer has been cultivating vegetables as a proxy for experience. Other relevant agricultural related variables included the vegetable type that constitutes the bulk of a farmer's production (0 = green leafy, 1 = fruit vegetables, 2 = marrow and cruciferous), and season of cultivation (0 = both wet and dry season, 1 = wet season only and 2 = dry season only). Consistent with the economic constraints model, we included several variables to mirror capacity to adopt including access to credit (0 = no, 1 = yes), household wealth computed based on assets (0 = poorest, 1 = poorer, 2 = middle, 3 = richer, and 4 = richest), made profit from last season's cultivation (0 = no, 1 = yes), household size, livelihood diversification (0 = only one livelihood activity, 1 = two livelihoods activities, 2 = three livelihood activities and 3 = 4 or more livelihood activities). Given the importance of sociocultural context in understanding intent to adopt, we also included the gender of the farmer (0 = man, 1 = woman) and women's autonomy index computed from a set of 5 questions on women's decision-making autonomy in the household on what to plant, when to sell, control of income from farm produce sales, ability to join a local agricultural organization and what postharvest management techniques to use (see Kansanga et al., 2024). In line with the perception paradigm on technology adoption described in our theoretical background, we also included relevant variables that can shape farmers' perception about agricultural technologies. This included prior training on postharvest management (0 = no, 1 = yes), timely access to extension services (0 = no, 1 = yes), perception of food loss as a problem (0 = no, 1 = yes), prior adoption of similar sustainable agricultural innovations (0 = no, 1 = yes) and use of modern synthetic inputs (0 = no, 1 = yes).

Analytical approach

We employed both descriptive and inferential statistical analyses to examine the correlates of willingness to adopt solar-powered cold storage. We used univariate analysis to visualize the distribution of the sample characteristics. We further employed a binary logistic regression model to examine the relationship between individual predictor variables and willingness to adopt solar-powered cold storage. A multivariate logistic regression model was further fitted to observe possible changes to the binary relationships observed when other theoretically relevant variables were introduced into the model. Given the dichotomous nature of the outcome variable, a logistic regression analysis was appropriate. The equation for the regression model is shown below.

$$\pi\ (\mathrm{X}) = \frac{\exp\left(\beta 0 + \beta 1\mathrm{X}1 + \ldots + \beta \mathrm{kXk}\right)}{1 + \exp\left(\beta 0 + \beta 1\mathrm{X}1\ + \ldots + \beta \mathrm{kXk}\right)}$$

Where π is the probability that a farmer's response falls in the affirmative category of the dichotomous Y on willingness to adopt solar-powered cold storage (i.e., 1 = yes), exp is the exponential function, $\beta 0$ is the intercept, $\beta 1$ is the coefficient of first predictor variable and βk is the coefficient of the last predictor variable. All regression coefficients are reported as odds ratios (OR), with odds ratios above one (OR > 1) denoting a higher likelihood of adopting solar-powered cold storage and odds ratios below one (OR < 1) indicating a lower likelihood of adoption. All statistical analyses were performed in Stata version 15.

Adoption analysis using logistic regression runs the risk of simultaneously including two or more highly correlated predictors in the model given the need to test all theoretically relevant variables with the potential to shape willingness to adopt. To mitigate the risk of multicollinearity, we performed a correlation analysis among the candidate variables (Garson, 2006; Malila et al., 2023). Inter-correlation between variables that exceeds 0.80 is indicative of the presence of multicollinearity. A backward elimination procedure was used in generating the final candidate variables included in our model.

Results

Sample characteristics

Table 1 shows the descriptive statistics of the sample. Overall, 79% of respondents were willing to adopt solar-powered cold storage for postharvest management. In terms of farmer demographics, the average age of farmers was 39 years while 60% of the sample were women. Almost two-thirds of the sample had no formal education with only 17% and 18% reporting primary and secondary education, respectively. Green leafy and fruit vegetables were the most cultivated vegetables, while the average landholding was 2 acres (0.8 hectares). Farm size for vegetables was much smaller compared to the widely reported average of 2.5 hectares for cereals and other food crops. Most farmers (69%) cultivated in the wet season only, with only 22% cultivating in both the wet and dry seasons. The average number of years cultivating vegetables was nine years, suggesting most farmers have ample experience in vegetable cultivation. In terms of capacity related factors, 66% of farmers reported making profit from vegetable cultivation the previous season while 28% reported having access to credit. Livelihood diversification was low among farmers—62% of farmers had no alternative livelihood aside from agriculture, suggesting only a third of farmers diversified into other ancillary livelihoods. There was high prior adoption of similar sustainable agricultural practices among farmers as 79% of farmers indicated adopting and implementing at least a sustainable land management practice on their vegetable plots. On average farmers traveled a distance of 21 km to the nearest market. About two-thirds of farmers reported adopting and using a combination of modern synthetic inputs—fertilizer, weedicides and pesticides. The average yield was 558 kg and farmers lost 25% of their total harvest to postharvest food loss, with almost all farmers perceiving food loss as a major challenge. Only 26% of farmers reported ever receiving training on postharvest management while only 20% reported having ready access to agricultural extension services.

Determinants of willingness to adopt solar-powered cold storage

Table 2 presents both bivariate and multivariate analysis of the correlates of willingness to adopt solar-powered cooling for

TABLE 1 Sample characteristics.

Variable	Percent/mean (SD)
Willingness to pay for green cooling	
No	21
Yes	79
Gender of farmer	
Man	40
Woman	60
Age†	39 (13.89)
Education	
No formal education	65
Primary	17
Secondary and above	18
Household size†	8 (5.02)
Category of vegetable cultivated	
Green leafy vegetables	42
Fruit vegetables	39
Marrow/tuberous/cruciferous	19
Number of vegetables cultivated†	3 (1.78)
Season of cultivation	
Wet season	69
Dry season	9
Both wet and dry	22
Number of years as a vegetable farmer†	9 (6.58)
Farm size (acres)†	2 (1.25)
Synthetic input use	
No	32
Yes	68
Distance to market (km)†	21 (16.76)
Perceive food loss as a major challenge	
No	5
Yes	95
Yield (kg per acre)†	558 (793.9)
Postharvest Loss†	25 (22.09)
Received postharvest loss training	
No	74
Yes	26
Ready access to extension service	
No	80
Yes	20
Made profit last season	
No	34
Yes	66
Access to credit	
No	72
Yes	28
Wealth	
Poorest	10
Poorer	12
Middle	10
Richer	15
Richest	53
Livelihood diversification	
One livelihood (only vegetable farming)	62
Two economic activities	20
Three economic activities	12
Four economic activities	6
Women's autonomy index†	4 (2.41)
Prior adoption of SLMP	
No	21
Yes	79
Total	1001

† For continuous variables, means and standard deviations are reported.

postharvest management of vegetables. At the bivariate level, several variables mirroring the hypothesis of the innovation diffusion, economic constraints, and adopter perception models were significantly associated with willingness to adopt. Specific to the economic constraints, wealth, returns to production (profit) and livelihood diversification were all positively associated with willingness to adopt solar-powered storage for postharvest loss reduction. Being wealthier was associated with higher likelihoods of adopting, with those in the richer and richest wealth quintiles being 15 and 29 times more willing to adopt than those in the poorer wealth category. Those who reported lacking access to credit facilities (OR = 0.452; $P < 0.001$) were significantly less likely to adopt cold storage technology than their counterparts who had access to credit. Similarly, vegetable farmers who reported not making profit (OR = 0.358; $P < 0.001$) in the previous season were significantly less likely to adopt. At the multivariate level, these capacity-related factors, except for access to credit, remained significantly associated with the adoption of cold storage technologies. While credit access predicted lover odds of adoption in the bivariate model, it emerged a positive predictor of willingness to adopt in the multivariate model in the environment of other theoretically relevant variables although the significance was attenuated. Overall, these findings suggest a strong role of economic factors in technology uptake in smallholder farming contexts.

Consistent with the innovation-diffusion paradigm, some knowledge-related variables emerged significantly associated with

TABLE 2 Bivariate and multivariate logistic regression analysis of the correlates of willingness to adopt solar-powered cold storage for post harvest management of vegetables.

Variable	Bivariate odds ratios (SE)	Multivariate odds ratios (SE)
Gender of farmer (ref: man)		
Woman	1.038 (0.163)	1.093 (0.248)
Age	0.995 (0.005)	1.012 (0.010)
Education (ref: no education)		
Primary	1.324 (0.278)	1.829 (0.573)*
Secondary and above	3.465 (0.960)***	2.612 (0.935)***
Household size	1.036 (0.018)**	1.00 (0.023)
Category of vegetable cultivated (ref: Green leafy)		
Fruit vegetables	0.492 (0.083)***	0.956 (268)
Marrow/tuberous/Cruciferous	1.451 (0.368)	4.852 (2.436)***
Number of vegetables cultivated	1.148 (0.056)***	1.099 (0.110)
Season of cultivation (re: Both)		
Wet season	0.387 (0.091)***	0.85 (0.262)
Dry season	0.355 (0.115)***	0.531 (0.223)
Number of years as a vegetable farmer	1.006 (0.012)	0.99 (0.018)
Farm size	0.935 (0.054)	0.756 (0.070)***
Synthetic input use (ref: No)		
Yes	1.524 (0.243)***	1.792 (0.454)**
Distance to market (km)	1.017 (0.005)***	1.019 (0.010)**
Perceive food loss as a major challenge (ref: yes)		
No	0.129 (0.039)***	0.166 (0.080)***
Yield (kg per acre)	1.001 (0.000)***	1.001 (0.000)***
Postharvest Loss	1.018 (0.004)***	1.005 (0.006)
Received postharvest loss training (ref: yes)		
No	0.179 (0.048)***	0.312 (0.112)***
Ready access to extension services (ref: no)		
No	0.217 (0.063)***	0.428 (0.171)**
Made profit last season (ref: yes)		
No	0.358 (0.056)***	0.378 (0.088)***
Access to credit (ref: yes)		
No	0.452 (0.090)***	1.048 (0.266)
Wealth (ref: poorest)		
Poorer	5.082 (1.517)***	3.89 (1.522)***
Middle	8.013 (2.561)***	2.939 (1.246)**
Richer	15.024 (4.786)***	5.953 (2.414)***
Richest	29.828 (8.176)***	20.373 (7.408)***
Livelihood diversification (ref: 1)		
Two economic activities	2.125 (0.462)***	0.989 (0.294)
Three economic activities	5.142 (1.939)***	2.433 (1.086)**
Four economic activities	2.177 (0.856)**	0.74 (0.358)
Women's autonomy index	1.176 (0.037)***	1.052 (0.050)

(Continued)

TABLE 2 (Continued)

Variable	Bivariate odds ratios (SE)	Multivariate odds ratios (SE)
Prior adoption of SLMP (ref: No)		
Yes	2.307 (0.400)	1.397 (0.382)
Constant		0.50
Pseudo r-squared		0.380
Prob > chi2		0.000
Akaike crit. (AIC)		707.451

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

willingness to adopt. Although all respondents had ample knowledge of the solar-powered cooling units, farmers who lacked access to other channels of information on agriculture—and were unlikely to encounter information on sustainable agricultural methods—including those who reported not receiving training on postharvest loss (OR = 0.179; $P < 0.001$) and those who had no access to agricultural information through extension (OR = 0.217; $P < 0.001$) were significantly less likely to adopt solar-powered cold storage. Similarly, familiarity could be important in shaping adoption decisions as farmers who reported already using other modern external inputs in farming (OR = 1.524; $P < 0.001$) were more likely to adopt solar-powered cooling. At the multivariate level, training on postharvest management, access to timely extension services and use of similar modern agricultural inputs remained significantly associated with willingness to adopt.

Specific to adopter perception, some factors that could potentially shape how farmers perceive new agricultural technologies such as level of education, actual experience of food loss, and perception of food loss as a major challenge were significantly associated with willingness to adopt. For instance, farmers with secondary education (OR = 3.465; $P < 0.001$) were about 4 times more likely to adopt solar cold storage than those with no formal education. Similarly, those who perceived food loss not to be a major challenge (OR = 0.129; $P < 0.001$) were significantly less willing to adopt solar-powered cold storage compared to those who perceived food loss to be a major challenge, with the relationship becoming even stronger at the multivariate level. Actual experience of food loss also positively predicted a higher willingness to adopt at the bivariate level. At the multivariate level however, all but the number of years cultivating vegetables and food loss rate were still significantly associated with willingness to adopt cold storage.

Some contextual socioeconomic and farm level variables emerged significant at the multivariate level, suggesting the important role of underlying contextual factors. The type of vegetables cultivated also had an influence on the willingness to adopt cold storage technologies as those cultivating marrow and cruciferous vegetables were about five times more willingness to adopt than those cultivating green leafy vegetables. Farm size was positively associated with the adoption of cold storage at the multivariate level, suggesting those cultivating smaller farm sizes were more likely to adopt cold storage technologies. Although the season of cultivation was significant at the bivariate level, in the multivariate model, the significance was attenuated. Similarly, women's decision-making autonomy in the household, which is a proxy of gender relations, was significantly associated with willingness to adopt at the bivariate level. Yield was also positively associated with willingness to adopt solar-powered cold storage at both the bivariate (OR = 1.001; $P < 0.001$) and multivariate (OR = 1.001; $P < 0.001$) levels, suggesting that as yield increases, the need for and willingness to adopt cold storage also increases.

Discussion

Nature-inspired solutions like solar-powered cold storage systems hold significant promise in the postharvest management of perishable agricultural produce in off-grid environments due to their relatively low cost and environmental sustainability co-benefits. That notwithstanding, our findings reveal important underlying factors and entry points that must be prioritized to ensure traction. The theoretical literature on technology adoption has tended to frame adoption in particular conceptual silos—a situation which heightens the risk of foreclosing other relevant issues that shape adoption (Karbo et al., 2024). Approaching adoption from a broader theoretical lens, we bring together variables that mirror the range of determinants highlighted by dominant adoption theories—economic constraints, innovation diffusion, and adopter perception. In the rest of the discussion, we contextualize these findings within the broader literature and make relevant policy recommendations.

Consistent with the economic constraints level, farmer capacity related factors such as household wealth and profit, emerged as important determinants of willingness to adopt solar-powered cold storage. Being in higher wealth categories and making profit from production both predicted higher odds of willingness to adopt. The financing aspect of technology uptake has long been stressed as central in adoption decision making of smallholder farmers (Benyam et al., 2021; Okorley et al., 2001; Rutta, 2022; Sugri et al., 2021). Social scientists have particularly flagged the central role of wealth in making initial adoption decisions since household wealth and access to credit typically determine the ability to pay the initial cost of adopting a particular technology (Adams et al., 2021; Fadeyi et al., 2022; Nwokoye et al., 2019). The emergence of profit as an important predictor of willingness to adopt may however provide further insights into the role of economic factors in shaping adoption. For shared technologies like solar-powered cold storage which require a service fee to maintain at the community level through a pay-as-you-go principle, farmers are likely to consider the current profit they make from production and the potential future profit in determining whether they can continue to pay user fees for a particular technology. Thus, we argue that while the household income situation may shape the payment of the immediate cost of adopting a given technology, for technologies like solar-powered cold storage that require periodic service fees, considerations of the profit outcomes from production could shape a smallholder farmer's perception of the utility of the technology. More importantly, profit levels also determine whether a farmer can meet future service fees for the technology. This is consistent with Hambye and Desmet's (2021) observation about farmer disengagement with digital technologies such as artificial intelligence, as not just due to high initial investment cost but also future maintenance cost. It is thus important for technology transition incentives to go beyond supporting farmers with subsidies for upfront costs to include considerations of the maintenance cost of adopting a given technology. Similarly, Gbénou-Sissinto et al. (2018) found that farmers with a higher level of prosperity and access to credit were willing to invest in durable modern storage structures. Given the important role of livelihood diversification in our analysis, and the volatility of agriculture in a changing climate, supporting farmers to diversify into other economic activities could have beneficial impacts on adoption as it creates multiple future income generating opportunities to pay the maintenance cost of technology use (Fadeyi et al., 2022). While farm size is considered a key proxy farmer capacity to adopt new technologies, it predicted lower odds of adoption in our study. This finding, which appears to contradict the economic constraints model, is however more connected to farmers' consideration of the attributes of the technology than a reflection of capacity to adopt. Given that the solar-powered cold storage systems in question are small and targeted at small scale producers, farmers with relatively larger farms may not consider these big enough to accommodate larger harvest as has been highlighted in other adoption studies (Abara and Singh, 1993; Munz and Schuele, 2022). Thus, this finding on farm size rather amplifies the arguments of the adopter perception paradigm since farmers with larger farms are likely to perceive small solar coolers to be limited in providing enough storage space for their harvest.

The innovation diffusion paradigm highlights the central role of knowledge flows in technology adoption. While knowledge specific to a given technology is crucial, our findings demonstrate access to broader agricultural training and extension services on food loss and other everyday farming issues can be reinforcing in technology adoption. Although such broader agricultural training opportunities and extension services may not promote specific technologies, they provide powerful platforms for farmers to engage with current science on agriculture and gain knowledge on how to navigate everyday agricultural issues using technology. The role of access to general agricultural services and training is reinforced by our finding that farmers who previously adopted sustainable land management practices were more willing to adopt solar-powered cold storage. These observations are consistent with several studies that demonstrate that smallholder farmers who have contact with extension officials are more likely to adopt modern storage solutions (Adegbola and Gardebroek, 2007; Gbénou-Sissinto et al., 2018; Hoang and Tran, 2023; Snider et al., 2023). Other adoption studies demonstrate how these community level training and extension platforms provide opportunities for farmer-to-farmer mentoring in the absence of trained agricultural officials, which indirectly shapes adoption decisions (Kansanga et al., 2021). While policy efforts on technology adoption have tended to focus exclusively on promoting specific technologies of interest, our findings demonstrate the need to frame technology promotion more broadly to include training and extension services that broaden the technical knowledge of farmers.

Similarly, although studies highlighting perception have mostly focused on farmers' perception of the technology itself (Castillo et al., 2021; Greiner et al., 2009; Kolady et al., 2021), our findings contribute to an emerging body of literature (Murage et al., 2015a,b) that demonstrates the important role of farmer's perception of the problem a given technology seeks to solve. In the context of our study, farmers who perceived food loss to be less of a problem were significantly less likely to be willing to adopt cold storage solutions. Indeed, actual experience of food loss positively predicted willingness to adopt cold storage technologies. This reinforces the assertion that how farmers perceive and experience the underlying problem a given technology is deployed to solve is fundamental to willingness to adopt.

Our findings also point to the important role of contextual and agricultural related variables in shaping willingness to adopt. For instance, the significant association between the type of crop cultivated and willingness to adopt suggest farmers consider the level of perishability or shelf life of the crop cultivated, which is a proxy of food loss risk, in making postharvest management decisions. Since some perishables, especially fruit and cruciferous vegetables tend to offer a relatively longer shelf life at ambient temperatures, often about a week (Lipinski et al., 2013), farmers may consider this window a good enough buffer to get their produce to the market compared to other perishables like green leafy vegetables which must be sold instantly. Based on contextual knowledge, smallholder farmers cultivating green leafy vegetables often cultivate relatively smaller plots and target selling immediately after harvest. It is therefore not surprising that farmers cultivating green leafy vegetables may not be keen to adopt cold storage as they are accustomed to the routine of selling immediately after market and often cultivating relatively smaller quantities. Consistent with the adoption literature (Anang, 2018; Fadeyi et al., 2022; Mwangi and Kariuki, 2015; Serote et al., 2021), it is therefore not surprising that our findings also demonstrate that both yield and farm size are positively associated with willingness to adopt.

Policy directions

Although considerable scholarship has emerged on agricultural technology adoption, very few studies have targeted postharvest management technology. The limited literature on postharvest technologies have also tended to focus on grains and legumes, for example the Purdue Improved storage bags (Jones et al., 2011; Rabé et al., 2021; Sudini et al., 2015; Williams et al., 2017). This is despite the fact that food loss is disproportionately high for vegetables. As one of the first studies on willingness to adopt cold storage technologies for vegetables, our findings provide timely insights for national and international food sustainability policy, including the sustainable cold chains agenda of the United Nations. First the complexity of drivers from this analysis demonstrates the need to approach adoption from a multifaceted lens, paying attention to economic constraints, knowledge flows, adopter perception and underlying agricultural variables. Second, even within major conceptual paradigms on adoption, there are noteworthy nuances that must be addressed to promote the uptake of cold storage technologies. Thus, while our findings align with the hypothesis of the key theoretical paradigms on adoption, we highlight key but often overlooked areas across these paradigms. For instance, specific to the economic constraints paradigm, literature tends to focus disproportionately on the upfront cost of adoption as the key driver. While this is crucial, our findings point to the important role of a farmer's considerations of capacity to pay for future service costs/user fees in willingness to adopt cold storage technologies. Notwithstanding, incentives to promote adoption are usually subsidies to cover initial adoption cost without emphasis on efforts to sustain adoption into the future. In this context, it is not surprising that economic variables such as livelihood diversification and profit—which are important proxies of economic stability—were significant predictors of willingness to adopt. On information flows, it is not uncommon for agents promoting technologies in smallholder farming settings to focus exclusively on knowledge dissemination specific to the technology of interest. Although this is important, paying attention to general agricultural education/extension could enhance technology adoption prospects. Overall, this contribution demonstrates the complex and multifaceted nature of agriculture technology adoption decision making for farmers and the need for development partners to approach technology adoption from a broader perspective that reflects attention to not just financial capacity and efficiency of a given innovation, but also broader issues such as access to general agricultural education.

Data availability statement

The datasets presented in this article are not readily available because the data contains identifiable information of participants. Anonymized versions may be shared upon request. Requests to access the datasets should be directed to Moses Mosonsieyiri Kansanga; mkansanga@email.gwu.edu.

Ethics statement

The studies involving humans were approved by George Washington University Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because Informed consent was sought verbally as most participants cannot read/write.

Author contributions

MK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Writing – original draft. LS: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. SL: Conceptualization, Writing – review & editing. DR: Writing – review & editing, Validation, Resources.

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Conflict of interest

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

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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