INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

IFPRI

IFPRI Discussion Paper 02047

October 2021

Solar-Powered Cold-Storages and Sustainable Food System Transformation

Evidence from Horticulture Markets Interventions in Northeast Nigeria

Hiroyuki Takeshima

Futoshi Yamauchi

Dauda Bawa

Salaudeen O. Kamaldeen

Hyacinth O. Edeh

Manuel Hernandez

Development Strategy and Governance Division

Markets, Trade, and Institutions Division

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

AUTHORS

Hiroyuki Takeshima (h.takeshima@cgiar.org) is a Senior Research Fellow in the Development Strategy and Governance Division of the International Food Policy Research Institute (IFPRI), Washington, DC.

Futoshi Yamaushi (f.yamauchi@cgiar.org) is a Senior Research Fellow in IFPRI's Markets, Trade, and Institutions Division, Washington, DC.

Dauda Bawa (dauda71bawa@gmail.com) is a Lecturer in the Department of Agricultural Economics & Extension, University of Jos, Plateau State, Nigeria.

Salaudeen O. Kamaldeen (ksk_deen@yahoo.com) is a Research Officer at the Nigerian Stored Products Research Institute, Kano, Nigeria.

Hyacinth O. Edeh (h.edeh@cgiar.org) is a Country Program Manager in IFPRI's Nigeria Office, Abuja, Nigeria.

Manuel Hernandez (m.a.hernandez@cgiar.org) is a Senior Research Fellow in IFPRI's Markets, Trade, and Institutions Division, Washington, DC.

Notices

Abstract

Modern cooling technologies that utilize renewable energy sources have been increasingly recognized as a promising tool to address a multitude of challenges emerging in progressively complex food systems in developing countries. When provided as cold-storages inside horticulture markets, cooling technologies can potentially contribute to improved quality of products and strengthened vertical linkages. Knowledge gaps about the actual impacts of these technologies in developing countries remain, especially in Africa south of Sahara (SSA). This study partly fills this knowledge gap by providing evidence from the evaluation of recent interventions in northeast Nigeria in which 7 small solar-powered cold-storages were installed across 7 horticulture markets. Combinations of difference-in-difference and variants of propensity-score-based methods suggest that using cold-storages significantly increased horticulture sales volumes and revenues of market-agents. Back-of-the-envelope calculations indicate that increased net revenues for market-agents may be sufficiently large to recoup the investments and operating costs of cold-storages within a reasonable time frame. Using cold-storage also reduced the share of food loss and lengthened the products' shelf-life, while raised prices received by both market-agents and farmers, which were associated with improved product quality, expanded value-adding activities by market-agents, and increased use of advance payments. We find no evidence of negative spillover effects inside horticulture markets. Finally, additional food-science experiments confirm that cold-storages preserve original physical and nutritional qualities of key horticultural products several days longer than products stored under ambient temperature.

Keywords: solar-powered cold-storage, horticulture, market-agents, Nigeria

Acknowledgments

We would like to thank the Government of Japan and the CGIAR Research Program on Policies, Institutions, and Markets (PIM), which is led by the International Food Policy Research Institute (IFPRI) and carried out with support from the CGIAR Trust Fund, for providing financial support to conduct this study. We also thank Cold Hubs Inc. of Nigeria, and Panasonic Corporation of Japan, for their support during the intervention project implementation. Authors also benefited from the constructive comments and suggestions received from Rob Vos, Kwaw Andam, and Masahito Enomoto. Authors are responsible for any remaining errors

1 Introduction

Modern cooling technologies have been increasingly recognized as a promising tool to address a multitude of challenges emerging in increasingly complex food systems in developing countries, including food loss and waste, food safety, food, and nutrition security; poverty, and economic growth; and environmental sustainability. Cold-storages have been increasingly important technologies to reduce food loss and food waste globally, including developing countries, by reducing microbial growth that causes spoilage (e.g., Lichtenberg & Ding 2008; Häsler et al. 2019; IFPRI 2020; Mayton et al. 2020; Kashyap & Agarwal 2020). Cold-storages are also expected to reduce the growth of most human pathogens, ensuring enhanced food safety (Uçar & Özçelik 2013). The use of cold-storages has also been advocated to contribute to improved food and nutrition security, including micronutrient-rich horticulture crops like vegetables and fruits (Ali & Tsou 1997; Schreinemachers et al. 2018; Surendran et al. 2020). Studies also advocate for the potential of cooling technologies, including cold-storages, to accomplish inclusive growth through poverty reduction and economic growth, either through its contributions in export growth of horticulture commodities (Gebreeyesus & Sonobe 2012; Whitfield 2012; Minten et al. 2012) or improved market functioning in the domestic market (Schreinemachers et al. 2018), including higher and/or more stable prices received by suppliers in the domestic market (Rakshit 2011; Lichtenberg & Ding 2008) combined with increased sales achieved through reduced loss (Allen & de Brauw 2018). Cooling-chain development had been a significant part of food system transformation in Japan during the second half of the 20th century (McDonald 2000). Cold-storage use for crops like potatoes started growing by the end of the 20th century in various developing countries in Asia, like Bangladesh (Lewis 1996) and India, where by 2010, 90% of potato producers had started using cold-storages (IFPRI 2020). Such growth offers some promise that similar technologies can start becoming relevant in SSA today (Tschirley et al., 2015).

One of the concerning issues associated with cold-storages is the increased energy consumption requirements and environmental effects like carbon emissions (Coley et al. 2009; Pelletier et al. 2011; Béné et al. 2019; Pueyo et al. 2020). Cold-storage has been one of the largest energy consumers for potato production in South Africa (Steyn et al. 2016). However, a growing set of potential solutions are being proposed, including community-based electric micro-grids (Kirubi et al. 2009), using biofuels like Jatropha (Hunsberger 2010) or biogas, and solar power in the case of milk cooling (Häsler et al. 2019). The declining cost of solar power manufacturing in recent years further offers tools to provide the electricity necessary for cooling technologies.

Questions about the viability of these technologies in developing countries like Nigeria remain because they depend on the actual effective demand for increased freshness and various quality attributes, including nutritional contents of perishable commodities, actual benefits that cold-storages bring over traditional cooling methods, and the extent of loss reduction, among others. The knowledge gap also exists as to whether cold-storage technologies can affect how quality improvement can be induced at various stages and how institutional linkages can be strengthened between market actors and producers, which have been considered critical elements of modernizing the value-chains (e.g., Fafchamps et al. 2008; Minten et al. 2012; Vandeplas & Minten 2015). Other studies also provided indirect evidence that large-scale cold-storages have often failed in Africa south of Sahara due to underutilization (Odoli et al. 2019; Behuria 2018). Some studies also raise the importance of highlighting potential costs of cold-storages relative to the economic value of food wastage (Ricciardi et al. 2018).

This study attempts to fill this knowledge gap by providing evidence of the impacts of recent interventions implemented by the International Food Policy Research Institute (IFPRI), whereby 7 small-scale, solar-powered cold-storages were installed in northeast Nigeria on horticulture sales and revenues earned, quality of products, and value-adding activities by horticulture market agents. We apply a combination of the difference-in-difference (DID) method and variants of propensity-score (PS) based methods to panel data of market-agents collected before and after the installation of cold-storages in 7 horticulture markets.

Northeast Nigeria is a suitable area to conduct this study because the demand for fresh horticulture commodities has been rising as a result of population growth and urbanization, and the region is one of the largest producers of major vegetable commodities within Nigeria (Nkonya et al. 2019). At the same time, the region's population continues to suffer from micronutrient deficiencies and lack of stable access to electricity.

This study contributes to various strands of literature. By providing evidence on field-level impacts in horticulture market settings in developing countries, this study contributes to the literature emphasizing ex ante the potential roles of cooling technologies in food systems in developing countries (e.g., Lichtenberg & Ding 2008; Schreinemachers et al. 2018; Häsler et al. 2019; Mayton et al. 2020; Kashyap & Agarwal 2020; Surendran et al. 2020), as well as reporting emerging trends for cooling technologies outside Africa (e.g., potato cold-storage in India by Minten et al. 2014). By focusing on the case of solar-powered cold-storages, this study also contributes indirectly to the literature on the potential of renewable off-grid electricity for modern cooling technologies (Kirubi et al. 2009; Hunsberger 2010; Häsler et al. 2019). The study also offers insights into addressing issues of food loss and waste (e.g., Spang et al. 2019). By providing linkage between cold-storage use and market-agents' transaction behaviors, this study also contributes to literature dealing with horticulture value-chain development, including the relationship between producers and market-agents (Minten et al. 2012), the nature of premiums on quality (Fafchamps et al. 2008), and how quality premiums are rising in India as income grows (Vandeplas & Minten 2015).

The paper proceeds as follows: Section 2 describes the interventions to install cold storages; section 3 discusses empirical approaches and data; section 4 presents the estimated results; and lastly, section 5 concludes our findings.

2 Interventions to install solar-powered cold-storages

In this study, a total of 7 cold storages were installed in 7 horticulture markets in Northeast Nigeria between December 2020 and January 2021. The project was intended by the donor (the Japanese Government) as an emergency response to rebuilding livelihood in a conflict-affected region, and northeast Nigeria was selected as the region had long suffered the destruction of livelihood by insurgent groups.

We first identified 14 eligible markets across 5 states (Adamawa, Bauchi, Gombe, Jigawa and Yobe states) in northeast Nigeria. These 14 markets were selected because they are horticulture markets, and operate daily, where installing cold-storages can have maximum potential. From these lists, we randomly selected 7 horticulture markets where cold-storages were installed (*intervention markets*), leaving the remaining 7 as comparable markets where cold-storages were not installed (*comparison markets*). Figure 1 illustrates the locations of these 14 markets. Both the 7 intervention markets and the 7 comparison markets are scattered across 5 states, with 2 markets each in Adamawa and Bauchi states, and 1 market each in Gombe, Jigawa and Yobe states.

[Insert Figure 1]

The installed cold storages were designed as prototypes and used and already operated by ColdHubs Ltd., a Nigeria-based social enterprise, in about 30 other horticulture markets across Nigeria at the time of our study. The cold-storages installed in this study are relatively small, each with a maximum capacity of 3 tons of common horticulture products.[1] Each cold-storage is powered by 5.6 kilowatt solar panels (18 of 380 watt photovoltaic panels manufactured by Panasonic).[2] The surplus electricity generated during the day is stored so that it can be released and enable continued refrigeration at night. The cold-storages also use environmentally friendly refrigerants like propane, which is less harmful to the ozone layer.

These cold storages were installed within the market premises; the exact locations depended on the negotiations between ColdHubs and market authorities, based on leveled-space availability, general ease of access from most market stalls, and the absence of nearby objects that block sunlight from cold-storage.

Selection of the initial set of users

The installation of cold-storages was advertised in each market through horticulture traders associations and horticulture producers associations, which exist in each horticulture market. All market agents selling horticulture crops belong to one or other of these associations. Anyone who showed an interest in potentially becoming a cold-storage user was required to participate in the 5 day postharvest management training first. As is described in later sections of this paper, a total of 350 market-agents from 4 markets participated in the training, and of these, 251 market-agents eventually became the initial group of cold-storage- users, while 99 decided not to use it after receiving the training. Anyone interested in using cold-storages later can do so after demonstrating understanding of the training materials and depending on the availability of remaining space in the cold-storage.

Operation of cold-storages

The temperature inside cold-storages is kept at 4 degrees Centigrade. Users rent the space by paying fees of ₦100 (approximately 28 US cents) per day per crate, which can typically hold 20 kilograms of products. ColdHubs manages the operations of cold-storages at each site, including use-fee collections, monitoring of storage conditions through remote-control technologies, ensuring security through contributions to market security guards, and maintenance work, which is typically minimal and confined to an occasional cleaning of solar panels, such as removing dust and sand.

Investment and operational costs of the storages

While the costs of materials and constructing cold-storage vary depending on the market conditions, typically it is on the order of US$40,000 per cold-storage. Once built, operational costs for cold-storages are relatively low, and variable costs are typically about US$150 per month (Table 1). Maintenance costs mostly consist of remote monitoring costs, payment for

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[1] These may be significantly smaller than cold-storages studied for other crops in Asia. For example, potato cold-storages in India that expanded significantly throughout between 2000 and 2009 have typically been larger, with a capacity of a few thousand tons per unit (Minten et al. 2014).

[2] For the 7 cold-storages, solar panels manufactured by Panasonic were used.

operators in charge of fee collections and other miscellaneous work, security guards, land rental fees, and simple cleaning of solar panels.[3]

[Insert Table 1]

Use of improved solar panels

While we do not assess the economic efficiency of particular types of solar panels used, it is informative to describe general specifications of particular solar panels used and their comparability with competing models. Solar panels used in our intervention are the 380 watt Monocrystalline (PERC) Solar PV Module manufactured by Panasonic. Table 2 compares these to competing products, including the ones previously used by the ColdHubs for similar cold-storages in other parts of Nigeria. Panasonic solar panels achieved significantly higher efficiency (conversion rate of solar energy to electricity outputs), 19.6% compared to 16.9% and 15.5% by the competing products. Their temperature coefficient (an indicator of how electricity output capability drops as the panel temperature rises above 25℃) is also slightly better than the competing products (–0.39% per ℃ vs. –0.40% and –0.41%).[4] Even though the use of Panasonic solar panels are slightly more expensive than competing products in terms of price per watt (US$0.58 per watt vs. $0.51 and $0.57), overall they are competitive and likely to be more efficient and stable in solar-power generation in the long-term.

[Insert Table 2]

Panasonic-solar panels used are also comparable to the other models in terms of resistance against dust and sand, which is a common challenge in the Sahel region like northeast Nigeria and certified through the International Electrotechnical Commission (IEC) 60068, and resistance against ammonium (certified through IEC 627168), which is important in horticulture markets that handle agricultural products. Similarly, as is common for typical solar panels, the electricity generation capacity lasts quite long, achieving at least 90% and 80% of initial capacity levels even after 12 years and 25 years, respectively.

3 Empirical methods for impact evaluations of cold-storages

The impacts of cold-storages have been evaluated through data collected from market-agents in pre- and post-intervention periods and the application of several econometric methods to these data.

3.1 Econometric methods

[3]Remote monitoring can be done through facilities like Microsoft's Azure Cloud, which allows monitoring of storage door opening and closure, conditions of batteries, outside and indoor temperature, as well as solar radiation. Security guard service is provided by the horticulture markets where cold-storages are located.

[4]While the differences appear small, these can lead to significant differences in environments like northern Nigeria where air temperature can reach 35℃ in the dry season. With such air temperature, the surface temperature of solar panels can reach around 70℃ (or even higher). Temperature coefficients typically measure the effects of deviations from 25℃. Therefore, with temperature coefficients in Table 2, the efficiency for competing manufacturer B can be lost by 18.45% (= 0.41*(70-25)), while the loss for Panasonic solar panels can be 17.55%, an almost 1 percentage point difference.

3.1.1 Difference-in-difference propensity score matching method

We estimate the impacts of cold-storages primarily through a combination of difference-in-difference (DID) method and propensity score-based model including propensity score matching (PSM) estimator. DID combined with PSM (DID-PSM) improves over a standard PSM, as the former can control for unobserved agents' specific effects, adding validity to the unconfoundedness assumption of PSM applied to DID transformed outcome variables (Heckman et al. 1997; Heckman et al. 1998; Smith & Todd 2005). DID-PSM has been increasingly used in impact evaluation studies (e.g., Todo 2011; Mason et al. 2017; Tranchant et al. 2019; Bravo-Ureta et al. 2021).

In a common DID-PSM approach used in these studies, the average treatment effects on the treated (ATT) for using cold-storage is estimated as (modified from exposition in Villa 2016),

$$DID_{PSM} = \left\{E\left(Y_{i,t=1} \middle| D_{i,t=1} = 1, C_i = 1\right) - w_i \times E\left(Y_{i,t=1} | D_{i,t=1} = 0, C_i = 0\right)\right\} - \left\{E\left(Y_{i,t=0} \middle| D_{i,t=0} = 0, C_i = 1\right) - w_i \times E\left(Y_{i,t=0} | D_{i,t=0} = 0, C_i = 0\right)\right\} \quad (1)$$

where $Y_{i,t}$ is the set of outcomes of interest for market agent i at period $t = 0$ (pre-intervention) or $t = 1$ (post-intervention), $C_i = 1$ if agent i are those who end up using cold-storage at $t = 1$ ($C_i = 0$ if otherwise), and $D_{i,t}$ denotes the actual use of cold-storage.

The method (1) improves over standard DID by weight w_i, which is defined in various ways by the propensity of agent i to use cold-storage,

$$p_i = \Pr(C_i = 1 | X_{i,t=0}) \quad (2)$$

which is a function of agent i's exogenous, observable characteristics X_i at the pre-intervention period.

The translation of p_i to w_i depends on the matching method used in PSM. In our primary specification, we use a nearest neighbor method with a caliper, which has generally been suggested as more consistent than other matching methods (e.g., Caliendo & Kopeinig 2008). We then also estimate kernel matching methods to check the robustness of the results.

Set of explanatory variables (X)

The observed characteristics X_i, as described in detail below, are identified from the past studies focusing on horticulture market-agents (e.g., Fafchamps et al. 2008; Minten et al. 2012; Vandeplas & Minten 2015). These variables include key characteristics of market-agents and key characteristics of market stalls where they conduct trading activities.

Characteristics of market-agents include basic demographics like age, gender, household size, and education level. It also includes whether the market-agent is a native of the Local Government Area (LGA) where the market is located, which can affect their social network in the locality. The number of languages spoken by the market-agent proxies the ability to explore networks with sellers and buyers. Having or not having similar market-agents among relatives is used to proxy trading skills and knowledge, access to market information, and additional social network. The number of credit sources that the market agent has ready access to for borrowing money when needed (both formal and informal sources) proxies the financial capacity of the agent.

The capacity of storage (ambient) owned, as well as the total values of business assets (mechanical scales, processing equipment, generator, motorized and non-motorized transportation equipment), capture the various aspects of the agent's capacity that can affect the use of cold-storage. Greater values of own storage and assets can either raise returns from using cold-storage, or lower returns if they are mostly substitutes. Having the market stalls for exclusive use, rather than shared space, may also affect the decision to use cold-storages.

One of the key characteristics of market stalls is the distance to where cold-storages were later installed. Other characteristics of market stalls include distances to various key public facilities, including entry gate of the market, public toilet, canteen, meeting room, market representative's office, and the nearest source of piped water. These can affect the ability to spend time at the market stalls and conduct various business transactions, and also the level of congestion, which can affect decisions to use cold-storages in complex ways.

Other characteristics of market stalls include their quality, such as whether the floor is made of superior materials (asphalt/tar, cement, or ceramic), whether the stall has a roof, whether the road in front of the stall is paved, whether there is drainage around the stall and the drainage is covered or not, and lastly whether the stall has access to the electricity grid.

In addition, X includes dummy variables for each of 7 horticulture markets. Among these variables, all distance variables, capacity of storage owned, and value of business assets are transformed into natural logarithms to reduce excess skewness.

3.1.2 Difference-in-difference inverse probability weighting (IPW) with bivariate probit for agent-crop level outcomes

DID-PSM (1) provides consistent estimates for market-agent-level outcomes Y_i. However, the estimation of effects measured at both market-agent and crop levels (Y_{ik}) requires further steps to address potential biases due to market-agents' self-selection for crop choice at pre- and post-intervention periods.

We therefore employ DID bivariate-IPW (DID-BIPW) for market-agent (i)-crop (k) level outcomes ($Y_{i,k}$). BIPW has been initially proposed as variants of the extensions of IPW (Imbens & Wooldridge 2009; Huber 2014), and applied by other studies (e.g., Kumar et al. 2020). We first estimate through a bivariate probit regression the joint probability p that a market-agent i uses the cold-storage and handles a crop k ($\hat{p}_{i,k}$), the joint probability that i does not use cold-storage and still handles crop k ($p^*_{i,k}$), as a function of $X_{i,t=0}$ where X_i consist of the same set of variables described in subsection 3.1.1. From this, we calculate inverse probability $\widehat{w}_{i,k} = 1/\hat{p}_{i,k}$, and $w^*_{i,k} = 1/p^*_{i,k}$.

We then estimate

$$\Delta Y_{i,k} = Y_{i,k,t=1} - \Delta Y_{i,k,t=0} = \alpha + \beta \cdot D_{i,k} + \gamma \cdot X_{i,k} + \varepsilon_{i,k} \quad (3)$$

by applying weights $\widehat{w}_{i,k}$ to cold-storage-using market-agent, and $w^*_{i,k}$ to non-using market-agent. $D_{i,k}$ indicates whether a cold-storage is used by agent i for crop k. $X_{i,k}$ include market and crop dummies; thus (3) is a IPW with regression adjustment, where adding $X_{i,k}$ further improves the balancing properties of samples across treatment statuses (Imbens & Woolridge 2009; Austin 2011). Standard errors are then estimated through paired-bootstrap. By incorporating weights $\widehat{w}_{i,k}$ and $w^*_{i,k}$, (3) consistently estimates the effect of cold-storage on improved product handling practices, β. Notations α, γ are intercept and other estimated coefficients, and $\varepsilon_{i,k}$ is idiosyncratic error.

3.1.3 Market-agent–crop-fixed effects model for crop-level outcomes

With a stronger assumption that the use of cold-storage is exogenous to certain outcomes when unobserved fixed effects associated market-agent and crops are controlled for, one can also estimate the effects of cold-storage through fixed effects model using post-intervention period data,

$$Y_{i,k} = \alpha + \beta \cdot D_{i,k} + \gamma \cdot X_{i,k} + \varepsilon_{ik} \quad \text{(only for } t = 1\text{)} \tag{4}$$

in which outcomes for market-agent i and crop k ($Y_{i,k}$) are regressed on cold-storage use $D_{i,k}$. Under the assumption that $D_{i,k}$ is exogenous to $Y_{i,k}$ conditional on unobserved, market-agent-crop fixed effects, the effects of cold-storage use β can be estimated consistently and efficiently. We, therefore, show results from (4) as supplementary results.[5]

3.2 Data

Our primary sample consists of three types of market agents: cold-storage users in intervention markets, non-users in intervention markets, and those in comparison markets.

The pre-intervention survey was conducted in November 2020. In each of the 7 intervention markets, 100 market-agents were interviewed, while 50 market-agents were randomly selected in each of the 7 comparison markets. At intervention markets, prior to the pre-intervention survey, we had been provided with the list of 350 market-agents who had decided to participate in the postharvest management training (aforementioned pre-requisite to use cold-storages). We interviewed them in the pre-intervention survey so that we are likely to have a sufficient sample size of eventual cold-storage-users because a majority of eventual users would belong to these groups, which ensures sufficient statistical power in our impact evaluation analyses. As described earlier, of the 350 market-agents who attended training, 251 market-agents eventually became the initial group of cold-storage users. We then randomly selected additional market-agents from the list of all market-agents in each market so that a total of 100 market-agents were interviewed in intervention markets. These sample sizes were determined based on the typical number of cold-storage users observed in other horticulture markets in Nigeria, where similar cold-storages have already been in operation by ColdHubs. We thus interviewed a total of 1,050 respondents (= 100 × 7 intervention markets + 50 × 7 comparison markets).[6]

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[5]For model (4), standard errors adjusted for two-way cluster correlation, that is, market-agents level and crop levels, following the approach by Cameron et al. (2011) and using the `vcemway` command in Stata (Gu & Yoo 2019).

[6]The proposed sample sizes are guided by similar studies on horticulture market-agents conducted earlier, including Fafchamps et al. (2008), Minten et al. (2012), and Vandeplas & Minten (2015). Fafchamps et al. (2008) interviewed a total of 400 market-agents (mostly traders) and 400 farmers, covering five crops (maize, potato, tomato, mango, and turmeric) and four states in India (Tamil Nadu, Uttar Pradesh, Maharashtra, and Orissa). With this sample size, geographical coverage, and variations in crops, Fafchamps et al. (2008) identified statistically significant effects of crop attributes, buyer types, places of sales, and payment timing, on crop prices (quality premiums). Minten et al. (2012) interviewed a total of 240 traders (mostly retailers) and 240 farmers of cauliflowers and green peas in three major wholesale markets in India. With this sample size, Minten et al. (2012) identified statistically significant effects of different modes of farmers-traders interlinkages, crop attributes on crop prices paid to farmers. Vandeplas & Minten (2015) interviewed 300 traders in the city of Dehradum (Uttarakhand), consisting of 151 rice traders and

The post-intervention survey was conducted in late March 2021, interviewing the same 1,050 market-agents. The timing for the post-intervention survey was determined based on a number of factors. We aimed to allow sufficient time for market-agents to become familiar with the use of cold-storages so that their benefits become more identifiable; 2 months post-installation was considered sufficient given the relatively short production season for many horticulture crops (especially vegetables). At the same time, the survey was timed early enough so that the maximum number of market-agents interviewed pre-intervention could be tracked, and attrition minimized. We were successfully able to track and interview all 1,050 cold-storage users who had been interviewed In November 2020 at the post-intervention survey.

Eventual sample breakdowns of cold-storage users and non-users in intervention markets are outcomes of agents' self-selection. Furthermore, while market-agents in control markets are selected randomly from all agents registered with corresponding associations in comparison markets, their characteristics may still differ significantly from market-agents in intervention markets. As described above, our empirical methods mitigate potential biases due to these sampling procedures through the combination of difference-in-difference and matching estimators.

Out of 700 and 350 market-agents interviewed in the intervention markets and comparison markets, 22 and 28, respectively, had to be dropped due to missing values for key explanatory variables. For each market-agent, we also asked for information about 20 horticulture commodities. After dropping the observations from crop-specific information, our primary final samples therefore consist of 678 market-agents in interventions consisting of 243 cold-storage users and 435 non-user market-agents, supplemented by information of 322 market-agents in comparison markets. However, since our analyses deal with varying units and missing outcome values, sample sizes are discussed in more detail in the results section.

3.3 Descriptive statistics

3.3.1 Key characteristics of market-agents at pre-intervention period

A majority of these market-agents are traders and wholesalers, while some are retailers or farmers who bring products directly from their farms. Widely handled crops include tomato, spring onions, and green peppers, traded by at least 1/3 of all three types of respondents. Other major vegetables that are relatively commonly traded are carrots, cabbage, cucumbers, okra, and lettuce; among fruits, watermelon and oranges are relatively commonly traded.

Table 3 summarizes the descriptive statistics of pre-intervention variables X_{it}. On average, respondents are around 40 years old, a majority of whom were born in the area where the markets are located. Typically, they had completed 6 years of formal education. About half of them have relatives who are likewise engaged in trading activities.

[Insert Table 3]

Relatively few respondents own market capital assets like personal storage space (ambient temperature), generators, or motorized vehicles. Inside the market, they typically have access to small market stalls with basic infrastructure, typically with the size of 10 square meters,

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157 tomato traders (mostly retailers) across several markets within the city. With these sample sizes, Vandeplas & Minten (2015) identified statistically significant effects of various crop attributes on prices (quality premiums). Based on these studies, our sample sizes of market-agents were considered likely to be sufficient to detect the effects of the use of cold-storage on similar sales activities by horticulture market agents.

located a few minutes from the market entry-gate, covered with roof or ceiling, and with access to drainage. A fraction of them also have electricity access, paved road in front of their stalls, and piped water. Very few of them had previously used cold-storage.

At the pre-intervention period, the three sample groups of market-agents were characteristically different from each other with respect to these observable characteristics. In intervention markets, those who later became cold-storage users had market stalls that were generally closer to where the cold-storage was later installed than those of non-users in intervention markets. Proximity to cold-storage might have been one factor inducing their use of storage. Generally, cold-storage users were relatively closer to various other facilities inside the market premises and tended to own more business assets, but they were less likely to have a space/stall for their exclusive use or located far away from piped water or were less likely to have a paved tar road in front of their stalls.

3.3.2 Key horticulture trading practices of market-agents

Table 4 through Table 6 present the key horticulture commodities trading practices of the interviewed market-agents. Typically, they earned gross revenues of US$365 per week from selling 480 kilograms of horticulture commodities, of which 6.9% is net revenue (Table 4). Typically, they wasted 9.4% of all horticulture commodities before they could be sold. In the pre-intervention period, cold-storage users were selling and generally earning less, and wasting a greater share of their commodities, than non-users in the intervention markets (a2).

[Insert Table 4]
[Insert Table 5]
[Insert Table 6]

Certain value-adding practices were used during the pre-intervention period (Table 5). In particular, a significant majority of agents use practices before sales like grading/sorting, bagging/boxing/packaging, and cleaning, including removing stones, foreign materials, and washing. Relatively few of them, however, treated products with pesticides or chemicals. About 20% of agents were receiving advance payments from buyers, an indicator of greater vertical linkages.

Based on the market-agents' standards, approximately 60 to 70% of commodities sold to them (mostly by farmers) are perceived as high quality across various attributes, including size, shape, color, smell, taste, moisture content, skin texture, and density. Conversely, 30 to 40% of commodities are still perceived as average or low quality, leaving room for further quality enhancement.

Sales prices, purchase prices, and price margins were US$0.712 per kilogram, US$0.563 per kilogram, and 22.5% at sample median, respectively, although they ranged across commodities (Table 6). At the pre-intervention period, when all commodities were stored at air temperature, commodities were typically considered to remain fresh for 4.5 days after being purchased by market-agents.

4 Results

4.1 Correlates of cold-storage uses

Table 7 presents the results from the first stage regression of DID-PSM. While these are not structural relations, and thus the estimated coefficients do not have economic meaning, they still offer insights into factors correlated with cold-storage use. First, a greater likelihood of cold-storage is associated with the proximity to cold-storage. This is possibly because, inside market premises that are typically densely populated, transactions costs of moving products between cold-storages and respective market stalls can be substantially high, as products are exposed to the sun and get damaged when moved, especially if products are valued in terms of freshness, suitable appearances, among other qualities. The use of cold-storage is also associated with greater proximity to certain market facilities and access to drainage at the stall.

[Insert Table 7]

The use of cold-storage is also more likely if the market stall is further away from the nearest piped water source, possibly because greater access to stable water that can keep products cool can sometimes substitute for cold-storages. More educated market-agents may also readily accept relatively new technologies like solar-powered cold-storages. Having more sources of credit, which can potentially allow taking loans for longer periods, may also encourage market-agents to avoid distress sales and instead keep products in cold-storages until prices improve.

Cold-storage use is more likely if market stalls are far from the market representatives' office. This may be because cold-storages tend to be installed further away from market-representatives' offices, as such offices tend to be in taller buildings that block sunlight needed for solar-powered cold-storages, or there is more competition for space around these offices. Cold-storage use is also more likely if the market-agent speaks fewer languages, has fewer business assets, does not have exclusive space, or does not have electricity in his or her stall. This may be because speaking fewer languages or having fewer business assets makes it more difficult to sell products more quickly without cooling. Not having exclusive stalls may induce using cold-storages as additional standard storage space and a lack of electricity in the stalls may also induce using cold-storage for not only cooling purpose but also other electricity needs like charging phones.

PSM also successfully achieves balancing properties (Table 15 in Appendix). Table 15 shows that, in PSM samples, only 3 out of 30 variables exhibit a statistically significant difference in means at 10% statistical significance level between treatment and control samples, which we would observe under the assumption of a null hypothesis that two samples are balanced. In addition, the computed Rubin's B value (0.4) and R value (0.78) suggest that the PS-matched samples are well-balanced.[7]

4.2 Market agent-level outcomes on sales revenue, profit, food loss

Table 8 summarizes the effects of using cold-storages on sales revenue, profitability, and sales volume, as well as perceived reduction of food loss, estimated at the market-agent level. Table 8 suggests that using cold-storages led to statistically significant improvements in many of these outcomes. It has led to net increases in gross sales revenues and sales volumes by as much

[7]In a well-balanced sample, Rubin's B should be less than 0.4, Rubin's R should be between 0.5 and 2.0 (Cochran & Rubin 1973; Rubin 2001), and few variables should have statistically significant differences in means between adopter and nonadopter samples.

as 69% and net increases in the share (%) of net revenues to gross revenues by 13 percentage points. It has also led to a net reduction in the share (%) of the value of loss to total gross revenue by 11.2 percentage points for items put in cold-storage, which was substantial enough that, even when considering all items sold by market-agents, the loss was reduced by 4.7 percentage points at the market-agent level. These effects are largely consistent with other PSM specifications. The estimated Rosenbaum bounds suggest that statistical significance holds even when the odds-ratio of using cold-storage changes by about 40 percent, meaning that the results are reasonably robust against hidden bias which PSM results are sometimes sensitive to. As is discussed in subsequent sections, the increase in sales may not only be due to reduced loss, but also to supply responses to increased prices.

[Insert Table 8]

4.2.1 Effects of using cold-storage on prices, shelf-life, quality, and value-adding practices

Table 9 through Table 11 present the estimated effects on prices, quality-enhancing practices by market-agents between purchase and sales, relation with buyers, and how farmers also improved quality when selling to cold-storage using market-agents. These are estimated at market-agent and crop levels, through equations (3) and (4) (Table 14 in Appendix presents the first-stage bivariate probit model. Both first-stage and second-stage show that many coefficients are statistically significant, suggesting that the DID-BIPW models estimated adequately identify the relationships between cold-storage usage, crop choice, prices, and quality-enhancing practices).

[Insert Table 9]
[Insert Table 10]
[Insert Table 11]

In Table 9 through Table 11, samples for fixed-effects methods consist of 2,604 price observations reported, differentiated by cold-storage use and crops, for each of 678 market-agent at post-intervention period (average 3.8 observation per market agent). The sample size for the first stage of DID-BIPW is 13,560, which consists of 678 market-agents in intervention markets multiplied by 20 horticulture crops of our focus. The second stage of DID-BIPW only uses observations for crops that were sold both at pre-intervention and post-intervention periods, and thus significantly smaller, 318 observations for all crops combined (of which 132 observations for tomato). This means that a majority of market-agents changed their crops between the pre-intervention and post-intervention periods. This validates our DID-BIPW models, which address potential biases arising from attrition and accretion of crops between the survey rounds.

Table 9 suggests that using a cold-storage increased sales price by approximately 15 to 20%, and increased price margins by 15 percentage points. These results are consistent in both estimation methods (3) and (4). The increased prices and price margins are consistent with the hypothesis that price premiums exist for the improved freshness of perishable horticulture products enabled by cold-storages. In addition to raising sales price, Table 9 also suggests that the effects on purchase price are also somewhat positive (i.e., using cold-storage also induced market-agents to pay higher prices to farmers). On average, market-agents perceived that using cold-storage allowed them to keep the products fresh for approximately 7 to 11 days longer.

Table 10 suggests that using cold-storages also induces various value-adding practices before sales by market-agents, including grading and sorting; packaging, including bagging and boxing; washing and cleaning, like removing stones or foreign materials; and application of chemicals and pesticides. Effects on grading and sorting are particularly consistent across estimation methods, including tomato which is most commonly sold across markets. These results are consistent with the hypothesis that access to cooling technologies that preserve freshness and attract price premiums induce improved trading practices.

Table 10 also shows that using cold-storage technologies increases the likelihood of receiving advance payments from buyers. This reflects buyer's demand for fresher commodities and trust in cold technologies, and is often considered as an indicator of institutional modernization of horticulture value chains (e.g., Minten et al. 2012).

Table 11 shows that use of cold-storage by market-agents for certain commodities also often induced farmers to sell horticulture products of improved quality in terms of size, shape, color, flavor, taste, moisture content, skin texture, and density. These results are consistent with the hypothesis that cooling technologies enhance economic returns to quality attributes, and farmers respond to such premiums.

4.2.2 Relative absence of (negative) spillover effects

Even when cold-storage usage has significant impacts, these impacts may simply reflect the reallocation of profits from non-users of cold-storage, due to negative spillover effects within the horticulture markets. One way to investigate the presence/absence of such negative spillover effects is to compare the patterns among market-agents who decided not to use cold-storages in intervention markets with those of market-agents in control markets by adjusting for self-selection among the former respondents. Specifically, we compare whether the average Δy_{it} differs statistically significantly in intervention markets among market-agents not using cold-storages, and among market-agents in control markets, by adjusting the values for the former through IPW. Statistically significantly lower values for the former would suggest that they experienced worse outcomes than the latter, which would indicate evidence of negative spillovers within intervention markets. However, statistically insignificant differences point to the relative absence of such negative spillovers. Results are shown in Table 12. The sample size for Table 12 consists of 757 market-agents, including 435 non-users in intervention markets and 322 market-agents in comparison markets.

Table 12 shows the statistical significance in differences for key outcome variables, such as sales volume, gross revenues, profit margins, and the proportion of the loss. None of these differences are statistically significant. Our results therefore provide indicative evidence that negative spillover effects are relatively absent within the intervention markets. The absence of differences in the changes in sales volumes, gross revenues, or profit margins suggest that prices received by non-users in intervention markets also were unaffected by the introduction of cold-storages.

[Insert Table 12]

While it is beyond the scope of this study to identify why the negative spillover may be absent, it may reflect relatively elastic demand for horticulture commodities (both over space and over time), such that increased transactions by cold-storage users do not significantly crowd-out the transactions by non-users.

4.3 Rough calculation of returns to cold-storage

It is beyond the scope of this study to obtain rigorous estimates of the economic returns to similar cold-storage investments. We can, however, roughly assess how the magnitude of the estimated impacts compare with the investment and operational costs and gain prospects in the viability of scaling up similar interventions (Table 13). Using the estimated results, the average characteristics of market-agents at the pre-intervention periods, and the average number of cold-storage users per intervention market, estimated economic impacts in Table 8, a cold-storage is expected to generate an additional profit of US$1,653 per month per market. After subtracting operating and maintenance costs (US$142–162 per month, Table 1), cold-storage still generates a net profit of approximately US$8,000 per year based on a conservative estimate that similar additional profits can be generated over 6 months per year. This is sufficient to recoup the investment costs of US$40,000 per cold-storage and interest rates in the order of 10 years even when interest rates are 7% per year (which doubles the investment costs in 10 years). Given that solar panels can still perform at more than 80% of initial efficiency after 25 years, and other major parts like inverters and batteries are equally long-lasting, the installed solar-powered cold-storages can be potentially promising technologies. While more rigorous analyses are needed based on longer-term monitoring of the impacts, the initial assessments offer promising views of the viability for installing similar solar-powered cold-storages in other suitable horticulture markets in Nigeria.

[Insert Table 13]

4.4 Effects of cold-storages on nutrients through food-science experiments

The aforementioned analyses confirm the effects of cold-storage on lengthened shelf-life and economic premiums. We further conducted food-science experiments to assess whether using cold-storage indeed leads to preservation of physical and nutritional quality of horticulture products. We specifically focused on 6 popular horticulture crops (cabbage, carrot, cucumber, orange, tomato) and placed randomly selected groups in cold-storage and in ambient temperature storage, and monitored the changes in measurements of three physical quality indicators (weight, firmness, and color), and five nutrient quality indicators (beta-carotene, beta-lycopene, vitamin C, titratable acidity, total soluble solid) (Appendix C describes the detail experiment procedures).

Figure 2 through Figure 4 show the estimated results. Cold-storage helped horticulture crops to retain their original quality and nutrients for a longer time than they do under the open-air conditions that prevail in northern Nigeria. For the 5 commodities studied (tomatoes, carrots, oranges, cucumbers, and cabbages), original weight, firmness, and colors tend to change quickly after a few days if they are kept outside, but are retained much longer in cold-storage. For vitamin C, the rates of loss over time are slowed by 1/2 to 1/3. For example, in the case of oranges, while vitamin C drops to half after 4 days and 1/3 after 7 days if kept outside, this is delayed to 10 days and 20 days if kept inside the cold-storage. For beta-carotene, similar to vitamin C, loss over time was slowed by 1/2 to 1/3. For beta-lycopene, loss over time was generally slowed by 1/2. For titratable acidity, loss over time was slowed by 1/2 to 1/3. For total soluble solid, quality was retained for at least 24 days in cold-storage, but tended to start declining after 7 days if kept outside.

These results suggest that cold-storage does not simply bring economic premiums by affecting buyers' perceptions of the products, but they do in fact preserve original physical and nutritional qualities even a few weeks after they were stored in cold-storages.

5 Conclusions

Cooling technologies are becoming increasingly integral elements of global food system transformation. For example, these technologies can potentially lead to a greater and more stable supply of perishable horticulture commodities and a reduction in food loss and waste, income growth for low-income producers and traders through strengthened linkages with more modern markets, and food and nutrition security through increased consumption of micronutrients. The declining cost of off-grid solar electricity in recent years has enhanced the potential economic viability of providing such cooling technologies in poor regions like northeast Nigeria, where access to a conventional source of electricity has remained costly. Improved efficiency of solar panels in high-temperature environments has also enhanced the potential for successful transfer of these technologies to tropical countries. However, the knowledge gap is still vast as to the actual impacts of certain cooling technologies, such as solar-powered modern cold-storages in developing countries.

This study provided critical evidence to fill this knowledge gap through an evaluation of an intervention to install solar-powered cold-storage in northeast Nigeria. Using these cold-storages led to a significant increase in horticulture products sold and profits earned by market-agents, while significantly reducing the share of products lost or wasted before sale. These increases in quantity sold by market-agents are not simply due to reduced loss but also supply responses to higher prices that market-agents were able to command when using cold-storages and were then able to pass through to farmers selling products to them. These benefits were realized without any negative spillovers to non-user market-agents in the same intervention markets. Higher prices were also likely to have provided economic incentives to improve the quality of horticulture products farmers sell to market-agents, and to engage in further value-adding practices by market-agents. These improvements characterize important elements of food system modernization, and solar-powered cold-storages can be one of the potentially viable technological triggers for such a process, particularly in developing regions like northeast Nigeria. The results also suggest that solar-powered cold-storages can potentially be a viable technology to address the dual goals of meeting growing electricity needs for transforming the global food system while also mitigating climate change through reduced carbon emissions.

References

Ali M & SC Tsou. (1997). Combating micronutrient deficiencies through vegetables—a neglected food frontier in Asia. *Food Policy 22*(1), 17–38.

Allen S & A de Brauw. (2018). Nutrition sensitive value chains: theory, progress, and open questions. *Global Food Security 16*, 22–28.

Austin P. (2011). A tutorial and case study in propensity score analysis: an application to estimating the effect of in-hospital smoking cessation counseling on mortality. *Multivariate Behavioral Research 46*(1), 119–151.

Behuria P. (2018). Examining effectiveness and learning in Rwandan policymaking: the varied outcomes of learning from failure in productive sector policies. *Journal of International Development 30*(6), 1023–1043.

Béné, C., Oosterveer, P., Lamotte, L., Brouwer, I. D., de Haan, S., Prager, S. D., ... & Khoury, C. K. (2019). When food systems meet sustainability–current narratives and implications for actions. *World Development 113*, 116–130.

Bravo-Ureta BE, D Higgins & A Arslan. (2020). Irrigation infrastructure and farm productivity in the Philippines: a stochastic meta-frontier analysis. *World Development 135*, 105073.

Caliendo M & S Kopeinig. (2008). Some practical guidance for the implementation of propensity score matching. *Journal of Economic Surveys 22*(1), 31 –72.

Cameron AC, JB Gelbach & DL Miller. (2011). "Robust Inference with Multiway Clustering." *Journal of Business and Economics Statistics 29*(2), 238–249.

Cochran WG & DB Rubin. (1973). Controlling bias in observational studies: a review. *Sankhyā: The Indian Journal of Statistics, Series A 35*(4), 417–446.

Coley D, M Howard & M Winter. (2009). Local food, food miles and carbon emissions: a comparison of farm shop and mass distribution approaches. *Food policy, 34*(2), 150-155.

Fafchamps M, RV Hill & B Minten. (2008). Quality control in nonstaple food markets: evidence from India. *Agricultural Economics 38*(3), 251–66.

Garnett T. (2011). Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Policy 36*, S23–S32.

Gebreeyesus M & T Sonobe. (2012). Global value chains and market formation process in emerging export activity: evidence from Ethiopian flower industry. *Journal of Development Studies 48*(3), 335–348.

Goldstein B, SF Hansen, M Gjerris, A Laurent & M Birkved. (2016). Ethical aspects of life cycle assessments of diets. *Food Policy 59*, 139–151.

Gu A & HI Yoo. (2019). vcemway: a one-stop solution for robust inference with multiway clustering. *The Stata Journal 19*(4), 900–912.

Häsler B. et al. (2019). Using participatory rural appraisal to investigate food production, nutrition and safety in the Tanzanian dairy value chain. *Global Food Security 20*, 122–131.

Heckman J, H Ichimura & P Todd. (1997). Matching as an econometric evaluation estimator: evidence from evaluating a job training programme. *Review of Economic Studies 64*(4), 605–654.

Heckman J, H Ichimura, J Smith & P Todd. (1998). Characterizing selection bias using experimental data. *Econometrica 66*(5), 1017–1098.

Huber M. (2014). Treatment evaluation in the presence of sample selection. *Econometric Reviews 33*(8), 869–905.

Hunsberger C. (2010). The politics of Jatropha-based biofuels in Kenya: convergence and divergence among NGOs, donors, government officials and farmers. *Journal of Peasant Studies 37*(4), 939–962.
International Food Policy Research Institute (IFPRI). (2020). *2020 Global Food Policy Report: Building Inclusive Food Systems*. Washington, DC: IFPRI.
Imbens G & J Woolridge. (2009). Recent developments in the econometrics of program evaluation. *Journal of Economic Literature 47*(1), 5–86.
Kashyap D & T Agarwal. (2020). Food loss in India: water footprint, land footprint and GHG emissions. *Environment, Development and Sustainability 22*(4), 2905–2918.
Kirubi C, A Jacobson, DM Kammen & A Mills. (2009). Community-based electric micro-grids can contribute to rural development: evidence from Kenya. *World Development 37*(7), 1208–1221.
Kumar A, H Takeshima, G Thapa, N Adhikari, S Saroj, M Karkee & PK Joshi. (2020). Adoption and diffusion of improved technologies and production practices in agriculture: insights from a donor-led intervention in Nepal. *Land Use Policy 95*, 104621.
Lewis DJ. (1996). 'Appropriating' technology? Tractor owners, brokers, artisans and farmers in rural Bangladesh. *Journal of International Development 8*(1), 21–38.
Lichtenberg E & C Ding. (2008). Assessing farmland protection policy in China. *Land Use Policy 25*(1), 59–68.
Mason NM, A Wineman, L Kirimi & D Mather. (2016). The effects of Kenya's 'smarter' input subsidy programme on smallholder behaviour and incomes: do different quasi-experimental approaches lead to the same conclusions? *Journal of Agricultural Economics 68*(1), 45–69.
Mayton H., et al. (2020). Conceptualizing sustainable diets in Vietnam: minimum metrics and potential leverage points. *Food Policy 91*, 101836.
McDonald MG. (2000). Food firms and food flows in Japan 1945–98. *World Development 28*(3), 487–512.
Minten B, A Vandeplas & J Swinnen. (2012). Regulations, brokers, and interlinkages: the institutional organization of wholesale markets in India. *Journal of Development Studies 48*(7), 864–886.
Minten B, T Reardon, KM Singh & R Sutradhar. (2014). The new and changing roles of cold storages in the potato supply chain in Bihar. *Economic and Political Weekly 49*(52), 98–108.
Nkonya E, D Bawa, E Kato, D Maurice, N Murtala, H Nuhu, P Kwaghe, Y Bila & R Sani. (2019). *Humanitarian assistance and resilience-building: Impact of Fadama III–AF II on food security and livelihood restoration in northeastern Nigeria*. IFPRI Project Note. IFPRI.
Pelletier N. et al. (2011). Energy intensity of agriculture and food systems. *Annual Review of Environment and Resources 36*, 223–246.
Pueyo A, M Carreras & G Ngoo. (2020). Exploring the linkages between energy, gender, and enterprise: evidence from Tanzania. *World Development 128*, 104840.
Rakshit S. (2011). Capital intensification, productivity and exchange–a class-based analysis of agriculture in West Bengal in the current millennium. *Journal of Agrarian Change 11*(4), 505–535.
Ricciardi V, N Ramankutty, Z Mehrabi, L Jarvis & B Chookolingo. (2018). How much of the world's food do smallholders produce? *Global Food Security 17*, 64–72.
Rosenbaum, P. R. (2002). *Observational studies.* New York: Springer.
Rubin D. 2001. Using propensity scores to help design observational studies: application to the tobacco litigation. *Health Services and Outcomes Research Methodology 2*(3–4), 169–188.

Schreinemachers P, EB Simmons & MC Wopereis. (2018). Tapping the economic and nutritional power of vegetables. *Global food security 16*, 36–45.
Smith J & P Todd. (2005). Does matching overcome LaLonde's critique of nonexperimental estimators? *Journal of Econometrics 125*(1–2), 303–353.
Spang ES, et al. (2019). Food loss and waste: measurement, drivers, and solutions. *Annual Review of Environment and Resources 44*, 117–156.
Steyn JM, AC Franke, JE Van der Waals & AJ Haverkort. (2016). Resource use efficiencies as indicators of ecological sustainability in potato production: A South African case study. *Field Crops Research 199*, 136–149.
Surendran S, et al. (2020). Characterising the fruit and vegetable environment of peri-urban Hyderabad, India. *Global Food Security 24*, 100343.
Todo Y. (2011). Impacts of aid-funded technical assistance programs: Firm-level evidence from the Indonesian foundry industry. *World Development 39*(3), 351-362.
Tranchant JP, A Gelli, L Bliznashka, AS Diallo, M Sacko, A Assima, EH Siegel, E Aurino & E Masset. (2019). The impact of food assistance on food insecure populations during conflict: Evidence from a quasi-experiment in Mali. *World Development 119*, 185–202.
Tschirley D, T Reardon, M Dolislager & J Snyder. (2015). The rise of a middle class in East and Southern Africa: Implications for food system transformation. *Journal of International Development, 27*(5), 628-646.
Uçar A & AÖ Özçelik. (2013). Individuals' knowledge and practices of the cold chain. *Ecology of Food and Nutrition, 52*(2), 116-129.
Vandeplas A & B Minten. (2015). Food quality in domestic markets of developing economies: a comparative study of two countries. *Agricultural Economics 46*(5), 617–628.
Villa JM. (2016). diff: simplifying the estimation of difference-in-differences treatment effects. *The Stata Journal, 16*(1), 52-71.
Whitfield L. (2012). Developing technological capabilities in agro-industry: Ghana's experience with fresh pineapple exports. *Journal of Development Studies 48*(3), 308–321.

Tables

Table 1. Operating costs of cold-storages

Cost items	**Cost (US$ / month)**
Internet data needed for remote monitoring - ColdHubs Advanced Remote Monitoring Systems using IoT Central on Microsoft Azure Cloud, regularly monitor door openings, battery state of charge, ambient temperature, cold room temperature, solar irradiation daily	50
Hub Operators (ladies)	52
Security	20
Land use fees	10 – 30
Cleaning of solar panels once from dust	10
Total	142 – 162

Source: Authors' computations based on information from ColdHubs Ltd.

Table 2. Panasonic solar-panels and competing products

Manufacturer	Model	Maximum power output per panel (Watt)	Price per maximum power output wattage （US$ / Watt）	Efficiency (%)	Temperature Coefficient (% / °C)
Panasonic	**380W Monocrystalline (PERC) Solar PV Module**	**380**	**0.58**	**19.6**	**- 0.39**
Competing manufacturer A	Competing model	330	0.51	16.9	- 0.40
Competing manufacturer B	Competing model	260	0.57	15.5	- 0.41

Source: Authors.

Table 3. Descriptive statistics (pre-intervention period)

Variables	Market agents in intervention markets		Market agents in comparison markets
	Market-agents who later become cold-storage-users	Market-agents who remain as non-users	
Sample size	**243**	**435**	**322**
Age (years)	41.720	38.762	41.834
Female (yes = 1)	0.028	0.056	0.149
Household size (count)	10.544	10.947	11.191
Education completed (years)	5.708	6.713	6.289
Native of the LGA of the market (yes = 1)	0.584	0.533	0.557
Number of languages spoken (number)	1.888	2.009	2.326
Traders among relatives (yes = 1)	0.520	0.629	0.417
Access to ready credit sources (number)	2.896	1.796	2.497
Capacity of own storage (ton)	2.551	1.717	0.984
Business assets (US$)	62.111	27.424	19.383
Having exclusive space in market stall (yes = 1)	0.476	0.727	0.717
Distance to cold-hub storage from market stalls (Euclidean distance)	0.134	0.243	N / A
Distance to entry gate (travel time, minutes)	5.580	7.769	4.272
Distance to public toilet (travel time, minutes)	5.215	8.054	6.617
Distance to canteen (travel time, minutes)	4.504	5.581	4.842
Distance to meeting room (travel time, minutes)	5.241	5.964	7.093
Distance to market representative's office (travel time, minutes)	5.592	5.885	7.052
Distance to the nearest piped water source (travel time, minutes)	15.313	8.298	26.563
Market stall has improved floor (yes = 1)	0.344	0.256	0.337
Market stall has a roof (yes = 1)	0.812	0.678	0.583
Market stall has paved road in front (yes = 1)	0.200	0.300	0.220
Market stall has drainage (yes = 1)	0.532	0.393	0.840
Market stall has covered drainage (yes = 1)	0.164	0.147	0.120
Market stall has electricity (yes = 1)	0.204	0.220	0.177
Market 1 (Dutse Daily Market: Jigawa State)	0.192	0.116	N / A
Market 3 (Gombe Main Market: Gombe State)	0.064	0.187	N / A
Market 6 (Jimeta Modern Market: Adamawa State)	0.116	0.158	N / A
Market 8 (Muda Lawal Market: Bauchi State)	0.060	0.189	N / A
Market 9 (Potiskum-Mamudo Market: Yobe State)	0.184	0.120	N / A
Market 11 (Wunti Market: Bauchi State)	0.188	0.118	N / A
Market 14 (Yola Bypass Market: Adamawa State)	0.196	0.113	N / A

Source: Authors. N / A = not applicable.

Table 4. Key characteristics at market-agent's level (pre-intervention period)

Variables	Cold-storage-users in intervention markets	Non-users in intervention markets	Market-agents in comparison markets	All
Sample size[a]	**243**	**435**	**322**	**1,000**
Gross revenue (US$ / week)	311	527	335	365
Net revenue margin (proportion)	0.060	0.070	0.064	0.069
Sales volume (kg / week)	372	745	448	480
Wastage (proportion of commodities not sold due to wastage to total quantity purchased, all crops combined)	0.130	0.095	0.091	0.094

Source: Authors.

[a]Due to omission of invalidate sample, the total sample size is less than the total number interviewed of 1,050.

Table 5. Quality and value-adding practices (pre-intervention period, market-agents and crop level)

Variables	Cold-storage-users in intervention markets	Non-users in intervention markets	Those in comparison markets	All
Sample size	**559**	**913**	**701**	**2,173**
Value-adding practices by market-agents				
grading / sorting before sales (yes = 1)	0.848	0.865	0.909	0.875
bagging, boxing, packaging before sales (yes = 1)	0.893	0.652	0.646	0.712
cleaning like removing stones, foreign materials, washing before sales (yes = 1)	0.970	0.890	0.889	0.910
treating products with pesticides / chemicals before sales (yes = 1)	0.102	0.036	0.030	0.051
receiving advanced payment from buyers (yes = 1)	0.206	0.269	0.117	0.225
Quality of products sold by farmers to market-agents (perceptions by market-agents)				
Size (high quality = 1)	0.701	0.691	0.679	0.689
Shape (high quality = 1)	0.664	0.575	0.659	0.625
Color (high quality = 1)	0.730	0.630	0.658	0.665
Smell (high quality = 1)	0.651	0.627	0.663	0.645
Taste (high quality = 1)	0.611	0.644	0.655	0.639
Moisture content (high quality = 1)	0.571	0.617	0.659	0.618
Skin texture (high quality = 1)	0.682	0.636	0.675	0.660
Density (high quality = 1)	0.585	0.610	0.670	0.623

Source: Authors.

Table 6. Prices, price margins, days products stay fresh (by major commodities, raw sample means at pre-intervention period)

Variables	Major commodities traded							All commodities
	Cabbage	Green Pepper	Okra	Spring Onions	Tomato	Orange	Watermelon	
Sample size	**145**	**354**	**147**	**332**	**487**	**91**	**91**	**2,173**
Sales price (US$ / kg)	0.365	1.183	0.496	0.875	0.786	0.261	0.285	0.712
Purchase price (US$ / kg)	0.255	1.000	0.404	0.828	0.634	0.182	0.197	0.563
Price margins (proportion to purchased price)	0.300	0.158	0.250	0.130	0.214	0.250	0.213	0.225
Days products remain fresh	5.9	3.2	3.2	5.8	3.2	6.6	4.1	4.5

Source: Authors.

Table 7. Factors associated with Propensity Scores of using Cold-Storage (First-stage; standard probit) (marginal effects of one-standard-deviation change of each variable on the probability (yes = 1), evaluated at sample means of all other exogenous variables)

Variables	Coef.	Standard error
Demographics		
Age	.069	(.089)
Female	.059	(.071)
Household size	-.059	(.090)
Education completed (years)	.149*	(.081)
Native of the LGA of the market	-.011	(.071)
Number of languages spoken	-.257***	(.074)
Traders among relatives	-.075	(.075)
Number of credit sources	.248***	(.095)
Asset		
Capacity of own storage	-.032	(.070)
Business assets (natural log)	-.804***	(.099)
Exclusive space	-.412***	(.075)
Location		
Distance to cold-hub storage from market stalls	-.197*	(.112)
Distance to entry gate	-.039	(.094)
Distance to public toilet	-.370***	(.138)
Distance to canteen	-.123	(.124)
Distance to meeting room	-.116	(.145)
Distance to market representative's office	.255*	(.135)
Distance to the nearest piped water source	.430***	(.105)
Facilities		
Improved floor	.119	(.114)
Roof	.064	(.081)
Paved road	-.188	(.146)
Drainage	.417***	(.151)
Covered drainage	.072	(.137)
Electricity	-.201**	(.097)
Market dummies	Included	
Sample size	678	
Pseudo-R^2	.418	
p-value (H_0: variables are jointly insignificant)	.000	
Variance inflation factor	2.87	

Source: Authors. *10% **5% ***1%.

Table 8. Impacts of cold-storage on agent level based on DID-PSM

Estimation methods	Outcome variables				
	Revenue (gross)	Share (%) of net revenue to gross revenue	Sales volume	Share (%) of the value of loss to total gross revenue[a]	Share (%) of the value of loss to total gross revenue (among cold-stored items only)[a]
	Percent increase / 100	Percentage point increase / 100	Percent increase / 100	Percentage point change / 100	Percentage point change / 100
Primary method					
Nearest neighbor (4) + caliper (0.005)	.691** (.342) [1.40]	.132*** (.040) [1.75]	.691** (.351) [1.40]	– .047*** (.013) [1.70]	– .112*** (.015) [4.00]
Robustness check through other matching methods					
Nearest neighbor (1) + caliper (0.005)	.873** (.396) [1.45]	.121*** (.049) [1.45]	.744* (.426) [1.60]	– .039*** (.016) [1.45]	– .104*** (.017) [4.10]
Kernel method[b]	.790** (.324) [2.00]	.139*** (.044) [3.25]	.650** (.304) [1.85]	-.047*** (.013) [2.20]	-.138*** (.014) [17.60]
Sample size	678	678	678	678	678

Source: Authors. *10% **5% ***1%. Numbers in brackets are Rosenbaum bounds (Rosenbaum 2002).

Note: [a]"Loss" includes loss for items kept outside cold-storage by cold-storage-user. "Loss among cold-stored commodities only" excludes loss for items kept outside cold-storage by cold-storage-user.

[b]Kernel matching methods had slightly poorer balancing properties than our primary method of nearest neighbor methods combined with caliper. Therefore, results should be interpreted with cautions.

Table 9. Effects on price margins, prices (sales / purchase), and shelf life

	Outcome variables			
Estimation methods	Price	Price margin	Price paid to farmers	Shelf life
	Sales price	Share (%) of price margin to purchase price	Purchase price	Number of days products remain fresh
	Percent increase / 100	Percentage point increase / 100	Percent increase / 100	Days
Market-agent-crop fixed effects methods	.159*** (.016)	.153*** (.053)	.066** (.021)	7.607*** (.525)
Sample size[a]	2,604	2,604	2,604	2,604
DID-BIPW	.218* (.120)	.125* (.072)	.094 (.134)	11.266* (5.961)
Sample size[b]	318	318	318	318
Sample size of first-stage bivariate probit	13,560	13,560	13,560	13,560

Source: Authors. *10% **5% ***1%

Table 10. Effects on quality enhancing practices and receipt of advance payment from buyers

Estimation methods	Grading / sorting before sales	Bagging, boxing, packaging before sales	Cleaning products before sales, like removing stones, foreign materials, washing	Applying pesticides / chemicals before sales	Receive an advance payment from the buyer
	Yes = 1	Yes = 1	Yes = 1	Yes = 1	Yes = 1
Market-agent-crop fixed effects methods	.014*** (.005)	.001 (.006)	-.001 (.006)	.036** (.015)	.116* (.062)
Sample size	2,604	2,604	2,604	2,604	2604
DID-BIPW	.155* (.093)	-.126 (.096)	.123* (.073)	.047 (.089)	.222* (.130)
Sample size	318	318	318	318	318
DID-BIPW for tomato	.541*** (.154)	.363** (.167)	.151 (.120)	.231* (.128)	.636*** (.196)
Sample size	132	132	132	132	132

Source: Authors. *10% **5% ***1%

Table 11. Effects on product quality sold by farmers: (dependent variable = 1 if the quality of products sold to market-agents is "high quality" in various attributes)

Estimation methods	Quality attributes of products sold to market-agents							
	Size	Shape	Color	Flavor	Taste	Moisture content	Skin texture	Density
Market-agent-crop fixed effects methods	.234*** (.055)	.217*** (.061)	.067 (.057)	.117** (.056)	.237*** (.056)	.095 (.059)	.114** (.055)	.081 (.057)
Sample size	2604	2604	2604	2604	2604	2604	2604	2604
DID-BIPW	.295*** (.110)	.218* (.118)	.214* (.116)	.244** (.107)	.315*** (.111)	.204* (.110)	.265** (.105)	.201* (.114)
Sample size	318	318	318	318	318	318	318	318

Source: Authors. *10% **5% ***1%

Table 12. Indicators of the absence of negative spillover effects within the intervention markets

	Sales volume	Revenue	Profit margin	Loss
Differences	-.251 (.397)	-.275 (.373)	-.006 (.034)	-.012 (.009)
p-value (H_0: differences are insignificant)	.527	.461	.853	.152
Sample size	757	757	757	757

Source: Authors.

Table 13. Back-of-the-envelope comparison of economic returns and costs of cold-storages

Parameters	Without cold-storage	With cold-storage
Average gross revenues (US$ per week)	365	617 (= 365*1.691)
Net revenue margin	6.9% of gross revenue	7.8% (= 6.9*1.132)
Assumed share of other operational costs	50% of net market margins	50% of net market margins
Net increase in profit per week		= 11.5 (617*0.078*0.5 – 365*0.069*0.5)
Average number of cold-storage-users per intervention market		35.9
Expected increase in net profit at market-level (US$ per week)		+ 413 (= 11.5*35.9)
Expected increase in net profit at market-level (US$ per month)		+ 1,653
Expected increase in net profit at market-level (US$ per year – assuming similar profit increase can be achieved in 6 months out of 12 months)		+ 9,918
Operating / maintenance costs of cold-storage per market (US$ per cold-storage per month)		142 - 162
Operating / maintenance costs of cold-storage per market (US$ per cold-storage per year)		1,704 – 1,904
Net profit from cold-storages at market-level (US$ per year)		7,975 – 8,215

Source: Authors' computations.

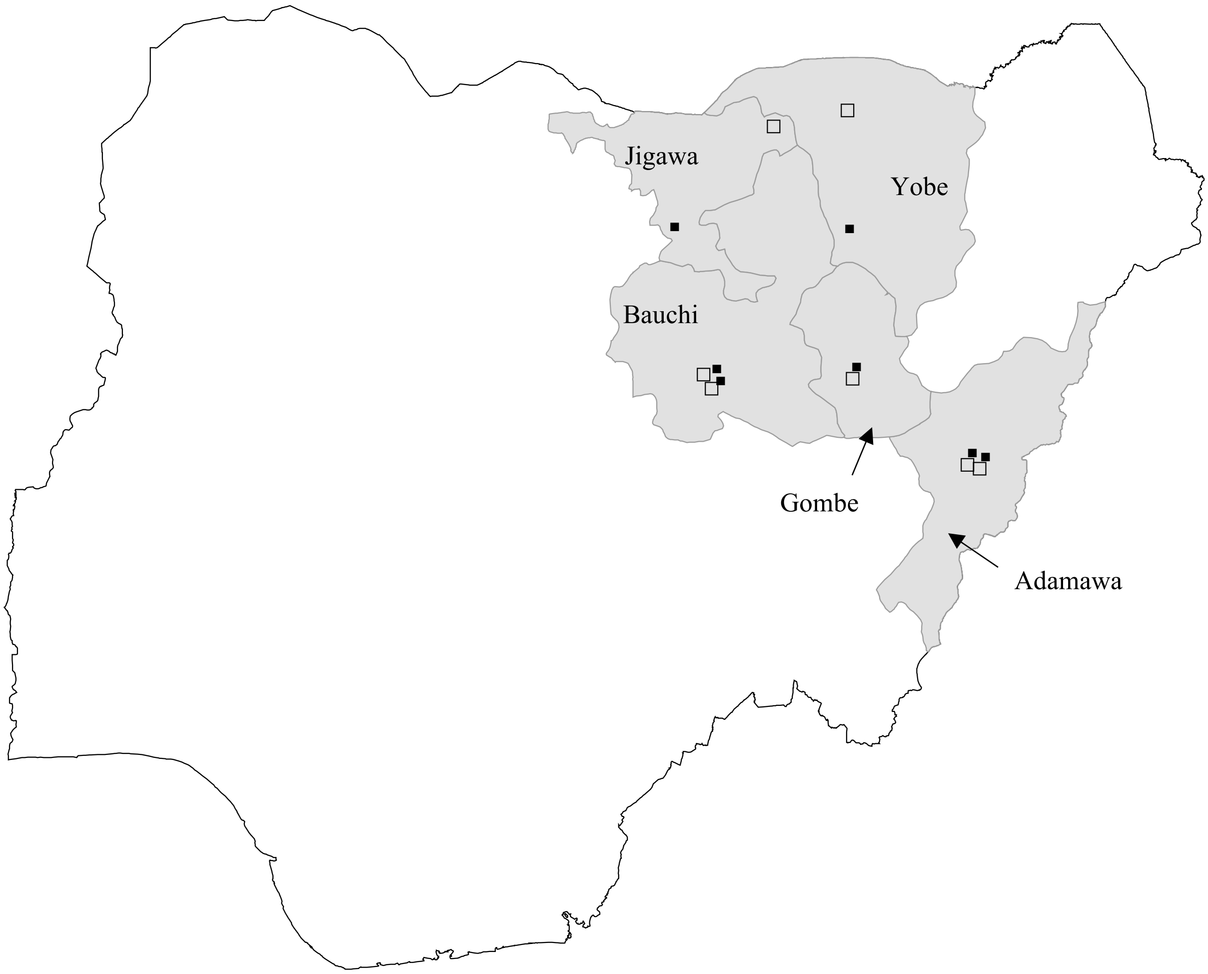

Figure 1. Locations of horticulture markets where cold-storages were installed (intervention markets)

Source: Authors based on IFPRI Survey (2020).

Note: ■ = Intervention markets; □ = Comparison markets

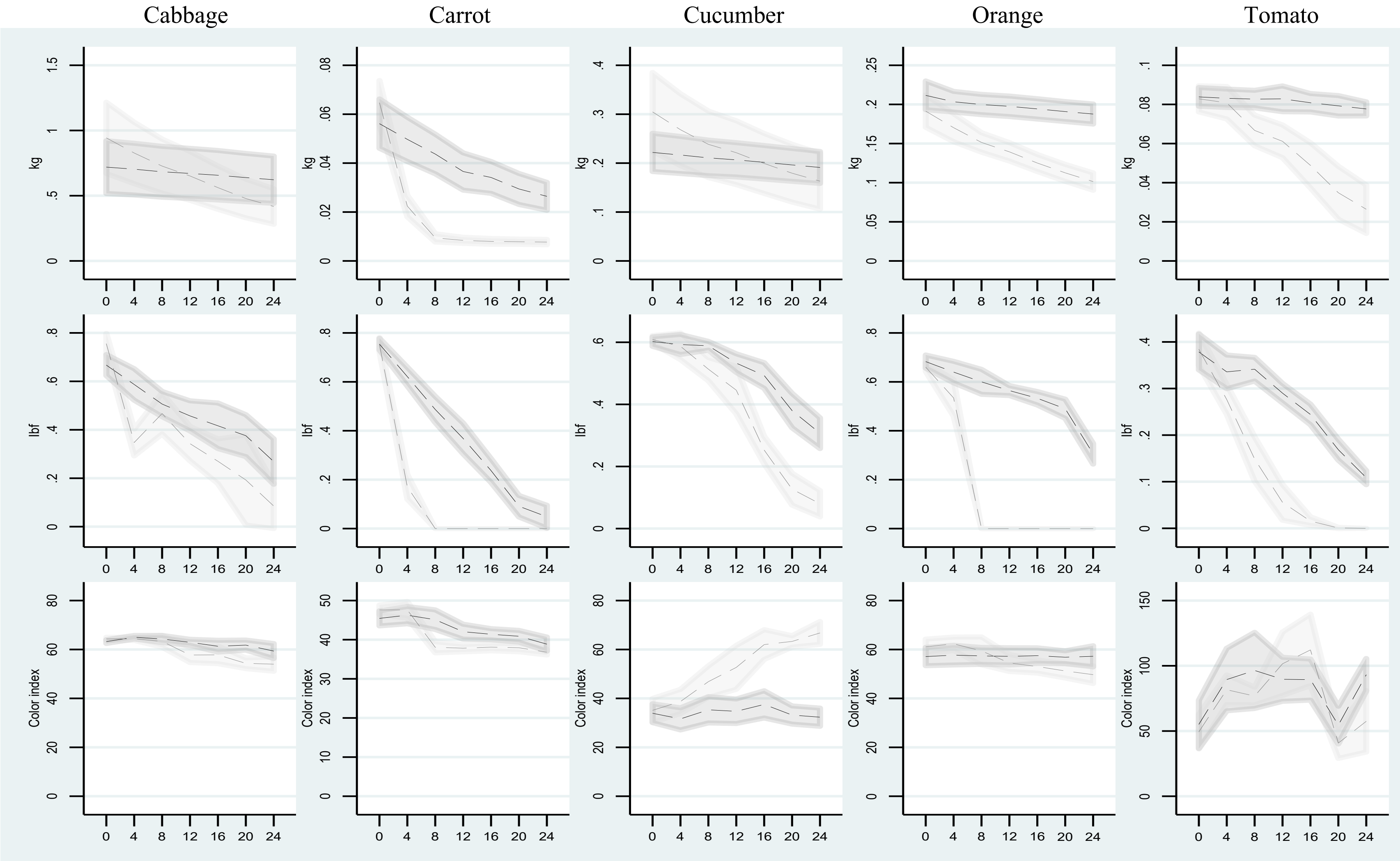

Figure 2. Changes in physical quality of horticulture products over time based on food science experiments

Source: Authors.

Note: First row = weight measured in kg; second row = firmness measured by resistance to compression or pounds-force (lbf); third row = color measured by color index.
Horizontal axes are number of days since the measurement started.
Shared areas reflect the 95% confidence intervals, while dotted lines indicate the average values.
Darker shades and lines correspond to products stored in cold-storage. Lighted shades and lines correspond to products kept under ambient temperature.

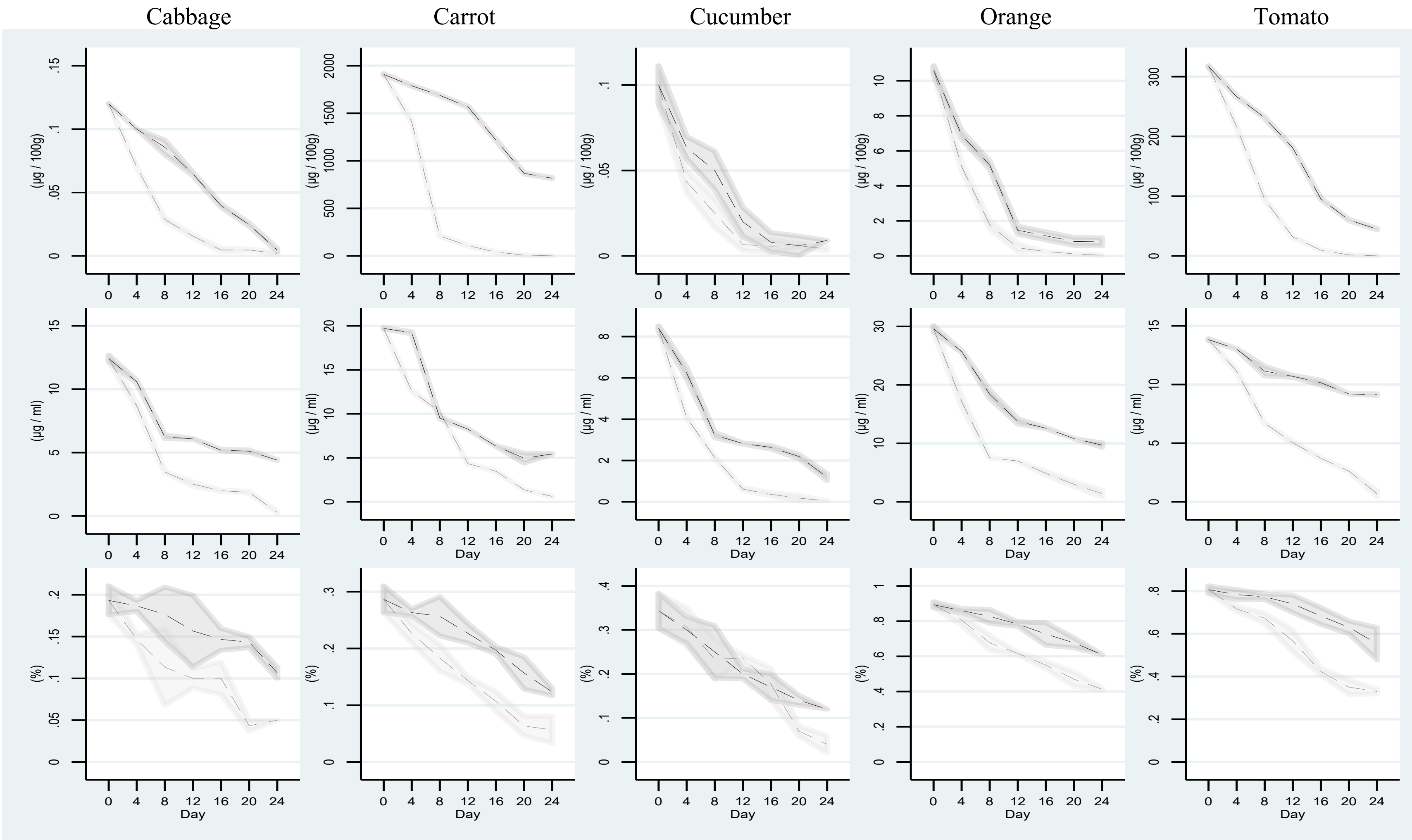

Figure 3. Changes in nutritional quality of horticulture products over time based on food science experiments

Source: Authors.

Note: First row = Beta carotene measured in µg per 100 g; second row = Vitamin C content measured in µg / ml; third row = Titratable Acidity measured in %. Horizontal axes are number of days since the measurement started.

Shared areas reflect the 95% confidence intervals, while dotted lines indicate the average values.

Darker shades and lines correspond to products stored in cold-storage. Lighted shades and lines correspond to products kept under ambient temperature.

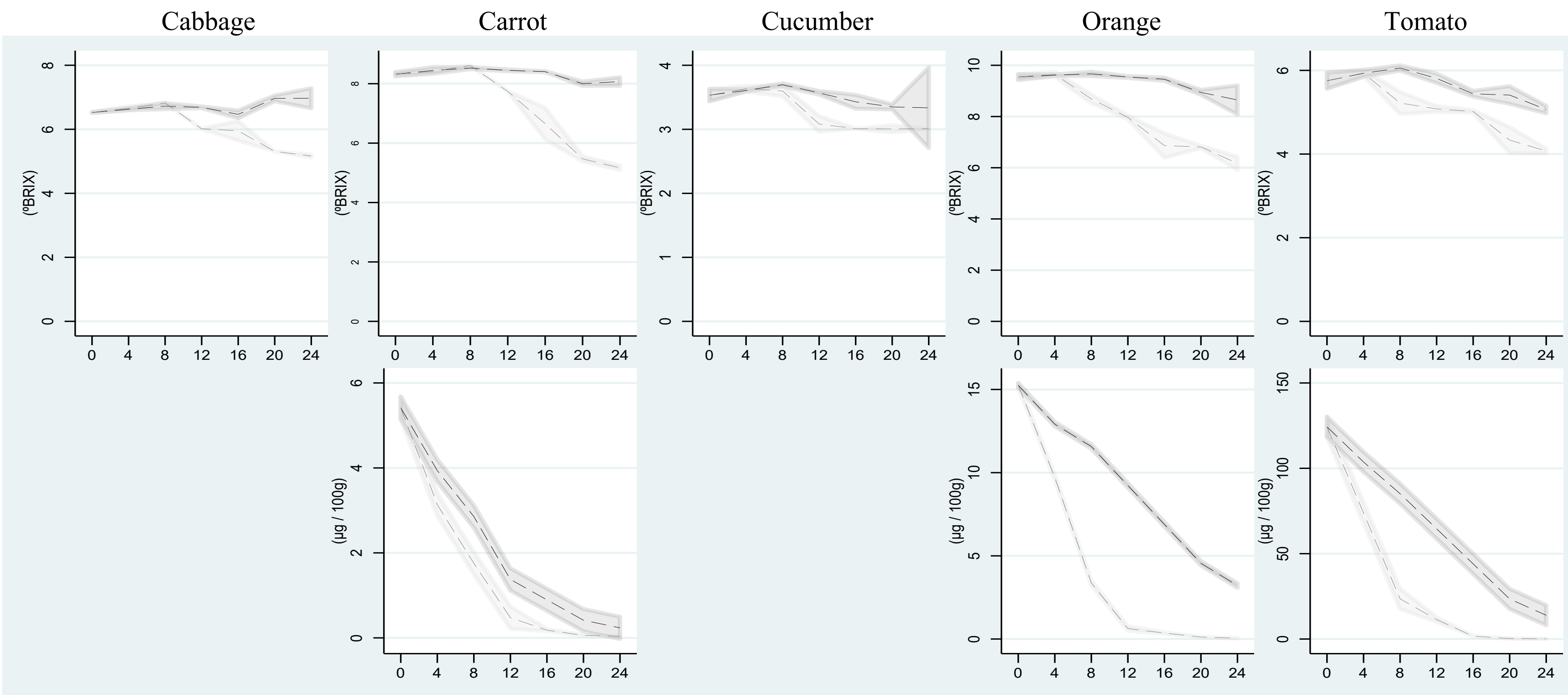

Figure 4. Changes in nutritional quality of horticulture products over time based on food science experiments

Source: Authors.

Note: First row = Total soluble solid measured as ^{0}Brix content; second row = Beta-lycopene measured as µg per 100 g. Horizontal axes are number of days since the measurement started.

Shared areas reflect the 95% confidence intervals, while dotted lines indicate the average values.

Darker shades and lines correspond to products stored in cold-storage. Lighted shades and lines correspond to products kept under ambient temperature.

Appendix A: Additional results

Table 14. Factors associated with Propensity Scores of using Cold-Storage, and selling the same crops at baseline and end-line surveys (Bivariate probit)

Variables	Determinants of using cold-storage		Determinants of selling the same crops at pre- and post- intervention survey periods	
	Coefficient	Standard errors	Coefficient	Standard errors
Demographics				
Age	.180***	(.023)	-.003	(.037)
Household size	-.084***	(.023)	.053*	(.030)
Education completed (years)	.235***	(.021)	-.003	(.033)
Native of the LGA of the market	-.061***	(.019)	.034	(.029)
Number of languages spoken	-.263***	(.019)	.036	(.031)
Traders among relatives	-.070***	(.019)	.036	(.031)
Number of credit sources	-.076***	(.027)	.053*	(.029)
Asset				
Capacity of own storage	.003	(.017)	-.014	(.028)
Business assets (natural log)	-.416***	(.022)	-.034	(.037)
Exclusive space	-.335***	(.019)	-.020	(.030)
Location				
Distance to cold-hub storage from market stalls	-.255***	(.028)	.022	(.040)
Distance to entry gate	.247***	(.028)	-.019	(.043)
Distance to public toilet	-.489***	(.038)	.004	(.063)
Distance to canteen	.008	(.034)	-.069	(.058)
Distance to meeting room	-.139***	(.038)	.073	(.064)
Distance to market representative's office	.366***	(.036)	-.005	(.059)
Distance to the nearest piped water source	.579***	(.028)	-.045	(.052)
Facilities				
Improved floor	.025	(.028)	.018	(.041)
Roof	.140***	(.019)	.000	(.036)
Paved road	-.144**	(.061)	-.080	(.092)
Drainage	.115***	(.038)	.079	(.064)
Covered drainage	.654***	(.046)	-.205***	(.072)
Electricity	-.012	(.025)	-.018	(.039)
Market dummies	Yes		Yes	
No. obs.	13,560		13,560	
p-value (H_0: variables are jointly insignificant)	.000			

Source: Authors. *10% **5% ***1%.

Table 15. Balancing properties (single PSM)

Variables	Non-adjusted raw sample		IPW-sample (common support)	
	Cold-storage-user	Non-user	Cold-storage-user	Non-user
Demographics				
Age	41.720	38.762***	40.907	40.761
female	0.028	0.056**	0.037	0.086*
Household size	10.544	10.947	10.642	10.845
Education completed	5.708	6.713**	6.605	5.734
Native of the LGA of the market	0.584	0.533*	0.580	0.628
Number of languages spoken	1.888	2.009**	1.926	1.886
Traders among relatives	0.520	0.629***	0.593	0.477**
Number of credit sources	1.105	0.786***	0.959	0.868
Asset				
Capacity of own storage	0.197	0.289	0.197	0.251
Business assets	1.398	2.133*	1.398	1.418
Exclusive space	0.476	0.727***	0.556	0.465
Location				
Distance to cold-hub storage from market stalls	-7.100	-6.876***	-7.083	-7.158
Distance to entry gate	1.247	1.399***	1.245	1.284
Distance to public toilet	1.210	1.398***	1.238	1.248
Distance to canteen	1.109	1.208***	1.120	1.163
Distance to meeting room	1.211	1.276**	1.210	1.278
Distance to market representative's office	1.262	1.276	1.261	1.311
Distance to the nearest piped water source	1.523	1.090***	1.357	1.470
Facilities				
Improved floor	0.344	0.256***	0.377	0.392
Roof	0.812	0.678***	0.753	0.747
Paved road	0.200	0.300***	0.259	0.267
Drainage	0.532	0.393***	0.500	0.538
Covered drainage	0.164	0.147	0.204	0.207
Electricity	0.204	0.220	0.167	0.226
Markets				
Market 1	0.192	0.116*	0.124	0.167
Market 3	0.064	0.187**	0.099	0.127
Market 6	0.116	0.158	0.160	0.130
Market 8	0.060	0.189**	0.093	0.116
Market 9	0.184	0.120*	0.185	0.204
Market 11	0.188	0.118**	0.185	0.188
Market 14	0.196	0.113**	0.154	0.068**
Rubin's B	0.404			
Rubin's R	0.780			

Source: Authors. *10% **5% ***1%.
Note: Asterisks indicate statistically significant differences from the figures among cold-storage-users.

Table 16. Balancing properties (bivariate IPW)

Variables	All crops combined				Tomato			
	Non-adjusted raw sample		IPW-sample		Non-adjusted raw sample		IPW-sample	
	Cold-storage-users	Non-users	Cold-storage-users	Non-users	Cold-storage-users	Non-users	Cold-storage-users	Non-users
Demographics								
Age	39.583	42.709***	39.579	39.036	41.125	43.136	42.804	42.225
female	0.101	0.017	0.131	0.209	0.101	0.017***	0.131	0.209
Household size	11.193	11.534	11.368	11.241	11.446	12.322	12.894	11.169
Education completed	6.081	5.466	7.106	8.209	6.030	4.797*	6.923	6.457
Native of the LGA	0.496	0.748***	0.619	0.780*	0.625	0.780***	0.488	0.699
Number of languages	2.178	1.874***	1.981	2.214	2.232	1.847***	2.232	2.063
Traders among relatives	0.526	0.456*	0.710	0.634	0.583	0.508	0.582	0.657
Credit sources	0.979	0.968	0.760	0.833	1.170	1.087	0.902	0.651
Asset								
Capacity of own storage	0.386	0.374	0.269	0.459	0.265	0.498*	0.302	0.254
Business assets	3.486	0.964***	1.989	1.018	3.668	0.851***	1.564	1.144
Exclusive space	0.768	0.524***	0.692	0.592	0.625	0.441***	0.632	0.474
Distance								
Distance to cold-storage	-4.706	-6.993***	-6.964	-6.810	-4.277	-7.067***	-7.323	-6.923
Distance to entry gate	1.243	1.255	1.487	1.300	1.153	1.267***	1.189	1.059
Distance to public toilet	1.325	1.203***	1.425	1.238	1.283	1.268	1.144	1.333
Distance to canteen	1.123	1.131	1.249	1.215	1.146	1.173	1.161	1.109
Distance to meeting room	1.268	1.295	1.217	1.160	1.212	1.341***	1.057	1.213
Distance to market representative's office	1.269	1.336***	1.274	1.209	1.210	1.352***	1.077	1.238
Distance to the nearest piped water source	1.265	1.686***	1.241	1.732	1.742	1.810	1.551	1.231
Facilities								
Improved floor	0.259	0.515***	0.310	0.326	0.298	0.475***	0.155	0.409*
Roof	0.664	0.854***	0.669	0.619	0.649	0.797***	0.600	0.573
Paved road	0.259	0.146***	0.334	0.138**	0.113	0.102	0.075	0.402**
Drainage	0.580	0.796***	0.423	0.469	0.685	0.712	0.345	0.517
Covered drainage	0.079	0.146**	0.227	0.129	0.065	0.102	0.056	0.221
Electricity	0.190	0.320***	0.230	0.183	0.101	0.288***	0.176	0.211
Market								
1	0.121	0.408***	0.091	0.187*	0.137	0.407***	0.100	0.152
3	0.084	0.029***	0.217	0.077	0.060	0.017**	0.349	0.209
6	0.183	0.136*	0.189	0.114	0.018	0.085**	0.075	0.193
8	0.079	0.049*	0.195	0.305	0.137	0.068**	0.233	0.144
9	0.057	0.165***	0.174	0.186	0.083	0.254***	0.243	0.151
11	0.007	0.214***	0.134	0.131	0.000	0.169***	0.000	0.150**

Source: Authors. *10% **5% ***1%.

Note: Asterisks indicate statistically significant differences from the figures among cold-storage-users.

Appendix B: Use of cold-storages installed

The cold-storages built have been extensively used. The quantity of major horticulture crops stored inside the cold-storage on an average day amounted to approximately 11 tons in total from all 7 storages combined, accounting for more than half (53%) of the maximum-possible storage capacity (Table 17). These figures are average amounts that are stored inside cold-storage at a typical point in time. For example, in the case of tomato, 560 kilograms in Dutse Daily Market means that, on average, there are 560 kilograms of tomato stored inside the cold-storage there at any point in time. Note that the actual utilization rates are higher than the figures shown in the table because some non-horticulture commodities, including meat and drinks, are also stored.

Table 17. Average quantity of horticulture crops stored (kg)

Horticulture Crops	Estimated storage quantity at a typical point in time (kg) (Based on the assumption of 20 kg per crate)							
	Horticulture markets							Total of 7 cold-storages (kg)
	Duste Daily Market	Gombe Main Market	Jimeta Ultra Modern Market	Muda Lawan Market	Potiskum – Mamudo Town Main Market	Wunti Market	Yola by-pass Market	
Tomato	560	220	270	240	1060	560	40	**2950**
Green Pepper	20	120	120	80	340	600		**1280**
Spring Onions (Bulbs)	80		100		80	140	800	**1200**
Spring Onions (Bulbs + Green tops)	340	40	40	20	320	20		**780**
Cabbage	180	60	120		60	40	240	**700**
Cucumber	120	80	160			20	240	**620**
Carrots	327	20	140	40			60	**587**
Okra	200	20			160	140		**520**
Lettuce	80		60	60	20	120		**340**
Watermelon	47		20			40	220	**327**
Pear						60	240	**300**
Spring Onions (Green tops only)					140	100		**240**
Pawpaw	240							**240**
Eggplant	47		20	7		60	80	**213**
Green Beans	60		100			10		**170**
Broccoli	100		40					**140**
Cauliflower	100		20			20		**140**
Orange	40					80		**120**
Cowpea	40		20					**60**
Pineapple	40					20		**60**
Strawberry	40		20					**60**
Grape			40					**40**
Total of major horticulture crops	2661	560	1290	447	2180	2030	1920	**11087**
Utilization rates based on horticulture crops only (% of possible capacity)	**89%**	**19%**	**43%**	**15%**	**73%**	**68%**	**64%**	**53%**

Source: IFPRI post-intervention survey data conducted in late March 2021.

Appendix C: Food-science experiment

Food-science impact evaluations were conducted using the cold-storage in Dutse Daily Market in Jigawa state, and the food-science lab at Ahmadu-Bello University (ABU), Zaria, Kaduna state, in March 2021. These were selected given the availability of advanced labs, as well as scientists with the required expertise at ABU and the proximity of Dutse Daily Market to ABU.

Following the established approaches employed in similar past studies, food-science experiments were implemented through completely randomized design (CRD):

- **5 fruits**: (1) Tomato (2) Carrot (3) Orange (4) Cucumber (5) Cabbage.
  These horticultural commodities are selected due to larger numbers of the traders in Dutse Market products are stored in cold storage.
  *One of Carrot, Cucumber, Cabbage, may be replaced by Eggplant.
- **2 Storage conditions:** Cold room and Ambient condition
- **8 quality indicators:**
  - 3 physical quality indicators (weight loss, color change, firmness)
  - 5 chemical conditions (Lycopene, Carotene, Vitamin C, Total soluble solid (TSS), Titratable acidity)
- **3 replications**

These were assessed through CRD in 10 (= 5 × 2) experiments. Each experiment evaluates 6 quality and nutrients indicators following dimensions. The table below summarizes each of the 10 experiments.

Experiment	**Storage**	**Fruits**	**Physical quality indicators**			**Chemical conditions**				
S/N			**Weight loss (kg)**	**Color Change**	**Firmness**	**Lycopene**	**Carotene**	**Vitamin C**	**Total soluble solid (TSS)**	**Titratable acidity**
1	Cold room	Cabbage								
2	Ambient	Cabbage								
3	Cold room	Carrot								
4	Ambient	Carrot								
5	Cold room	Cucumber								
6	Ambient	Cucumber								
7	Cold room	Orange								
8	Ambient	Orange								
9	Cold room	Tomato								
10	Ambient	Tomato								

These 10 experiments were replicated 3 times, resulting in a total of 30 experiments. Each of the 30 experiments was then conducted 7 times on every fourth day from the day products were put in cold storage.

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INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
www.ifpri.org

IFPRI HEADQUARTERS
1201 Eye Street, NW
Washington, DC 20005 USA
Tel.: +1-202-862-5600
Fax: +1-202-862-5606
Email: ifpri@cgiar.org