Bottlenecks in Nigeria's fresh food supply chain: What is the way forward?

Daniel Onwude[1], Thomas Motmans[2], Kanaha Shoji[1], Roberta Evangelista[2], Joaquin Gajardo[1], Divinefavor Odion[1], Nnaemeka Ikegwuonu[3], Olubayo Adekanmbi[4], Soufiane Hourri[4,5] , Thijs Defraeye[1*]

[1]Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland

[2]BASE, Basel Agency for Sustainable Energy Elisabethenstrasse 22, 4051 Basel, Switzerland

[3]ColdHubs Limited, 1 Umugakwo-Umuoba road, off MCC-Uratta Road, P.O. Box 3508, Owerri, Nigeria

[4]Data Science Nigeria, 33 Queen Street, Alagomeji-Yaba, 101245, Lagos, Nigeria

[5]Cadi Ayyad University, Boulevard Al Kouliyate, Marrakech, Morocco

Nigeria is one of the leading producers of fresh produce, most of which is grown by smallholder farmers. Over 40% of this fresh produce is lost after harvest, resulting in more than 30% loss in smallholders' income. We identify the major bottlenecks in Nigeria's fresh food supply chain responsible for the high food losses. We propose possible solutions to mitigate them. A key bottleneck is that most fresh food produced in the northern region is largely consumed in the south, with the produce traveling long distances through a poor road network. The lack of a continuous cold chain is another key causative factor for food loss. Less than 10% of the fresh food produced passes through a cold chain despite the long distances it needs to travel. There is also limited access to supply chain data and expert market intelligence to assist stakeholders in the decision-making process and process optimizations. To mitigate food losses, smallholder farmers and retailers need better access to clean cooling solutions at affordable prices, enabled for example, by the innovative Cooling as a Service business model (CaaS). This will help them extend produce shelf life and sell produce at attractive market prices by being able to cool their produce. Simple and small-scale passive cooling solutions may also help preserve food for these stakeholders, but are currently rarely used. Furthermore, the available open data needs to be made easily accessible to stakeholders along the fresh supply chain so they can make informed decisions on how best to reduce food losses and maximize profit. Smallholder farmers would also significantly benefit from easier access to expert intelligence on postharvest storage and market information. Providing such expertise via mobile apps can be a powerful tool for remote farmers in a country like Nigeria. Otherwise, it could be difficult to reach them. Nigerian governmental agencies can create the largest gains in the cold chain by implementing policies that support stakeholders financially and improve rural infrastructures such as roads and electricity.

Keywords: Sustainable supply chain; reducing hunger; farmer's income; food security; smallholder farmers

* *Corresponding author: daniel.onwude@empa.ch (D. Onwude) Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland*

1 NIGERIA'S FRESH PRODUCE SUPPLY CHAIN IN PERSPECTIVE

With a growing population of over 200 million people, the largest in Africa, Nigeria accounts for ~50% of West Africa's population [1], [2]. Agriculture plays a critical role in Nigeria's society and economy. For example, in 2020, agriculture accounted for over 24% of the total gross domestic product (GDP) and two-thirds of the labor force [3], [4]. Nigeria is also the world's fifth largest producer of vegetables and eighth largest producer of fruits, making it an agricultural giant of Africa[5]. The most common fruits and vegetables produced are plantains, cassava, yam, citrus, sweet potato, tomato, cocoyam, okra, pineapple, onions, potato, and mango[5]. The production of these fresh produce is largely carried out by smallholder or marginal farmers who often grow them on farms under 4 hectares [6]. These farmers, who primarily rely on traditional farming practices, account for almost 90% of the total food production [1], [7]. Food losses are exceptionally high within this category of farmers, with more than 40% losses postharvest; translating to underutilization of land and wastage of several other farm resources [8]. These postharvest losses also imply a more than 30% loss in income and a significant contribution of up to 5% to the country's greenhouse gas emissions [8].

A critical bottleneck contributing to these substantial postharvest losses is the lack of cold storage or refrigerated transport facilities. A low temperature is maintained during refrigerated storage and transport logistics, decreasing the rate of several temperature-driven biochemical degradation reactions, thereby increasing the shelf life and overall quality of fresh produce [9]. Reducing the temperature by 10 °C typically doubles or triples the postharvest life of fresh produce. However, less than 10% of fresh produce moves through a cold chain in developing countries, including Nigeria [10]. The primary reason being that smallholder farmers, due to their limited financial resources, cannot afford cold storage facilities and refrigerated transport. Another reason is the lack of proper energy access. These farmers require electricity to run commercially available refrigerated storage systems. However, most rural farming communities are not directly connected to the national energy grid. When they are, the electricity supply is unstable. Other cold storage strategies, such as small-scale solar power-driven cooling units, are either inaccessible or too expensive for most smallholder farmers, especially those in remote, off-grid areas. Moreover, there are limited companies currently offering decentralized cooling as a service to smallholder farmers or suppliers. Cooling as a service is a business model that enables cold chain users to only pay for the cooling service they need rather than having to purchase, own, operate and maintain the infrastructure. The few available decentralized cold storage facilities use paper-based inventory systems, resulting in poor traceability of farmers' stored produce and difficulties scaling up the operations. There are also very few companies offering refrigerated transport services. The major reason for the limited use of decentralized solar-powered cold storage units and refrigerated transport vehicles is the upfront investment costs for equipment and limited access to finance. According to a cooling service provider in Nigeria, setting up a 100 tons cold room with a 5000 standard crate capacity (0.5m x 0.3m x 0.4m outer dimension) costs approximately $350'000 USD (₦145 million naira) [11]. Such capital costs may be difficult to raise by small-scale companies. Another contributing factor is that most stakeholders (farmers, suppliers, retailers, etc.) are unaware of the abundant benefits of cold storage and refrigerated transport logistics. This could be due to the low educational level and access to training and extension services on cold chain technologies. Hence, they are unwilling to invest in or use such a system. Fresh produce are therefore often stored only under natural shade or transported locally without refrigeration. Here, high exterior temperature and low humidity induce accelerated aging, wilting and decay.

Another factor causing food loss is the poor conditions of the roads between farmgate and consumer markets (Figure 1). Most fruits and vegetables such as tomato, cabbage, pepper, green beans, and potato are produced in the northern part of Nigeria, but are largely consumed in the southern regions. Kano, Kaduna, and Plateau States in the Northern region produce more than 50% of the major fruits and vegetables consumed in Nigeria [12]. From the farm, a fresh produce journey of typically 12-14 hours could take between 2 – 3 days to get to the retail or open market, due to the deplorable state of the roads. Despite being the country with the largest road network in West Africa (195,000 km), as of 2019, only about 31 % of the road network in Nigeria is paved. Due to all these, the fresh produce, often over-loaded in trucks or saloon cars, risks falling off the transport vehicles during their journey and can get mechanically damaged by the large vibrations and shocks it is exposed to (Figure 1). In some Northern states such as Katsina, where tomatoes are also largely produced, clusters are formed that collect the produce from various farmers in the state. The "middlemen" buy directly from the farmers and then sell to the clusters, where they are kept in natural shades for days. After collecting a large enough quantity to fill an unrefrigerated truck, the clusters sell the fresh produce to the suppliers, who in turn transport them down to the south. The long transport time, the fruit's mechanical damage due to vibrations during travel, and the lack of cold chain result in suboptimal fruit quality at the point of sale. This implies that a significant amount of the produce is sorted out and thrown away upon arrival at the local markets in the southern region, or sold at a very low price. This is especially true for climacteric fruits and vegetables such as tomatoes, mango, apples, and bananas. The further down in the supply chain that the food is lost, the higher its environmental impact becomes.

There is a growing demand for digital technology to address the current and future global food security issues more efficiently [13]. A key component needed for implementing data-driven digital solutions in the global food system is the access to actionable data for the different agricultural value chains [13], [14]. This is yet another critical bottleneck in Nigeria's fresh produce supply chain. Different agricultural value chain stakeholders in Nigeria, including farmers, policymakers, suppliers, and retailers, do not have access to ready-to-use actionable data on fresh food supply chains to inform their decisions. For example, data on remaining shelf life could help farmers in making better decisions on when to sell their produce. However, they lack the expertise to interpret the current hygrothermal sensor data they have available. Spatial and temporal data on solar radiation, climate, the road network, food production, mobile coverage, water availability, market location and farm locations in different localities in Nigeria would help cooling service providers to better site their future cold storage facilities. A lot of these data are openly available and findable in principle by the stakeholders, but it is a time-consuming task to distill this data or group it all together in a ready-to-use form. The stakeholders do not have the time to do so. The lack of access to such ready-to-use, easy-digestible data results in less-informed decisions that drive postharvest losses.

Another key bottleneck is the current agricultural policies that support postharvest activities. The recent Agricultural Promotion Policy (APP), which expired in 2020, centers on providing rural infrastructure and increasing access to affordable funding [15]. However, this policy only recorded limited success with little implementation in the greater agricultural community. Smallholder farmers and other stakeholders like cooling service providers still find it difficult to access loans or more sophisticated services to meet their needs. Financial institutions consider this category of farmers too small or high risk, and are unfamiliar with investments in cold chain assets. As a result, cooling service providers are limited in scaling up their offerings, and farmers cannot access cooling solutions that would help them reduce food loss and increase their income. All of these factors result in significant postharvest losses and cause these farmers to be trapped in a seemingly endless cycle of poverty.

Suppose advances can be made in the aforementioned bottlenecks in Nigeria; we could reduce food loss, increase rural farmer's income, and make cheap and more nutritious food available. This will also reduce the environmental impact of food waste. In this paper, we present possible cold chain solutions to help achieve this. This is inspired by the findings gathered in the framework of the "Your Virtual Cold Chain Assistant (YVCCA)" project [16]. YVCCA is a project commissioned by The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), and data.org targeting the use of digital solutions to improve Nigeria's fresh produce supply chain.

Figure 1. A map of Nigeria depicting the fresh produce supply chain (with farms in the northern region and markets largely in the south).

2 TOWARDS A MORE REFRIGERATED SUPPLY CHAIN: WHAT IS THE WAY FORWARD?

We identify and discuss several solutions to address the major bottlenecks of Nigeria's fresh produce supply chain while evolving into a sustainable digital supply chain (Figure 2).

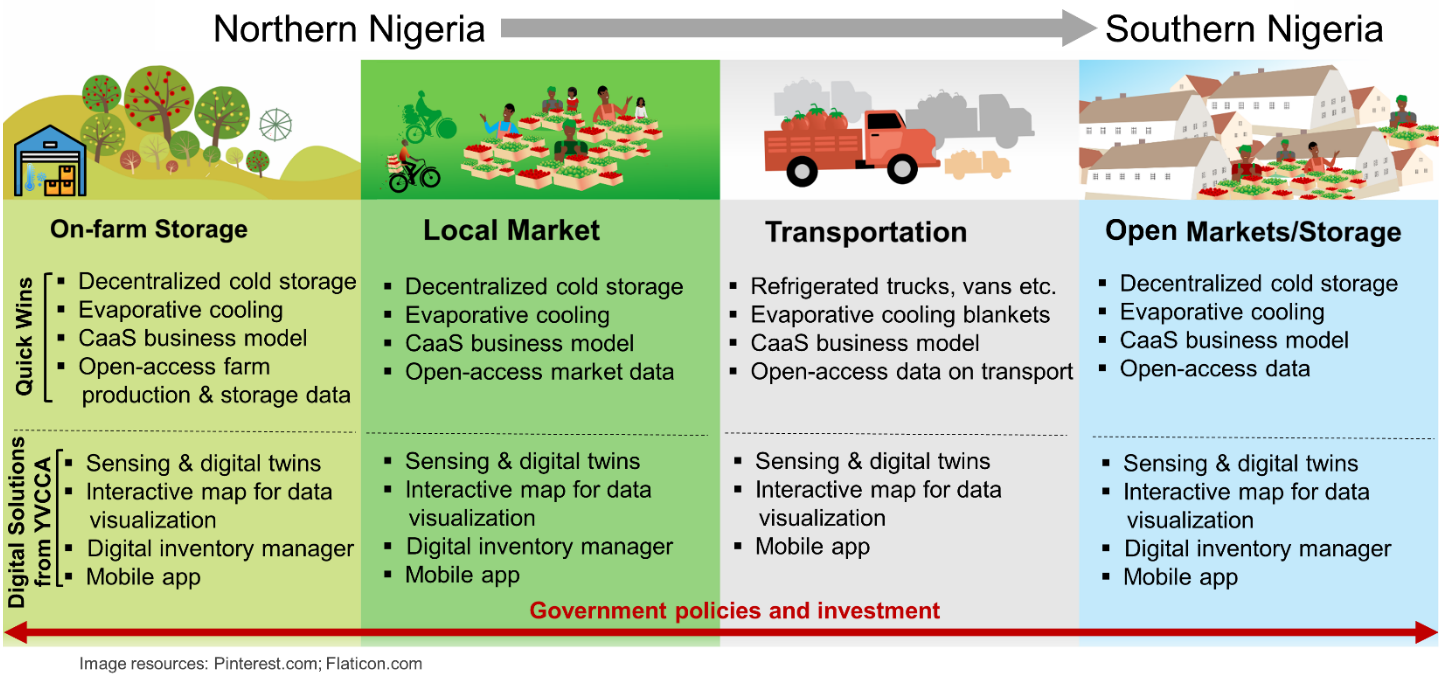

Figure 2. Potential solutions addressing the major bottlenecks in Nigeria's fresh produce supply chain, including findings from YVCCA project.

2.1 Decentralized cold storage and refrigerated transport solutions

Cold storage and transport of fresh produce in a local supply chain have been shown to reduce food losses and improve farmer's income in developing countries. A recent study in India has shown that using cold storage and refrigerated trucks in the local fresh produce supply chain reduced food loss by more than 70% and CO_2 emissions by up to 16% [17]. The study also found that the income of smallholder farmers and the refrigerated transport providers increased by 15% and 23%, respectively. Decentralized solar-powered cold storage systems in Nigeria's rural communities as a cooling service can help to reduce the postharvest losses of fresh produce and simultaneously build an efficient supply chain. This active cooling solution could help smallholders store their fresh produce at affordable prices to keep it fresh until ready for sale to suppliers or consumers at nearby farmgate markets. Additionally, such a system could provide a buffer when commodities are low in demand and increase the supply window. Similarly, refrigerated transport of fresh produce as a service from the farms in the north of Nigeria to the markets in the south will significantly reduce food losses and increase access to fresh quality food. This is because maintaining a low temperature for a long period of time will slow down respiration rate, reduce moisture loss and delay thermally-driven decay reactions. Doing so, especially along the Lagos-Kano-Jibiya (LAKAJI) corridor (Nigeria's largest agricultural trade corridor), will help fight micronutrient deficiency, hunger, and decrease the need to produce more food. This will also increase the income of stakeholders and further drive attractive financial and social returns. Furthermore, reducing food loss by enabling refrigerated cold storage and transport could also increase the low exports of Nigerian fresh fruit and vegetables. In 2002, Nigeria export of fresh produce was valued at $355'000 USD (₦ 147 million naira), ranking 113 for fresh fruits and 78 for vegetables out of 146 exporting countries [18].

2.2 Innovative business models for decentralized cooling solutions

A pay-per-use business model could potentially address the financial barriers that prevent smallholder farmers from accessing decentralized cold storage and refrigerated transport solutions. By applying such a service-based model, also called "Cooling as a Service" or "CaaS," smallholder farmers gain access to the most efficient, reliable and sustainable off-grid cooling. They do not need to purchase and maintain an entire cooling facility. They only pay for the amount of food they store (per crate-day) in the cold rooms, avoiding any upfront investment. Service providers own and maintain the cooling facilities, thereby covering the operational costs. This long-term commitment serves as an incentive for them to install the most energy-efficient equipment and perform high-quality maintenance. With some cold storage providers, users pay between $0.2USD – $0.5USD (₦100 - ₦200) naira per crate per day for storage, corresponding to only a fraction of the value of the commodities being saved from spoilage [11]. This payment is made only at the end of storage, especially for frequent users, when they are ready to sell their produce based on market demand. This offers the flexibility for the users to only pay for the number of days in storage, and reduces the duration between the outlay of cash to pay for the cooling and the income from the sales of the produce. This service-based business model can be implemented in all stages of Nigeria's fresh produce supply chain, including on-farm cold storage in the north, refrigerated transport across the supply chain, and open or retail markets in the southern region. Furthermore, implementing this model requires the small and medium enterprises (SMEs) offering these cooling services to invest large amounts of capital. Even in highly liquid markets, which is not typical for Nigeria, SMEs face significant challenges in accessing financing due to high collateral requirements. Credit guarantees covering a significant portion of defaults to lenders could unlock such finance, offered both by local investors and banks as well as by international investors. Entities like InfraCredit are looking to establish such products specifically for the agricultural cold chain [19]. InfraCredit is a Nigeria-based private company that provides local currency guarantees to enhance the quality of debt instruments issued to finance projects.

2.3 Low-tech passive cooling solutions

To widely implement decentralized cold storage and refrigerated transport logistics in Nigeria's fresh produce supply chain will require an incremental target investment in individual cold chain corridors and commodities. Achieving this requires time as Nigeria is a large country measuring approximately 910,770 km^2 [20]. Even then, some remote off-grid areas and farmers with limited financial resources will still remain underserved. As a quick win, passive evaporative cooling solutions can be an alternative. This high-potential sustainable cooling solution is simply based on the use of water to cool warm air and to provide a humid storage environment. This technology is considered one of the top 22 investable innovations that can transform food systems in emerging markets [21], [22]. In principle, these low-risk, high-gain solutions could be implemented with little training and low capital costs, making them suitable for marginal and smallholder farmers in remote, off-grid areas. Examples are the zeer pot, sand and brick coolers, khus-mat coolers, and charcoal coolers [23]. These coolers can cool down the air and food products by typically 3 - 10 ºC and increase the relative humidity inside the cooler up to 70 - 100% [23]. They slow down thermally-driven food degradation, reduce moisture loss, and increase shelf life by typically 2 - 6 days [23]. However, evaporative coolers are still rarely deployed. One reason is that of scale for smallholder farmers combined with the fact that it required access to expertise and materials to build the coolers [24]–[26]. There are too many smallholder farmers and limited resources to have direct access to expertise, training, and sufficient capital to efficiently build and operate evaporative coolers. Evaporative coolers also require suitable materials, such as wood, brick, metal meshes, or piping, which often cannot all be sourced locally. There is also little economic incentive for companies to produce and disseminate such small-scale cooling facilities, despite the huge potential of this technology to help preserve food. In this case, one would need to interact with and train hundreds of farmers individually. Therefore, simple and affordable small-scale passive cooling blankets should be targeted and training programs that can reach all these farmers at the same time. Using digital platforms with DIY multimedia tools in local languages could help reach many more farmers compared to in-person workshops and trainings.

2.4 Open-access data

Reliable agricultural data, especially commodity market prices, market volume, food loss and waste, farm-market transport cost, cold room location and soil-related data, are often unavailable or not readily accessible or interpretable. If they are openly accessible, they are not easily digestible to smallholder farmers or cooling service providers to help in decision making. Some current agricultural-related data that are openly accessible include rural demography [27], weather [28], market locations [29], farm-to-market distance [30], crop production [31], [32], socioeconomic [33], rural roads [34], farm locations [35] and soil-related data [36]. These data can also be combined, turning millions of data points into actionable insight. Improving the quality and access of supply chain data collection and monitoring can help reduce the current information gap and increase data access to different fresh produce stakeholders in Nigeria. This can be done through crowd-sourcing, among others. Here, stakeholders could post real-time information on postharvest activities of certain commodities online using smartphones. Such online platforms are currently available for Nigeria and include the DataCrowd app, Open Data Kit, Ushahidi, and DataM-Food Price Crowdsourcing Africa web-based platform. Alternatively, the community members could also upload information on their value chain experiences and opinions online via the citizen-generated data (CGD) and citizen voice and action approaches [37]. With reliable open data on postharvest activities as listed above, supply chain stakeholders such as smallholder farmers, cooling service providers, and retailers can make informed decisions on how best to reduce food loss and maximize profit. Government or policymakers could also rely on such data to make decisions on appropriate interventions and commodity-based investments.

2.5 Digital cold chain optimization solutions

2.5.1 Interactive map enabling data-driven decision making

A significant aspect of open-access data is its usability in making logistical and operational decisions on food loss reduction and improving financial and social returns by stakeholders in the value chain. However, the current openly accessible data are scattered in different repositories and thereby difficult and time-consuming to collect. Making open-access data broadly accessible to the cold chain stakeholders via a web-based digital dashboard, using visually engaging interactive maps and graphs, could help solve this challenge. Several agricultural-related interactive maps are already available for the world. They include HungerMap [38], Ocean Observations Viewer [39], Water Risk Atlas [40], SoilGrids and WoSIS [41], and Agricultural land maps [42]. An example of such a map for Nigeria is shown in Figure 3 [43]. Here, data are represented on water access, water scarcity, crop production, road network, food insecurity, solar radiation, temperature, population density, shelf life gain, market location, among others. These maps empower policymakers and other stakeholders to draw their own conclusions from the insights and stories embedded in the data. For example, such multiparameter map visualization (Figure 3) can help cooling service providers better identify locations to install cooling facilities, while it can help farmers easily locate the nearest cold room. With the power to improve decision making, this kind of tool has a high potential to save food by increasing access to – and knowledge about - cooling, thereby increasing stakeholder's revenue.

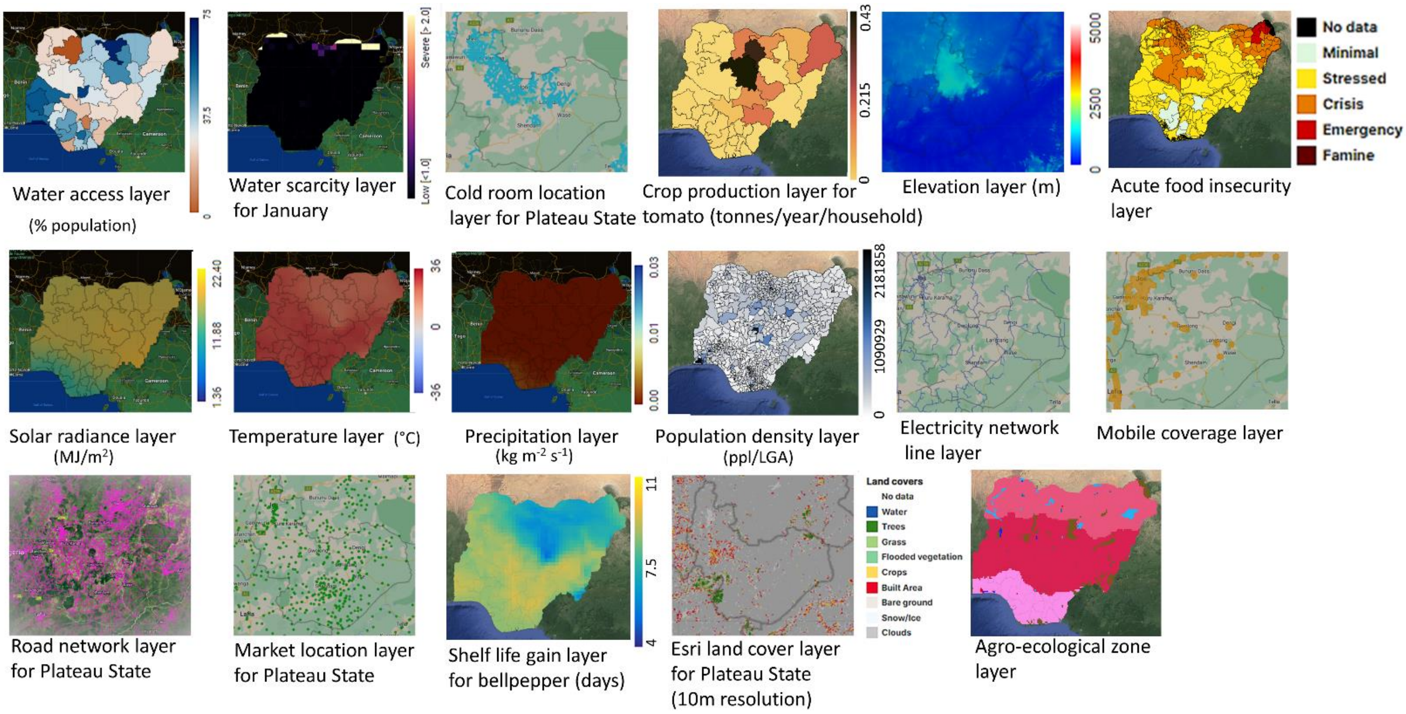

Figure 3. An interactive map of Nigeria showing different GIS layers to enable decision makers and greater agricultural community to make more informed and timely decisions relating to increasing food security [43].

2.5.2 Food sensing and digital twin

Food sensors can monitor the origin, quality, or degree of contamination of fresh produce in a supply chain, thereby estimating losses[44]. They can further reduce losses by improving traceability and transparency in food distribution, identifying areas of high food waste, and improving decisions by supply chain stakeholders. Sensors could typically be placed in a cold room, a passive cooler or in a truck loaded with fruits at the farm in the north and then travel with the cargo to retail or open markets in the southern region of Nigeria. Different sensors are used to measure each of the process parameters affecting fruit quality, such as air temperature and humidity and fruit pulp temperature. In more advanced capabilities, gas concentrations of metabolic gasses (O_2, CO_2, C_2H_4), airspeed, and mechanical response to vibrations are measured [45]. Examples of such sensors are hygrothermal sensors (e.g., SENSIRION SHT31 Smart Gadget; SENSITECH TempTale GEO Eagle; RFID Trade HF/UHF; DeltaTrak FlashLink; RF Xsense® HiTag sensor; Aqara WSDCGQ11LM) based on wireless monitoring of environmental conditions. Most of these hygrothermal sensors, so temperature and humidity are affordable, some costing less than $30 USD (i.e., ₦12,000 naira) per piece.

The data from these sensors could also be used to map the quality evolution in fruit cargo from farms to the markets or cold rooms by feeding them into physics-based food models. The physics-based model delivers back, in turn, complementary data on fruit quality attributes such as mass loss, overall fruit quality and expected shelf life of the fruit at the different monitored locations [46]–[48]. Thereby, a digital twin of different fruits and vegetables in a supply chain can easily be developed (see Figure 4). A digital fruit twin in a supply chain of fresh produce is a 'virtual' food model that contains essential product characteristics such as geometry and material properties, and simulates relevant hygrothermal and metabolic processes of the fruit[49]. A digital twin is linked to the real-world processes by sensor data input, preferably in real-time. With this, we can identify where and when the most significant food loss in the entire supply chain occurs. This enables proactive action to be taken to reduce food losses, improve the income of supply chain stakeholders and result in optimized postharvest handling due to improved decisions on planning logistics.

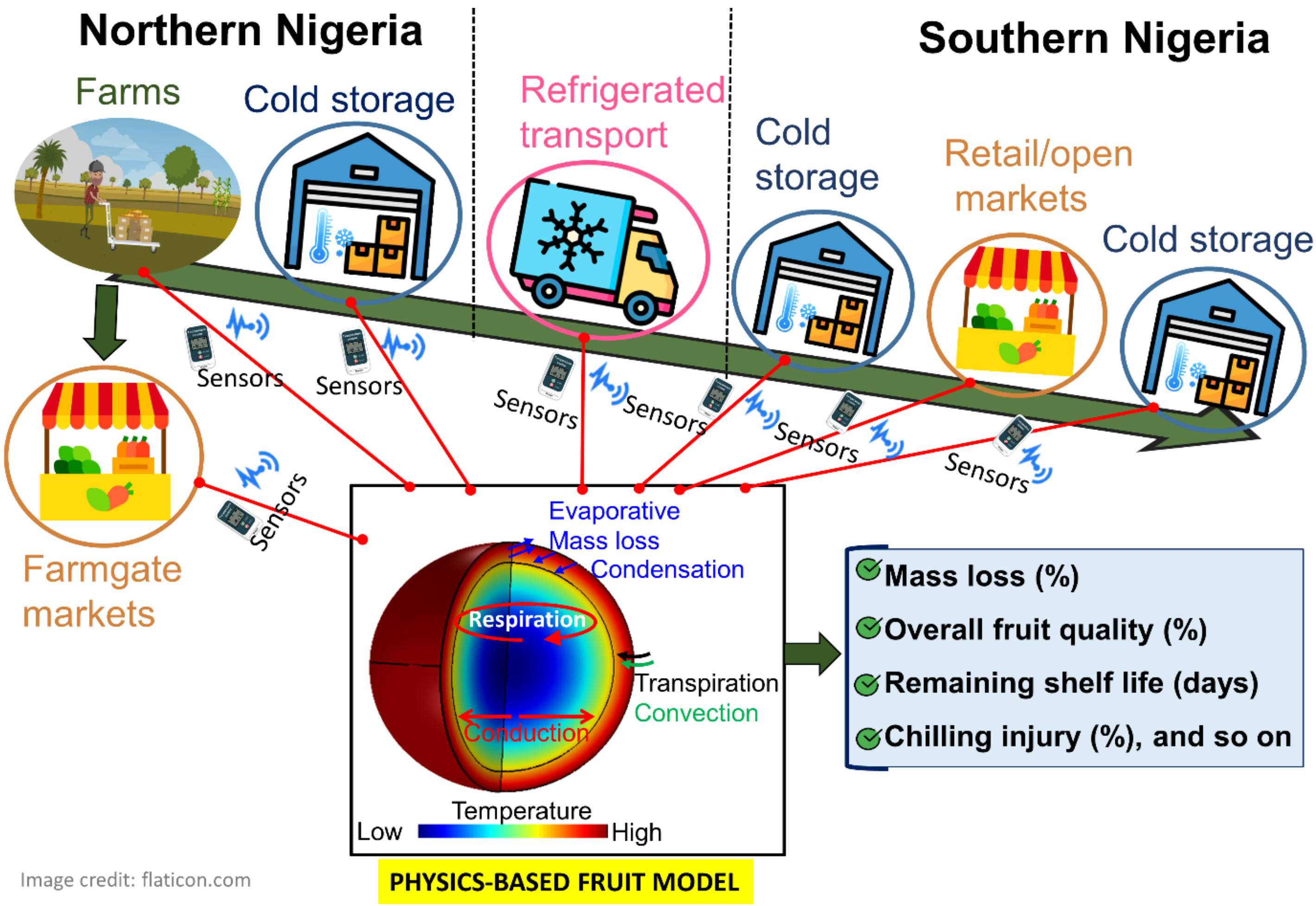

Figure 4. Digital twin concept of the fresh produce supply chain.

2.5.3 Mobile app for postharvest intelligence and inventory management

Integrating most of the solutions above, such as the open-access data collection platform, digital food twins, interactive maps, cooling management and sensor monitoring APIs, into a mobile app could help improve their accessibility, accelerate their adoption, and leverage synergies between them. We see mobile platforms as an essential component to reach more smallholder farmers and downstream small business owners in the fresh produce supply chain. For instance, a mobile app could collectively digitalize the inventory management of the CaaS model, and forecast the remaining postharvest life of stored produce based on virtual food models. Such a digital solution could also be used to monitor and predict fruit ripening and progressive defect in the supply chain and forecast commodity market prices using machine learning models. Thus, improving postharvest practices and reducing food waste. The app could also provide remote guidance on cooling benefits and the optimum storage conditions of different commodities. Smallholders, farmer's cooperative societies, cooling service providers, cooling room operators, and suppliers could have access to easy-to-use information to make optimal decisions on produce, farm management, and other supply chain services. Using an SMS-based messaging system will allow stakeholders who do not have smartphones or internet access to such an app. As an example, an open-access mobile app called Coldtivate (as part of the Your Virtual Cold Chain Assistant project) is being developed for smallholder farmers and cooling service providers in Nigeria [16]. This app incorporates 'virtual' food models that predict the quality and shelf life of fresh produce stored in a cold room based on measured sensor air temperature and humidity data. Additionally, the app digitalizes the cold rooms' check-in and check-out storage processes to enable Cooling as a Service. The team is working on expanding the app to include machine learning models that will guide farmers on when best to sell their produce at the best price yet based on open-sourced market price data. Similarly, Clarifruit has been developed to predict the quality of fruits and vegetables at different supply chain stages using computer vision and machine learning models [50]. Other mobile apps for postharvest quality checks of fresh produce include Intello Track [51], Greenlight Quality Control 2 [52], Agrinorm [53] and Fruit QC [54]. With the ability to monitor the quality of fresh produce in real-time, these mobile apps help stakeholders make informed decisions to reduce fruit waste and improve final fruit quality.

2.6 Government policies and investment

To further stimulate and encourage private-sector investment towards a sustainable cold chain, the Nigerian government should develop and implement policy on high-level financial support to stakeholders. They should also develop and enforce cold chain regulations, and policies on rural infrastructure investment, such as good roads and stable electricity supply. The 1965 Admonishment of Cold Chain in Japan is an example of a cold chain policy [55], [56]. The policy enabled the expansion of cold chain logistics in Japan, increasing the accessibility to different food and drastically reducing food waste. Government policy could also consist of facilitating small & medium size cooling companies by fostering partnerships with private agricultural financial entities such as InfraCredit [19]. Governments are also in a position to regulate stakeholders across the fresh produce supply chain to utilize sustainable cold chain storage and transport solutions. Furthermore, the Nigeria open data policy [57] should further be strengthened to focus on agricultural and nutritional data. Enabling these policies would help reduce the aforesaid bottlenecks.

AUTHOR CONTRIBUTIONS

DO[Onwude]: Conceptualization, Methodology, Investigation, Writing-Original draft, Review & Editing. **TM:** Methodology, Review & Editing. **KS:** Review & Editing. **RE:** Review & Editing. **JG:** Review & Editing. **DO[Odion]:** Review & Editing. **NI**: Review & Editing. **OA:** Review and Editing. **SH:** Review & Editing. **NK:** Review & Editing. **TD**: Conceptualization, Methodology, Review & Editing.

Acknowledgments

This work was funded partially by the data.org Inclusive Growth and Recovery Challenge grant "Your Virtual Cold Chain Assistant", supported by The Rockefeller Foundation and the Mastercard Center for Inclusive Growth, as well as by the project "Scaling up Your Virtual Cold Chain Assistant" commissioned by the German Federal Ministry for Economic Cooperation and Development and being implemented by BASE and Empa on behalf of the German Agency for International Cooperation (GIZ). The funders were not involved in the study design, collection, analysis, interpretation of data, the writing of this article, or the decision to submit it for publication.

REFERENCES

[1] AgriFin, "Nigeria, AgriFin's West African Frontier," *All, Climate, Data & Tech Acceleration, Digital Financial Services, Distribution Channel Logistics, Farmer Capability & Smart Farming, Market Access, News and Events, Women & Youth*, 2022. .

[2] World Bank, "Population, total - Nigeria," 2020. [Online]. Available: https://data.worldbank.org/indicator/SP.POP.TOTL?locations=NG. [Accessed: 08-Jun-2022].

[3] World Bank, "Agriculture, forestry, and fishing, value added (% of GDP)-Nigeria," *World Bank national accounts data, and OECD National Accounts data files*, 2020. .

[4] FAO, "Nigeria at a glance," *Food Agric. Organ. United Nations*, pp. 3–4, 2022.

[5] FAO, "FAOSTAT: Statistics Division of the Food and Agriculture Organization of the United Nations," 2020. [Online]. Available: https://www.fao.org/faostat/en/#data/QCL. [Accessed: 05-May-2022].

[6] V. Ricciardi, N. Ramankutty, Z. Mehrabi, L. Jarvis, and B. Chookolingo, "How much of the world's food do smallholders produce?," *Glob. Food Sec.*, vol. 17, no. January, pp. 64–72, 2018, doi: 10.1016/j.gfs.2018.05.002.

[7] B. S. Babura and B. U. Polytechnic, "Role of Smallholder Farmers in Nigeria ' s Food Security Role of Smallholder Farmers in Nigeria ' s Food Security," vol. 7, no. May, pp. 1–5, 2018.

[8] E. Cassou *et al.*, "Nigeria Food Smart Country Diagnostic," 2020.

[9] D. I. Onwude *et al.*, "Physics-driven digital twins to quantify the impact of pre- and postharvest variability on the end quality evolution of orange fruit," *engrXiv*, pp. 1–32, 2022.

[10] D. Coulomb, "Refrigeration and cold chain serving the global food industry and creating a better future: two key IIR challenges for improved health and environment," *Trends Food Sci. Technol.*, vol. 19, no. 8, pp. 413–417, 2008, doi: 10.1016/j.tifs.2008.03.006.

[11] N. Ikegwuonu, "Personal communication," 2022. .

[12] C. Plaisier, Y. Dijkxhoorn, F. van Rijn, J. Bonnand, and O. Talabi, *The vegetable and potato sector in Nigeria: an overview of the present status*, no. 2019–119. 2019.

[13] L. Goedde, R. McCullough, A. Ooko-Ombaka, and G. Pais, "How digital tools can help transform African agri-food systems," *McKinsey Co.*, no. January, 2021.

[14] N. M. Holden, E. P. White, M. C. Lange, and T. L. Oldfield, "Review of the sustainability of food systems and transition using the Internet of Food," *npj Sci. Food*, vol. 2, no. 1, 2018, doi: 10.1038/s41538-018-0027-3.

[15] O. A. (PhD) Oladunni, "Nigeria's Agriculture Promotion Policy (App) (2016 – 2020): Perspectives And Excerpts From The Policy Document," 2021.

[16] BASE and Empa, "Your Virtual Cold Assistant," 2022. [Online]. Available: https://yourvcca.org/nigeria/.

[17] Carrier, "Reimagining the Cold Chain in a Post-Pandemic World," 2020.

[18] FAOSTAT, "Crops and livestock products," *Food and Agriculture Organization of the United Nations*, 2020. [Online].

Available: https://www.fao.org/faostat/en/#data/TCL.
[19] InfraCredit, "Financing Agribusiness Infrastructure in Nigeria - Insights from Babban Gona," *Infrastructure Capacity Building Programme & Investor Roundtable Discussion*, 2021. [Online]. Available: https://infracredit.ng/backend/wp-content/uploads/2021/11/Financing-Agribusiness-Infrastructure-in-Nigeria-Roundtable-Discussion_vf.pdf. [Accessed: 22-May-2022].
[20] The World Bank, "Land area (sq. km) - Nigeria," *World Development Indicators*, 2021. .
[21] E. Verploegen, "Affordable, Scalable, Overlooked: Evaporative Cooling Can Fight Food Loss – Why isn't the Development Sector Embracing It?," 2021. .
[22] GKI, "Innovating the future of food systems - A global scan for the innovations needed to transform food systems in emerging markets by 2035," 2017.
[23] T. Defraeye *et al.*, "The charcoal cooling blanket: A scalable, simple, self-supporting evaporative cooling device for preserving fresh foods," Engineering Archive, 2022.
[24] E. Verploegen, "Determining if evaporative cooling has the potential to provide value in a specific context," 2021. .
[25] E. Verploegen, "Evaporative Cooling for Vegetable Preservation," 2021. .
[26] T. Defraeye *et al.*, "The charcoal cooling blanket: A scalable, simple, self-supporting evaporative cooling device for preserving fresh foods," *engrXiv*, 2022.
[27] Grid3Nigeria, "National State Administrative Boundaries," 2017. [Online]. Available: https://grid3.gov.ng/dataset/national-state-administrative-boundaries/resources. [Accessed: 10-Jun-2022].
[28] Copernicus, "Climate Data Store," 2022. [Online]. Available: https://cds.climate.copernicus.eu/cdsapp#!/home. [Accessed: 10-Jun-2022].
[29] Grid3Nigeria, "National Markets," 2020. [Online]. Available: https://grid3.gov.ng/dataset/national-markets/resources. [Accessed: 10-Jun-2022].
[30] HarvestChoice; International Food Policy Research Institute (IFPRI), "Travel Time to Markets in Africa South of the Sahara," *Harvard Dataverse, V2*, 2018. [Online]. Available: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/YKDWJD. [Accessed: 10-Jun-2022].
[31] International Food Policy Research Institute, "Spatially-Disaggregated Crop Production Statistics Data in Africa South of the Sahara for 2017," *Harvard Dataverse, V2*, 2020. .
[32] NBS/FMARD, "National Bureau of Statistics/ Federal Ministry of Agriculture And Rural Development Collaborative Survey on National Agriculture Sample Survey (Nass), 2010/2011," *National Agriculture Sample Survey*, 2010. [Online]. Available: http://nigeria.countrystat.org/documents/detail/en/c/454834/. [Accessed: 10-Jun-2022].
[33] I. F. P. R. I. HarvestChoice, "Segmentation Data for Nigeria and India States of Bihar, Odisha, and Uttar Pradesh," *Harvard Dataverse, V2*, 2017. [Online]. Available: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/K5NSAF. [Accessed: 10-Jun-2022].
[34] OpenStreetMap, "OpenStreetMap data for Nigeria," 2021. [Online]. Available: http://download.geofabrik.de/africa/nigeria.html. [Accessed: 10-Jun-2022].
[35] Grid3Nigeria, "National Farmlands," 2018. [Online]. Available: https://grid3.gov.ng/dataset/national-farmlands/resources. [Accessed: 10-Jun-2022].
[36] ISRIC, "SoilGrids — global gridded soil information," 2020. [Online]. Available: https://www.isric.org/explore/soilgrids. [Accessed: 10-Jun-2022].
[37] A. Farina, Y. Rana, and F. Nelson, "How can innovations advance the nutrition data revolution?," *DATA INNOVATIONS*, 2022. [Online]. Available: https://datadent.org/2022/01/11/how-can-innovations-advance-the-nutrition-data-revolution/. [Accessed: 11-Jan-2022].
[38] World Food Programme (WFP), "HungerMap," *World Food Programme (WFP)'s global hunger monitoring system*, 2022. [Online]. Available: https://hungermap.wfp.org/. [Accessed: 10-Jun-2022].
[39] NOAA/PhOD, "NOAA/PhOD Ocean Observations Viewer V2.0," 2022. [Online]. Available: https://cwcgom.aoml.noaa.gov/cgom/OceanViewer/index_phod.html. [Accessed: 10-Jun-2022].
[40] Aqueduct, "Water Risk Atlas," 2019. [Online]. Available: https://www.wri.org/applications/aqueduct/water-risk-atlas/#/?advanced=false&basemap=hydro&indicator=w_awr_def_tot_cat&lat=3.886177033699361&lng=17.578125000000004&mapMode=view&month=1&opacity=0.5&ponderation=DEF&predefined=false&projection=absolute&scena. [Accessed: 10-Jun-2022].
[41] ISRIC, "SoilGrids and WoSIS," 2022. [Online]. Available: https://soilgrids.org/. [Accessed: 10-Jun-2022].
[42] World Bank, "Agricultural land (% of land area)," 2018. [Online]. Available: https://data.worldbank.org/indicator/AG.LND.AGRI.ZS?view=map. [Accessed: 10-Jun-2022].
[43] D. Odion *et al.*, "Your VCCA Nigeria Map," *Interactive map to identify cold room locations*, 2022. [Online]. Available: https://divinefavour.users.earthengine.app/view/yourvcca-map-nigeria-test.
[44] M. Weston, S. Geng, and R. Chandrawati, "Food Sensors: Challenges and Opportunities," *Adv. Mater. Technol.*, vol. 6, no. 5, pp. 1–16, 2021, doi: 10.1002/admt.202001242.
[45] R. Jedermann, U. Praeger, and W. Lang, "Challenges and opportunities in remote monitoring of perishable products," *Food Packag. Shelf Life*, vol. 14, no. February, pp. 18–25, 2017, doi: 10.1016/j.fpsl.2017.08.006.
[46] T. Defraeye *et al.*, "Digital twins probe into food cooling and biochemical quality changes for reducing losses in refrigerated supply chains," *Resour. Conserv. Recycl.*, vol. 149, no. June, pp. 778–794, 2019, doi: 10.1016/j.resconrec.2019.06.002.
[47] K. Shoji, S. Schudel, D. Onwude, C. Shrivastava, and T. Defraeye, "Mapping the postharvest life of imported fruits from

packhouse to retail stores using physics-based digital twins," *Resour. Conserv. Recycl.*, vol. 176, p. 105914, 2022, doi: 10.1016/j.resconrec.2021.105914.
[48] C. Shrivastava, T. Berry, P. Cronje, S. Schudel, and T. Defraeye, "Digital twins enable the quantification of the trade-offs in maintaining citrus quality and marketability in the refrigerated supply chain," *Nat. Food*, 2022, doi: 10.1038/s43016-022-00497-9.
[49] D. I. Onwude, G. Chen, N. Eke-emezie, A. Kabutey, A. Y. Khaled, and B. Sturm, "Recent Advances in Reducing Food Losses in the Supply Chain of Fresh Agricultural Produce," *Processes*, vol. 8, no. 11, p. 1431, Nov. 2020, doi: 10.3390/pr8111431.
[50] ClariFruit, "One Automated Platform to Manage your Fresh Fruit and Vegetable QC," *Products*, 2022. [Online]. Available: https://www.clarifruit.com/solutions/product/. [Accessed: 11-Jun-2022].
[51] IntelloLabs, "Intello Track," 2022. [Online]. Available: https://www.intellolabs.com/intellotrack. [Accessed: 11-Jun-2022].
[52] Muddy Boots, "Greenlight Quality Control 2," 2018. [Online]. Available: https://muddyboots.com/.
[53] Agrinorm AG, "Agrinorm," *Agrinorm Quality Management Platform*, 2021. [Online]. Available: https://www.agrinorm.com/.
[54] Tellspec, "Fruit QC," 2022. [Online]. Available: https://tellspec.com/howitworks/. [Accessed: 11-Jun-2022].
[55] N. Kato, "A Cold Chain Proposal for Food Losses – Learning from the Past and Present of Japan," 2013.
[56] FAO, "Services and Infrastructure for Refrigerated Road Transport," *Food Loss and Waste in Fish Value Chains*, 2022. [Online]. Available: https://www.fao.org/flw-in-fish-value-chains/value-chain/transport/refrigerated-road-transport/services-infrastructure/en/. [Accessed: 05-May-2022].
[57] FMoCDE, "Nigeria open data policy," *Fed. Minist. Commun.*, no. July, 2018.
[1] AgriFin, "Nigeria, AgriFin's West African Frontier," *All, Climate, Data & Tech Acceleration, Digital Financial Services, Distribution Channel Logistics, Farmer Capability & Smart Farming, Market Access, News and Events, Women & Youth*, 2022. .
[2] World Bank, "Population, total - Nigeria," 2020. [Online]. Available: https://data.worldbank.org/indicator/SP.POP.TOTL?locations=NG. [Accessed: 08-Jun-2022].
[3] World Bank, "Agriculture, forestry, and fishing, value added (% of GDP)-Nigeria," *World Bank national accounts data, and OECD National Accounts data files*, 2020. .
[4] FAO, "Nigeria at a glance," *Food Agric. Organ. United Nations*, pp. 3–4, 2022.
[5] FAO, "FAOSTAT: Statistics Division of the Food and Agriculture Organization of the United Nations," 2020. [Online]. Available: https://www.fao.org/faostat/en/#data/QCL. [Accessed: 05-May-2022].
[6] V. Ricciardi, N. Ramankutty, Z. Mehrabi, L. Jarvis, and B. Chookolingo, "How much of the world's food do smallholders produce?," *Glob. Food Sec.*, vol. 17, no. January, pp. 64–72, 2018, doi: 10.1016/j.gfs.2018.05.002.
[7] B. S. Babura and B. U. Polytechnic, "Role of Smallholder Farmers in Nigeria ' s Food Security Role of Smallholder Farmers in Nigeria ' s Food Security," vol. 7, no. May, pp. 1–5, 2018.
[8] E. Cassou *et al.*, "Nigeria Food Smart Country Diagnostic," 2020.
[9] D. I. Onwude *et al.*, "Physics-driven digital twins to quantify the impact of pre- and postharvest variability on the end quality evolution of orange fruit," *engrXiv*, pp. 1–32, 2022.
[10] D. Coulomb, "Refrigeration and cold chain serving the global food industry and creating a better future: two key IIR challenges for improved health and environment," *Trends Food Sci. Technol.*, vol. 19, no. 8, pp. 413–417, 2008, doi: 10.1016/j.tifs.2008.03.006.
[11] N. Ikegwuonu, "Personal communication," 2022. .
[12] C. Plaisier, Y. Dijkxhoorn, F. van Rijn, J. Bonnand, and O. Talabi, *The vegetable and potato sector in Nigeria: an overview of the present status*, no. 2019–119. 2019.
[13] L. Goedde, R. McCullough, A. Ooko-Ombaka, and G. Pais, "How digital tools can help transform African agri-food systems," *McKinsey Co.*, no. January, 2021.
[14] N. M. Holden, E. P. White, M. C. Lange, and T. L. Oldfield, "Review of the sustainability of food systems and transition using the Internet of Food," *npj Sci. Food*, vol. 2, no. 1, 2018, doi: 10.1038/s41538-018-0027-3.
[15] O. A. (PhD) Oladunni, "Nigeria's Agriculture Promotion Policy (App) (2016 – 2020): Perspectives And Excerpts From The Policy Document," 2021.
[16] BASE and Empa, "Your Virtual Cold Assistant," 2022. [Online]. Available: https://yourvcca.org/nigeria/.
[17] Carrier, "Reimagining the Cold Chain in a Post-Pandemic World," 2020.
[18] FAOSTAT, "Crops and livestock products," *Food and Agriculture Organization of the United Nations*, 2020. [Online]. Available: https://www.fao.org/faostat/en/#data/TCL.
[19] InfraCredit, "Financing Agribusiness Infrastructure in Nigeria - Insights from Babban Gona," *Infrastructure Capacity Building Programme & Investor Roundtable Discussion*, 2021. [Online]. Available: https://infracredit.ng/backend/wp-content/uploads/2021/11/Financing-Agribusiness-Infrastructure-in-Nigeria-Roundtable-Discussion_vf.pdf. [Accessed: 22-May-2022].
[20] The World Bank, "Land area (sq. km) - Nigeria," *World Development Indicators*, 2021. .
[21] E. Verploegen, "Affordable, Scalable, Overlooked: Evaporative Cooling Can Fight Food Loss – Why isn't the Development Sector Embracing It?," 2021. .
[22] GKI, "Innovating the future of food systems - A global scan for the innovations needed to transform food systems in emerging markets by 2035," 2017.
[23] T. Defraeye *et al.*, "The charcoal cooling blanket: A scalable, simple, self-supporting evaporative cooling device for preserving fresh foods," Engineering Archive, 2022.

[24] E. Verploegen, “Determining if evaporative cooling has the potential to provide value in a specific context,” 2021. .
[25] E. Verploegen, “Evaporative Cooling for Vegetable Preservation,” 2021. .
[26] T. Defraeye *et al.*, “The charcoal cooling blanket: A scalable, simple, self-supporting evaporative cooling device for preserving fresh foods,” *engrXiv*, 2022.
[27] Grid3Nigeria, “National State Administrative Boundaries,” 2017. [Online]. Available: https://grid3.gov.ng/dataset/national-state-administrative-boundaries/resources. [Accessed: 10-Jun-2022].
[28] Copernicus, “Climate Data Store,” 2022. [Online]. Available: https://cds.climate.copernicus.eu/cdsapp#!/home. [Accessed: 10-Jun-2022].
[29] Grid3Nigeria, “National Markets,” 2020. [Online]. Available: https://grid3.gov.ng/dataset/national-markets/resources. [Accessed: 10-Jun-2022].
[30] HarvestChoice; International Food Policy Research Institute (IFPRI), “Travel Time to Markets in Africa South of the Sahara,” *Harvard Dataverse, V2*, 2018. [Online]. Available: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/YKDWJD. [Accessed: 10-Jun-2022].
[31] International Food Policy Research Institute, “Spatially-Disaggregated Crop Production Statistics Data in Africa South of the Sahara for 2017,” *Harvard Dataverse, V2*, 2020. .
[32] NBS/FMARD, “National Bureau of Statistics/ Federal Ministry of Agriculture And Rural Development Collaborative Survey on National Agriculture Sample Survey (Nass), 2010/2011,” *National Agriculture Sample Survey*, 2010. [Online]. Available: http://nigeria.countrystat.org/documents/detail/en/c/454834/. [Accessed: 10-Jun-2022].
[33] I. F. P. R. I. HarvestChoice, “Segmentation Data for Nigeria and India States of Bihar, Odisha, and Uttar Pradesh,” *Harvard Dataverse, V2*, 2017. [Online]. Available: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/K5NSAF. [Accessed: 10-Jun-2022].
[34] OpenStreetMap, “OpenStreetMap data for Nigeria,” 2021. [Online]. Available: http://download.geofabrik.de/africa/nigeria.html. [Accessed: 10-Jun-2022].
[35] Grid3Nigeria, “National Farmlands,” 2018. [Online]. Available: https://grid3.gov.ng/dataset/national-farmlands/resources. [Accessed: 10-Jun-2022].
[36] ISRIC, “SoilGrids — global gridded soil information,” 2020. [Online]. Available: https://www.isric.org/explore/soilgrids. [Accessed: 10-Jun-2022].
[37] A. Farina, Y. Rana, and F. Nelson, “How can innovations advance the nutrition data revolution?,” *DATA INNOVATIONS*, 2022. [Online]. Available: https://datadent.org/2022/01/11/how-can-innovations-advance-the-nutrition-data-revolution/. [Accessed: 11-Jan-2022].
[38] World Food Programme (WFP), “HungerMap,” *World Food Programme (WFP)’s global hunger monitoring system*, 2022. [Online]. Available: https://hungermap.wfp.org/. [Accessed: 10-Jun-2022].
[39] NOAA/PhOD, “NOAA/PhOD Ocean Observations Viewer V2.0,” 2022. [Online]. Available: https://cwcgom.aoml.noaa.gov/cgom/OceanViewer/index_phod.html. [Accessed: 10-Jun-2022].
[40] Aqueduct, “Water Risk Atlas,” 2019. [Online]. Available: https://www.wri.org/applications/aqueduct/water-risk-atlas/#/?advanced=false&basemap=hydro&indicator=w_awr_def_tot_cat&lat=3.886177033699361&lng=17.578125000000004&mapMode=view&month=1&opacity=0.5&ponderation=DEF&predefined=false&projection=absolute&scena. [Accessed: 10-Jun-2022].
[41] ISRIC, “SoilGrids and WoSIS,” 2022. [Online]. Available: https://soilgrids.org/. [Accessed: 10-Jun-2022].
[42] World Bank, “Agricultural land (% of land area),” 2018. [Online]. Available: https://data.worldbank.org/indicator/AG.LND.AGRI.ZS?view=map. [Accessed: 10-Jun-2022].
[43] D. Odion *et al.*, “Your VCCA Nigeria Map,” *Interactive map to identify cold room locations*, 2022. [Online]. Available: https://divinefavour.users.earthengine.app/view/yourvcca-map-nigeria-test.
[44] M. Weston, S. Geng, and R. Chandrawati, “Food Sensors: Challenges and Opportunities,” *Adv. Mater. Technol.*, vol. 6, no. 5, pp. 1–16, 2021, doi: 10.1002/admt.202001242.
[45] R. Jedermann, U. Praeger, and W. Lang, “Challenges and opportunities in remote monitoring of perishable products,” *Food Packag. Shelf Life*, vol. 14, no. February, pp. 18–25, 2017, doi: 10.1016/j.fpsl.2017.08.006.
[46] T. Defraeye *et al.*, “Digital twins probe into food cooling and biochemical quality changes for reducing losses in refrigerated supply chains,” *Resour. Conserv. Recycl.*, vol. 149, no. June, pp. 778–794, 2019, doi: 10.1016/j.resconrec.2019.06.002.
[47] K. Shoji, S. Schudel, D. Onwude, C. Shrivastava, and T. Defraeye, “Mapping the postharvest life of imported fruits from packhouse to retail stores using physics-based digital twins,” *Resour. Conserv. Recycl.*, vol. 176, p. 105914, 2022, doi: 10.1016/j.resconrec.2021.105914.
[48] C. Shrivastava, T. Berry, P. Cronje, S. Schudel, and T. Defraeye, “Digital twins enable the quantification of the trade-offs in maintaining citrus quality and marketability in the refrigerated supply chain,” *Nat. Food*, 2022, doi: 10.1038/s43016-022-00497-9.
[49] D. I. Onwude, G. Chen, N. Eke-emezie, A. Kabutey, A. Y. Khaled, and B. Sturm, “Recent Advances in Reducing Food Losses in the Supply Chain of Fresh Agricultural Produce,” *Processes*, vol. 8, no. 11, p. 1431, Nov. 2020, doi: 10.3390/pr8111431.
[50] ClariFruit, “One Automated Platform to Manage your Fresh Fruit and Vegetable QC,” *Products*, 2022. [Online]. Available: https://www.clarifruit.com/solutions/product/. [Accessed: 11-Jun-2022].
[51] IntelloLabs, “Intello Track,” 2022. [Online]. Available: https://www.intellolabs.com/intellotrack. [Accessed: 11-Jun-2022].
[52] Muddy Boots, “Greenlight Quality Control 2,” 2018. [Online]. Available: https://muddyboots.com/.
[53] Agrinorm AG, “Agrinorm,” *Agrinorm Quality Management Platform*, 2021. [Online]. Available: https://www.agrinorm.com/.

[54] Tellspec, “Fruit QC,” 2022. [Online]. Available: https://tellspec.com/howitworks/. [Accessed: 11-Jun-2022].
[55] N. Kato, “A Cold Chain Proposal for Food Losses – Learning from the Past and Present of Japan,” 2013.
[56] FAO, “Services and Infrastructure for Refrigerated Road Transport,” *Food Loss and Waste in Fish Value Chains*, 2022. [Online]. Available: https://www.fao.org/flw-in-fish-value-chains/value-chain/transport/refrigerated-road-transport/services-infrastructure/en/. [Accessed: 05-May-2022].
[57] FMoCDE, “Nigeria open data policy,” *Fed. Minist. Commun.*, no. July, 2018.