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Solar-Powered Cold Storage Technology: A Sustainable Energy Solution for Preservation of Fruits and Vegetables

Omodara, M. A., Akomolafe, O. P., Ajiboye, O., Adebiyi, A. O., Akinyera, O. A., Ogunbiyi, A. O., Zubair, O. M., Oyebanji, A. I., Alabi. I. T., and Ogunjirin, O. C.

Postharvest Engineering Research Department, Nigerian Stored Products Research Institute, Ilorin

Corresponding Author: omodaramikeresearch@gmail.com

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Abstract

Electricity supply from the national grid in rural communities in Nigeria is rarely available, making it practically difficult for farmers to preserve their fresh commodities. Poor cold chain infrastructure is a major contributor to the high postharvest losses of fruits and vegetables, which are estimated to be about 50%. While solar-powered cold storage offers great potential in providing sustainable energy for cutting down the losses during transportation and storage, conventional designs face challenges such as battery drain, unstable temperature control, low humidity, and dependence on imported components. To address these limitations, a 7.2 m³ (250 kg) solar-powered cold storage system (SCSS) with a thermal storage unit and a remote monitoring system for temperature was developed at the Nigerian Stored Products Research Institute (NSPRI) using locally sourced components. The system enables real-time monitoring of chamber conditions and energy inputs, thus ensuring that sufficiently low temperatures and high relative humidities are maintained to preserve stored commodities. The performance of the system was evaluated with tomato. Test results showed an average daily ice production of 11.25 kg and a coefficient of performance of 2.1 (210% efficiency). The system also maintained 10–12 °C temperature and 80–95% relative humidity, with tomato stored for 7 days with in-crate values averaging 9.4 °C and 93%. The thermal storage unit ensures continuous cooling even during cloudy days, thus minimizing battery use and reducing the cost of operation. The solar-powered cold room offers a sustainable and energy-efficient solution for preserving fresh agricultural commodities, particularly in off-grid areas.

Keywords: Solar cold storage, Sustainable energy, preservation, postharvest losses.

1. Introduction

Fruits and vegetables are vital food commodities that form an essential component of a balanced diet, providing dietary fiber, vitamins, minerals, and phytochemicals that play key roles in human health. These bioactive compounds exhibit antioxidant, anti-inflammatory, antigenotoxic, anticancer, and antidiabetic properties (Slavin and Lloyd, 2012; Vasco *et al.,* 2008). According to the Food and Agriculture Organization (FAO, 2020), Nigeria produced over 28 million tonnes of fruits and vegetables for both domestic consumption and export in 2018. Despite this large output, postharvest losses remain a critical challenge, with estimates ranging between 25–50% in developing countries, compared to 5–25% in developed nations (FAO, 2011; Gustavsson *et al.,* 2011; Buzby et al., 2014). In Nigeria, losses are particularly severe in rural communities, often reaching 50% (CBI, 2021).

These high losses are attributed to poor handling practices, underdeveloped cold chain infrastructure, and irregular electricity supply (Mogaji and Fapetu, 2011). The perishability of fruits and vegetables resulting from their continuous respiration, accelerates biochemical and physiological changes that compromise their nutritional value, texture, and appearance (Fonseca *et al.,* 2002). Effective preservation therefore requires storage at low temperatures (0–15 °C) and high relative humidity (85–95%) to slow down deterioration (Lal Basediya *et al.,* 2013; Pace and Cefola, 2021; UC Davis, 2024). Cold storage systems including cold rooms, industrial blast freezers, and refrigerated trucks are widely applied globally to extend shelf life and maintain produce quality (Makule *et al.,* 2022). However, energy costs represent about 28–30% of the total operating expenses of conventional cold storage systems (Krishnakumar, 2002), and unreliable grid electricity supply in rural Nigeria has severely limited their adoption. Consequently, many farmers are forced to sell produce immediately after harvest at low prices, resulting in market gluts and waste (Mohammad et al., 2018).

Solar-powered cold storage has been proposed as a sustainable alternative for developing countries with abundant solar resources and limited access to grid electricity (Vadiee, 2022). Such systems harness renewable energy to provide affordable and eco-friendly preservation solutions. However, conventional solar cold storage units often face challenges of inadequate monitoring, inefficient energy use, and limited adaptability to dynamic storage conditions. Nigerian Stored Products Research Institute (NSPRI) started research on solar cold storage systems (SCSS) in 2019 and installed 11 m^3 (500 kg capacity) solar cold room (SCR) at the headquarters, Ilorin in 2020. The installation was performed in collaboration with Solar Cooling Engineering (SCE), a private spinoff company of the Agricultural Engineering Institute of the University of Hohenheim in Germany. Over the years, the system has been modified to improve its performance. Evaluation result of this system show that the system is able to provide an environment with sufficiently low temperature required for storage of most crops (5 – 20 °C). However, some of the limitations of the system include, battery drain especially during the night, wide temperature fluctuation due to the inability of the system to maintain the desired range and low relative humidity (≥ 80%). Another major limitation of the system was that most of the major components were imported from Germany. This affects its affordability, sustainability and adoption in Nigeria.

To address these gaps, a 7.2 m^3 (250 kg capacity) solar cold storage system with the integration of remote monitoring capability was constructed at the technology garden at NSPRI headquarters in Ilorin. All major components of this system were locally sourced and assembled. key parameters such as chamber temperature, relative humidity, solar energy input, and battery status can be tracked in real time. This innovation ensures that the storage environment consistently meets preservation requirements, improves operational reliability, and provides users with actionable data for informed decision-making.

The paper outline included materials and methods (study area, design of the storage chamber, design of the cooling units, selection and installation of components, description of the solar cold storage system, ice production capacity of the cooling unit, coefficient of performance of the cooling unit, installation of remote monitoring and control system, evaluation of the solar cold room, data analysis), results and discussion, conclusion and future work.

2. Materials And Methods

2.1 Study Area

The study was carried out at the technological garden of Nigerian Stored Products Research Institute (NSPRI), Ilorin, Nigeria (N 8° 27’ 14.77”; E 4° 33’ 21.47”).

2.2 Design of the Storage Chamber

The following assumptions and considerations were made in designing the storage chamber.

i. Reference crop was tomato
ii. Capacity to be designed for (quantity of produce to be cooled (W_t) = 250 kg
iii. Crates to be used for loading produce of dimension 600 mm, 400 mm, and 200 mm (length, width and height)

iv. Weight of tomato per crate (W_{fc}) = 13 kg
v. Arrangement of Crates on pallet (1.2 x 1.0 x 0.15 m)
vi. Four (4) crates per layer of stack
vii. Loading clearance from the wall = 0.3 m
viii. Head space = 0.4 m
ix. Wall, floor and ceiling thickness of 0.1 m
x. Specific heat of tomato = 3.74 kJ/kg K
xi. Heat transfer coefficient of polyurethane panel is 0.22 kJ/mK
xii. Average Ambient temperature of Ilorin is 28 °C (https://www.climate.top/nigeria/ilorin/)
xiii. Desired cold room temperature is 5 °C
xiv. Cooling unit is intended to be in operation throughout the day
xv. Density of air at 28 °C is 1.178 kg/m^3
xvi. Specific heat capacity of air at °C is 1.0067 kJ/kgK

2.2.1 Determination of Number of Crates to be Loaded into the Cold Room (N_C)

$$N_c = \frac{W_T}{W_{fc}} \qquad (1)$$

where; N_c is the number of crates to be loaded into the cold room, W_T is the total capacity of the cold room in kg and W_{fc} is the weight of fruits per crate in kg.

Using equation 1;

$$N_c = \frac{250}{13} \approx 20 \text{ Crates}$$

2.2.2 Determination of the Dimensions of the Storage Chamber

The dimensions of the storage chamber were estimated using the assumptions vii, viii and ix above. The internal dimensions are 2.2 x 1.8 x 1.9 m (LWH).

2.3 Design of the Cooling Units

The system power was estimated in terms of the expected heat load. The heat loas are product heat load, heat gain through insulated surfaces, infiltration heat losses and respiratory heat load. The expected heat loads of the system were estimated using equations (2) to (6) and the estimated quantities are presented in Table 1.

Product heat load Q_p (W)

$$Q_p = m * C * \Delta\theta \qquad (2)$$

Heat Flow through Insulated Surfaces Q_{losses} (W)

$$Q_{losses} = \frac{K}{T} * A * \Delta\theta \qquad (3)$$

Heat gain from external air infiltration Q_i (W)

$$Q_i = V_{cr} * \rho_{air} * C_{air} * \theta \qquad (4)$$

Respiratory Heat Load Q_r (W)

$$Q_r = \rho_p * q_r * V_p * t \qquad (5)$$

$$q_r = 0.003f(T_p + 32)^g \qquad (6)$$

where; m is the weight of the fruits to be cooled (kg), θ is the difference in the temperature of the fresh fruits and desired storage temperature (°K), C is the specific heat of the fruit (Wh/kg K), K is the thermal conductivity of the insulation (W/mK), A is the area of the insulated surface (m^2), T is the thickness of the insulation (m), V_{cr} (m^3)is the cold room volume, ρ_{air} is outside air density (kg/m^3), C_{air} is the specific heat capacity of air (kJ/kg K), ρ_p is product density, V_p is product volume , q_r is respiration heat per unit product mass (W/kg), t is cooling time (hr) and T_p is product storage temperature, while f and g are crop specific coefficients.

Table 1: Summary of the expected heat load of the cold room

Source of heat	Quantity of heat (W)
Cooling of produce	248.9
Heat flow through insulation	133.6
Infiltration of air	2.3
Heat equivalent of respiration	4.2
Total heat load	389

2.4 Selection and installation of components

The compressors, pump, heat exchanger and the solar components were selected based on the estimated system total heat load, availability and cost. The components installed are presented in Table 2.

Table 2: Components of the solar cold storage system

S/N	Components	Units
1	360 W monocrystalline solar panels	8
2	80 A MPPT charge controller	1
3	45 A Felicity primary charge controller	1
4	75 W AGLAC 12-24 V DC compressing units	4
5	70 W DC Water pump	1
6	30 W DC heat exchanger	1
7	DC Thermostat	3
8	100 A DC Breakers	2
9	DC Surge protective devices	2
10	230 AH Eastman 12 V tubular batteries	4

2.5 Description of the Solar Cold Storage System

The solar cold storage system composes of 3 major components; storage chamber, thermal energy storage unit and solar energy system.

- The Storage chamber is an insulted enclosure constructed with 100 mm thick polyurethane panels having shelves made of 1.54 mm square pipes on which fresh produce to be cooled are arranged in crates. The storage chamber also houses a DC heat exchanger through which cool air is transferred and distributed within the storage chamber.
- The thermal energy storage unit consists of four (4) cooling units, water bath and DC water pump; Each cooling unit is made up of compressor, condenser with fan connected to an evaporator plate. The evaporator plates are immersed in a water bath to produce ice which serves as energy storage. Cold water is transferred from the water bath into the storage chamber by a pump through the heat exchanger thereby releasing the coolness from the water and picking up heat from the storage chamber.
- The solar energy unit which supplies electricity to the system consists of photovoltaic panels, charge controller which regulates voltage; and battery as electrical storage unit.

The system was divided into primary and secondary unit for enhanced performance. The primary unit consist of the four 5 solar panels supply power to (4) cooling units and charging three (3) batteries for continuous ice production. The secondary unit consists of three (3) solar panels charging one (1) battery and powering the heat exchanger and pump. This arrangement was done to prevent over draining the battery and eventual system short down especially during bad weathers (with prolonged cloud cover). Figure 1 shows the wiring diagram of the installed components

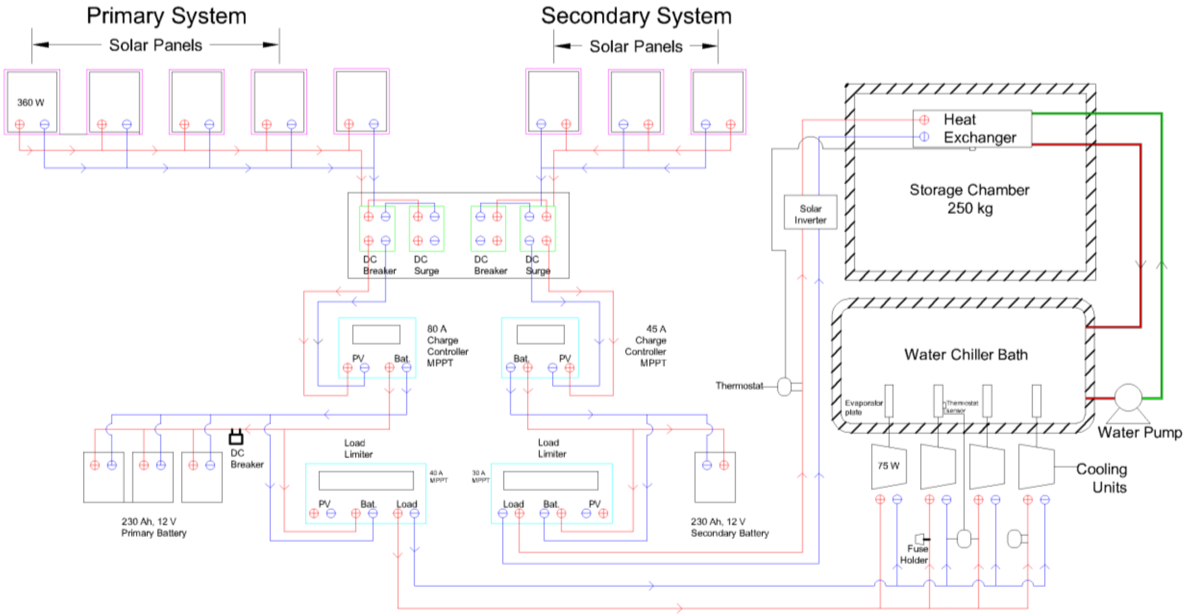

Fig. 1: Layout of installed components

2.6 Ice Production Capacity of the Cooling Unit

The capacity of the system to utilize solar energy from the sun to cool water was accessed. This was achieved by evaluating the ice building capacity of individual cooling units. To achieve this, a small water bath (0.15 cubic meter) was constructed using 1.2 mm mild steel and 1.5 mm stainless plates with the stainless being the inner container. The spacing (100 mm) between both boxes was insulated with 100 mm polyurethane panels. The inside of the bath was lined with tarpaulin to prevent water leakage. A new cooling unit (compressor, evaporator plate, condenser, fan, capillary and copper tubes) was installed with the evaporator plate inside the water chiller bath to build ice. The water bath was filled with 100 litres of water (100 kg) to cover the evaporator plate in the bath. Figure 1 shows the experimental set up of the study.

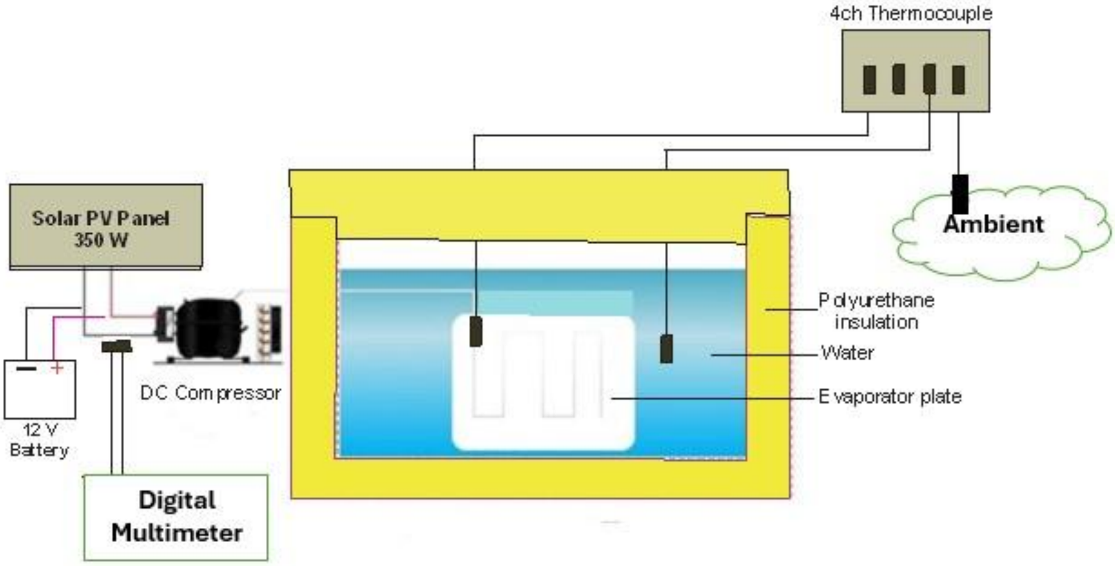

Fig. 2: Schematic diagram of experimental setup for determination of ice production

To measure the ice production by the cooling unit, the compressor was put on and run for 24 hours after which water was drained from the water chiller bath and weighed using a digital Camry weighing balance (150 kg capacity, accuracy ± 0.01 kg). The energy consumed by the cooling unit during operation was monitored at 1 hour interval from 8 am to 6 pm (sunshine hours) daily throughout a study period of 96 hours. The voltage and current consumed by the cooling unit was measured using a digital multimeter (Voltcraft VC-330, Germany). Also, a four channels K-Type thermocouple was installed to measure the temperature fluctuations during the study. Channels 1 and 2 were positioned to measure the temperature of the evaporator plate at the gas inlet, and outlet respectively while channels 3 and 4 measured the temperature of cold water in the bath and ambient respectively.

2.7 Coefficient of Performance of the Cooling Unit.

The Coefficient of performance was estimated using relevant equations (Table 3).

Table 3: Determination of Coefficient of Performance

Quantity	Equation	No
Mass of ice produced in 24 hr	$Mi = Mt - Mw$	(7)
Energy available in the ice	$Q_i = L_{f(ice)} * M_i$	(8)
Daily energy consumption by the cooling unit	$E_{daily} = P_{mean} * 24$	(9)
Overall heat transfer Coefficient of the wall	$U = \left[\frac{1}{\left(\frac{x1}{h1} + \frac{x2}{h2} + \frac{x3}{h3} + \frac{x4}{h4} \right)} \right]$	(10)
Heat loss through insulated surfaces	$Qlosses = UA * \Delta T * \Delta t$	(11)
Coefficient of Performance	$COP = \frac{Q\ daily\ ice + Q\ daily\ losses}{E\ daily}$	(12)

Where, M_i is daily mass of ice produced (kg), M_t is the total weight of water filled into the water bath (kg) and M_w is the weight of water drained during measurement (kg), Qi is the of energy in the ice (Wh), $L_{f(ice)}$ is the latent heat of fusion of ice (Wh/kg), Mi is the mass of ice produced (kg), E_{daily} and P_{mean} are daily energy consumption (Wh) and mean power consumption (W) respectively, U is the overall heat transfer coefficient through the walls (Kj/mK), A is the total area of insulation (m^2), ΔT is the temperature change between cold water in the bath and ambient (K) and Δt is the change in time (hour).

2.8 Installation of Remote Monitoring and Control System

A Wi-Fi enabled monitoring and control device was installed to replace the initial analogue controller. The device serves as a switch that controls the operation of the secondary system (pump and heat exchanger) which transfers the cooling energy from the water chiller bath into the storage chamber Figure 3. The device also has a user-friendly app through which the cold room temperature can be controlled and monitored, so that it operates within a required range for optimum storage of produce.

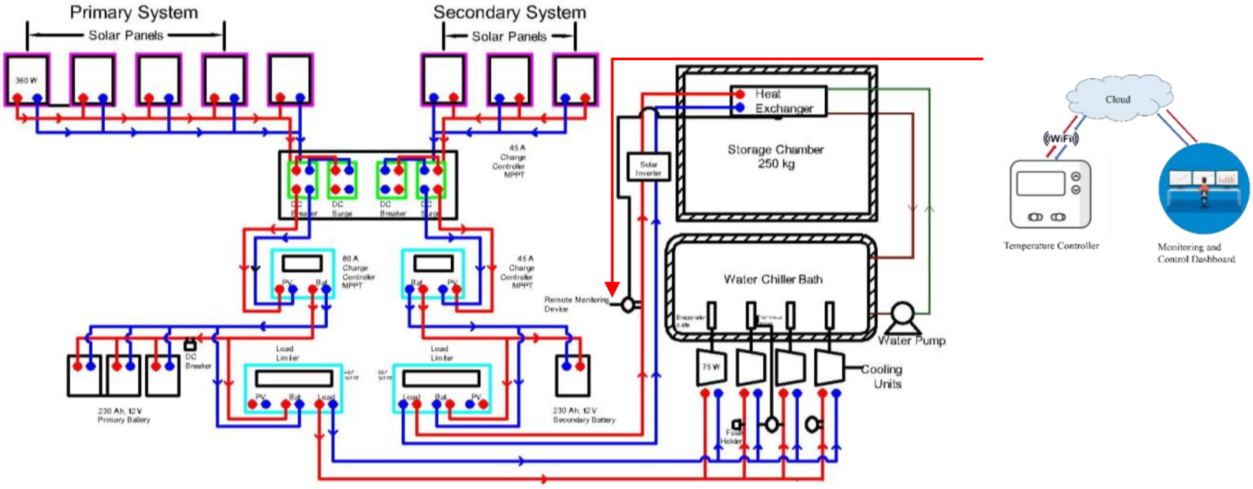

Fig. 3: Experimental Setup with components and instrumentations

2.9 Evaluation of the Solar Cold Room

2.9.1 No-load evaluation

The remote control and monitoring device was set to operate at 10 °C and 12 °C minimum and maximum temperature respectively. Nine (9) Temtop® (model: TemLog 20H, version: V1.0) data loggers were used to monitor the temperature and relative humidity in the cold room. The test was carried out over a period of 7 days. The temperature and humidity data from the loggers were plotted using Python® v.3.11 software.

2.9.2 Evaluation of the Cold Room Using Ripe Tomato

300 kg of ripe tomato was purchased and transported to NSPRI Ilorin in plastic crates (Figure 4). The tomatoes were sorted, washed with clean water and drained. Twenty (20) plastic crates were filled with 10 kg of tomato each and placed inside the solar cold room. The cold room was set up to operate between 10 °C and 12 °C. Nine (9) temperature and relative humidity data loggers were placed in the cold room to map the cold room condition. Four sensors were placed inside the crate of tomato (Figure 5). Sensors were also set up outside the cold room to record the ambient temperature. The study was conducted for seven (7) days.

Fig. 4: Procurement, sorting, cleaning and weighing tomatoes in plastic crates

Fig. 5: Arrangement of tomato crates inside the cold room

2.10 Data Analysis

Data collected were analyzed using Python software version 3.11.3 with the graphs plotted using Matplotlib version 3.8.4.

3. Results and Discussion

3.1 Ice Production Capacity of the Cooling Unit

Table 4 shows the daily ice production of the cooling unit over a study period of 96 hours. The result shows an average daily ice production of 11.25 kg. Therefore, for a system with 4 cooling units operating under the same condition, 80% ice production will be achieved in about one week.

Table 4: Daily ice production of the cooling unit

Sampling time (hour)	Mass of water (kg)	Mass of Ice (kg)	Cumulative mass of Ice (kg)	Total daily Energy in ice (Wh)
0	100.00	0.00	0.00	0.00
24	92.30	7.70	7.70	714.39
48	75.45	16.85	24.55	2277.69
72	65.20	10.25	34.80	3228.67
96	55.00	10.20	45.00	4175.00

3.2 Coefficient of performance of the cooling unit.

The daily coefficient of performance of the cooling unit is presented in Table 5. The result shows an average daily coefficient of performance of 2.1 which is equivalent to a system efficiency of 210%. This implies that the system was able convert the electrical energy supplied from the solar energy unit into about double of useful cooling energy which can be available for ice production.

Table 5: Coefficient of performance of the cooling unit

Day	Q ice (Wh)	Q losses (Wh)	E daily (Wh/day)	COP
1	714.4	1991.3	1531	1.8
2	1563.3	2109.0	1522.2	2.4
3	951.0	2230.4	1543.2	2.1
4	946.4	2143.1	1561.44	2.0
Average				2.1

1.3 Evaluation of the Solar Cold Room

3.3.1 Result of no-load Evaluation of the Solar Cold Room

Figure 6 shows the result of no-load evaluation before and after the installation of remote monitoring. The temperature within the cold room ranges from 7 to 15 °C without the remote monitoring system with the temperature set at 10 °C while with the remote monitoring the cold room was able to maintain a preset range of 10 to 12 °C. This shows that the cold room was able to maintain the preset optimum storage condition.

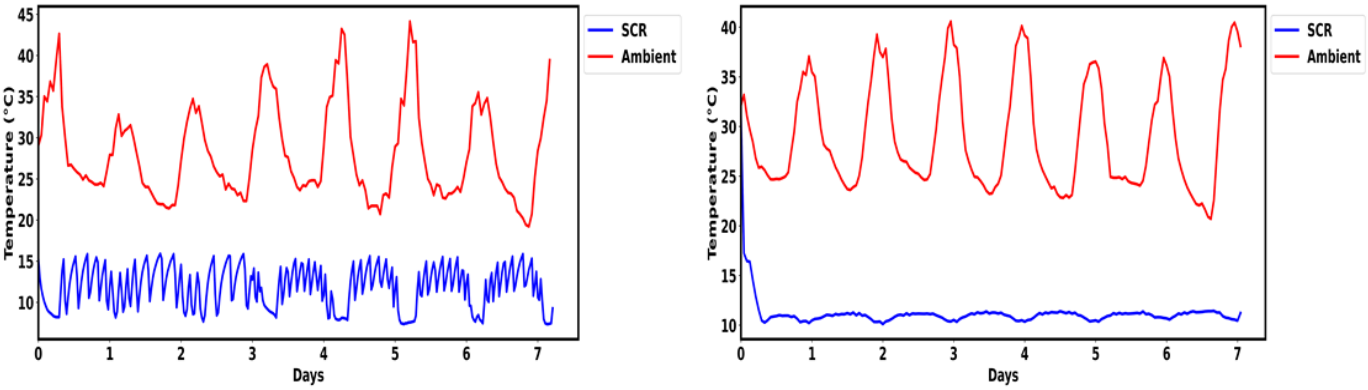

Fig. 6: Temperature profile in the cold room before and after the installation of remote monitoring.

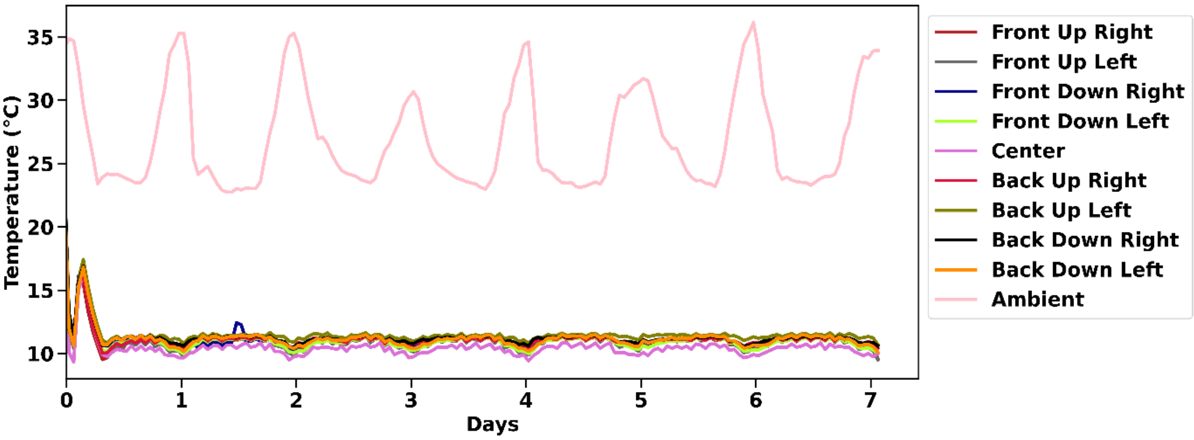

Fig. 7: Temperature distribution in the cold room during tomato storage

3.3.2 Temperature and relative humidity distribution in the cold room during tomato storage

The temperature and relative humidity distribution inside cold room is shown in Figures 7 and 8. Temperature of the cold room was maintained within the set boundaries of 10 °C and 12 °C while humidity was between 70 and 95% during the storage period. The average ambient temperature was 29 °C during the tomato storage trial. The result also showed that it took about 16 hours after loading with tomatoes for the cold room temperature to fall within the preset boundaries.

Figures 9 and 10 show the temperature and relative humidity inside the tomato crates during the loading performance evaluation. The temperatures recorded within the tomatoes ranged between 8.6 °C and 12.0 °C with an average of 9.4 °C, which is lower than the air temperature inside the cold room. While the relative humidity recorded within the produce ranged between 70% to 98% with an average of 93 %. The values recorded fall within the optimum storage condition of ripe tomato as reported by Ndukwu *et al.* (2013) and Kailaku *et al.* (2019).

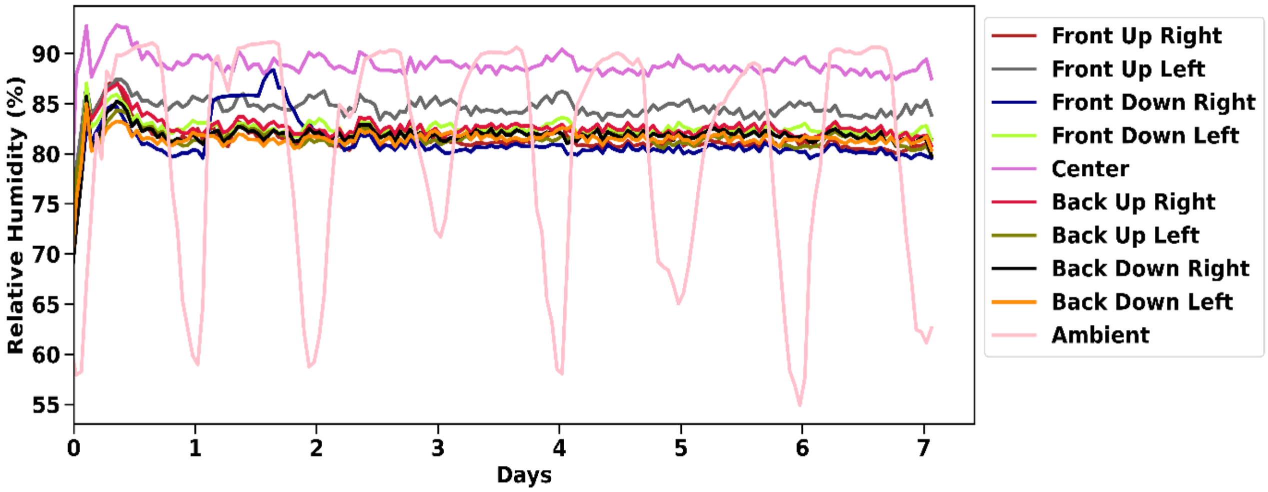

Fig. 8: Relative humidity distribution in the cold room during tomato storage

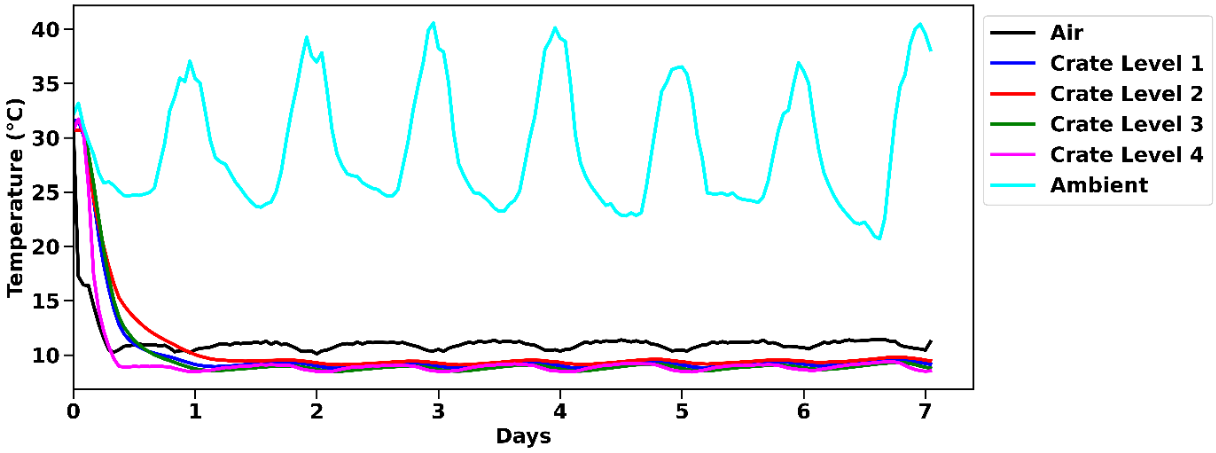

Fig. 9: Temperature profile within the stored ripe tomato in the cold room

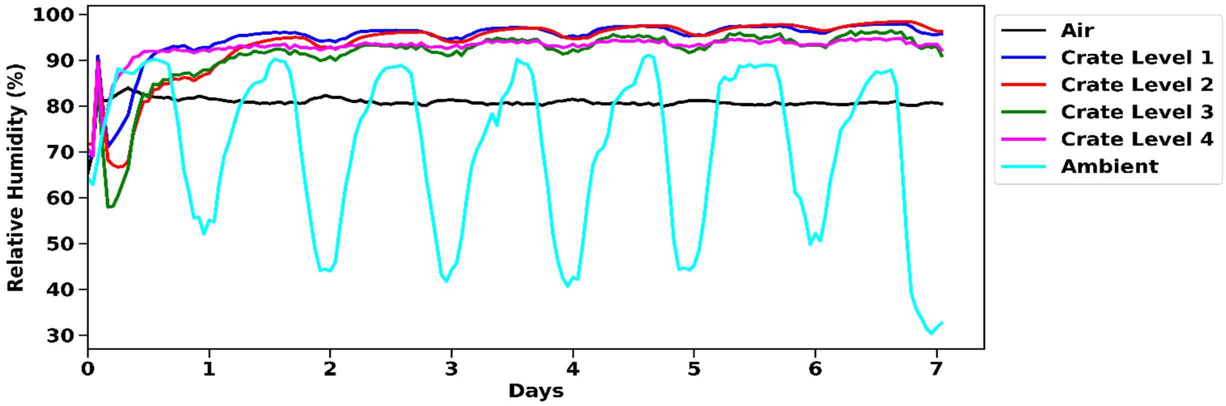

Fig. 10: Relative Humidity profile within the stored ripe tomato in the cold room

2. Conclusions

The optimized 7.2 m³ solar cold storage system with remote monitoring effectively addressed key limitations of conventional designs by maintaining stable conditions of 10–12 °C and 70–95% relative humidity. The cooling unit achieved a coefficient of performance of 2.1 (210% efficiency), producing more than double the cooling energy relative to input energy. Average ice production was 11.25 kg/day, with 40% utilized during storage. The monitoring device enabled precise regulation of system operations, ensuring stability while the thermal storage unit cut down the number of batteries required for optimal performance. The Optimized solar cold storage system proved efficient and reliable for tomato preservation. The use of locally sourced components enhances affordability and adaptability, making it a sustainable energy solution for preserving fresh agricultural commodities and bridging the Nigeria's cold chain infrastructural gap.

5. Future Work

Future work will focus on refining the optimized solar cold storage system through both technical and experimental advancements. Key areas will include integrating automated humidification to ensure consistent relative humidity, and the development of intelligent, data-driven control algorithms for adaptive energy management and operational efficiency. Further experimental studies will extend to other perishable crops such as carrot, pepper, onion, and leafy vegetables, to establish crop-specific storage parameters and assess quality retention under varying storage conditions. Additional investigations will examine long-term system performance, durability, and scalability through pilot installations in rural communities. These future studies will provide the technical evidence needed for large-scale deployment and commercial integration of the system into Nigeria's postharvest management framework.

References

Buzby, J. C., Farah-Wells, H., & Hyman, J. (2014). The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States. *Economic Information Bulletin No. (EIB-121).* U.S. Department of Agriculture. https://doi.org/10.2139/ssrn.2501659

CBI. (2021). Exporting fresh fruit and vegetables to Europe. *Centre for the Promotion of Imports from Developing Countries.* https://www.cbi.eu

FAO. (2011). *Global food losses and food waste: Extent, causes and prevention.* Food and Agriculture Organization of the United Nations.

FAO. (2020). *FAOSTAT statistical database.* Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat

Fonseca, S. C., Oliveira, F. A. R., & Brecht, J. K. (2002). Modelling respiration rate of fresh fruits and vegetables for modified atmosphere packages: A review. *Journal of Food Engineering, 52*(2), 99–119. https://doi.org/10.1016/S0260-8774(01)00106-6

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., & Meybeck, A. (2011). *Global food losses and food waste: Extent, causes and prevention.* Food and Agriculture Organization of the United Nations.

Kailaku, S. I., Nurjanah, R., & Charles, F. (2019). Advances in the development of a tomato postharvest storage system: towards eradicating postharvest losses. https://doi.org/10.1088/1742-6596/1378/2/022064.

Krishnakumar, J. (2002). Energy use pattern in cold storage. *Indian Food Industry, 21*(5), 64–70.

Lal Basediya, A., Samuel, D. V. K., & Beera, V. (2013). Evaporative cooling system for storage of fruits and vegetables – A review. *Journal of Food Science and Technology, 50*(3), 429–442. https://doi.org/10.1007/s13197-011-0311-6

Makule, E. E., Rwiza, M. J., & Kaale, L. D. (2022). Cold storage technologies and their applications in developing countries: A review. *Food Control, 133,* 108632. https://doi.org/10.1016/j.foodcont.2021.108632

Mohammad, S., Mustafa, A. M., & Musa, A. E. (2018). Assessment of postharvest losses of fruits and vegetables in Sudan. *Journal of Agricultural Science and Food Research, 9*(2), 1000238.

Mogaji, T. S., & Fapetu, O. P. (2011). Development of an evaporative cooling system for the preservation of fresh vegetables. *ARPN Journal of Engineering and Applied Sciences, 6*(9), 62–67.

Ndukwu, M. C., Manuwa, S. I., Olukunle, O. J., & Oluwalana, I. B. (2013). Development of an active evaporative cooling system for short-term storage of fruits and vegetable in a tropical climate. *Agricultural Engineering International: CIGR Journal*, 15(4), 307–313.

Pace, B., & Cefola, M. (2021). Postharvest handling of fruits and vegetables to reduce food losses and waste. In *Postharvest physiology and biochemistry of fruits and vegetables* (pp. 561–590). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-822153-4.00009-7

Slavin, J. L., & Lloyd, B. (2012). Health benefits of fruits and vegetables. *Advances in Nutrition, 3*(4), 506–516. https://doi.org/10.3945/an.112.002154

UC Davis. (2024). *Postharvest technology center: Recommended storage conditions for fresh produce.* University of California, Davis. https://postharvest.ucdavis.edu

Vadiee, A. (2022). Solar cooling technologies for sustainable food storage: A review. *Renewable and Sustainable Energy Reviews, 165,* 112537. https://doi.org/10.1016/j.rser.2022.112537

Vasco, C., Ruales, J., & Kamal-Eldin, A. (2008). Total phenolic compounds and antioxidant capacities of major fruits from Ecuador. *Food Chemistry, 111*(4), 816–823. https://doi.org/10.1016/j.foodchem.2008.04.054