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Assessment of a Modular Solar-Powered Cooling System Integrated with a DC-Remote Monitoring and Control System for Fruits and Vegetables Storage

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ABSTRACT

This study examines the applicability of solar energy for cooling in the tropical climate and focuses on the performance assessment of a modular solar-powered cooling system (MSPCS), integrated with a DC-Remote monitoring and control (RMC) system, installed on a 10 m³ cooling chamber for the storage of fruits and vegetables. The RMC capability to stabilise the MSPCS operation was assessed through real-time monitoring and control of system parameters, including temperature and relative humidity, water chiller temperature, and DC voltage utilisation by the components. This was achieved by connecting sensors for monitoring via an internet-enabled data box linked to a PC dashboard. The system cooling performance was assessed by measuring chamber temperature, humidity, voltage consumption and weight loss of the stored produce. The results demonstrated effective tracking/control of the system parameters and enhanced activation of components to stabilize the operation of the entire cooling system at temperature of (8.40 ±0.455^{a} °C), relative humidity of (88.91 ±1.571 %) inside the cooling chamber, the water chiller temperature at (2.75 ±1.25 °C) and system voltage (25.61±0.033 V) at no-load and loading conditions. The integration of the DC-RMC system significantly enhanced both the cooling chamber's thermal performance and the overall voltage efficiency of the system, resulting in 20% physiological weight loss and a delay in ripening by 10 days for stored tomatoes in the solar

1. INTRODUCTION

The deployment of cold rooms with smart renewable energy components is gaining relevance, particularly for the quality preservation of fruits and vegetables in tropical climates. This is crucial for food and nutrition security, livelihood, and economic development [3]. Among existing methods for preventing postharvest losses of bulk fresh horticultural products in the tropics are evaporative cooling [14] and a hybrid evaporative cooling system utilising solar-powered aeration [8]. While the conventional evaporative cooling has limited energy capability and lacks effective control over the operational parameters owing to weather variations, refrigeration-based cooling is considered to be a more advanced and reliable method, particularly under harsh temperature environmental conditions [9]. However, the epileptic supply of electricity in the remote areas is a serious deficiency in the conventional refrigeration and cooling system. Similarly, [16] demonstrated improved conventional cooling by incorporating solar-powered indirect air cooling with direct evaporative cooling for the storage of fruits and vegetables to observe better cooling. Therefore, application of solar-cooling systems, which are currently gaining relevance in the tropics are suitable alternative, promoting affordable cooling solutions in the off-grid as an alternative to grid-powered conventional refrigeration [7]. A decentralised solar-grid hybrid cold room with cooling jute pads was demonstrated for perishables storage by [17]; [21] with observation of effectiveness. However, limited control over the storage conditions exists. Also, [14] reported evaporative cooling with a clay wall for improved fruit & vegetable storage under Ethiopian weather; however, short-term cooling performance is still a challenge. Hence, a need for improved cooling performance in terms of the control of

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cooling operation and parameters. Solar-powered cooling is designed to leverage the abundant sunshine in tropical climates [8], harnessing renewable (solar) energy for food crop storage [11;12]. The deployment of solar cooling into postharvest storage of fresh fruits in Nigeria has not been effectively validated due to meteorological differences, variations in daily sunshine within certain locations, and a lack of control over the system's operational parameters in the storage of horticultural produce, which affects the system's performance. In 2021, the Nigerian Stored Products Research Institute (NSPRI), Ilorin, Nigeria, developed a modular solar-powered cooling system (MSPCS) for the storage of fruits and vegetables [1]; an advancement to the existing conventional evaporative cooling structure [18]. To better maximize the MSPCS efficiency, precise monitoring and control of the system's operational parameters, such as temperature, relative humidity, thermal energy storage (TES), and voltage, are required to be stabilized to achieve effective cooling performance. The system has been integrated with a DC-Remote Monitoring and Control (RMC) system. [15] studied the applicability of remote monitoring to a cold storage warehouse in maintaining temperature, humidity, gases, and light. For the preservation of fresh fruits and vegetable products, like fresh tomato (*Solanum lycopersicum*) fruits, which is a widely demanded food commodity in Nigeria. Stability of storage temperature, which plays a key role in its post-harvest storage condition, is crucial. Tomato is highly susceptible to spoilage under a harsh temperature environment [13]. Therefore, for such thermally sensitive bulk fresh produce in cold storage, [10] suggested, timely tracking and control of the storage parameters are necessary for effective cooling and energy utilization. Application of remote monitoring and control has been reported to enhance operability of cold storage systems [4; 6]. They rely on Internet of Things (IOT) mechanisms comprising sensors, microcontrollers, and electromechanical relays to transmit data to cloud servers, enabling real-time access and control of physical systems [20]. While many IoT-based remote monitoring systems offer basic data logging and remote parameter viewing, the SelfChill® RMC used in this research integrated an optimized monitoring and control platform for off-grid, solar-powered cold storage in tropical climates that enhances cold storage performance, combining energy management with environmental stability control features, which is often absent in generic IoT monitoring systems. Typically, incorporating a remote monitoring and control unit on a modular solar-powered cooling system can efficiently regulate the system at preset thresholds to enable system parameters stability to improve the off-grid cooling efficiency driven by solar energy. While many IoT-based remote monitoring systems offer basic data logging and remote parameter viewing, the SelfChill® RMC used in this research integrated monitoring sensors and a control platform facilitated by an electrotechnical relay to optimized off-grid, solar-powered cold storage system in the tropical climates that enhance cold storage performance, combining energy management with environmental stability control features which is often absent in generic IoT monitoring systems.

2. Materials and Methods

2.1 Description of The Modular Cooling System and the SelfChill® DC-Remote Monitoring and Control System

A 10 m^3 cooling chamber with 45-W heat exchangers and pump units, and 300 W DC cooling units in a 500-litre capacity water chiller bath, was connected to a 3.5 kW Photovoltaic module Fig.1. The chamber and bath were made of 100 mm polyurethane-insulated panels installed at NSPRI, Ilorin (N 8°26′35.5″ E 4°34′4.8″). The cooling chamber is meant for fruit and vegetable storage, while the water chiller is for thermal energy storage (TES) in ice-water. A SelfChill® DC-Remote Monitoring and Control RMC System (Figure 2) was incorporated and connected to the DC components in a 24 V series, sending signals through electromechanical relays and sensors. The DC-Remote Monitoring and Control (RMC) system operates using Ecophi's in-built IoT software, which integrates temperature and humidity sensors (Model: BGT-WSD1, accuracy Temperature: ±0.3 °C; Humidity ±3% RH) and a battery voltage sensor (Model: BGT-13; +5 – 50V). The circuit diagram describing wiring connections of the modular components to the DC-RMC unit is shown in Figure 1. Figure 2 shows the schematic configuration of the RMC and component points.

The solar irradiance of the study site was monitored during the assessment using a DT-1037 solarimeter (Resolution: min. – 1Wh/m^2; max. – 1999 W/m^2; accuracy: ±10 Wh/m^2) at the experimental site (Nigerian Stored Products Research Institute, Ilorin; N 8°26′35.5″ E 4°34′4.8″), and which ranges between 277 Wh/m^2 and 1253 Wh/m^2. From November 2023 to January 2024.

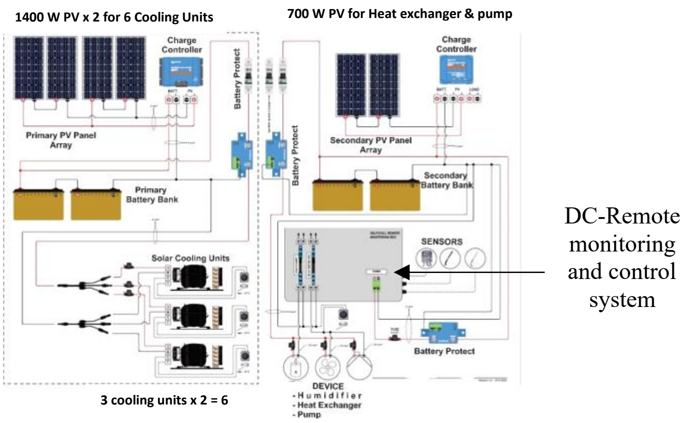

Fig. 1. Wiring diagram of the Solar Cold SelfChill® Remote monitoring connected to the solar components

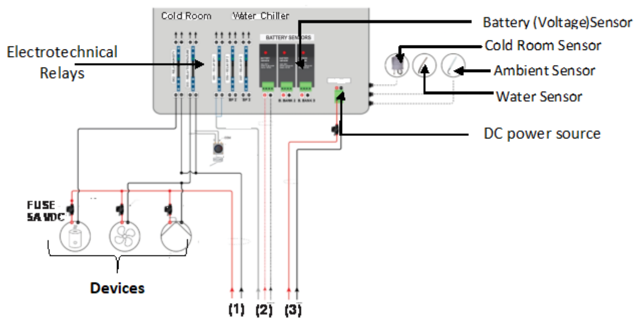

Fig. 2. Schematic diagram of the SelfChill® DC-Remote Monitoring and Control System (1 = Device power source, 2 = Relays power source, 3 = Remote monitoring power source). Incorporated on the MSPCS.

The DC-RMS is mounted to the cooling chamber (Figure 3) to enable access to the real-time data monitoring and control (temperature, relative humidity and photovoltaic and battery voltage) as well as ambient environmental data transmitted with the aid of sensors and are accessed via the Ecophi dashboard on a PC or mobile phone interface (Figure 4). Data transmission to the cloud is enabled by the Wi-Fi-connected Ecophi data box, to access on either a PC or mobile devices.

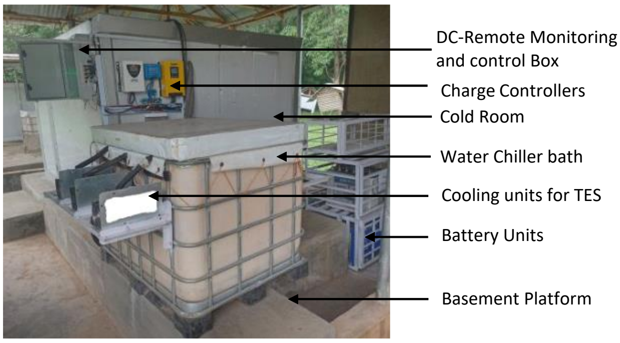

Fig. 3. The DC-Remote monitoring system box mounted to the solar-powered cooling chamber

The remote monitoring facilitates continuous tracking of key operational parameters of the modular solar-powered cooling systems for prompt activation and corrective actions when necessary.

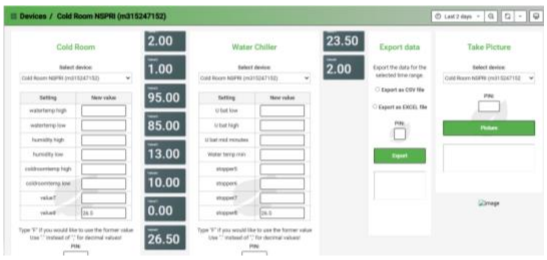

Fig. 4. Typical Ecophi control dashboard of the SelfChill® DC-remote monitoring system

2.2 Operation of the Selfchill® DC-Remote Monitoring and Control System.

The SelfChill® remote monitoring and control system Fig. 3 operates with 24 VDC power supply, comprise of electrotechnical relays and sensors configured for the real-time monitoring of temperature, relative humidity, and voltage of the DC cooling units, while temperature sensors are placed inside the water chiller bath to monitor water temperature and voltage sensors are placed on the battery terminals to monitor the transient voltage supply. The RMC devices in (Fig. 2) are a heat exchanger fan, water pump, and a humidifier, which were controlled by the relays, which receive signals from dedicated sensors to maintain a logical set-point that stabilises the solar cooling system performance.

2.3 Ecophi Sensor Calibration and Accuracy Validation

Before deploying the Ecophi® sensors for the performance assessment of the solar cold room integrated with DC – RMS under no-load and loading, the sensors were subjected to calibration and accuracy verification to ensure the reliability of data measurements. The temperature and humidity sensors (BGT-WSD1) and voltage sensors (BGT-13) were tested against certified reference instruments under controlled conditions. Calibration points were selected to cover the expected operational range during the modular solar-powered cooling system assessment, as in:

i. **Temperature and humidity Sensors (BGT-WSD1)** were calibrated against a certified digital thermo-hygrometer with an accuracy of (±0.3 °C, ±2% RH) with ISO/IEC 17025 standards. By placing the Sensor inside the cold room at three setpoints (e.g., 5 °C, 15 °C, and 20 °C for temperature; 50%, 70%, and 90% for RH). The readings were logged over a 30-minute stabilization period at each set point.

ii. **Voltage Sensors (BGT-13):** This was calibrated using a precision digital multimeter, VOLTCRAFT meter; Current: +/_ 0.001 A, Voltage range: 0.1 – 100 V, 20 Ω. (±0.02% DC voltage accuracy). The Voltage outputs from a regulated DC power supply were compared against the sensor readings at multiple setpoints (e.g., 12 V, 24 V, 28 V).

Thereafter, the observed deviations were then compared with the RMS sensor's manufacturer-specified accuracy limits.

2.4 Performance Assessment of the Solar Cold Room

The MSCR was accessed at a no-load and under loading with tomato storage over a period of 14 days, while the control setup was placed in the ambient.

2.3.1 Performance Assessment with Tomato storage at non-remote-controlled conditions and using the DC-Remote Monitoring and Control System

The solar cold room was first set up for tomato storage in April 2023 at a set point of 10 °C using a non-remote Rainbow TS-Series Bulb & Capillary Adjustable DC Thermostat (of accuracy: -30 °C to 320 °C), mechanical thermostat fixed to the cold room/chamber. Followed by integration of the DC-Remote Monitoring and Control System for a no-load performance assessment conducted for 4 days in November 2023, when day and night average temperatures were 33 °C and 26 °C, respectively, the experimental assessment "with and without" the remote monitoring control was further conducted to establish the stable operation of the modular solar cooling system. The RMC logics were set to operate at cooling temperatures, relative humidity and voltage of 10 - 12 °C, and 65 – 70 % and 24 – 26.5 V, respectively. Bulk ripe tomato was further loaded for a repeat storage experiment in the cold room for 14 days in January 2024, to assess the effect of the RMC unit on the cooling system's stability. For the storage assessment, data logging sensors were placed inside the cold room and the crates containing tomatoes, while the RMC system logic was set to operate the MSPCS between temperature and relative humidity of 8 and 10 °C and relative humidity 90 – 95%, respectively, following the UCDavis recommendations for storage of tomatoes. Three (3) quality indices, namely weight loss, Total Soluble Solid (TSS), and colour change magnitude and hue angle) were measured at an interval of 48 hours over 14 days, and data were analysed to assess the quality retention of stored tomato fruit. The percentage weight loss of tomato in the MSPCS represents the difference between the initial weight of stored tomato and its apparent weight during storage, the TSS was monitored using

A laboratory bench type Digital Refractometer (Atago ATC-1, Tokyo, Japan), and Colour difference (ΔE) is the magnitude of the colour change of stored tomato represented by CEILab components [2]. In contrast, the Total colour index (TCI) quantifies the green-red component (a*), product of lightness (L) with the ratio of chroma component (b*) measured over the 14 days.

2.4 Percentage Weight Loss of Stored Ripe Tomato: Equation 2.1 was used to determine the % weight loss of stored ripe tomato in (kg) within 14 days inside the cooling chamber, monitored using a Camry digital weighing balance (Model: ACS-30-JE11 with ± 0.01 accuracy).

$$WL\ (\%) = \frac{W_i - W_{i+1}}{W_i} \text{ x } 100 \quad (1)$$

Source: [2]

Where: WL = % weight loss, Wi = initial weight of stored ripe tomato in crates, and Wi+1 as apparent weight for subsequent sampling for 14 days.

2.5 Total Colour Change and Hue angle:

The stored tomato colour changes were measured using a digital Fru CIELab colourimeter during the 14-day storage period. The measured values L, a, and b were reported by [2]. The FRU Portable Digital Colourimeter WR10QC 4mm was calibrated with a white paper before taking measurements from day 0 to day 14. Each sampled tomato colour component L*, a* and b* at three points (blossom end, stem-end and mid-way) on the spherical surface of the sampled tomatoes were measured and averaged to determine the overall values using the procedure [2]. The colour changes of stored tomatoes were measured in terms of the L* value and the hue angle (h°) using equation from [19] to establish quality parameters as metrics for the market value of tomatoes using equations 2.2a and 2.2b, for the colour components monitored using a FRU Portable Digital Colorimeter WR10QC instrument for 14 days inside the cooling chamber and ambient.

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^{*2} + \Delta b^{*2}} \quad (2)$$

Source: [2]

Hue angle (h°) equation 2.3 was used to calculate and quantify the ripening based on colour change measurements to represent the perceived colour direction expressed in degrees.

$$h° = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (3)$$

Source: [9]

Where: (ΔE) is the Total colour difference is the magnitude of the colour change of stored tomato represented by CEILab components; (TCI) is the Total colour index quantifies the green-red component (a*), product of lightness (L) with the ratio of chroma component (b*).

2.6 Data Analysis

The parameters Temperature (°C), relative humidity (%), photovoltaic (PV) voltage, and battery voltage (V) recorded by the (RMC) system were analysed using Microsoft Excel 2021 and further processed in Python (version 3.1) to plot the data. The Matplotlib library in Python was employed to generate cooling performance curves to visualize the parameter trends, and SPSS version 21 by 2-Tail test was used to determine the significance levels (P<0.05).

3. Results and Discussion

3.1 Performance with Tomato Storage at Non-remote-Controlled Cooling.

Figures 5 and 6 show the trend of the environmental conditions (temperature and relative humidity) of the solar cold room compared to the ambient conditions during the storage of tomato with the non-remote control mechanical thermostat. It shows the unstable trend of temperature and relative humidity profile over a period of 14 days, ranging from 6.8 – 15.2 °C and 75 to 95%, which is not a suitable condition to ensure the quality preservation and storage stability of the stored tomato. Hence, a need for effective control for better stability of storage conditions.

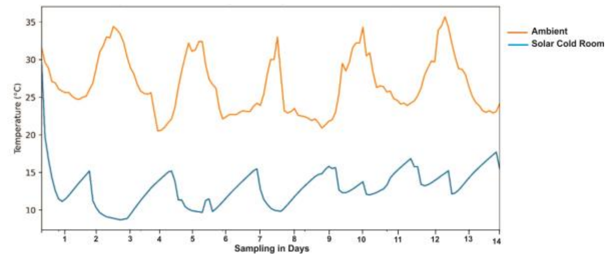

Fig. 5. Temperature for non-remote-controlled Solar Cold Room and ambient with Tomato storage

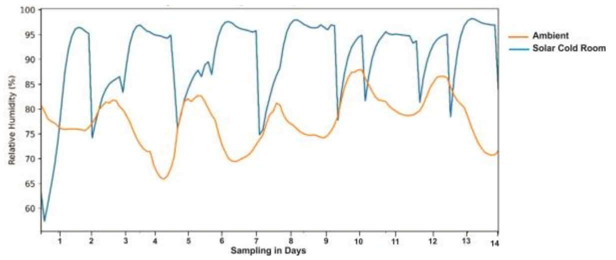

Fig. 6. Relative humidity for non-remote-controlled Solar Cold Room and ambient with Tomato storage

3.2 Ecophi Sensor Calibration and Accuracy Validation

Table 3.1 presents the calibrated sensors and mean deviations from the reference values of the Ecophi® sensors (BGT-WSD1 for temperature and relative humidity, BGT-13), with ±1 °C has ±0.6 °C for temperature, and ±3% for RH. While for voltage exceeded the manufacturer's stated accuracy by ±0.2 V, respectively, from the reference measurement. The calibration confirmed that the sensors operated within the manufacturer's stated ranges. This validation step provides confidence that the recorded temperature, humidity, and voltage data used in the analysis accurately reflect actual system conditions for the system's reliability on subsequent performance evaluations. Table 3.1 shows that the calibration stayed within acceptable error margins.

Table 1. Calibration and Accuracy Validation of Ecophi® Sensors

Parameter Sensor	Model	Calibration Points	Accuracy	Observed Deviation
Temperature (°C) and Humidity (%) Sensor	BGT-WSD1	5 °C, 15 °C, 20 °C	±1 °C	±0.6 °C
		50%, 70%, 90% RH	±5% RH	±3% RH
Voltage (V) Sensor	BGT-13	12 V, 24 V, 28 V	±0.5 V	±0.2 V

3.3 Effect of the Integrated DC-Remote Monitoring and Control System on Temperature and Relative Humidity in the Cold Room at No-Load

Figures 7 and 8 present the temperature and relative humidity profiles recorded inside the modular solar-powered cold room compared to the ambient conditions, both with and without the activation of the DC-Remote Monitoring and Control (RMC) system under the no-load conditions. It was observed that without the RMC system activating in response to temperature, there was a high variation in temperature within the cold room, non-uniform and unstable, with the degree of fluctuations ranging from 7 °C to 16 °C without stability. In contrast, activation of the RMC system significantly improved the cold room temperature regulation at (8.40±0.455 °C) while ambient (26.72±0.26 °C) at $p<0.005$. However, the system maintained a 'daily' stable internal temperature within a controlled range of 10 and 12 °C (Figure 7). This stability is essential for maintaining optimal cooling conditions for the preservation of fresh produce. Similarly, as shown in Figure 8, relative humidity was erratic without the use of the RMC system. Although the target setpoint for humidity in the cooling chamber was 80%, fluctuations ranged between 70% and 90% without stability, reflecting poor humidity control. Upon activation of the RMC system, the chamber achieved a more stable average relative humidity of 70% (88.91 ±1.571 %) inside the cooling chamber and 42.12 ±2.045 %) in the ambient at a significant level of $P<0.005$. This indicates the system's improved capability to maintain humidity levels within the desired range against the ambient, which is crucial for reducing moisture and weight loss to prolong the shelf life.

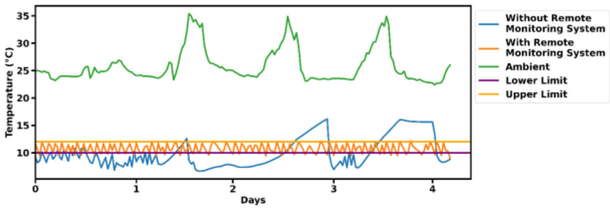

Fig. 7: Cold Room Temperature at No-load "with and without" RMC system.

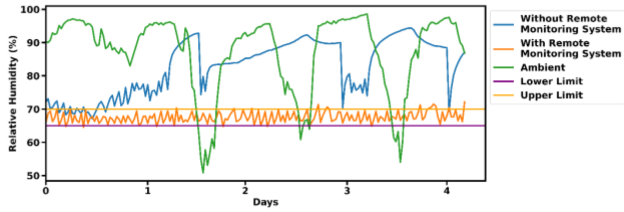

Fig. 8: Cold Room Relative humidity at No-load "with and without" RMC system.

3.4 Effect of the DC-Remote Monitoring and Control on the Water Chiller Temperature at No-Load Assessment

Figure 9 illustrates the temperature profile of the chilled water in the water bath, monitored using the Remote Monitoring and Control (RMC) system's temperature sensor under no-load conditions. The temperature of the water chiller determines the amount of thermal energy in the form of ice available for cooling of produce inside the cooling chamber. The recorded water temperature ranged between 1.5 °C and 2.25 °C, indicating effective thermal energy storage (TES) from the ice production by the solar cooling unit, for use in the cooling of the produce storage chamber. This is achieved via the integrated heat exchanger (fan and coil) and water pump units. During monitoring, an average temperature rise of 0.6 °C during the day and 0.2 °C at night was observed in the circulating chilled water. These variations are attributed to differential heat gains in the water chiller bath, influenced by ambient temperature fluctuations and solar system dynamics across day and night periods. The minimal rise in the water temperature demonstrates the system's stability to retain stored thermal cooling energy with less thermal losses, highlighting the role of the RMC system in maintaining the thermal efficiency and responsiveness of the thermal energy storage component.

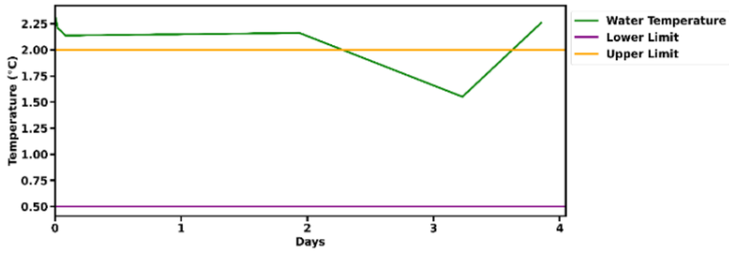

Fig. 9: Water Chiller Temperature at No-load Assessment

3.5 Effect of DC-Remote Monitoring and Control on the Voltage Supply to the Cooling System at No-Load Assessment

Figure 10 presents the voltage profile of the solar-powered cooling system components, including the water bath and cold room units, under no-load conditions. The system maintained a mean operating voltage of 26 V, with values ranging between 24.5 V and 28.0 V. The voltage demand of the heat exchanger was comparatively lower, averaging ±2.25 V less than that of the water chiller cooling units. During peak sunlight hours (approximately 8 hours of sunshine daily), a maximum voltage of 27.8 V was recorded, enabling efficient operation of the cooling components. The cooling units ran for an average of 16 hours daily, while the heat exchanger operated for approximately 8 hours during nighttime conditions. Additionally, the system recorded an average daily voltage boost of 3.0 V, ensuring that the battery bank remained fully charged to support uninterrupted operations. These findings demonstrate the effectiveness of the Remote Monitoring and Control (RMC) system in stabilizing voltage distribution throughout both day and night cycles.

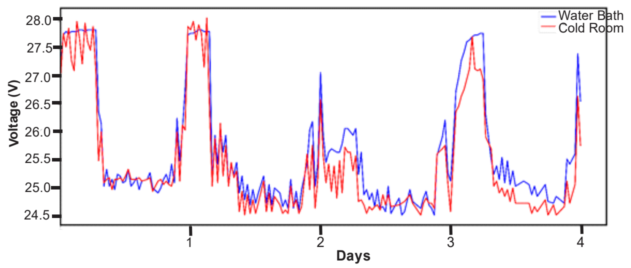

Fig. 10: Profile of Voltage supply to the DC-Components water bath and cold room at no-load evaluation

By maintaining voltage within defined operational bounds, the RMC prevents system shutdowns during off-peak periods, thereby ensuring reliable and continuous operation of the modular cooling system.

3.6 Effect of the Remote Monitoring and Control on Temperature and Relative Humidity of Tomato Storage

Figures 11a and 11b illustrate the temperature and relative humidity profiles recorded within the cooling chamber during the storage of ripe tomatoes, with the Remote Monitoring and Control (RMC) system activated. The system maintained an average of 11.5 °C internal temperature and relative humidity of 90.3%, indicating a stable and effective cooling performance. The humidity range of 80 – 90 % is suitable for preventing the water loss from fresh fruits and vegetables. The controlled cooling environment offered by the MSPCS significantly reduced tomato weight loss by 80% compared to the ambient storage conditions, which increased otherwise, as shown in Table 1. The RMC system successfully maintained the preset temperature and humidity (10-12 °C) required for the tomato storage, with minimal fluctuations observed in the relative humidity. However, during periods of elevated ambient temperatures, an increased thermal loss from the cooling chamber resulted in to change in the temperature profile. This led to extended operation (running time) of the heat exchanger, thereby increasing thermal energy storage (TES) consumption and higher voltage utilization from the water chiller and the battery banks, as presented in Figures 6 and 7.

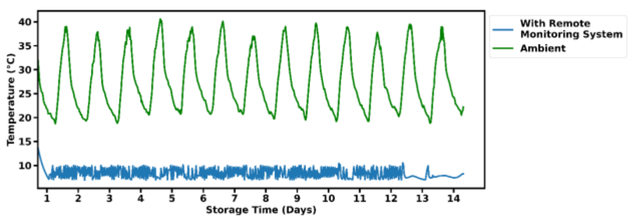

Fig. 11a: Temperature profile of the Modular Cold room and Ambient during tomato storage

The Ambient conditions during the 14-day storage period ranged between 18 °C and 40 °C for temperature and 15% to 92% for relative humidity. These sharp contrasts between ambient and cold room storage conditions underscore the system's effectiveness and further support findings by [9], highlighting the detrimental effects of high ambient temperatures on fresh tomato quality preservation.

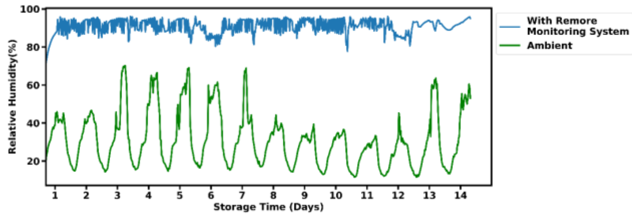

Fig. 11b: Relative humidity of the Modular Cold room and Ambient during tomato storage

Table 2. Effect of the non-remote control and remote monitoring control on the solar cold room operational parameters

Operational Parameter	Without remote control	With remote control	Ambient
Temperature (°C)	12.10±0.462^b	8.39±0.455^a	26.72±0.26^b
Relative Humidity (%)	74.3±3.255^b	88.91±1.571^a	42.12±2.045^a
Voltage (V)	25.39±0.031^a	24.69±0.01^a	-

3.7 Effect of the storage conditions controlled by DC-RMS on the weight loss and colour change of stored Tomatoes

Figure 12a and 12b depict the appearance of the stored tomatoes in the crates inside the cold room of the MSPCS and the ambient, showing an obvious difference in appearance in the colour change from day 1 to day 14. The red pigment in the stored tomatoes MSPCS showed appealing than that of the ambient.

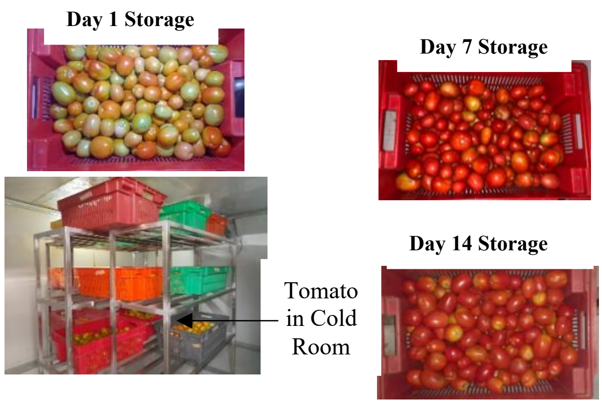

Fig. 12a: Tomatoes stored in the Solar Cold room for 14 days.

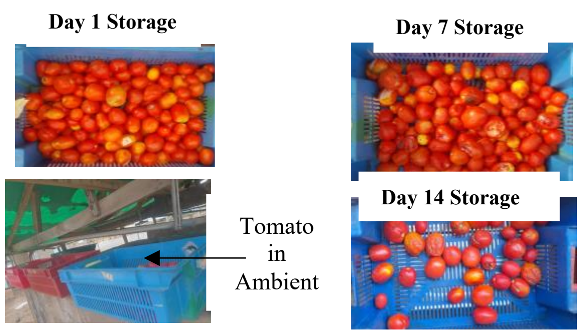

Fig. 12a: Tomatoes stored in the Ambient for 14 days.

Figures 13 and 14 show the colour analysis and the trend of colour change magnitude of the stored tomatoes. This is to evaluate the effect of the remote-control cooling process on the colour reactions of the stored tomatoes. The colours in terms of magnitude of change have a stable trend between day 1 to day 5, while tomatoes stored inside the cold room have a steady increase in colour to maintain the brilliant red pigment. In contrast tomato in the ambient appeared to have an irregular colour change to record a lower magnitude, similarly hue angle trend indicates that to falls between 45 – 57° in the ambient, while that of the cold room falls between 54 - 57°. The hue angle indicates a higher value for tomatoes inside the MSCR. Higher values mean greener (i.e., less ripe), while lower values mean redder (i.e., more ripe). This implies, tomatoes stored in the MSCR retained higher hue angles for a longer time, staying greener, while tomatoes stored in the ambient condition showed a faster drop in hue angle, meaning they ripened more quickly. The modular cold room performs better because the operation is effectively controlled with the DC-RMC to preserve the colour qualities better by smart activation of cooling units.

In addition, with the controlled operation of the MSPCS maintained, the hue values of the tomato inside were between 54 –57°, indicating slower ripening due to cooler and more humid conditions. In contrast, tomatoes stored in ambient conditions dropped to about 46° by Day 14. This highlights the effectiveness of the DC-Remote monitoring and controlled MSCR in extending shelf life by delaying 'red' color development, which is a key quality indicator in tomato storage.

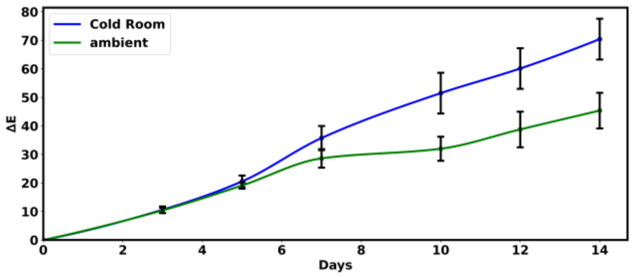

Fig. 13. Magnitude of colour change inside the Cold room and Ambient during tomato storage.

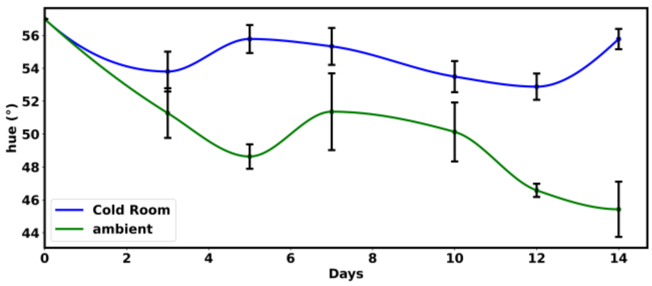

Fig. 14. Hue angle profile and colour change in stored tomato

Table 3.2 shows the periodic percentage weight loss recorded for the stored tomatoes in the cold room and the ambient conditions. Higher colour retention was observed on the tomatoes stored inside the cold room of the MSPCS, much better than the ambient, with about 5 percent loss after 3 days, showing evidence of high rot and shrinkage. The ambient condition causes an inconsistent ripening and loss of freshness of stored tomatoes. Apart from colour, there was an increase in shrinkage and shrivelling in the ambient. About 80% weight retention in the stored tomatoes was achieved inside the cold room, against 25% at ambient after 14 days. The MSPCS, due to its controlled temperature capability by the DC-RMC system and the humidity control, succeeded in reducing the weight loss of the stored tomatoes under constant low temperature and higher humidity. While the weight reduction of tomatoes in the ambient increased by about 10% daily, this may be due to higher fluctuating temperature resulting in rot and shrinkage; that of MSPCS recorded 6.3% weight reduction until day 12, when it increased to 14%. Although the remote-control function does not directly affect the weight loss, but allowed the stability of high relative humidity at 88.91±1.571% which reduced water loss from stored tomatoes inside the cold room. This observation indicates the effective performance of the DC-RMC in regulating the activation of the DC components that make up the entire MSPCS in minimizing the weight loss of stored tomatoes. This aligns with findings of [2], who reported similar reductions in tomato weight loss under controlled temperature at 18 °C.

Table 3. Percentage weight loss of stored tomatoes in the Solar Cold Room

Days	Solar Cold Room (%)	Ambient (%)
0	0	0
3	0.73	4.83
5	1.49	11.83
7	2.69	30.42
10	6.36	46.58
12	14.54	56.92
14	19.91	74.75

3.8 Effect of DC-Remote Monitoring and Control System on Total Soluble Solid of Stored Tomatoes

The effects of the storage conditions on the Total Soluble Solids (TSS) of stored tomato fruits are shown in Fig. 15; the TSS increased progressively under both ambient and cold storage, though at different rates. While ambient-stored fruits showed a faster rise to about 5.2 °Brix by day 12, followed by a slight decline due to over-ripening, cold-stored fruits exhibited a slower, steadier increase (4.2–5.0 °Brix) without decline, indicating delayed ripening and better sugar conservation. Although statistical differences were not significant at all points, the distinct trends demonstrate that cold storage effectively slows metabolic activity, preserves sugar reserves, and extends fruit quality and marketability compared to ambient storage.

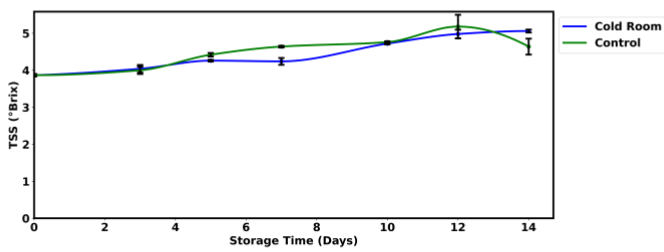

Fig. 15. Total Soluble Solid of stored tomatoes in the cold room and the ambient.

3.9 Effect of the DC-Remote Monitoring and Control System on Water Chiller Temperature during Storage of Tomatoes

Figure 16 illustrates the temperature profile of the cold water circulating from the water chiller bath during the tomato storage period. The Remote Monitoring and Control (RMC) system effectively maintained water temperature in the chiller bath within the range of 2–6 °C, before it further fluctuated to 8 °C at day 13 and 14. This consistent thermal regulation ensured that the cold water supplied through the water pump to the heat exchanger provided sufficient thermal energy to maintain stable and optimal cooling conditions within the cold storage room, where temperatures remained between 7–10 °C throughout the storage period (Figure 7). The slight upward trend in chiller water temperature observed toward the end of the storage period is attributed to increased thermal energy storage (TES) demand. This was likely driven by the cumulative respiratory heat released from the stored tomatoes as ripening progressed, especially after day 14. The rise in fruit respiration and associated metabolic heat load generated from the bulk tomato while ripening during storage placed additional demand on the cooling system, leading to a gradual reduction in the cooling capacity of the chiller bath over time.

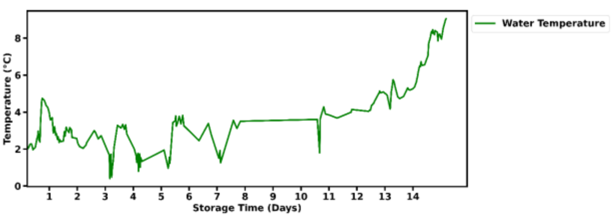

Fig. 16. Temperature profile of the Water Chiller bath circulation during tomato storage

Additionally, the elevated water temperature at day 14 may also be due to thermal losses through the insulated surfaces from increased ambient temperature affecting the water chiller bath, as suggested by [5], who highlighted the impact of transmission losses in cooling media. In the study, the rise in water chiller temperature on days 13-14 can be due to increased tomato respiration heat production, which was recorded under similar temperature ranges on the 14th day due to accelerated ripening stage progression caused by ethylene production. This is in coherence with respiration heat values for ripe tomato at 7–10 °C (Thompson et al., 2008; Kitinoja & Kader, 2015), which range from 10–18 mW/kg. Applying these values to the stored tomato mass of (300 kg) yields an increased heat load demand. Over-extended storage with increased ripening on days 13–14, this metabolic heat load would contribute to additional demand on the thermal energy storage (TES) system, resulting in the observed gradual water chiller temperature increase Fig. 16. The resulting higher cooling load likely reduced the water chiller's ability to maintain sub-4 °C temperatures towards the end of storage. Future work will incorporate direct respiration measurements, such as CO_2 production monitoring or calorimetric analysis, to quantify metabolic heat contribution more precisely and validate its impact on TES performance. Interestingly, the lowest chill-water temperature, below 1 °C, was recorded during night-time periods when the ambient temperature average was 24 °C. This thermal change effect is likely due to increased ice formation within the chiller bath system, which enhances thermal absorption and subsequently reduces the water temperature during (night) hours.

3.10 Effect of DC-Remote Monitoring and Control on the System Voltage During Storage of Tomatoes

Figure 17 presents the voltage profile of the cooling chamber and water bath components as monitored and controlled with the DC-RMC throughout the tomato storage period. Figure 11 presents the voltage profile for the cooling chamber components and water bath during the storage of ripe tomatoes. A voltage range of 24.5–28.0 V was maintained for powering the DC components throughout the storage period, with an average daily boost of approximately ±3.5 V. This stability ensured continuous system operation, enabling the cold room to maintain the storage temperature between 7–10 °C (Fig. 8), with an average operational voltage of 25.3 V. While the RMC system played a central role in regulating and distributing voltage in real time, voltage stability was also supported by other critical system elements. The 2800 Ah battery bank provided a substantial energy buffer, compensating for fluctuations in solar input and load demand. The 3.5 kW PV array, operating at high conversion efficiency during peak sunlight hours, consistently charged the batteries, ensuring a steady supply of DC power. Additionally, priority-based load management, programmed within the RMC, allocated power to essential cooling components first, cycling or delaying non-critical loads during periods of low irradiance. The combined effect of the RMC's intelligent control, ample battery capacity, efficient PV generation, and strategic load scheduling enabled the MSPCS to operate without voltage-related interruptions during both sunny and cloudy conditions. This integrated approach ensured optimal cooling performance, improved energy efficiency, and enhanced system reliability for off-grid tomato storage applications.

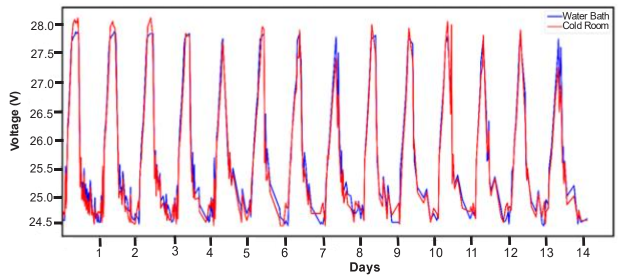

Fig. 17. Voltage supply to cold room and water bath DC-components during storage of tomatoes

Additionally, the MSPCS, equipped with the 2800 Ah battery bank and 3.5 kW PV array, maintained high conversion efficiency from current-voltage during peak sunlight hours, ensuring consistent charging of the batteries and adequate power supply to all DC components. This directly supported voltage stability in the battery unit during operation. providing substantial charge storage to reduce short-term fluctuations in solar energy supply. Also, the voltage stability observed during tomato storage was a combined effect of the DC-RMC's smart logic set point activation and control capabilities, the high-capacity 2800 Ah battery bank providing electrical energy storage, the high-efficiency PV array ensuring consistent charging, and load management logics at 24 -26 set points with cooling demand regulations that reduced peak demand stress on the system. Together, these enabled the MSPCS to maintain an average operational voltage of 25.61± 0.033 V at a significant level of p<0.05 without system failure under both sunny and cloudy conditions, maintaining a stable voltage.

4. CONCLUSION

The integration of a DC-Remote monitoring and control (RMC) system into the modular solar-powered cooling system caused a smart response of the cold room components and significantly enhanced the stability and overall cooling performance, efficiency, and reliability of the system. The IoT-enabled SelfChill® DC-RMC system stabilized the key operational parameters (temperature, humidity and voltage), maintaining the desired logic set conditions essential for the effective storage of produce in the system, such as tomatoes. With the real-time data sensing and remote-control capability of the operational parameters, the RMC facilitated optimal regulation of temperature, humidity, voltage and water chiller thermal storage. These findings demonstrate the potential of off-grid remote monitoring and control systems to enhance the operability of solar-powered cold storage systems, particularly in remote and off-grid areas of Nigeria, supporting resilient and sustainable utilization of renewable energy technologies. Future research should explore machine learning ML integration of advanced data analytics, and predictive control algorithms based on: Data types to be collected for environmental conditions: ambient temperature, solar irradiance, relative humidity. System performance metrics: cold room temperature and humidity, PV generation, battery state-of-charge (SOC), cooling unit energy consumption, and chiller water temperature. Produce quality indicators: weight loss, firmness, colour change, and spoilage rate to further optimise system performance and maximise the system usage. Also, economic viability and cost benefits analysis of the modular solar-powered cooling system in off-grid agricultural value chains should be explored.

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REFERENCES

[1] Adebiyi, A. O., Ogunbiyi, O. A., Gbabe, E. K., Idris, Y. D., Adeiza, A. & Omodara, M. A. (2023). Solar Cooling: A Sustainable Technology for Reducing Postharvest Losses in Fruits in Nigeria. Book of Abstracts of the 4th All-Africa Postharvest Congress and Exhibition (Hybrid). Held at the African Union Commission, Addis Ababa, Ethiopia. 19 - 22. September 2023. Pp 77.

[2] Concepcion, R., Janairo, A. G., Palconit, M. G., Carpio, J., Bandala, A., Vicerra, R. R., Cuello, J., & Dadios, E. (2021). Influence of Storage Periods and Temperatures on Postharvest Quality of Fresh-Marketed Lycopersicon esculentum Mill. 2021 IEEE 13th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management, HNICEM 2021, pp. 1–6. doi: https://doi.org/10.1109/HNICEM54116.2021.9731896.

[3] FAO. (2022). Sustainable food cold chains: Opportunities, challenges and the way forward. In Sustainable food cold chains: Opportunities, challenges and the way forward. doi: https://doi.org/10.4060/cc0923en.

[4] Jain, S., & Paul, S. (2020). Advances in Intelligent Systems and Computing 1124 Recent Trends in Image and Signal Processing in Computer Vision. http://www.springer.com/series/11156 doi: https://doi.org/10.1007/978-981-15-2740-1.

[5] Khiro, H. A. Al, & Boukhanouf, R. (2024). Energy and Exergy Performance Analysis of Solar-Assisted Thermo-Mechanical Vapor Compression Cooling System doi: https://doi.org/10.3390/su16198625.

[6] Mashayamombe, T., Mhlanga, S., Muusha, P., & Muusha, N. (2023). Design of a Remote Monitoring System for Solar Thermal Energy: A Case Study in an Educational Institution. International Journal of Research Publication and Reviews, 4(11), pp. 2436–2445. doi: https://doi.org/10.55248/gengpi.4.1123.113130.

[7] Ogumo, E. O., Kunyanga, C. N., Kimenju, J. W., & Okoth, M. (2020). Performance of a fabricated solar-powered vapour compression cooler in maintaining post-harvest quality of French beans in Kenya. African Journal of Food Science, 14(7), pp. 192–200. doi: https://doi.org/10.5897/AJFS2020.1968.

[8] Olosunde, W. A., Aremu, A. K., & Onwude, D. I. (2016). Development of a Solar Powered Evaporative Cooling Storage System for Tropical Fruits and Vegetables. Journal of Food Processing and Preservation, 40(2), pp. 279–290. doi: https://doi.org/10.1111/jfpp.12605.

[9] Sambo, B. E., Ahmed, A., Omotugba, J. T., Adedapo, J. O., & Shekwolo, G. (2016). The Challenge of Infrastructure Development on Preservation of Perishable Horticultural Produce for Sustained Urban Food Nutrition in Metropolitan Kaduna, Nigeria. International Journal of Horticulture and Forestry Research, 1(1), pp. 13–26. doi: https://eajournals.org/ijhfr/vol-1issue-1-march-2015.

[10] Shao, D., Venkitasamy, C., Li, X., Pan, Z., Shi, J., Wang, B., Teh, H. E., & McHugh, T. H. (2015). Thermal and storage characteristics of tomato seed oil. Lwt, 63(1), 191–197. doi: https://doi.org/10.1016/j.lwt.2015.03.010.

[11] Sinha, A., & Karale, S. R. (2013). A review on Solar Powered Refrigeration and the Various Cooling Thermal Energy Storage (CTES) Systems. International Journal of Engineering Research & Technology (IJERT), 2(2), 1–14. id: IJERTV2IS2198. www.ijert.org.

[12] Takeshima, H., Yamauchi, F., Edeh, H. O., & Hernandez, M. A. (2023). Solar-powered cold-storage and agrifood market Modernization in Nigeria. Agricultural Economics (United Kingdom), 54(2), 234–255. doi: https://doi.org/10.1111/agec.12771.

[13] Thole, V., Vain, P., & Martin, C. (2021). Effect of Elevated Temperature on Tomato Post-Harvest Properties. Mdpi.Com/Journal/Plants, 10(10), 2359. https://doi.org/10.3390/plants10112359.

[14] Verploegen, E., Ekka, R., Gill, G., & Faso, B. (2019). A Research Report of Evaporative Cooling For Improved Fruit & Vegetable Storage In Rwanda & Burkina Faso. MITD-Lab, May 2019.

[15] Yadav, R. K. (2020). Remote Monitoring System for Cold Storage Warehouse using IOT. International Journal for Research in Applied Science and Engineering Technology, 8(5), 2810–2814. doi: https://doi.org/10.22214/ijraset.2020.5473.

[16] Sibanda, S. (2021). Development Of A Solar-Powered Indirect Air Cooling Combined With a Direct Evaporative Cooling System For Storage Of Fruits And Vegetables In Sub-Saharan Africa. doi: https://doi.Org/10.13140/Rg.2.2.13604.60808.

[17] Munir, A., Ashraf, T., Amjad, W., Ghafoor, A., Rehman, S., Malik, A. U., Hensel, O., Sultan, M., & Morosuk, T. (2021). Solar-Hybrid Cold Energy Storage System Coupled with Cooling Pads Backup : A Step towards Decentralized Storage of Perishables. Energies, 14(22), 7633. MDPI, pp. 2–20. doi: https://doi.org/https://doi.org/10.3390/en14227633.

[18] Babarinsa, F. A., & Omodara, M. A. (2016). Preservation of Tomatoes in a Brick-Walled Evaporative Cooler Journal of Postharvest Technology jpht, 4(1), pp. 1–5. link:

[19] Saad, A., & Jaiswal, P. (2014). Non-destructive quality evaluation of intact tomato using VIS-NIR spectroscopy. International Journal of Advanced Research (2014), 2(12) pp. 632-639 l

[20] Ishaque, F., Hossain, A., Sarker, A. R., & Rahman, H. (2019). A Study on Low-Cost Post-Harvest Storage Techniques to Extend the Shelf Life of Citrus Fruits and Vegetables. 9(1), pp. 1–17. doi: https://doi.org/10.9734/JERR/2019/v9i117009.

[21] Zakari, M. D., Abubakar, Y. S., Muhammad, Y. B., Shanono, N. J., Nasidi, N. M., Abubakar, M. S., Lawan, I., & Ahmad, R. K. (2016). Design and Construction of an Evaporative Cooling System for the Storage of Fresh Tomatoes. ARPN Journal of Engineering and Applied Sciences, 11(4), pp. 2340–2348.