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Article

Development of a Mobile Solar Cooling System for Enhanced Shelf Life of Fruits and Vegetables

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Abstract: This study presents a novel Mobile Solar Cooling System (MSCS) designed to enhance the cold chain for leafy vegetables by leveraging solar energy for sustainable and cost-effective refrigeration. The MSCS maintained an average storage temperature of $9 \pm 4^\circ\text{C}$ and relative humidity of $85 \pm 10\%$, significantly improving the preservation of green amaranth compared to ambient conditions (average temperature: $30 \pm 2^\circ\text{C}$). Key system metrics include a coefficient of performance (COP) of 1.6, indicating efficient energy use, with an average daily energy consumption of 1190 Wh. The system extended the shelf life of green amaranth to 18 days, as opposed to 5 days under ambient storage, while minimizing weight loss, retaining up to 87.25% moisture, and preserving essential nutrients such as Vitamin A (51.35 mg/100 g) and beta carotene (22.49 mg/100 g). The microbial load remained within internationally acceptable limits, with bacterial counts below 10^5 and fungal counts of 10^3 - 10^4 . This innovative system has the potential to reduce postharvest losses, ensure food safety, and enhance food security in regions with limited access to conventional refrigeration infrastructure. The MSCS is recommended for scaling and adoption by stakeholders in fruit and vegetable supply chains, with further potential for application across a variety of perishable crops.

Keywords: mobile solar cooling system; leafy vegetables; food security; postharvest loss; energy efficiency; sustainable agriculture

1. Introduction

Food is one of the basic needs of life for the survival of human beings. It is essential in order to provide opportunities for physical, mental and social development of an individual. Provision of food that is healthy, sufficient in quality and quantity, affordable, safe and culturally acceptable for all inhabitants of the world is a necessity [1,2]. All people have a right to adequate food that does not only meet the minimum requirements for survival but is also nutritionally adequate for health and well-being [3]. Fruits and vegetable are good sources of vitamins and minerals without which human body cannot maintain proper health and develop resistance to disease [4]. Nigeria is one of the major producers of fruit and vegetable commodities in the world [5] and ranked the one hundred and fifty ninth largest producers [6,7]. Leafy vegetables have tremendous potential to address poverty alleviation and nutritional security because they are affordable, easily available, easy to grow, require minimum production input, rich in vitamins, minerals, phytochemicals and antioxidants [8]. Leafy vegetables are eaten in a variety of ways as part of meals and snacks. The consumption of fruits and vegetables is important due to the nutrients they contain, which can limit the risk of cardiovascular diseases and cancer [9]. They possess considerable quantities of vitamins A, B, C, D, E and K, which generally help in protecting the human body against diseases and contribute in no small measure to good health [10]. Poor and inadequate postharvest infrastructure results to significant losses of these produces [11].

Storage of fresh fruits and vegetables after harvest is one of the most pressing problems faced by farmers and handlers of these commodities. Due to their high moisture content, fruits and vegetables are liable to spoil and as such, making postharvest losses to result in direct food and income losses to farmers and consumers globally [12]. The metabolic activities of fruits and vegetables continue after harvest because they live, transpire, respire and continue to ripen and the deterioration rate increases due to ripening, age and unfavourable environmental factors [13]. Hence, preserving these commodities in their fresh form demands that the chemical, bio-chemical and physiological changes are restricted to a minimum by controlling of space temperature and humidity [14]. Sizeable quantity of produce deteriorates by the time it reaches the consumer due to inappropriate handling methods. This is mainly because of the perishable nature of the produce which requires a cold chain arrangement to effectively maintain the quality and extend the shelf-life [15]. Therefore, there is the need for the improvement of the thermodynamics of agricultural processing systems [16]. Most of the fruits and vegetables produce require a cooling temperature between 0 °C and 5 °C for safe storage and transit purposes [17]. Postharvest losses of about 50% of the total production are recorded for these commodities [18]. In the absence of cold storage and related cold chain facilities, the farmers are forced to sell their produce immediately after harvest which results to glut and low price realization [19]. The usage of electrically powered cold storage is a challenge in Nigeria due to non-availability of electricity and in some areas where it is available, it is epileptic in supply. It is desirable in this modern time that there is the necessity to develop viable energy sources with unlimited duration and smaller environmental impact than the traditional one because of the high energy demand all over the world for industries as well as in the domestic sector [20]. Maintaining physical and nutritional qualities entails utilization of cold chain facilities, therefore the study was aimed at design, constructing and evaluating a mobile solar cooling system with green amaranth vegetable adopting a comparative approach between storage under ambient conditions (under shed and in the mobile solar cooling system).

2. Materials and Methods

The **Materials** used for this study were categorized into three main groups:

1. Construction Materials:

Insulation materials: Various types of insulation materials were selected to minimize heat loss and maintain the internal temperature of the mobile solar cooling system (MSCS). The choice of insulation material was guided by its thermal resistance, durability, and cost-effectiveness.

Frame and Enclosure: These were made from lightweight, corrosion-resistant materials such as aluminum and polycarbonate. The design aimed at achieving a balance between structural integrity and portability.

Solar Panels: High-efficiency photovoltaic (PV) panels were selected to capture sunlight effectively and convert it into electrical power for cooling. The orientation and mounting of these panels were optimized to maximize solar energy absorption.

2. Evaluation Materials (Green Amaranth):

Sample Selection: Fresh green amaranth was selected as the test material due to its sensitivity to temperature variations. This choice provided a representative case to study the effectiveness of the MSCS in preserving the freshness and shelf life of perishable vegetables.

Preparation for Testing: The green amaranth was cleaned, sorted, and weighed before being placed inside the MSCS. The weight and condition of the amaranth were monitored at regular intervals to evaluate the cooling system's performance.

3. Instruments/Equipment:

Measuring Devices: A set of digital thermometers, hygrometers, and data loggers were used to monitor the internal temperature and humidity levels within the MSCS during operation. These instruments allowed for precise tracking of environmental conditions inside the system.

Power Meters: Used to measure the energy consumption of the MSCS and the output from the solar panels. This data helped in assessing the system's energy efficiency and sustainability.

Load Cells: To measure the weight of the vegetables, providing insights into moisture content and loss over time due to cooling.

2.1. Design Considerations

In designing the mobile solar cooling system (MSCS), the following factors were taken into account:

i. **Capacity and Total Weight of the MSCS:**

The capacity was designed to hold up to 50 kg of fresh vegetables, balancing cooling efficiency with portability.

The total weight was minimized to ensure easy mobility, especially important for users in remote areas.

ii. **Insulation Materials:**

The selection of insulation materials was critical to maintaining the internal temperature. The design aimed at optimizing the thermal resistance to prevent heat ingress from the external environment, thereby enhancing the cooling efficiency of the system.

iii. **Heat Load Calculations:**

Calculations were conducted to determine the thermal load based on the amount of heat generated by the solar panels and the ambient temperature conditions. These calculations guided the selection of cooling capacity and the design of the ventilation system to effectively manage the heat within the system.

iv. **Compactness and Availability of Construction Materials:**

The system was designed to be compact yet sturdy, making use of readily available construction materials to reduce costs and facilitate easy maintenance and repair. The goal was to create a practical solution that could be easily replicated in different settings.

2.2. Materials Needed for the Mobile Solar Cooling System (MSCS)

The materials needed for this work are classified into construction materials:

- i. Mobile devise: A tricycle
- ii. Solar components: solar panels, charge controller, deep cycle solar battery, circuit breakers, cable and cable connectors and switch board.
- iii. Cooling component materials: DC compressor accessories, condenser with fan, water bath with water as phase change material, evaporator plates on which ice was formed, a brushless DC water pump to convey chilled water to the storage chamber, water hoses, clips and refrigerant (R600a) isobutene which is environmental friendly.
- iv. Storage chamber component materials: polyurethane panels of 60mm insulation thickness for rectangular shape storage chamber construction, stainless pipe for construction of racks and shelves, stainless mesh was used for construction of trays where produce were arranged, heat exchanger (evaporator) with fan to circulate thermal cooling energy in the storage chamber.
- v. Other items for construction are galvanized metal sheets, bolts, nuts and screws to fasten the walls of storage chamber and other parts together, a 45 litres (from calculation) insulated plastic container was used for water chiller bath to avoid thermal losses, electrodes (both stainless and mild steel type will be used for welding the various metal parts.

2.3. Instrumentation devises for the research work

The following instruments, equipment and apparatus were used in the study,

- i. A digital camry weighing scale (30 kg) and (600 g) capacity of 0.001 kg accuracy, ACS – 30 – JE 11, made in china – was used for measuring the weights of samples.
- ii. Hobo Humidity/Temperature automated Data logger (ONSET MX2301, WXF – ONST3) - It monitors temperatures from -40 to +85°C. It has built-in temperature sensor, Case waterproof to ip68, User programmable alarms, User-replaceable battery, 32,000 reading capacity, High reading resolution, Fast data offload and Low-battery monitor.
- iii. Fruit and vegetable portable colourimeter (WR10QC – 8, 10QC230754) was used to monitor the test commodity's colour change.
- iv. Solar power meter (NO. 11128388, LCD display, w/m² or BTU) – this was used in measuring solar insolation of the sun in the study location.
- v. AC and DC multimetre (Etekcity-C600 digital clamp metre) – this was used to measure the current in solar panels, batteries, compressors and charge controller.
- vi. Four channel thermocouple: 3 (three) of this channel was used to record the temperature of water in the water chiller bath and the remaining 1 channel is to record ambient temperature.
- vii. Thermostat was used to control the temperature both in the storage chamber and in the water chiller bath.
- viii. Smart Sensor Digital Anemometer AR826 (Graigar, China) measuring to an accuracy of 0.3 m/s. This is to measure the air velocity in the storage chamber

2.4. Design Calculations

2.4.1. Calculation of Total Heat Loads

Heat loads is the total amount of heat that the cooling system will remove from the storage chamber. The leaks and splashes of heat transmitted in a storage chamber of a cold room will be generated from several critical heat sources which are: Heat of conduction, infiltration heat load, product heat load (sensible and respiration) and miscellaneous heat load

- (1) The total heat of conduction through the insulated walls of the storage chamber of the MSCS will be obtained using Equation (1) as reported by Ogumo *et al.* [6]

$$Q = U \times A \times (t_2 - t_1) / d, \quad (1)$$

where Q = heat load kwh/day

U = thermal conductivity of insulation material (0.023 to 0.026)

A = Area of sides, roof and floor of storage chamber (m²) = 3.68 m²

t₁ = Air temperature inside storage chamber (10 °C) for mango

t₂ = Ambient temperature (28 °C) average of min. and max. temperature

d = thickness of the wall (m) = 0.06

- (2) Calculation of field heat of produce in the storage chamber

This is the sensible heat /field heat load that is needed to be extracted from the produce, heat that is picked up by produce from the farm and it is required be cooled to the required storage temperature, this will be obtained in line with Kazem *et al.* [21] using Equation 2

$$Q_{PS} = M \times C_p \times (t_2 - t_1), \quad (2)$$

where:

Q_{PS} = Produce sensible heat (kwh/day),

M = Mass of produce (kg), = 25 kg

C_p = Specific heat of vegetable, (3.77 kJ /kg °C)

t₂ = initial temperature of produce (°C), = 28 °C

t₁ = Storage temperature (°C), = 10 °C

- (3) Calculation of heat of respiration of produce in the storage chamber

This is heat generated by the produce as a natural by-product of its respiration, this will be obtain using Equation 3 in accordance with Kazem et al. [21].

$$Q_{resp} = M \times h \quad (3)$$

where Q =Heat of respiration of produce (kwh/day)

m = mass of produce to be stored in (kg) = 25 kg

h = heat transfer coefficient of vegetable = 0.55 (w/m² k)

(4) Calculation of air infiltration load in the storage chamber

This is heat generated from lights, and warm or moist air entering through cracks or through the door when opened. This was calculated getting values from psychometric chart in Figure 3.3 and in accordance with Ogumo et al. [6] using standard equation as shown in equation 4.

$$P_a = M_a \times (h_a - h) + m_w CP_w (T_a - T) \quad (4)$$

where P_a = air infiltration load

M_a = mass of air entering the storage chamber /hr. Kgs^{-1} (calculated)

h_a = enthalpy of ambient air $kJ.kg^{-1}$ (psychometric chart)

m_w = mass of water condensing in storage chamber /hr kg (psychometric chart)

h = enthalpy of air in storage chamber ($kJ.kg^{-1}$) (psychometric chart)

CP_w = specific heat capacity of water (4.186 j/g °C)

T_a = ambient air temperature in °C

T = air temperature in storage chamber

Mass of air (M_a) entering the storage chamber will be obtained according to Ogumo et al. [6] as shown in equation 5

$$\text{Density}(\delta) = \frac{\text{mass}(m)}{\text{volume}(v)} \quad (5)$$

where density is the density of ambient air entering the storage chamber = 1.29 kg/m³

Mass is to be calculated and Volume is the volume of the storage chamber of the MSCS = 0.19 m³. Mass of air = 1.29 × 0.19 = 0.25 kg of air entering the storage chamber

(5) Calculation of miscellaneous heat load (Equipment load) in the storage chamber of the MSCS

Miscellaneous heat load is made of heat generated from equipment (evaporator fan), lights and people in the cold room. Heat generated by number of people working in the cold rooms and lightening will not be applicable in this work (Since it is a prototype). Heat generated by DC evaporator motor and fan will be calculated using the formula according to Ogumo et al. [6] and Gupta and Dubey [22] as shown in equation 6

$$Q_{equip} = f_n \times f_p \times t + (p \times t \times \eta) \quad (6)$$

where Q_{equip} = equipment heat load

f_n = number of fans (4 fans on heat exchanger and 1 fan on the condenser)

f_p = power rating on fan = (0.61 + 0.29) amps = 0.9 amps, P = IV = 0.9 × 12 = 10.8 W

t = time of operating the fan (hr) = 14 hr

p = power rating of motor heating element = 1.2 W

t_i = motor run time = 14 hr

η = efficiency (% of heat transferred to cooling space) = 30 %

$$Q_{total} = \Sigma Q_{cond} + Q_{air} + Q_{equip} + \Sigma Q_{resp} + Q_{sens} \quad (7)$$

$$Q_{total} = 0.68 + 0.002 + 0.16 + 0.00382 + 0.47 = 1.32 \text{ kwh/day}$$

Total heat load and the volume of storage chamber will be used in selection of cooling units to extract the total heat load from the storage chamber.

2.4.2. Safety factor for the calculated total heat loads

According to American Society of Heating, Refrigerating and Air Conditioning Engineers [23], it is necessary to apply a safety factor to the calculation to take care of errors and the risk of failure and any incompatibility between the design criteria and actual calculation. A factor of safety between the ranges of 10 to 30 percent of the calculation is recommended, for this work, 20% of the heat load is chosen in line with Babaremu et al. [24].

$$\text{Safety factor} = \frac{20}{100} \times 1.32 = 0.26$$

Thus, the heat load safety factor of 0.26 will be added to the calculated heat load to give us the total cooling load

$$0.26 + 1.32 = 1.58 \text{ kWh/day}$$

2.4.3. Determination of refrigeration cooling capacity of the MSCS

The total refrigeration cooling capacity of the MSCS will be determined according to method use by Sharad and Virendra [25] and Babaremu et al. [24] as expressed in equation 8. This will be done by dividing the total heat load by the run time of the refrigeration unit (D.C compressor). Considering the off and on time of the cooling unit, it is estimated to run for fourteen (14) hours in a day [24].

Table 1. Summary of the Heat Load of the MSCS.

Source of Heat	Quantity of Heat (Kwh/day)
Heat of conduction	0.68
Produce heat (sensible)	0.47
Produce heat (respiration)	0.00382
Air infiltration heat	0.002
Miscellaneous (equipment) heat	0.16
Total heat load	1.32
Safety factor (20%) of total heat load	0.26
Total heat load + safety factor calculated	1.58

$$\text{Refrigeration cooling capacity} = \frac{\text{total heat load}}{\text{compressor run time}} \quad (8)$$

The cooling unit needs to have a capacity of $\frac{1.58}{14} = 0.113 \text{ kW}$ to sufficiently overcome the total heat load. Selection of compressor suitable to meet this heat load and cooling capacity was done using Table 3.2. From the table Aglag compressor is selected having 120 - 350 w.

A prototype mobile solar cooling system of 0.2m³ capacity and of 75kg weight was designed, constructed and mounted on a tricycle to transport the amaranth green leafy vegetable obtained from lasoju farms along Ilorin-Ogbomoso Road to the experimental site in Nigerian Stored Products Research Institute (NSPRI) Ilorin, Kwara State. The site lies between latitude 8° 22' 42" and 10° 50' 42" N and longitude 4° 41' 35" and 7° 9' 35" E [26].

The MSCS as shown in Figure 1 converts the solar energy collected by photovoltaic panels into electrical energy which is used to power the compressor and other electrical components. The compressor through evaporator plates cools the water in the water chiller bath storing thermal energy in form of ice. The cold water from the ice is transported into the storage chamber via an arrangement a DC pump and heat exchanger to cool the produce arranged therein.

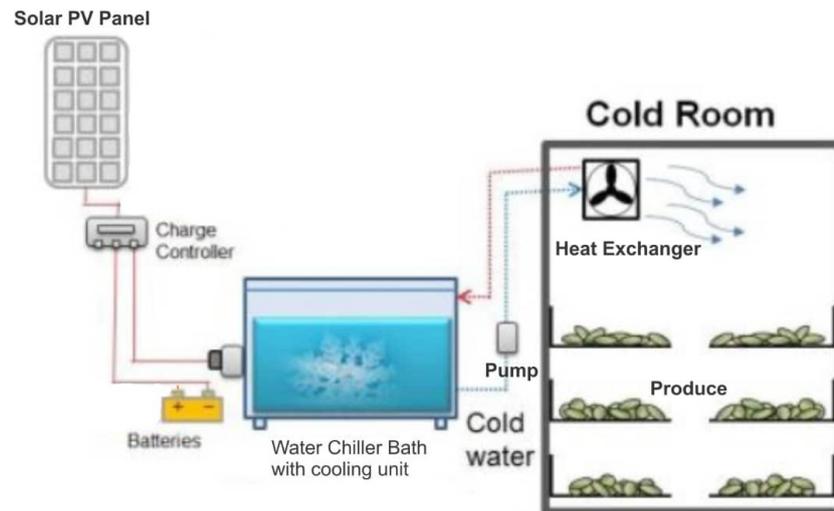


Figure 1. An overview of the solar cooling system.

2.5. Fabrication Process and Description of the MSCS

The procedure adopted in the fabrication (construction) of the MSCS is as presented:

A 60 mm polyurethane panel was cut into length = 0.59 m, breadth = 0.4 m and height = 0.79 m to make the storage chamber which has 4 trays made of stainless materials, this was fastened together with galvanized metal plates, screws, bolts and nuts. The solar panel of 550W was connected to the 12 v solar charge controller and charge controller connected to 12/24 V 150 AH battery and DC compressor was used to power the solar cold room. Coupling of the components of the MSCS begins by filling the compressor with 43.73 g (0.04 ltrs) of R600a refrigerant which is environmentally friendly. The construction of each unit was assembled to form a single system and mounted and tightened properly on a mobile devise (tricycle) using bolts and nuts. The discharge low suction line (pipe) of the compressor was welded to the inlet of the condenser pipe coils mounted at the back of the cold room. A capillary tube was welded to the outlet of the condenser pipe coils the other end of the capillary tube in turns welded to the inlet of the evaporator pipe coils and outlet of the evaporator pipe coils welded back to the return low suction line of the D.C compressor, the cold room storage chamber has heat exchanger and fans to exchange heat by convention, the system was put to a test to ensure that all the parts were properly fixed. Figure 2 shows the isometric view of the system.

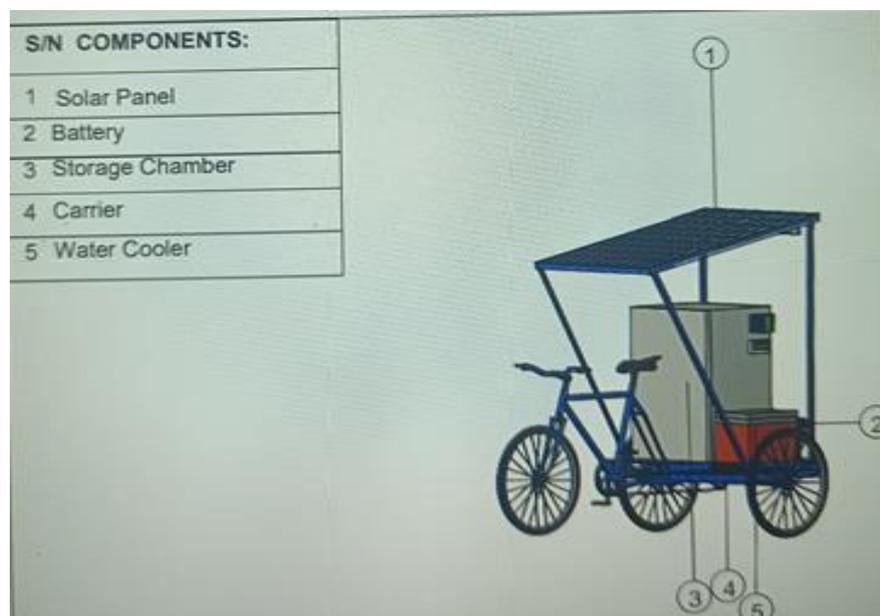


Figure 2. Isometric view of the MSCS.

2.6. No-load test evaluation of the MSCS

Tests were conducted to evaluate the performance of the MSCS following the procedure outlined by Olosunde et al. [27]. The performance evaluation was carried out in two stages. The system was first tested at no load (testing without samples) to inspect the system for safe operation and smooth running [28] and to calculate daily ice production from chiller bath, to determine energy available in the ice (energy output), to determine energy consumption of the compressor (energy input). For this first operation, the current and voltage of the compressor was measured and recorded at hourly interval for 1 month, the ice production in the chiller bath, solar radiation value and ambient temperatures were recorded to calculate the Coefficient of Performance (COP) of the system. Cooling unit and ice formation test in the water chiller bath (Preconditioning).

To obtain data of the environmental conditions in the storage chamber the temperature and relative humidity hobo data loggers were used.

2.6.1. Ice production capacity of the MSCS

Table 1 shows an average daily ice production (M_i) of 7.7 kg from the system which was calculated using Equation 9

$$M_i = M_t - M_w, \quad (9)$$

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 (kg),

Table 1. Daily ice production of the compressor.

S/N	Date	Time	Quantity of water (M_t)(L)	Weight of water (M_w)(kg)	Weight of Ice (M_i)(kg)	Cummulative weight of ice (kg)	Temperature of water ($^{\circ}$ C)	Mean Current in the compressor(I)	Mean Voltage in the compressor (V)	Mean ambient temp. ($^{\circ}$ C)
1	25/3/24	5 pm	36	32.21	0	0	14	4.30	11.40	28.4
2	26/3/24	5 pm	22	19.6	12.61	12.61	-2	4.28	11.50	29.7
3	27/3/24	5 pm	11	9.2	10.4	23.01	-2.8	4.03	12.37	30.0
4	28/3/24	5 pm	4	3.6	5.6	28.61	-3.8	3.89	12.32	31.3
5	29/3/24	5 pm	2	1.6	2.0	30.61	-1.2	4.01	12.54	31.9
					Mean	7.7		4.1	12.01	30.26

2.6.2. Determination of quantity of energy available in the ice (energy output)

$$Q_i = Lf(ice) * M_i$$

Q_i is the quantity of energy available in the ice (Wh) = $M \times C \times \theta$

M = mass of water in the chiller bath

C = specific heat capacity of water ($kJ/kg^{\circ}C$) = 4.18

θ = change in temperature (initial and final temp)

$$Q_i = 32.21 \times 4.18 \times (14 - 0) = 1885$$

2.6.3. Determination of energy consumption by the compressor (Energy Input)

$$P = V \times I = 12.01 \times 4.1 = 49.61$$

$$E_{\text{daily}} = P_{\text{mean}} \times 24 = 49.61 \times 24 = 1190$$

where P is Power (watt), V is voltage (V) and I is current (A),

E_{daily} and P_{mean} are daily energy consumption (Wh) and mean power consumption (W) respectively

2.6.4. Determination of heat loss from insulated surfaces (Q losses)

$$Q_{\text{losses}} = UA \times \Delta T \times \Delta t$$

where U is the conductivity of polyurethane = 0.026 w/mk

A is the total surface area of insulation (m^2) = 0.127 m^2

ΔT is the temperature change between cold water in the bath and ambient (K) = (14 – 0)

Δt is the change in time (hour) = 1 hr

$$Q_{\text{losses}} = 0.026 \times 0.127 \times 14 \times 1 = 0.05$$

2.6.5. Determination of coefficient of performance (COP) of the system

$$COP = \frac{Q_{\text{daily ice}} + Q_{\text{daily losses}}}{E_{\text{daily}}} = \frac{\text{energy output}}{\text{Energy input}} = 1.58 = 1.6$$

A COP of 1.6 from the system indicates that the system is outputting 1.6 units of energy for every 1 unit of energy input. This is a good result as it means the system is operating efficiently.

2.7. Load Test (evaluation with green amaranth)

About 11 kg of the green amaranth was purchased, 5.5 kg was stored in the Mobile Solar Cooling System (MSCS) and 5.5 kg stored at ambient in a (ventilated plastic crate under shed. Sampling was carried out on each sample at 2 days interval to monitor weight loss, moisture, and colour change, proximate qualities, bacterial and fungal count. Data loggers were placed in the storage chamber of the ambient and MSCS storage to record temperature and relative humidity data. Temperature and relative humidity data collected from the storage experiment were downloaded from dataloggers and were subjected to statistical analysis using IBM SPSS Statistics 25. Analysis of variance (ANOVA) was used to compare the means at significant difference ($P \leq 0.05$).

2.8. Experimental Design for the Research Work

The experimental design that was employed for the research for green amaranth storage was 2 by 3 factorial randomized complete design. This design allows for the investigation of two factors (temperature and relative humidity), each having three replicates, in order to assess their individual and combined effects on the storage quality of the green amaranth leaves. The first factor considered is temperature, which is a critical parameter in maintaining the freshness and quality of perishable produce. The temperature levels chosen for the experiment was (5°C), in line with ASHRAE [23]. The second factor is humidity, which also plays a significant role in preserving the moisture content and preventing dehydration of the produce. The range is between 80 to 95 in line with ASHRAE [23].



Figure 3. Ambient storage and MSCS storage.

3. Results

The storage experiment considered temperature and relative humidity as key factors influencing the preservation of green amaranth. Ambient storage exhibited higher temperatures and fluctuating relative humidity compared to the stable environmental conditions maintained by the Mobile Solar Cooling System (MSCS). The MSCS effectively stabilized temperature at $9 \pm 4^\circ\text{C}$ and relative humidity at $85 \pm 10\%$, while ambient storage conditions showed significant variability. These controlled conditions in the MSCS extended the shelf life of green amaranth to 18 days, compared to just 5 days under ambient storage. This aligns with findings by Yousuf et al. [29], who emphasized the effectiveness of low-temperature storage in preserving the chemical composition of perishable crops.

Table 1. Effect of storage on Physicochemical characteristics of green amaranth at ambient and MSCS storage;

Treatment	Moisture	Crude fibre %	Crude Protein %	Vit A	Iron mg/100g	Beta Carotene mg/100 g	Weight loss kg	Observation
Fresh	90.35	2.07	3.04	1.57	53.14	24.01	5	leaves were green and very attractive
Ambient at day 3	85.09	1.91	2.99	0.99	48.88	19.21	4.4	leaves withering
MSCS at day 3	89.01	2.03	3.23	1.21	52.61	23.52	4.8	Still fresh
Ambient at day 5	67.91	1.56	2.04	0.89	41.39	15.36	2.7	leaves fallen, experiment ended.
MSCS at day 5	88.98	2.1	3.12	1.11	52.08	22.76	4.44	still fresh
MSCS at day 12	87.25	2.04	3.11	1.02	51.35	22.49	4.06	leaves wither and colour change

3.1. Effect of Temperature and Relative Humidity on Storage Quality

Lowering storage temperatures reduces the respiration rate, delays senescence, and minimizes weight loss in green amaranth. Conversely, high ambient temperatures accelerate senescence, leading to rapid deterioration. The steady relative humidity within the MSCS further helped retain moisture and reduced dehydration stress on the produce [25]. These factors collectively resulted in better preservation of the physicochemical properties of green amaranth in the MSCS.

3.2. Physicochemical Changes in Storage

Various parameters, including weight loss, crude fiber content, crude protein, vitamin A, beta-carotene, bacterial, and fungal counts, were evaluated during the storage experiment. The results (Table 1) showed that while both storage conditions led to changes in these parameters over time, the deterioration was significantly slower in the MSCS.

- **Weight Loss:** Weight loss in ambient storage was 45% higher than in the MSCS, primarily due to moisture loss induced by high temperatures and low relative humidity [15].
- **Nutrient Retention:** Crude fiber, crude protein, vitamin A, and beta-carotene content decreased in both storage conditions, but the decline was more pronounced in ambient storage. For example, beta-carotene content at day 5 was 15.36 mg/100 g in ambient storage compared to 22.76 mg/100 g in the MSCS.

- **Microbial Growth:** The bacterial and fungal loads in the MSCS remained within acceptable limits ($< 10^5$ CFU/g for bacteria and 10^3 – 10^4 CFU/g for fungi) as stipulated by the International Commission for Microbiological Specifications. In contrast, microbial loads in the ambient storage exceeded these limits by day 5, making the produce unsafe for consumption [30].

3.3. Performance of the MSCS

The MSCS demonstrated a coefficient of performance (COP) of 1.6, indicating its efficient energy utilization. The average daily ice production of 7.7 kg provided sufficient cooling capacity to maintain optimal storage conditions. Minimal heat losses ($Q_{\text{loss}} = 0.05\text{Wh}$) through the insulation underscore the effectiveness of the system's design.

The system's ability to significantly extend shelf life and preserve nutritional quality highlights its utility for smallholder farmers and agribusinesses in regions with limited access to grid electricity. The energy efficiency of the MSCS and its reliance on renewable energy further enhance its appeal as a sustainable cooling solution.

3.4. Comparison to Ambient Storage

Storage in ambient conditions resulted in rapid degradation of green amaranth, with visual signs of spoilage such as withering and discoloration occurring within 5 days [28]. This rapid deterioration underscores the inadequacy of ambient storage in preserving fresh produce, especially in tropical climates.

4. Conclusions

The MSCS demonstrated a high efficiency with a COP of 1.6, utilizing energy effectively to maintain optimal storage conditions. The system extended the shelf life of green amaranth by approximately 60% compared to ambient storage. The MSCS significantly preserved the nutritional quality and safety of the produce, meeting international microbiological standards throughout the storage period. The prototype MSCS presents a scalable and sustainable solution for post-harvest preservation, particularly in off-grid regions.

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Data Availability Statement: We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section "MDPI Research Data Policies" at <https://www.mdpi.com/ethics>.

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