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Development of a Mobile Solar-Powered Cooling System to Extend Shelf Life of Jute Leaves

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Abstract

Proper cooling systems are essential for preserving perishable agricultural produce and ensuring food security. However, in developing countries, inadequate cold storage results in significant spoilage, posing a threat to farmers' income and food availability. Conventional refrigeration, in rural areas is energy intensive making sustainable alternatives necessary. Therefore, this study developed a Mobile Solar-powered Cooling System (MSCS) as renewable energy solution for perishable crops. The MSCS was built on a tricycle base with 550 W, 42.5 V, solar panel, 12 V, MPPT, charge controller, 12 V, 150 Ah deep-cycle solar battery, and Aglac ZH55G, 75 W, DC compressor using isobutane (R600a) refrigerant. The storage chamber, made of 60 mm polyurethane panels, housed stainless steel trays and racks for commodity storage. Jute leaves were sourced from Lasoju farms, Kwara State to evaluate the performance of the MSCS. A 2 by 3 factorial complete randomized design evaluated two storage conditions (ambient and MSCS) to monitor the effect of temperature and relative humidity on the quality and shelf life of jute leaves. The MSCS maintained an average storage temperature of 5 ± 4°C and relative humidity of 85 ± 10%, significantly improving the preservation of jute leaves compared to ambient conditions (average temperature:

30 ± 2°C) and fluctuating relative humidity of 65 ± 10%,. Key system metrics include a coefficient of performance (COP) of 2.02, indicating efficient energy use, with an average daily energy consumption of 1190 Wh. The system extended the shelf life of jute leaves to 11 days, compared to 4 days under ambient storage, jute leaves lost 80 and 8% of weight in 4 days for ambient and MSCS, respectively preserving essential nutrients such as Vitamin A (51.35 mg/100 g) and beta carotene (22.49 mg/100 g). Colour of test samples changed from deep green to yellow and dirty brown. Microbial results for jute leaves under ambient storage was 3.8 x 10^2 cfu/g as against 1.0 x 10^2 cfu/g obtained for MSCS. This study established that controlled low-temperature, high-humidity environments enhance the shelf life of jute leaves. The system is recommended for stakeholders in vegetable supply chains especially in off grid areas.

Keywords: Mobile Solar Cooling System, Renewable Energy, Sustainable Agriculture, Cold Chain Innovation, Food Security, Energy Efficiency

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 (Manaf *et al.*, 2018, *Rahiel et al*., 2018). 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 (UN, 2013). Fruits and vegetable are good sources of vitamins and minerals without which human body cannot maintain proper health and develop resistance to disease (Tushar, 2018). Nigeria is one of the major producers of fruit and vegetable commodities in the world and ranked the one hundred and fifty ninth largest producers (Ogumo *et al.*, 2020 and FAO, 2018). 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 (Tushar, 2018). Leafy vegetables are eaten in a variety of ways as part of meals and snacks. 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 (Stathers, 2017). The metabolic activities of fruits and vegetables continue after harvest because they live, transpire, respire and continue to ripe and the deterioration rate increases due to ripening, age and unfavourable environmental factors. 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 (Mohammad *et al.*, 2018). 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 (Ajayi *et al*., 2018). Most of the fruits and vegetables produce require a cooling temperature between 0 and 5 °C for safe storage and transit purposes (Akorede *et al*., 2017). Postharvest losses of about 50% of the total production are recorded for these commodities. 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 (Osadare *et a*l., 2019). 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. 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 jute leaves adopting a comparative approach between storage under ambient conditions (under shed and in the mobile solar cooling system).

Aim and Objectives of the Study

The aim of this research is to develop an effective mobile solar powered cold storage system for shelf life extension of jute leaves.

The specific objectives are to:

i. Design and construct a prototype mobile cooling system for jute leaves using renewable source of energy.
ii. Evaluate (by conducting no-load test) for ice thermal energy balance to calculate the Coefficient of Performance (COP) of the system,
iii. Evaluate (by conducting load test) the effectiveness of the cooling system on quality parameters (physical, nutritional and microbial) of jute mallow leaves ‘ewedu’ (*Corchorus olitorus*).

Materials and Methods

The Materials used for this work is classified into Construction materials, Evaluation materials [Jute leaves] and Instruments/equipment [measuring devices].

Design Considerations

In carrying out this design work, the following were put into consideration

i. Capacity and total weight of the MSCS
ii. Insulation materials
iii. Heat load calculations
iv. Compactness and availability of construction materials

Materials Needed for the Mobile Solar Cooling System (MSCS)

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

a. Mobile devise: A tricycle
b. Solar components: solar panels, charge controller, deep cycle solar battery, circuit breakers, cable and cable connectors and switch board.
c. 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 environment friendly.
d. 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.
e. 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.

Instrumentation Devices 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/m^2 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-channels thermocouple: 3 (three) of these channels were 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.

Design Specifications for the Dimensions and Capacity of the Storage Chamber of the MSCS

Some engineering properties of test samples were considered to obtain the storage chamber's dimension.

Design asumptions were made as follows:

Proposed capacity of the prototype storage chamber = 25 kg (Olosunde *et al.* 2019).

Area or space occupied by one bunch of jute leaves (L x B) = (9 x 6) cm = 54 cm^2.

By arranging 6 jute leave bunch on length and 5 jute leave bunch on breadth of a tray with a space of 1 cm in-between, give a tray length of (9 x 6 + 5) 59 cm and a tray width of (7 x 5 + 5) 40 cm. Using a rectangular mesh for tray, the area is length multiplied by breadth.

Assuming a tray area of 59 cm x 40 cm = 2360 ≈ 2400 cm^2 to accommodate 15 jute leaves bunch on a tray this is in accordance with the method used by Ogumo *et al*.

(2020). The storage chamber has four (4) shelves, therefore total jute leaves bunch stored were 60 pieces to occupy the storage area (Osadare *et al*. 2019).
Calculation of storage chamber capacity was done in accordance with the method used by Gupta and Dubey (2018), Ogumo *et al.* (2020) and Babaremu *et al*. (2018) with standard equation from literatures as shown in equation 2.1.

$$A = L \, x \, B \quad (2.1)$$

where, A = Area, L = Length, B = Breadth
The storage chamber was divided into four shelves using tray that is made of stainless pipe and mesh wire. The (outer) dimension of the storage chamber was Length = 0.74 m, Breadth = 0.72 m, and height = 0.92 m and the (inner) dimension of the storage chamber was length = 0.59 m, breadth = 0.4 m and height = 0.79 m (Ogumo *et al*. 2020). To avoid thermal losses, high insulation materials was used in constructing the storage chamber of the MSCS. Polyurerthane panel was selected because it has high insulation value compare to other insulation materials like cork sheet, fibre glass bats, extruded polystyrene and saw dust (Babaremu *et al*. 2018). Polyurethane panel of 60 mm insulation thickness was recommended for mobile solar cold room because of the weight, this was used for the construction (Babaremu *et al*. 2018). This was cut into dimension of rectangular parts to produce the four (4) sides, roof and floor of the storage chamber.
After obtaining the dimension for length, breadth and height of the storage chamber, the capacity was calculated. The volume of the storage chamber was determined by equation 2.2 in accordance with Ogumo *et al*. (2020).

$$V = L \times B \times H \quad (2.2)$$

where, V = Volume, L = Length, B = Breadth, and H = Height

$$V = 0.59 \text{ m x } 0.4 \text{ m x } 0.79 \text{ m} = 0.19 \text{ m}^3$$

The capacity of the storage chamber of the mobile solar cooling system is ≈ 0.2 m^3 which gives 190 litres approximately 200 litres.

Design Calculations

Calculation of heat of conduction from the storage chamber of the MSCS

To calculate the heat generated from the storage chamber of the MSCS, this was obtained from total heat of conduction through the four sides, roof and floor of the storage chamber, this was achieved by obtaining the area of each polyurethane rectangular panels for constructing each sides, floor and roof in accordance with Babaremu *et al*. (2018) using Equation 2.3

$$A = L \times B \quad (2.3)$$

where, A = Length in metres. B = Breadth in metres,

Area of side 1 = 0.74 m x 0.92 m = 0.68 m^2
Area of side 2 = 0.74 m x 0.92 m = 0.68 m^2
Area of side 3 = 0.70 m x 0.92 m = 0.64 m^2
Area of side 4 = 0.70 m x 0.92 m = 0.64 m^2
Area of roof = 0.70 m x 0.74 m = 0.52 m^2
Area of floor = 0.70 m x 0.74 m = 0.52 m^2
Total Area = area of all the sides, roof and floor = 3.68 m^2

The total heat of conduction through the insulated walls of the storage chamber of the MSCS was obtained using Equation 2.4 as reported by Ogumo *et al.* (2020).

$$Q = {U \times A \times (t_2 - t_1)} / {d} \tag{2.4}$$

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 (m^2) = 3.68 m^2

t_1 = Air temperature inside storage chamber (10 °C) for jute leaves

t_2 = Ambient temperature (30 °C) average of min. and max. temperature

d = thickness of the wall (m) = 0.06 m

$$Q = \frac{0.026 w/m.k \times 3.68 \times (28-10)}{0.06}$$

°C

Q = 28.7 W/m^2 k = $28.7 \, x \, 24/_{1000}$ = 0.68 kWh/day

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 was obtained in line with Kazem *et al.* (2017) using Equation 2.5

$$Q_{PS} = M \times C_P \times (t_2 - t_1) \tag{2.5}$$

where, Q_{PS} = Produce sensible heat (kWh/day), M = Mass of produce (kg), *Cp* = Specific heat of mango (crops higher than jute in specific heat), (3.77 kJ /kg °C), t_2 = initial temperature of produce (°C), t_1 = Storage temperature °C.

Q_{PS} = 25 x 3.77 x (28 – 10)

= 1696.5 kj/kg °C = $1696.5/_{3600}$ = 0.47 kWh/day

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 was obtained using equation 2.6 in accordance with Kazem *et al*. (2017).

$$Q_{resp} = M \times h \qquad (2.6)$$

where, Q =Heat of respiration of produce (kWh/day)

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

h = heat transfer coefficient of mango = 0.55 (w/m^2 k)

$Q_{resp} = 25 \times 0.55 \text{ w/m}^2 = {}^{13.75}/_{3600} = 0.00382$ kWh/day

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 and in accordance with Ogumo *et al*. (2020) using standard equation as shown in Equation 2. 7.

$$P_a = M_a \times (h_a - h) + m_w CP_W (T_a - T) \qquad (2.7)$$

where, P_a = air infiltration load,

M_a = mass of air entering the storage chamber $/h.kgs^{-1}$(calculated)

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

m_w = mass of water condensing in storage chamber /h. 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 ℃)

T_a = ambient air temperature in ℃

T = air temperature in storage chamber

Mass of air (Ma) entering the storage chamber was obtained according to Ogumo et al. (2020) as shown in Equation 2.8

$$\text{Density } (\delta) = \frac{mass\ (m)}{\text{volume (v)}} \qquad (2.8)$$

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

Mass = to be calculated, and

Volume = volume of the storage chamber of the MSCS = 0.19 m3

$$1.29 \text{ kg/m}^3 = {}^{\text{mass (kg)}}/_{0.19}$$

Mass of air = 1.29 x 0.19 = 0.25 kg of air entering the storage chamber

$P_a = 0.25 \times (58 - 29) + 0.013 \times 4.2 \times 10^{-6} (28 - 10)$ ℃

$P_a = 7.25 + 9.83 \times 10^{-6} \times 20 = 7.25$ W

$P_a = {}^{7.25}/_{3600} = 0.002$ kWh/day

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 was not applicable in this work (Since it is a prototype). Heat generated by DC evaporator motor and fan were calculated using the formula according to Ogumo *et al*. (2020) as shown in Equation 2.9

$$Q_{equip} = f_n \times f_p \times t + (p \text{ x } t \text{ x } \eta) \qquad (2.9)$$

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 for the 5 fans = (0.61 + 0.29) amps = 0.9 amps,

P = IV = 0.9 x 12 = 10.8 W

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

p = power rating of motor heating element =1.2 W

t_1= motor run time = 14 h

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

Q_{equip}= (10.8 W x 14 h) + (1.2 W x 14 h x 0 .3 = (151.2 + 5.04) kWh/day

$^{156.2}/_{1000}$ = 0.16 kWh/day

The total heat energy from various heat load is obtained by addition of all heat load calculated as shown in Equation 2.10

$$Q_{total} = \Sigma Q_{cond} + Q_{air} + Q_{equip} + \Sigma Q_{resp} + Q_{sens} \qquad (2.10)$$

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

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

Safety Factor for the Calculated Total Heat Loads

According to American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE, 2018), 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,* 2018).

Safety factor = $^{20}/_{100} \times 1.32 = 0.26$

Thus, the heat load safety factor of 0.64 will be added to the calculated heat load to give us the total cooling load

0.26 + 1.32 = 1.58 kWh/day

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, 2015) and (Babaremu *et al*, 2018) 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 (Babaremu *et al*, 2018).

Table 1: Summary of the Heat Load of the MSCS

Sources 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

Determination of refrigeration cooling capacity of the MSCS

The cooling capacity of the MSCS was determined to meet the specific requirements of the intended application. It is essential to consider factors such as the size of the space to be cooled and the desired cooling temperature. Balancing cooling performance with energy consumption is crucial to optimize efficiency. The total refrigeration cooling capacity of the MSCS was determined according to method use by Sharad, (2015) and Babaremu *et al.* (2018) as expressed in Equation 3.11.

This was 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 (Babaremu *et al.* 2018).

$$\text{refrigeration cooling capacity} = {}^{total\ heat\ load}\!/_{compressor\ run\ time} \quad (3.11)$$

$$= {}^{1.584}\!/_{14} = 0.113 \text{ kW}$$

The cooling unit needs to have a capacity of ${}^{1.58}\!/_{14} = 0.113$ 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 $0.2m^3$ capacity and of 75kg weight was designed, constructed and mounted on a tricycle to transport the jute leaves 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 8^0 22' 42" and 10^0 50' 42"N and longitude 4^0 41' 35" and 7^0 9'35" E (Olubanjo, 2019).
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 with fans to cool the produce arranged therein.

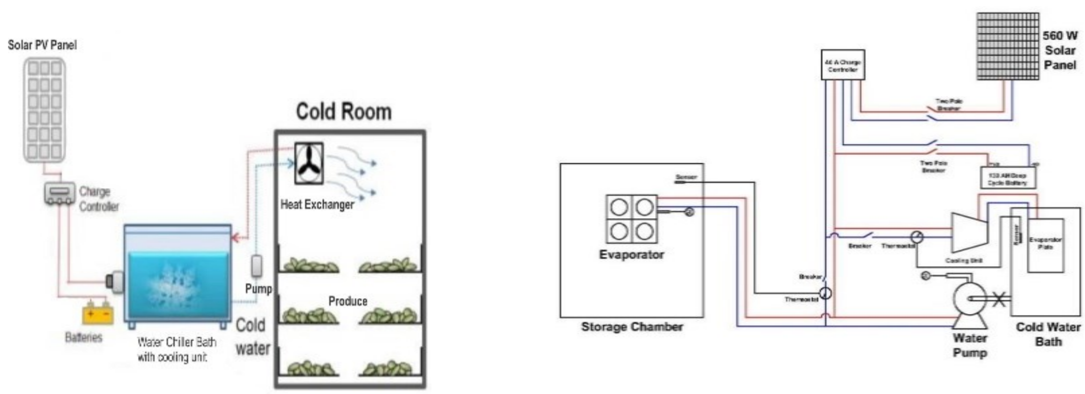


Figure 1: An overview and circuit diagram of the solar cooling system

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.

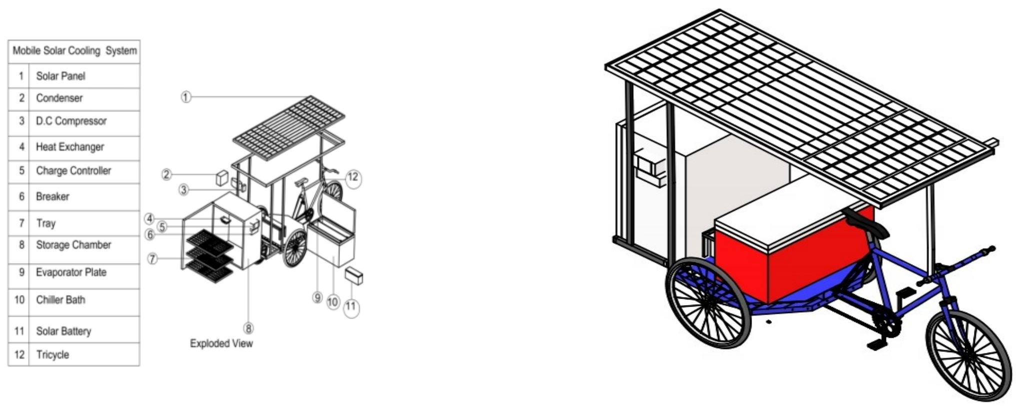


Figure 2: Exploded and Isometric view of the MSCS

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.,* 2019). 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 (Bradbury *et al*., 2017) 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.

Table 2: Daily ice production of the water chiller bath

S/NO	Date	Time	Quantity 0f water (M_t)(L)	Weight of water (M_w)(kg)	Weight of Ice (Mi) (kg)	Cummulative weight of ice (kg)	Temperature of water (^{0}C)	Mean Current in the compressor(I)	Mean Voltage in the compressor (V)	Mean ambient temp. (^{0}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

Determination of energy consumption by the compressor (Energy Input)

$P_{mean} = V \, x \, I = 12.01 \text{ x } 4.1 = 49.61$

$E_{daily} = P_{mean} * 24 = 49.61 \text{ x } 24 \text{ h} = 1190$

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.

Determination of heat loss from insulated surfaces (Q losses)

The formula for calculating heat loss from insulated surfaces according to Kazem *et al.,* 2018 was shown in equation 3.1

$$Qlosses = UA * \Delta T * \Delta t \quad 3.1$$

Where U is the conductivity of polyurethane = 0.026 w/mk (ASHRAE handbook – refrigeration (2018)

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

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

$Qlosses =$ 0.026 x 0.127 x 17.7 x 1 = 0.058

Determination of coefficient of performance (COP) of the system

$$COP = \frac{Q\ daily\ ice + Q\ daily\ losses}{E\ daily} = \frac{energy\ output}{Energy\ input} = \frac{2397.9+0.058}{1190}$$

COP = 2.02. A COP of 2.02 from the system indicates that the system is outputting 2 units of energy for every 1 unit of energy input. This is a good result as it means the system is operating efficiently.

LOAD TEST (evaluation with jute leaves)

About 11 kg of jute leaves 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 ($P \leq 0.05$).

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 handbook (2018). 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 handbook (2018).

Figure 3: Ambient storage and MSCS storage

Results

The storage experiment considered temperature and relative humidity as key factors influencing the preservation of jute leaves. 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 ± 4ºC and relative humidity at 85 ± 10%, while ambient storage conditions showed significant variability. These controlled conditions in the MSCS extended the shelf life of jute leaves by 11 days, compared to just 4 days under ambient storage. This aligns with findings by Yousuf (2018), who emphasized the effectiveness of low-temperature storage in enhancing the shelf lives and preserving the chemical composition of perishable crops.

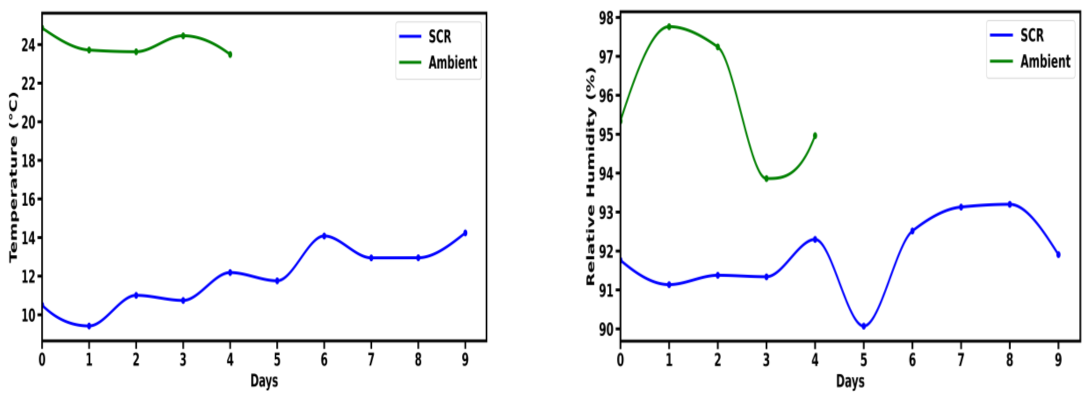
Table 3: Effect of storage on Physicochemical characteristics of green amaranth at ambient and MSCS storage

Quality Parameters	Control/Ambient	MSCS	sig
Total weight loss	72.41 ± 1.341^b	13.92 ± 0.837^a	$F(1, 4) = 1369.074, p=0.000$
Temperature	24.03 ± 0.267^b	6.77 ± 0.445^a	$F(1, 8) = 652.843, p=0.000$
Relative humidity	85.83 ± 0.728^a	91.58 ± 0.206^a	$F(1, 8) = 31.588, p=0.000$
Dew point	23.31 ± 0.224^b	9.59 ± 0.591a	$F(1, 8) = 471.465, p=0.000$
Total colour index	2.69 ± 2.698^b	12.29 ± 1.222^a	$F(1, 18) = 25.553, p=0.000$
Colour change	18.47 ± 2.312^b	9.54 ± 1.708^a	$F(1, 18) = 9.632, p=0.006$
Bacteria	400.0 ± 28.868^b	50.0 ± 50.0^a	$F(1, 4)=183750. p=0.004$
Coliform	210.0 ± 20.817^b	0.0 ± 0.0^a	$F(1, 4) = 101.769, p=0.001$

Note: Means with different superscripts on a row are significantly different at P < 0.05

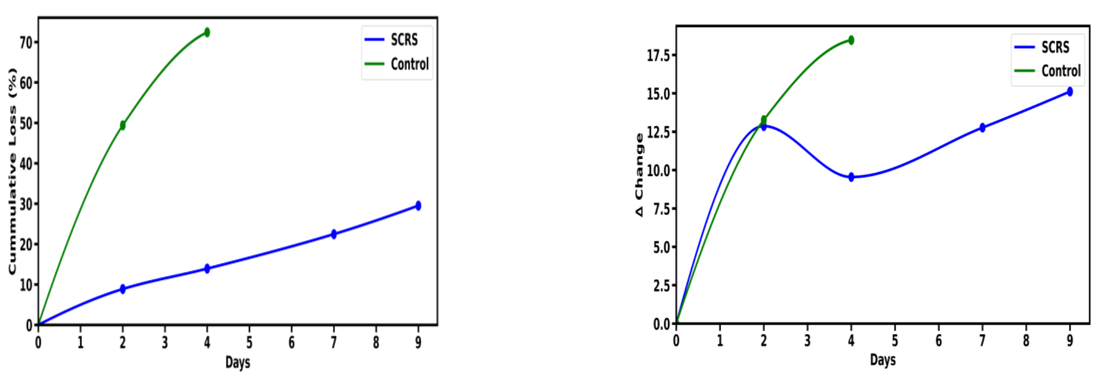
Effect of Temperature and Relative Humidity on Storage Quality

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 (Nabi *et al*., (2017). These factors collectively resulted in better preservation of the physicochemical properties of green amaranth in the MSCS.



Jute leaves *Jute leaves*

Figure 4: Effects of temperature and relative humidity on jute leaves



Weight loss *colour change*

Figure 5: Effects of storage environment on weight loss and colour change of jute leaves

Physicochemical Changes in Storage

Various parameters, including weight loss, colour change, 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, this is the same as what Ayanda *et al.,* (2019) reported.

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 4 was 15.36 mg/100 g in ambient storage compared to 22.76 mg/100 g in the MSCS this is in line with what was published by olosunde *et al*., 2019.

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 (2006). In contrast, microbial loads in the ambient storage exceeded these limits by day 4, making the produce unsafe for consumption, this is in line with findings of Adekalu *et al*., (2022).

Performance of the MSCS

The MSCS demonstrated a coefficient of performance (COP) of 2.02, 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_{loss} = 0.05Wh) 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.

Comparison to Ambient Storage

Storage in ambient conditions resulted in rapid degradation of jute leaves, with visual signs of spoilage such as withering and discoloration occurring within 4 days (Olosunde *et al*, 2019). This rapid deterioration underscores the inadequacy of ambient storage in preserving fresh produce, especially in tropical climates.

Limitations

The limitations of the research work eliminated the usage of an inverter, this is because the solar components like compressor, water pump and other components are Direct Current (DC) mode.

Recommendations

The system is recommended for all stakeholders of fruits and vegetables for shelf life extension. Scaling up the technology and testing with other fruits and Vegetables is also recommended. Further research should be carried out to optimize the system performance and expand the application of mobile solar cooling systems.

Conclusions

The MSCS demonstrated a high efficiency with a COP of 2.02, utilizing energy effectively to maintain optimal storage conditions. The novelty of the system include its mobility, back up batteries for usage during no sunshine hours and using chilled water and air cooling as opposed to other cooling system which are only air cooled, also the eco-friendly refrigerant R600a used. The system extended the shelf life of jute leaves 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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