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Design and development of a low-cost storage system for improving shelf life of perishable agricultural produce

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Abstract

This study presents the design and development of a low-cost cold storage system aimed at reducing post-harvest losses and improving the shelf life of perishable farm produce, particularly for smallholder farmers in resource-constrained settings. The system was developed using a combination of engineering design calculations, detailed design drawings, and instrumentation for effective monitoring and control of internal storage conditions. Key design considerations included thermal insulation, energy efficiency, cost-effectiveness, and ease of construction using locally available materials. The instrumentation system integrated sensors for temperature and humidity monitoring, ensuring that optimal storage conditions are maintained. Powered by electricity, the cold storage unit demonstrated reliable performance in maintaining the required temperature range for preserving fruits and vegetables. The outcome of this work highlights the potential of affordable, locally adaptable cold storage solutions in enhancing food preservation, reducing losses, and supporting food security in rural agricultural communities.

Keywords: Development; Cold storage system; Shelf life; Agricultural produce; Temperature sensors

1. Introduction

Agricultural production, particularly in developing countries, is often constrained by inadequate post-harvest handling and storage systems, leading to significant food losses. Globally, about 1.3 billion tons of food roughly one-third of all food produced for human consumption is lost or wasted annually [1]. Post-harvest losses remain a significant challenge in the agricultural value chain, particularly in developing countries where access to adequate storage infrastructure is limited. In sub-Saharan Africa, it is estimated that between 30% to 50% of perishable agricultural produce is lost before reaching the final consumer due to poor post-harvest handling and lack of storage facilities [2]. One of the most effective solutions to mitigate these losses is cold storage, which helps extend the shelf life of perishable produce such as fruits, vegetables, dairy, and meat by maintaining them at optimal temperature and humidity conditions [3]. However, conventional cold storage systems are capital-intensive, energy-demanding, and often inaccessible to smallholder farmers due to high costs and unreliable electricity supply in rural areas [4]. This has led to a growing interest in the development of low-cost, energy-efficient cold storage alternatives that are adaptable to rural and off-grid environments. Such systems can contribute to food security, income stability, and poverty reduction among small-scale producers [5]. A substantial portion of these losses occurs post-harvest, especially in perishable commodities such as fruits, vegetables, dairy products, and meats. In many cases, the absence of effective cold storage infrastructure is a major contributing factor to this issue [6]. Cold storage systems play a crucial role in maintaining the quality, safety, and shelf life of perishable produce by slowing down metabolic processes and microbial growth through controlled

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temperature and humidity conditions. However, traditional cold storage facilities are often expensive to build and maintain, and require uninterrupted electricity supply conditions that are frequently unattainable in rural and low-income regions [7, 8]. This limits access for smallholder farmers and traders, resulting in increased post-harvest losses and reduced income.

Recent studies have highlighted the need for decentralized, solar-powered cold storage technologies that can operate independently of the national electricity grid. Solar energy presents a promising solution, particularly in regions with abundant sunlight, where photovoltaic systems can be harnessed to power cold rooms at a fraction of the cost of diesel generators or grid electricity [9]. Additionally, integrating thermal energy storage materials such as phase change materials (PCMs) can enhance energy efficiency and allow for temperature stability during periods without sunlight [10]. These innovations not only reduce reliance on conventional power sources but also make cold storage solutions more accessible and sustainable in rural communities. Furthermore, mobile cold storage units have shown potential in addressing last-mile connectivity challenges by bringing cold chain infrastructure closer to remote farms and markets [11].

Community-based models of shared cold storage facilities have also gained traction as a cost-effective approach for smallholder farmers. These models promote collective investment, reduce individual costs, and foster cooperation within farming communities. Research indicates that farmer cooperatives managing shared cold storage units experience improved bargaining power and reduced post-harvest losses, leading to increased incomes and market participation [12].

The objective of this study is to design, develop and instrument a low-cost cold storage system specifically tailored for farm produce preservation in resource-constrained settings. The design considers affordability, ease of construction, energy efficiency, and adaptability to rural environments, with the ultimate goal of enhancing post-harvest management and reducing food losses. The research integrates locally available materials and appropriate technologies to create a scalable model for adoption by smallholder farmers.

2. Material and methods

The materials used for the construction of the cold storage system such as compressor, evaporator, condenser, cooler, frame components were sourced locally from markets in Ilorin, ensuring cost-effectiveness and accessibility. While the temperature controller, solid state relay and hygrometer were procured from international sources via AliExpress, allowing access to affordable and suitable electronic parts necessary for effective system functionality.

2.1. Description of the Cold storage system:

Figure 1 Pictorial View of the cold storage

The cold storage which has a cuboid shape is made up of a cooler mounted on a frame with the instrumentation accessories attached. The cooler dimension is 530 x 400 x 400mm and the frame which is supported with rollers for easy movement of the cold storage is made up of 1-inch square pipe covered with wire gauge to protect the compressor.

The inner part, which is an evaporator, is lagged with polyurethane and covered with aluminum foil. It has a capillary tube that comes from the dryer to the condenser and also a gas valve which conveys gas to the compressor. The dryer is located at the end of the condenser's pipe. The pictorial view of the cold storage is shown in Figure 1.

2.2. Design Consideration of the Cold Storage System

Gas selection: The refrigerant R600a was selected based on the fact It has numerous advantages, including an exceptionally low ozone depletion potential, excellent compatibility with various components, favorable thermodynamic properties, high energy efficiency, and minimal contribution to global warming.

Moving unit: The moving unit is made up of angle iron welded together to form the frame and also serve as the handle for the machine. Attached to the base of the frame are two rollers for easy movement.

Further considerations are:

- Capacity of the cold storage
- Power requirement
- Nature of agricultural materials to be stored.

2.3. Design Calculations

The required calculation needed in this project was done in this section.

2.3.1. Calculation of the cooler storage capacity

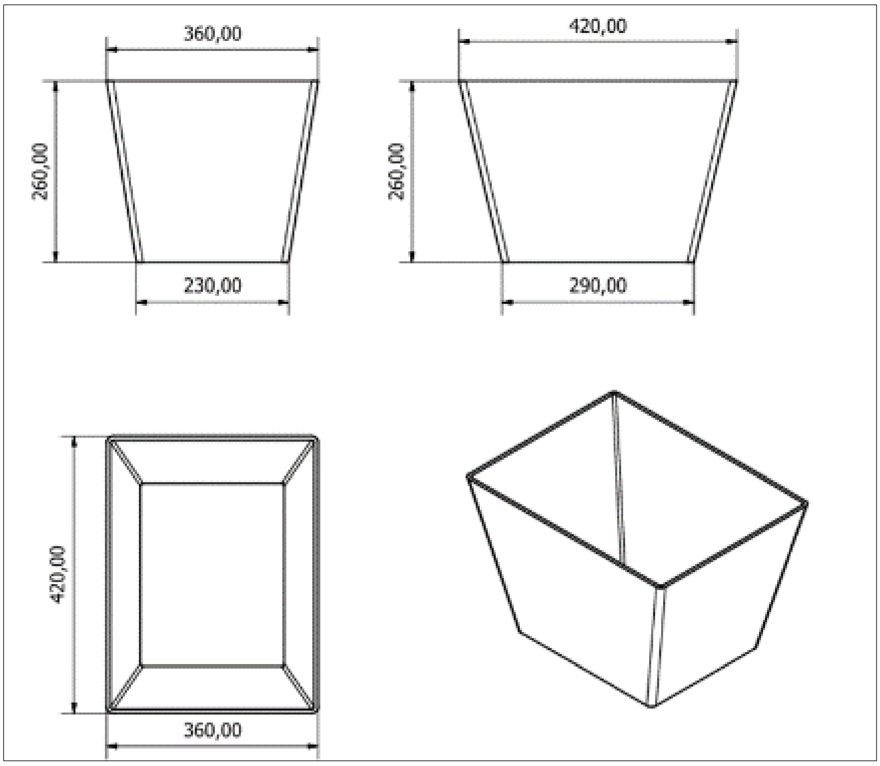

Figure 2 Orthographic projection of the aluminium foil paper

Since the aluminium foil paper used in the cooler is a pyramid frustum with trapezoidal faces as shown in Figure 2, the volume can be calculated thus:

$$volume = \frac{h}{3}(A_1 + A_2 + \sqrt{A_1 A_2}$$

Where;

- h = vertical height of the frustum
- A_1= Area of the top of the frustum
- A_2 = Area of the base of the frustum

Since both the top and base of the frustum are rectangular, the area can be determined thus;

$$A_1 = A_2 = lb$$

Where,

- l = length of the rectangle and
- b = breath of the rectangle.

$$\therefore A_1 = lb = 0.29 \times 0.23 = 0.0667\, m^2$$

$$\therefore A_2 = lb = 0.42 \times 0.36 = 0.1512\ \ m^2$$

$$\therefore volume = \frac{0.26}{3}(0.0667 + 0.1512 + \sqrt{0.0667 \times 0.1512} = 0.0276\, m^3$$

The mass of the products to be stored was calculated thus;

$$m = \rho v$$

Where,

- ρ = density of the product and
- v = volume of the cooler.

2.3.2. Determination of the surface area of the foil paper to be used.

Since the cooler is trapezoidal frustum, when the foil is folded to fill the inner space, it will be trapezoidal in form as shown in Figure 2. Therefore, the surface area of two (2) similar sides of the foil paper can be calculated thus:

$$S_A = 2(\frac{1}{2}(A + B)h)$$

Where;

- S_A = surface area
- A = length of the top of the trapezoid
- B = length of the base of the trapezoid

While, the total surface area of the foil paper was calculated thus;

$$TS_A = S_1 + S_2$$

Where;

- TS_A= Total surface area of the foil paper
- S_1 = surface area of similar sides 1
- S_2 = surface area of similar sides 2

$$\therefore S_1 = 2\left(\frac{1}{2}(0.23 + 0.36)0.26\right) = 0.1534\, m^2$$

$$\therefore S_2 = 2\left(\frac{1}{2}(0.29 + 0.42)0.26\right) = 0.1846\, m^2$$

$$\therefore TS_A = S_1 + S_2 = 0.1534 + 0.1846 = 0.338\, m^2$$

Therefore, the total surface area of the foil paper used for the cold storage was 0.338 m^2

2.3.3. Determination of the heat transfer of the cold storage.

The heat transfer of the cold storage was determined thus;

$$Q = \frac{KADT}{x}$$

Where;

- k = heat transfer coefficient (235)
- A =total surface area of the foil paper
- DT = change in temperature in the cooler (19°C) and
- x = thickness of the foil paper (0.06 m)

$$\therefore Q = \frac{235 \times 0.338 \times 19}{0.06} = 25152.83\ W = 25\ kW.$$

2.4. Material Selection

The materials to be used for the construction of the cold storage system were selected based on the following considerations:

- The cost of the material.
- The availability of the material.
- Physical and mechanical properties.
- The load bearing capacity of the material.
- Ozone depletion potential of the refrigerant.

2.5. Fabrication procedure and installation of components parts

The components parts of the cold storage are frame, cooler, compressor, condenser, evaporator, capillary, dryer filter and valve.

Frame: The frame dimensions are 580 x 480 x 490mm constructed with 25 mm hollow square pipe. The hollow pipe was measured, cut and welded together using an arc welding machine to achieve the frame structure.

Cooler: This was a bought item of external dimensions 530 x 400 x 400mm.

- Compressor: The compressor serves as the essential component of a refrigerator. It circulates the refrigerant throughout the system, increasing pressure in the warmer section of the circuit and elevating the refrigerant's temperature.
- Condenser: The condenser is a slender coil of copper tubing situated at the rear of the refrigerator. The refrigerant from the compressor flows into the condenser, where it is cooled by ambient air. Consequently, it loses heat absorbed in the evaporator and the compressor.
- Evaporator: The refrigerant, at significantly low pressure and temperature, enters the evaporator. The evaporator is a heat exchanger composed of many coils of copper or aluminum tubing. The refrigerant absorbs heat from the substance to be cooled in the evaporator, evaporates, and is subsequently compressed by the compressor.
- The capillary: The capillary is a slender copper tube composed of multiple turns of copper coil. As the refrigerant traverses the capillary, both its pressure and temperature experience a rapid decline.

Dryer filter: Usually found in the liquid line of the compressor and its purpose is to ensure that the refrigerant system stays clean and dry.

Valve: Valves are used within a compressor to allow gas flow to and from the cylinder area. The Isometric and Orthographic, dimensioned and parts drawing of the cold storage system is presented in Figure 3 to Figure 6.

Figure 3 Isometric projection of the cold storage system

Figure 4 Orthographic projection of the cold storage system

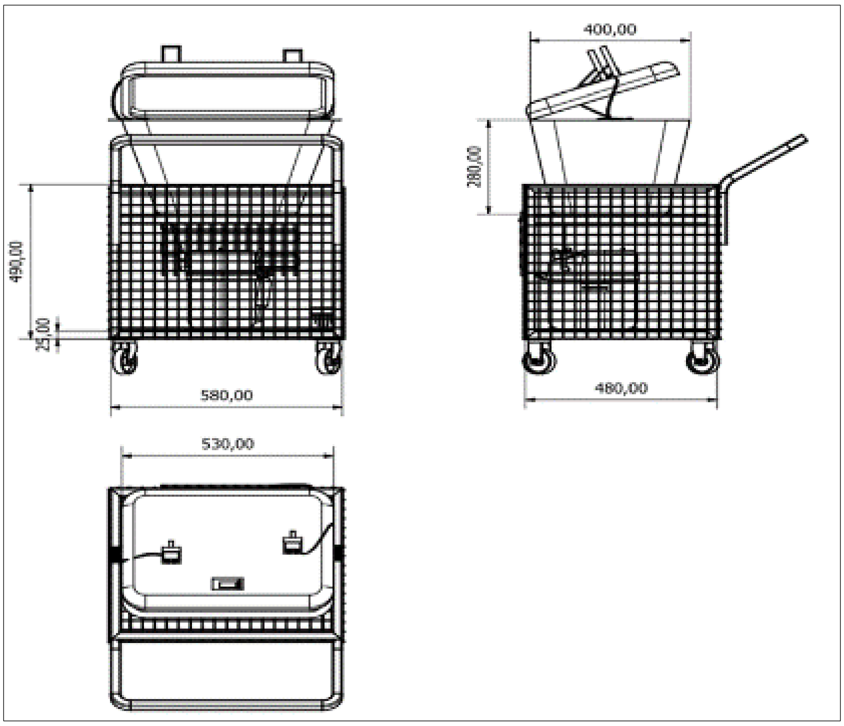

Figure 5 Dimensioned drawing of the cold storage system

S/N	COMPONENTS
1	HYGROMETER
2	COLD STORAGE LID
3	TEMPERATURE CONTROLLER
4	ALUMINUM FOIL PAPER
5	SENSOR
6	EVAPORATOR
7	CONDENSER
8	COLD STORAGE FRAME
9	DRYER FILTER
10	WIRE GUAZE
11	COLD STORAGE COOLER
12	COLD STORAGE HANDLE
13	COMPRESSOR
14	SOLID STATE RELAY
15	ROLLER

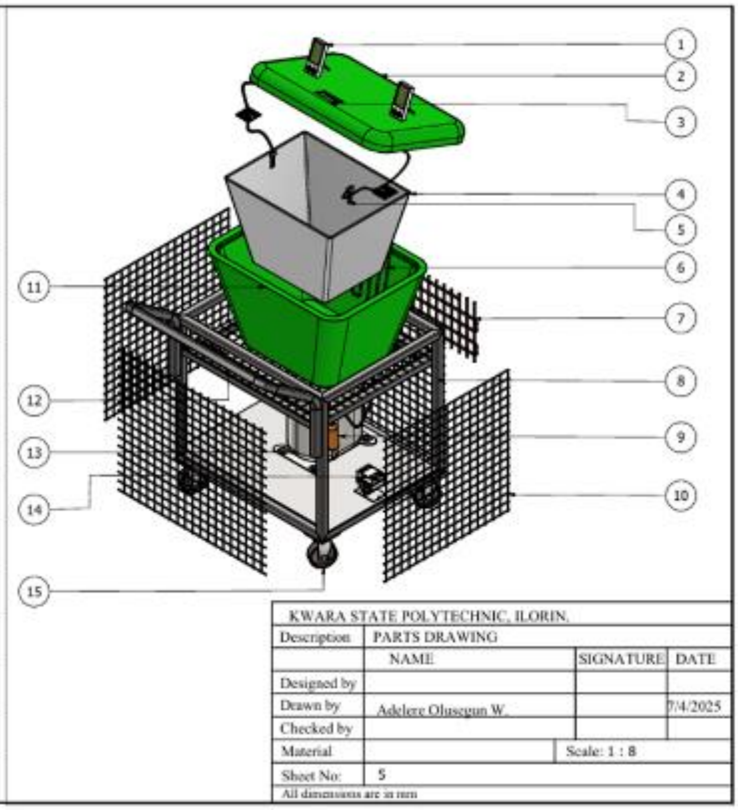

Figure 6 Parts Drawing of the Cold Storage System

2.6. Principle of operation of the cold storage

The principle of operation of the cold storage system is based on the removal of heat from a space to lower and maintain its temperature below the ambient level to preserve perishable goods like fruits, vegetables, meat, and dairy products. This is achieved through the refrigeration cycle which is explained below:

A liquid refrigerant (refrigerant R600a) in the evaporator coil absorbs heat from the stored goods and surrounding air. As it absorbs heat, it evaporates into a gas, cooling the air inside the storage chamber. The compressor then draws in the low-pressure refrigerant vapor and compresses it to a high-pressure, high-temperature gas which increases the refrigerant's temperature and pressure. The hot, high-pressure vapor enters the condenser coil, usually outside the storage room and releases heat to the surroundings (often through air or water cooling) and condenses back into a liquid. After which, the high-pressure liquid refrigerant passes through an expansion valve, where it rapidly expands, reducing its pressure and temperature. This cold, low-pressure refrigerant re-enters the evaporator, repeating the cycle.

The XH-W3001 Temperature Controller attached to the system is a compact, user-friendly device designed for accurate temperature measurement, display, and control, making it suitable for a wide range of temperature-sensitive applications. It supports both heating and refrigeration functions, with an adjustable control range from -50°C to 110°C. The controller offers a measuring accuracy of ±0.2°C and a control precision of ±0.1°C, ensuring reliable performance. It utilizes an NTC10K waterproof probe with a 1-meter cable for temperature sensing. It controls the temperature inside the storage system by regulating the operation of the compressor through the solid-state relay and it operates at 220V with a maximum current of 10A and power capacity of 1500W which makes it ideal for applications like cold storage units and seafood preservation systems. Its compact size (60 × 45 × 30 mm)

2.7. Preliminary test result

Table 1 and Figure 7 shown the preliminary test result and the following can be deduced from it:

- the maximum the cooling storage at no load is -7.4°C
- it takes the cooling system 100 minutes to attain the maximum cooling level of the storage system
- the ambient temperature of the cooling system is 32.1°C

Table 1 Cooling Storage Temperature at no-load and at load

S/no	Time		Temperature at no load	Temperature at load
	1	0	32.1	31.1
	2	10	25	25.1
	3	20	0.85	20.7
	4	30	-0.9	16.2
	5	40	-3.7	13.1
	6	50	-5.2	10
	7	60	-6.2	8.2
	8	70	-6.8	6.7
	9	80	-7.2	5.1
	10	90	-7.3	3.7
	11	100	-7.4	2.8
	12	110	-7.4	1.8
	13	120	-7.4	1

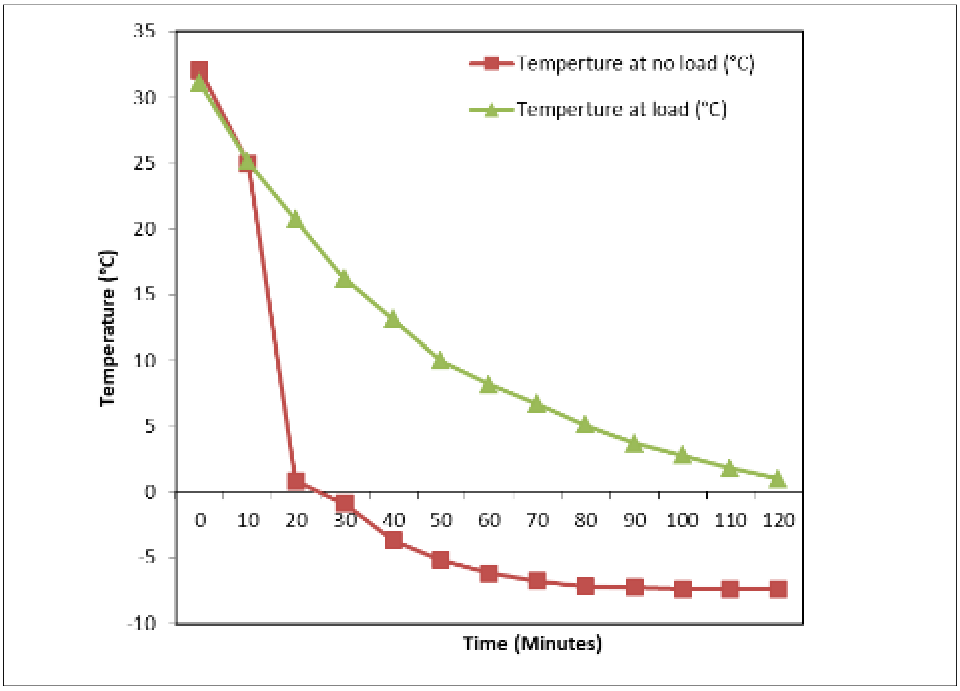

Figure 7 Graph of the Cooling Storage temperature at no-load and at load against time

3. Conclusion

The study successfully designed, developed, and instrumented a low-cost cold storage system powered by electricity to preserve farm produce and reduce post-harvest losses, particularly for smallholder farmers and agro-processors in developing countries. The system demonstrated reliable temperature regulation, energy efficiency, and affordability, making it suitable for extending the shelf life and maintaining the quality of perishable agricultural products. Its integrated instrumentation allows for effective monitoring and control of storage conditions, while the use of locally available, low-cost materials supports its scalability and adaptability in rural settings.

Recommendations

Based on the outcomes of this study, it is recommended that future designs of the cold storage system focus on integrating solar renewable energy to enhance sustainability and ensure functionality in energy-deficient rural areas. Furthermore, long-term field evaluations under diverse environmental conditions should be conducted to assess the system's reliability, durability, and adaptability in practical agricultural settings. These will lead to further improvement that will provide an efficient, accessible, and sustainable solution for post-harvest storage, thereby contributing to increased food security and improved livelihoods for farmers.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they do not have any conflict of interest.

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