Design and Experimental Test on Solar Powered Evaporative Cooling to Store Perishable Agricultural Products

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Abstract. This paper is dealt with the design and experimental test on solar powered evaporative cooling system which is maintaining inside temperature lower than ambient temperature with higher level of relative humidity for the storage of fresh Agricultural products such as tomato, carrot and green chili (pepper). The experimental setup is a rectangular shaped storage space made of galvanized steel for external cover, aluminum for internal cover insulated with fiber glass. Axial fan supplies 0.78 m^3/s air at a speed of 0.93 m/s to wet pad and for recycling of water through copper tube, an axial pump having flow rate of 0.054 kg/s is used to remove the heat from the commodities. The results reveal that the shelf life of the vegetables is increased 12 days when compared with ambient conditions. The temperature range of the cooling cabinet is found 16.2 to 22.1 °C during the hottest time of the day and the ambient temperature varied from 22.6 to 29.8 °C. The relative humidity is found between 75 and 90% when the outside condition is recorded between 66 and 80%. The maximum weight loss found after the sixth day for carrot, tomato and pepper are 8, 10 and 16% in cabinet conditions and 50.6, 38 and 50% in ambient conditions respectively. The commodity decay is found in an ambient condition is faster compared with the commodity stored in the present cooling system. Evaporative cooling efficiency is found 82%.

Keywords: Solar powered evaporative cooling systems · Perishable products · Preservation · Relative humidity · Vegetables

1 Introduction

In Ethiopia the farmers are cultivating different types of fruits and vegetables such as carrot, peppers, mango, tomato etc., after the harvest, the fruits and vegetables are stored in high ambient temperature and below the required relative humidity by the farmers and investors, that causes these fruits and vegetables spoilage and they may get economical loss. Also, the post-harvest deterioration contributes towards a significant fraction of the total loss in food grains, owing to poor storage facilities and lack of infrastructure. By providing thermal cooling for this issue would be minimize the post-harvest losses [1]. An issue of food losses leads to combat hunger and improve the food insecurity,

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especially in the poor and developing countries. Such losses not only affect the farmer societies, but also it leads waste of resources where employed during the production. The exact reasons and extent of such losses varies around the world and are most dependent on the specific conditions, as well as native factors predominant in a specific country [2].

The post-harvest deterioration contributes towards a significant fraction of the total loss in food grains, especially in the developing nations, due to existing poor storage facilities and lack of infrastructure. The quality of fruit and vegetables and their related shelf life are reduced by loss of moisture, decay, and physiological breakdown. Such deterioration is directly related to the storage temperature, relative humidity, air circulation, mechanical damage, and improper post-harvest sanitation [3]. An evaporative cooling process is operates using spontaneous processes of heat and mass transfer, where water and air are the working fluids to vary the temperature and moisture as per the local requirement. In water evaporation, an air flow is induced by the passage and thereby decreasing the air temperature. Based on the evaporative coolant system, waxing and hot water treatment have been found to be an efficient and economical means of reducing post-harvest storage loss [5]. Cold storage is one way of protecting the deterioration agricultural products such as fruits and vegetables using evaporative cooling technology. The purpose of the design is creating cold storage by adding cold air to it that increases the shelf life of the perishable agricultural products.

Design of evaporative cooling system powered by solar PV panel can be found everywhere at which the perishable agricultural products are highly produced. The present designed and developed evaporative cooling system is benefited for farmers, merchants, investors and consumers who are associated with the production and logistics chain of fruits and vegetables.

2 Design and Fabrication of Evaporative Cooling System

In this study, a solar powered evaporative cooling system was designed and constructed to preserve fresh vegetables of 80 kg storage capacity. The solar power evaporative cooling system basically consists of the solar energy conversion (PV panel, charge regulator, battery and invertor) cold storage space, cooling fan and the evaporative unit (cooling pad). the cooling system contains a rectangular shape with total storage space of 0.735 m^3, made of stainless steel for external cover, aluminum for internal cover and insulated between them by 0.05 m thick of fiber glass, a cooling fan provides air flow of 0.9 m/s velocity and consumes 35 W of power with a speed of 2800 rpm, cooling pad is made of natural fiber of 0.03 m thickness which is easily available in local. A water pump with discharge capacity of $5.4 \times 10–5\ m^3/s$ and power rating of 50 W is used to recirculate the water. A water reservoir of capacity 60 L is linked the cooling water with the cooling system at the bottom through pipe and to keep the cooling pad/mesh continuously wet. The cold storage consists of four shelves and water circulating pipe below each shelf used to remove heat generated by fruits and vegetables. The basic principle relies on solar powered cooling by evaporation, when the system is set in operation, the dry air from the suction fan passes over the wet surface (cooling pad) and evaporates the soaked water away from the cooling pad. When water evaporates, it draws latent heat from the air surroundings the cold storage, which produces considerable cooling effect in the storage chamber. The picture of solar powered evaporative cooling system developed by solid work modeling is shown in Fig. 1.

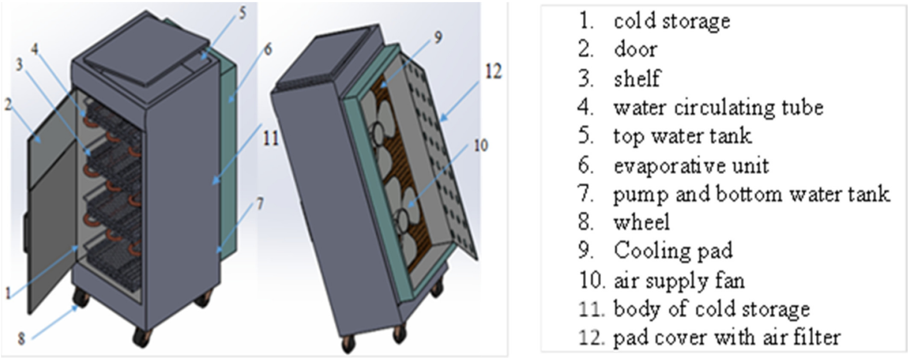


Fig. 1. Solid work modeling of the cold storage

3 Heat Transfer and Heat Generation

The heat balance is calculated through the cabinet wall using the methods of heat transfer modes and the heat generation due to commodities respiration load, Air change load, Fruit and vegetable load, Power Loads.

3.1 Heat Transfer Through the Wall, Q_w

The conduction heat transfer through the wall or roof will depend on the thickness and thermal conductivity of the material used [27].

$$\mathrm{Q}_w = \text{Heat gain} = UA_{os}(T_o - T_i) \tag{1}$$

Where Q_w is Heat loss through wall, Aos is the outside surface rea of cold storage (m^2), U is The overall heat transfer coefficient (W/m^2 °C), Ti is the inside air temperature of cold storage (°C), To is outside atmosphere air temperature (°C).

3.2 Convection Heat Transfer Effect on Cold Storage, Q_{cov}

Heat transferred from the wall of cold storage to the cabinet air, it led to Newton's cooling law equation.

$$Q_{\mathrm{cov}} = hA_c(T_w - T_c) \tag{2}$$

Where Q_{cov} is convective heat transfer, h is convective heat transfer coefficient obtained from dimensionless number using film temperature in W/m^2 °C, A_c is area of the cabinet in m^2, T_w is wall temperature of cold storage in °C is T_c is cabinet temperature in °C.

3.3 Heat Transfer Through Cooling Pad

The cooling pad is a plain porous wall bounded by two convective fluids (air) outside the pad surface and inside the cooler, each at different temperature, the elementary sensible heat flux in terms of overall temperature and thermal properties of the pad as shown in Fig. 2.

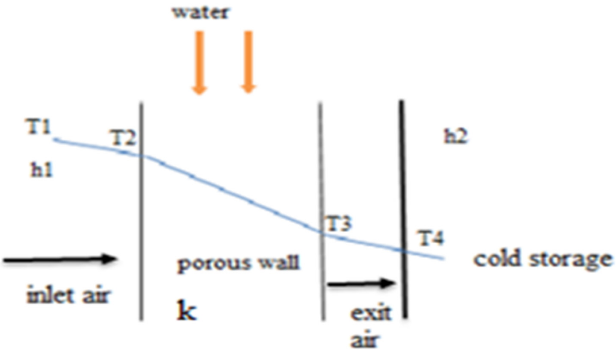


Fig. 2. Scheme of the heat transfer process across the porous evaporative cooling pad

Basic model equations

$$Q = h_1 A(T_1 - T_2) \tag{3}$$

$$Q = \frac{A(T_2 - T_3)}{X/K} \tag{4}$$

$$Q = h_2 A(T_3 - T_4) \tag{5}$$

The heat balance for the three equations gave

$$Q = \frac{A(T_1 - T_4)}{\frac{1}{h_1} + \frac{X}{K} + \frac{1}{h_2}} \tag{6}$$

Where h_1 and h_2 are the convective heat transfer coefficient, A is the area of the pad, k is the thermal conductivity of the pad, x is the thickness and T is the temperature.

3.4 Effect of Solar Radiation, Q_{rad}

Radiation is the energy emitted from a surface as particles or waves.

$$Q_{rad} = \varepsilon\sigma(T_c^4 - T_a^4) \tag{7}$$

Where Q_{rad} *is* radiative heat energy, ε is emissivity of the product kept in the cabinet, σ is Stephen boltzmaan constant, J/m^{2}K^4, T_c is cabinet temperature (°C), T_a is ambient temperature (°C).

4 Heat Generation

4.1 Fruit and Vegetable Load, Q_{veg}

Commodity is warmed in the warmer available in the conditioned space. The commodities loaded in the cold storage, than it is cooling up to the required temperature [18]. The heat transfer to the vegitables will be calculated using the following Eq. 8.

$$Q_{veg} = MC(\Delta T) \tag{8}$$

where Q_{veg} is the quantity of heat in W, M is the mass of the product in kg/day, C is the specific heat of vegetables above freezing in kJ/kg. K, ΔT is temperature difference in °C.

4.2 Respiration Load

Fruits and vegetables are still alive after harvesting and continue to undergo changes while in storage the more important of these changes are produced by respiration, a process during which oxygen from the air combine with the carbohydrates in the plant tissue and results in the release of CO_2 and heat [27].

$$Qr = M\,(respriationload) \tag{9}$$

Where Qr is quantity heat in W, M is mass the product in kg.

4.3 Air Change Load, Q_{ACH}

Air that enters a storage space must be cooled. Air needs to be renewed, and consequently there is a need for ventilation. When air enters the refrigerated space, heat must be removed from it [21].

$$Q_{ACH} = (V)\ \times\ (ACH)\ \times\ (h_o - h_i)\ \times\ (\rho) \tag{10}$$

Where Q_{ACH} is air change load due to door opening infiltration and ventilation in (W), V is volume of cold chamber in m^3, ρ is density of commodity, kg/m^3, h_o is enthalpy of air at T_o in kJ/kg, h_i is enthalpy of air at T_i in kJ/kg, ACH is air change per hour.

4.4 Power Loads, Q_{power}

In cold storage applications use various equipment's such as fans and pump which add significantly to the heat gain [30].

$$Q_{power} = 2545\ \times\ \frac{P}{Eff}\ \times\ FUM\ \times\ FLM \tag{11}$$

Where is Q_{power} is power load in W, P is horsepower rating from electrical power plans or manufacturer's data, Eff is equipment motor efficiency, as decimal fraction, FUM is Motor use factor (normally = 1.0), FLM is motor load factor (normally = 1.0).

The amount of heat must be removed from cold storage to cool the stored fruits and vegetables based on the storage capacity known as cooling load. Total Cooling load = heat transfer through cold storage cabinet wall + air change load + product load + respiration load + equipment load + convective heat transfer effect + effect of radiation.

4.5 Insulation Thickness Calculation

The insulation barrier of cold storage is defined as bulk materials with single- or multi-layer insulation. The complete insulation thickness formula containing insulation layers and interior/exterior wall structures is as below:

$$L = K\,[R - (\frac{1}{h_e} - \frac{1}{h_i}) \tag{12}$$

Where K denotes insulation material thermal conductivity, R denotes wall structure thermal resistance, he and hi represent heat transfer coefficients of interior and exterior walls, respectively.

5 Fan Selection Based on the Cold Storage Size

The volume of air flow required to cool the cold storage [33] can be determined from equation

$$\dot{V} = k(\frac{Q}{\Delta T} - U \times A) \times s.f \tag{13}$$

Where, k is the coefficient factor, and the required air velocity (v) is given by (Table 1)

$$v = \frac{flow\ rate}{area\ of\ the\, pad} \tag{14}$$

Table 1. Fan selection specifications.

Items		Letter	Specification
Cabinet	Size	H W D	1.5m 0.7m 0.7m
	Total surface area	A	4.1 m^2
	Materials		Steel, Aluminum & fiber glass
	Over all Heat transfer coefficient	U	4.1 W/m. °C
Temperature difference		ΔT	14 °C
Total heat generation/cooling load		Q	711.42 W
Safety factor		Sf	1.15

5.1 Fan Power Consumption

Fan power consumption is directly proportional to system flow rate and static pressure. For theoretically perfect efficiency, the minimum power required to move air against resistance is defined as [34]:

$$P_f = \frac{V \times p}{6356} \tag{15}$$

Where p_f is horse power of fan, V is volumetric flow rate (cubic meter per minute), p is max static pressure of air, N/m^2.

5.2 Pumping Energy Requirements Analysis

The energy of a pump for a particular day can be determined in Eq. 16.

$$E = \frac{mgh}{\eta} \tag{16}$$

Where m is mass of water needed in kg, g is acceleration due to gravity (m/s^2), h is height from the pump to top water tank (m), η *is e*fficiency of the system.

The flow rate of the pump can be calculated as in Eq. 16.

$$\dot{Q} = \frac{24}{PSH} x \underset{day}{\dot{m}} \tag{17}$$

Where Q is water flow rate, m is amount of water per day, PSH is peak sunshine hour.

5.3 Power Requirements from Solar Panel

The amount of power required from the solar panel can be calculated from Eq. (18) by changing kWhr to kW.

$$P = \frac{E}{hr} = \frac{\frac{V}{hr} \times h}{367\eta} kw \tag{18}$$

6 Selection of PV Array

The size of PV array has to have a relationship to the pump requirements. The depreciation of the panel due to ageing and environmental features (dust, etc.). Take the depreciation of 20% is allowed for:

$$\mathrm{P_{array}} = 1.2\mathrm{P} \tag{19}$$

6.1 Solar Energy Analysis

Base condition: 2 fans (35 W each) for a day, 1 micro pump (50 W) for recirculating water through the cabinet [4].

- The total energy requirement of the system (total load) i.e. Total connected load to PV panel system is = No. of units × rating of equipment = (2 × 35) + 50 = 120 W
- Total watt-hours rating of the system = Total connected load (watts) × Operating hours, take the operating hour 10 h
- The battery required is calculated based on the operating hour and the voltage obtained from the solar panel which is 12V the battery current becomes

$$I = \frac{power}{voltage}$$

Inverter size is to be selected as:

- Total connected load to PV panel system = 200 W
- Inverter are available with rating of 600, 1000, 1500W etc.
- Therefore, the choice of the inverter should be 1000 W.

Evaporative cooling efficiency of the system is found from the experimental result by using the following formula 15.

$$\varepsilon = \frac{T_1 - T_4}{T_1 - T_w} \tag{20}$$

Where ε is direct evaporation efficiency in %, T_1 is ambient temperature is °C, T_4 is cabinet temperature is °C, T_w is wet-bulb temperature on pad is °C.

7 Result and Discussion

7.1 Experimental Setup

An experimental test was conducted with natural fiber as the cooling pad material with inlet air velocities of 0.93 m/s. The characteristic length of the pad is 30 mm, height 1.4 m and width 0.7 m. The pad was divided into two equal parts by area and an axial fan deliver air at the rate 0.00376 kg/s to the wet pad and water vapor could easily pass in to cold storage area. The experiment was performed as shown in Fig. 3.

7.2 Temperature and Relative Humidity Variation

The performance of evaporative cooling system with a sample load to be cooled was evaluated daily at intervals of two hours from 8:00 am and 12:00 pm for 12 days and tabulated in Table 2. Within these periods of evaluating the performance of the cooling system, the ambient temperature is found that it is increasing up to 12 noon and then it is decreasing but the cabinet temperature dropped from 21.5 °C at 2.00 pm and thereafter

Fig. 3. Pictures of experimental test set up of evaporative cooling

it is maintained an appreciable average temperature of 17 °C for the remaining testing period. However, the average temperature inside the cooling chamber varied from 16.2 °C to 22.1 °C while in the ambient air temperature varied from 22.6 °C to 29.8 °C. And the evaporative cooling chamber relative humidity is found between 75% and 90% while at outside relative humidity is measured and it is varied from 66% to 80%.

Table 2. The average temperature and relative humidity measured inside the cabinet and ambient air conditions for different local time.

Local time	Ambient		Cabinet		
	Temperature (°C)	RH%	Temperature (°C)	RH%	WBT(°C)
08 am	23.7	71	16.2	75	16.5
10 am	25.2	70	18.6	79	17
12 noon	28.9	69	19.9	83	18.4
02 pm	28.2	69	21.5	85	19
04 pm	26.5	70	20.7	88	19.5
06 pm	23	75	19.9	90	19.2

7.3 Physiological Weight Loss During Storage

It is observed that during the experiment, the commodity such as pepper, carrot and tomato, the weight loss is found that minimum for every day when stored in the evaporative cooling system chamber compared with an ambient storage and it is presented in Figs. 4 and 5.

(a) Cabinet (b) Ambient

Fig. 4. Weight loss difference on seven days of cabinet and four days of ambient.

(a) Cabinet (b) Ambient

Fig. 5. Weight loss difference on seven days of cabinet and four days of ambient.

Table 3 shows the variation of weight loss of pepper, tomato and carrot right from the first day to sixth day.

Figure 6a, shows the variation of weight of carrot, tomato and pepper from the first day to the sixth day mentioned in circle, triangle and square respectively. The continuous line is for cabinet conditions and the dotted lines are corresponds to ambient conditions when the commodities were kept. The figures also show that there is an appreciable weight loss found when the commodities were kept in ambient conditions. This is meant that the evaporation is higher in ambient condition than in the cabinet condition so that the commodity decay very fast as compared as that of the commodity stored in an evaporative cooling system.

Figure 6b, shows the percentage weight loss calculated by every day with respect to the first day. It is found that the commodities kept in the cabinet condition are show that less weight loss compared to the commodities kept in the ambient conditions. Among the samples, a high weight loss happened on pepper due to skin resistance of moisture loss in both cabinet and ambient conditions. Also, it is found that the carrot and tomato kept

Table 3. Physiological weight loss measured in peppers, carrot and tomatoes

Day	Carrot (kg)		Tomato (kg)		Pepper (kg)	
	Cabinet	Ambient	Cabinet	Ambient	Cabinet	Ambient
1	0.75	0.75	1.00	1.00	0.50	0.50
2	0.75	0.71	1.00	0.91	0.45	0.35
3	0.73	0.65	0.98	0.79	0.43	0.30
4	0.71	0.50	0.90	0.73	0.43	0.25
5	0.69	0.43	0.92	0.65	0.42	0.25
6	0.69	0.37	0.90	0.62	0.42	0.25

in the cabinet conditions after four days there is no change in the weight loss because it may be the saturated conditions after that the carrot and tomato gets decayed. From this, it is concluded that the carrot and tomato can preserve up to five days by maintaining this cabinet condition. It can be extended some more days by maintaining the cabinet conditions with more humidity and less temperature. Whereas, in the ambient condition, it is found that the carrot and pepper are decayed after three days. Furthermore, in the case of tomato, the weight loss is increases in the first three days and then it comes to saturated during the next days because it losses it water content fastly by evaporation for the first three days and there is no evaporation is found in the forthcoming days. The maximum weight loss found after the sixth day for carrot, tomato and pepper are 8, 10 and 16% in cabinet conditions and 50.6, 38 and 50% in ambient conditions respectively. Till more experimental investigation to be carried out to get the optimum result.

Theoretical efficiency of the direct evaporative cooling using the standard values available in Metrological department of Ethiopia for Bahir Dar city and it is calculated 84%. From the actual experimental values it is found that 82%. The difference is due to the air leakage from the cabinet through which some heat is transferred to the system from ambient.

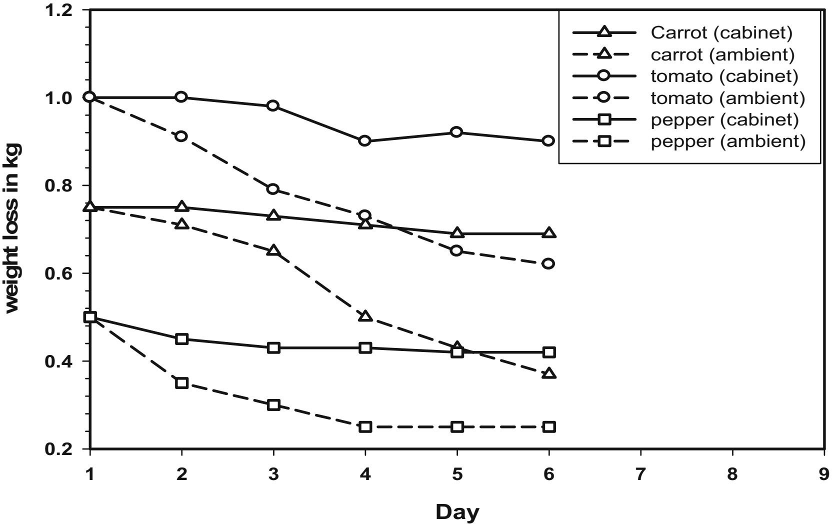
7.4 Feasibility Analysis

The time in which the initial cost out flow of a cold storage is expected to recovered from the cash inflows generated by the cold storage, which means the cost reduced by PV panel from grid power payment and cost by avoiding the spoilage of fruits and vegetables

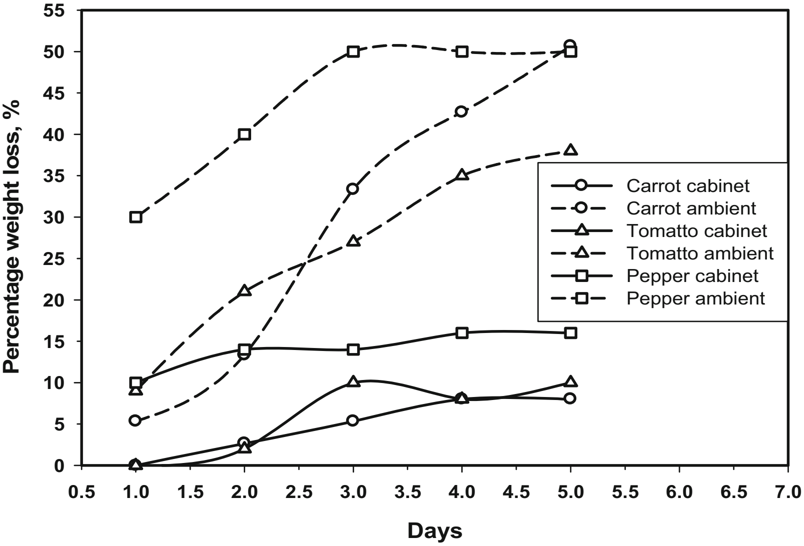
$$payback\ period = \frac{initial\ cost}{cash\ inflow/year} \tag{21}$$

$$payback\ period = \frac{27,680 birr}{15040.8 birr/year} = 1.8\,yrs$$

From this solar powered evaporative cooling, reducing the spoilage of fruits and vegetables and also avoid grid power payment will pay back the total cost of the cold storage within 1.8 years.



a. Variation of weight loss of carrot, tomato and pepper



b. Variation of weight loss of carrot, tomato and pepper

Fig. 6. (a) Variation of weight loss of carrot, tomato and pepper (b) Variation of weight loss of carrot, tomato and pepper

8 Conclusion

In this study, a solar powered evaporative cooling system is designed and developed, to store the products such as carrot, tomato and pepper and exposed to their required storage temperatures and relative humidity's. This system can also be used to preserve fresh vegetables with their quality still maintained at least 12 days by providing an appropriate humidity and temperature. The conclusions of this investigation are: The developed system is easy to operate, efficient and affordable most especially for farmers in developing countries like Ethiopia may find other methods of preservation quite unaffordable. It can preserve fresh vegetables, which if adopted will reduce post-harvest losses, and hence increase income generated from agricultural produce. From the transient experimental test, the required storage temperature and relative humidity for the preservation of the selected vegetable samples was achieved a minimum temperature 16.2 °C and the maximum relative humidity 90%. The maximum weight loss found after the sixth day for carrot, tomato and pepper are 8, 10 and 16% in cabinet conditions and 50.6, 38 and 50% in ambient conditions respectively. The commodity decay is found very fast in the ambient conditions as compared as that of the commodity stored in an evaporative cooling system. Evaporative cooling efficiency by experimentally found 82%. Till more experiment should be conducted in future to get the optimum result.

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