Design, Development and Performance Evaluation of Low Cost Zero Energy Improved Passive Cool Chamber for Enhancing Shelf-life of Vegetables

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ABSTRACT

High ambient temperature accelerates the process of dehydration in fruits and vegetables, which lead to reduction in its water content, decrease in shelf-life and consequent spoilage in due course of time. To enhance shelf life of fruits and vegetables, conventional methods of air conditioning and refrigeration are costly and require electricity. To overcome this problem, a low cost, eco-friendly zero-energy improved passive cool chamber, based on evaporating cooling principle, was designed and developed at ICAR-CAZRI, Jodhpur. It consisted of a double walled chamber made of baked bricks with coarse sand filled annular space. The improved cool chamber was found to achieve maximum depression in temperature in one hour as compared to 2-3 hours required by the old chamber. The performance evaluation of the improved cool chamber was carried out and temperature reduction of 12-14°C during summer and 6-8°C during winter was observed with RH varying from 80-95%. The vegetables were safely stored for 7 days in winter and 4-5 days during summer without any spoilage. The improved cool chamber with easy maintenance shall be a boon to reduce the spoilage of fruit and vegetables specifically in remote villages of Indian Thar desert where proper storage facilities are lacking. The improved cool chamber also saves huge amount of electricity that is otherwise used to preserve fruits and vegetables.

Key words*: Zero energy passive cool chamber, Evaporative cooling, Vegetable storage, Shelf life, Postharvest losses.*

INTRODUCTION

In India, the deterioration of the quality of fruits and vegetables starts immediately after harvest due to lack of farm storage. India is the second largest producer of fruits and vegetables in the world after Brazil and China. Total production of fruits and vegetables in India is about 256.10 million tonnes of which 86.60 million tonnes and 169.50 million tonnes are fruits and vegetables, respectively (Anonymous, 2014). Storage of fresh horticultural produce after harvest is one of the most pressing problems of tropical countries like India. Due to high moisture content, fruits and vegetables have very short life and are liable to spoil. Moreover, transpiration, respiration and ripening processes are continued in fruits and vegetables even after harvest. Thus, the deterioration rate increases due to ripening, senescence and unfavourable environmental factors. Hence, preserving fruits and vegetables in their fresh form is required to restrict chemical, bio-chemical and physiological changes to a minimum level and may be achieved through controlling temperature and humidity (Basediya *et al.,* 2013). Due to highly perishable in nature, about 20-30% of total fruit production and 30- 35% of total vegetable production in India are wasted during various steps of the post-harvest chain (Chadha, 2001; Suryawanshi *et al.,* 2005; FAO, 2006; Arya *et al.,* 2009; Kitinoja *et al.,* 2010; Basediya *et al.,* 2013; ASSOCHAM, 2017) and the monetary losses are about Rs 2 lakh crore per annum in India (ASSOCHAM, 2017).

Relative humidity and temperature are two most important environmental factors influencing the quality and the storage life of fresh produce (Nunes *et al.,* 2009; Choudhury, 2006). Proper storage and transport practices of fruits and vegetables include control of temperature and relative humidity, satisfactory ventilation by maintaining space between containers etc (Basediya *et al.,* 2013). Deterioration of fruits and vegetables during storage and transportation is generally affected by temperature (Getinet *et al.,* 2008; Pathare *et al.,* 2012). Relative humidity is another essential aspect that is considered important for handling of fruits and vegetables under controlled environment (Prusky, 2011).

Several simple practices are useful for cooling and enhancing storage system efficiency wherever they are used, and especially in developing countries, where energy savings may be critical. Mechanical refrigeration is however, energy intensive, expensive, and requires uninterrupted supply of electricity which is not always readily available. Such facilities of mechanical refrigeration system e.g. cold storages are available in India but most of them are used for storage of potato only. Therefore, appropriate cool storage facilities are required in India for on-farm storage of fresh horticultural produce. Low-cost, low-energy, environment-friendly cool chambers made of locally available materials, which utilize the principle of evaporative cooling, were therefore developed in response to this problem. Evaporative cooling is an environment friendly air-conditioning system that operates using induced processes of heat and mass transfer where water and air are working fluids (Camargo, 2007). Very recently Sharma and Mansuri (2017) developed solar photovoltaic (SPV) power system based evaporative cooled storage structure (ECSS) for storage of vegetables to increase their shelf life. These cool chambers are able to maintain temperature at 10–15°C below ambient, as well as at a relative humidity of 90%, depending on the season.

The evaporative cooled storage structure has proved to be useful for short term on-farm storage of fruits and vegetables in hot and dry regions (Chaurasia *et al.,* 2005; Jha and Chopra, 2006; Vala and Joshi, 2010). Evaporative cooling is an efficient and economical means for reducing temperature and increasing the relative humidity of an enclosure, and has been extensively tried for enhancing the shelf life of horticultural produce (Jha and Chopra 2006; Dadhich *et al.* 2008; Odesola and Onyebuchi 2009;) which is essential for maintaining the freshness of the commodities (Dadhich *et al.* 2008).

Maintenance of low temperature is a great problem in India particularly, under the hot arid condition of Western Rajasthan commonly known as the “Thar desert” (second largest desert of the world). The hot arid zone of India, which is located in north-west part of country is spread in 31.7 m ha and is characterized by limited and erratic rainfall, extreme temperatures with large diurnal and seasonal variation, strong solar radiation and wind regime resulting in demand for high water requirement (Rao and Roy, 2012). The weather, even in normal years, for most part of the year, remains too dry and inhospitable for human and livestock. Prevailing low humidity and high temperature regulate physiological activities of fresh vegetables that affect their physio-chemical characteristics during the storage period. The high ambient temperature accelerates the process of dehydration in fruits and vegetables, which leads to reduction in its water content, decrease in shelf-life and consequent spoilage in due course of time.

Due to low humidity (13-33%) prevailing in the arid region particularly in summer, the cooling effect based on evaporative cooling principle becomes prominent and effective as it causes high evaporation and therefore, results in more depression in temperature. Considering this, a low-cost, eco-friendly and energy saving new storage system called “Zero energy passive cool chamber (ZEPCC)” was designed and developed at ICAR-CAZRI, Jodhpur. This system is based on evaporative cooling for preservation and enhancing shelf - life of fruits and vegetables without using any active source of energy.

MATERIALS AND METHODS

Study Area: The study was carried out at ICAR-Central Arid Zone Research Institute, Jodhpur, India (26°18′N and 73°04′E) in 2016 and 2017. Mean monthly annual rainfall in Jodhpur varies from

1.5 mm to 128.1 mm with mean annual rainfall of about 379 mm. About 80-90% of the annual rainfall is received during southwest monsoon period from June-September. The temperature distribution is uniform with a mean monthly minimum value of 20.3°C and maximum value of 33.9°C (Singh *et al.,* 2011) and relative humidity of 13% - 33% (Table 1).

Principle of evaporative cooling system: The passive cool chamber is based on the principle of evaporation. Evaporation is the process of changing liquid phase into gaseous phase at a temperature below its boiling point. The fastest moving molecules (those with the highest kinetic energy) at the surface of the liquid have enough energy to break the attractive bonds with other molecules. They then escape the surface of the substance. Obviously, this only occurs with the molecules at the surface of the substance. Since at higher temperatures the molecules have more kinetic energy, more of them are likely to escape, and so evaporation occurs more quickly at higher temperatures. In general, evaporation occurs because systems seek equilibrium (there is a low concentration of molecules in the air, and a high concentration in the liquid). During evaporation, the required latent heat is provided by the sensible heat of adjoining air resulting in reduced air temperature. Evaporation takes place as long as there is vapour pressure deficit between wet surface and adjoining air ($Psws>rh.P_{sta}$)

Energy balance of cool chamber: The energy balance study of improved cool chamber was carried out and the relationship for determining the temperature of cool chamber (T_{ch}) was developed as given below;

$$\rho V C_a \left(\frac{dT_{ch}}{dt}\right) = H_Q + UA_c\ (T_a - T_{ch}) - (h_p + h_{ep})\ A_c\ (T_{ch} - T_w) \quad \text{--- (1)}$$

At steady state condition,

$$\rho V C_a \left(\frac{dT_{ch}}{dt}\right) = 0, \text{ which leads to}$$

$$T_{ch} = \frac{\lfloor H_Q + UA_c T_a + (h_p + h_{ep})\ A_c\ T_w) \rfloor}{\lfloor UA_c + (h_p + h_{ep}) \rfloor} \quad \text{--- (2)}$$

The inside temperature of cool chamber was computed by using the developed eq (2) where H_Q = Sensible heat gain, U = overall heat transfer coefficient, A_c = surface area, T_a = ambient

Table 1: Detailed summary of weather condition at CAZRI Jodhpur*

Month	Relative humidity (%)		Temperature (°C)		Wind speed (km/h-)	Evaporation (mm day-1)	Sunshine hours (h day-1)	Rainfall (mm yr-1)
	07: 30h	14:30 h	Max	Min				
Jan.	57	24	24.9	10.6	5.0	4.2	8.8	2.7
Feb.	52	20	27.8	12.7	5.3	5.8	9.1	4.4
Mar.	41	15	33.6	17.9	5.8	8.6	9.3	2.2
April	37	13	38.8	23.1	6.8	12.0	9.9	9.5
May	50	20	41.1	26.9	10.0	14.2	10.1	16.2
June	64	33	40.0	28.1	11.5	12.8	9.2	38.9
July	77	51	36.0	26.8	10.2	8.5	6.5	128.1
Aug.	82	57	34.0	25.5	7.9	6.3	6.7	117.4
Sept.	75	43	35.5	24.2	5.8	6.9	9.0	47.8
Oct.	55	22	36.2	20.1	3.6	6.6	9.6	6.3
Nov	51	21	31.5	15.5	3.5	4.9	9.2	4.1
Dec.	56	24	26.9	11.9	4.1	4.0	8.7	1.5
Annual mean	58	28	33.9	20.3	6.6	7.9	8.8	379.2

**Meteorological data reported are the average values of 40 years (1971 - 2010); (Singh et al., 2011)* temperature, h_p = Convective heat loss coefficient h_{ep} = Evaporative heat transfer coefficient, T_w = wet bulb temperature, V = inside volume of cool chamber, ρ = Density of air, V = Volume of cool chamber and C_a = Specific heat of air. The depression in temperature (10-12°C) predicted was found in close proximity with the observed values for summer condition.

Background: In the initial study, a cool chamber (double walled) based on evaporative cooling principle was constructed (Chaurasia *et al.,* 2002). The cool chamber utilized the water evaporation from the surrounding walls (vertical walls only) for the reduction of temperature that maintains high humidity. The data for reduction of temperature and humidity were recorded in different months. The cool chamber was also tested for preservation of vegetables to study the shelf-life of the vegetables as compared to stored in room. Encouraged with its performance, another similar cool chamber was made with additional facility of water evaporation from bottom side in addition to surrounding vertical walls (Chaurasia *et al.,* 2005). Better results were obtained from it compared to previous cool chamber. Further design of the cool chamber was improved by making the holes in both chambers by using drilling machine. These holes increased the evaporating area of the cool chamber for faster cooling. Provisions were also made for water evaporation from the bottom side of the cool chamber by providing suitable channels which further enhanced temperature reduction and maintained high humidity in the chamber. This paper describes the improved design of cool chamber with its performance for preservation of vegetables in different seasons.

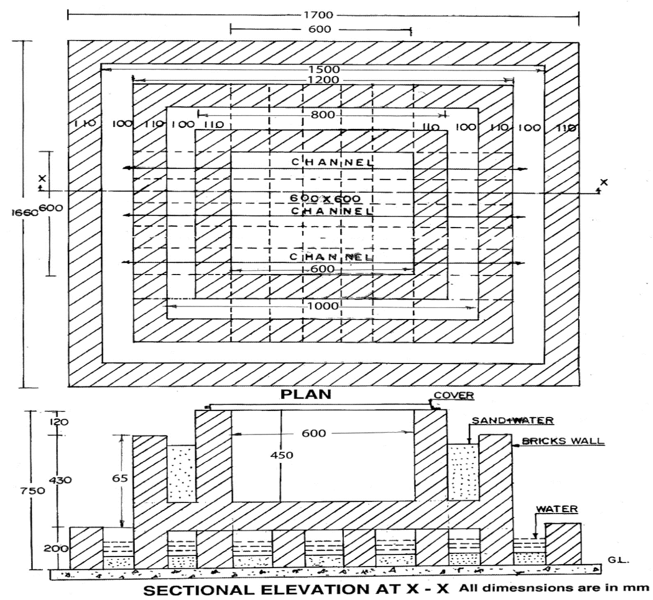

Fig. 1: Schematic diagram of improved low cost zero energy passive cool chamber

Fig. 2: Improved zero energy passive cool chamber for preservation of vegetables.

Design and construction of improved ZEPCC at CAZRI: The design of passive cool chamber was improved by increasing the evaporating area and installed in the solar energy yard of CAZRI, Jodhpur (Fig. 1). It consisted of a double walled system having inner & outer chambers made of baked bricks as shown in Fig. 2. In both chambers bricks were stacked in vertical walls and joined together with cement plaster in the ratio 1:10. The inner chamber is surrounded by outer chamber and coarse sand is filled between the two. The dimensions of both chambers are 1200 mm × 1200 mm (outer chamber) and 800 mm × 800 mm (inner chamber). The height of the chambers were 730 mm (outer chamber) and 420 mm (inner chamber). The water was also filled between inner & outer chamber. The baked bricks of cool chambers are porous enough and water filled between the cool chambers seeps through it. The water seeping through walls of outer chamber evaporates and consequently reduces the temperature of the cool chamber. The seepage of water through walls of the inner chamber also reduces temperature and as well increases humidity that provides sufficient moisture inside the chamber for preservation of vegetables under reduced temperature. The holes were made in both chambers by using drilling machine. In the outer chamber, 40 holes (dia 1.5 cm, depth 40 cm) were bored and the distances between these holes were 12 cm. In the inner chamber, 28 holes were bored (dia 1.5 cm, depth 20 cm) with a distance of 11.5 cm between the holes. These holes have increased the evaporating area of the cool chamber for faster cooling. Provisions were also made for water evaporation from the bottom side of the cool chamber by providing suitable channels which further enhanced temperature reduction and maintained high humidity in the chamber. The water filled up in the annular side walls helps to maintain high humidity inside the inner chamber and reduces temperature. To cut-off solar radiation, a slanting shed (3250 mm × 3000 mm) was fabricated. The improved cool chamber was found to achieve maximum depression in temperature in one hour compared to 2-3 hours by old chamber. About 15 to 40 liters water was required daily in the cool chamber to keep the walls wet depending upon the season and the climatic conditions of the day (15 to 30 litre water in winter and 20 to 40 liters in summer). Kitchen or waste water may also be used. About 2 to 3 litre water is sprinkled on the cotton cloth provided on the top side of the lid of the cool chamber to conserve moisture that maintained high humidity inside the cooling area.

Experimental arrangement and procedure: On-field experiments on cool chamber were carried out at the solar yard of ICAR-Central Arid Zone Research Institute, Jodhpur, India during 2016 and 2017. These experiments were carried out using the old and improved evaporating passive cooling systems to preserve carrot, brinjal, cabbage and tomato vegetables for 7 days. In these experiments, the temperature of room and both cool chambers were measured using digital thermometer whereas relative humidity was measured by digital hygrometer. Weight of products (both preserved and unpreserved) was recorded by digital weight balance at different stages of the storage period. The thermometer was suspended in the chamber through a small hole in the cabinet to ascertain the variation of temperature inside the chamber. The observations on temperature and humidity were recorded daily at 2 hours interval from 10:00 to 16:00 hour.

Qualitative evaluation of stored vegetables: The vegetables used for the experiment were carrot, brinjal, cabbage and tomato, which were uniform in shape and size and free from fungal infection. Weights of vegetables were recorded before keeping them in storage units. After storage, changes in weight were noted on 2nd, 3rd, 4th and 5th days, in the month of June, 2016. Physiological loss in weight (PLW) was determined by weighing the carrot, brinjal, cabbage and tomato at 5 days interval during May, 2016 and at 7 days interval during February, 2017 using Eq (3) as given below (Taye *et al.,* 2011):

$$\text{Physiological loss in weight; (\%)} = \left(\frac{W_1 - W_2}{W_1}\right) \times 100 \quad \text{--- (3)}$$

where, W_1: Weight of sample before storage; W_2: Weight of sample after storage

RESULTS AND DISCUSSION

Diurnal changes in inside temperature and humidity of the improved ZEPCC: Observed values of temperature inside improved cool chamber (T_{ch}) were compared with predicted ones using Eq (2) and both were found in close proximity (Fig. 3). Variations of temperature and humidity inside improved cool chamber and old cool chamber as well as of room and ambient conditions during the month of May, 2016 are presented in Fig. 4 and 5. May month is the hottest month in the arid region and receives mean daily horizontal solar insolation of 6.67-8.12 kWh/m^2/day (Pande *et al.,* 2009). From Figures 4 and 5, it was observed that the variation in temperature and relative humidity inside the improved passive cool chamber were in the range of 17.9°-31.1°C and 82-96%, respectively, as compared to the ambient temperature and humidity of 31.9°-45.3°C and 13-40%, respectively. The decrease of temperature and increase of relative humidity were found to be in the range of about 14-14.2°C and 56-69% as compared to the ambient condition. This may be due to the higher rate of evaporation of the prevailing dry ambient air in

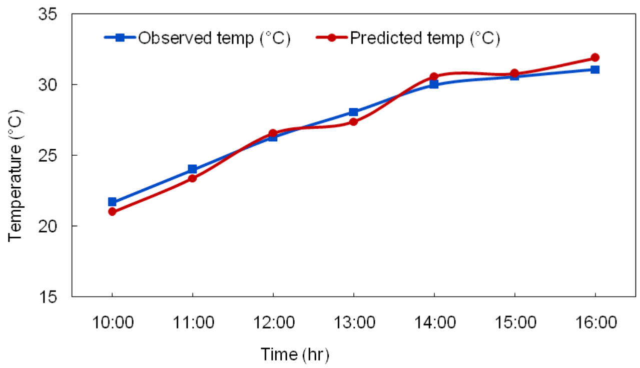

Fig. 3: Hourly variation of observed and predicted temperature (°C) of improved ZEPCC

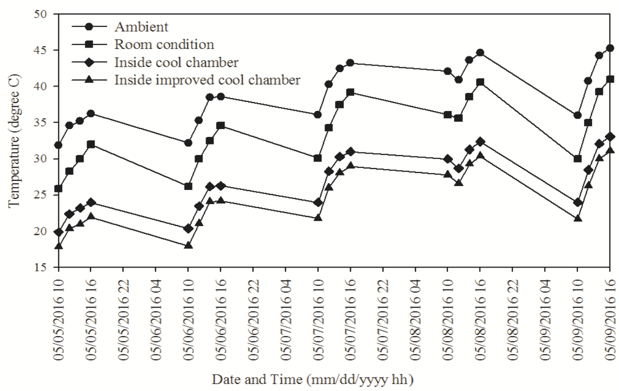

Fig. 4: Hourly variation of temperature (°C) inside and outside the improved ZEPCC

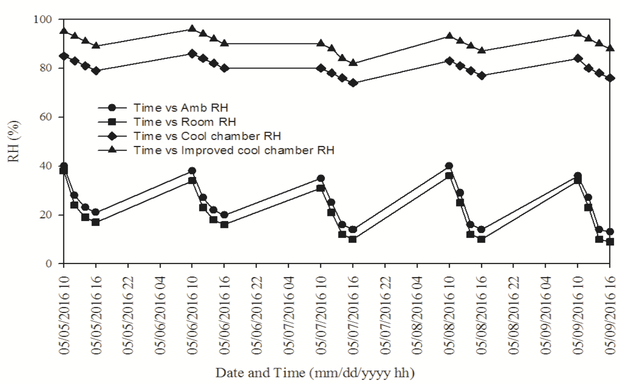

Fig. 5: Hourly variation of humidity (%) inside and outside the improved ZEPCC

summer days. The depression of temperature with high humidity in cool chamber is conducive condition for retaining freshness of vegetables and increases its shelf life for short period.

Physiological loss in weight: The changes in quality of stored vegetables in the cool chamber as well as in room are presented in Fig. 6 and 7. The criteria for change of quality of vegetables depend upon visual examination, shrinkage and weight loss. Fig. 6 and 7 show preservation of vegetables for a period of five days in the month of June, 2016 and eight days in the month of February, 2017, which indicate good appearance and freshness observed for tomato, carrot, brinjal and cabbage preserved in improved cool chamber compared to old cool chamber and room condition after five and eight days.

The total weight of vegetables decreased due to

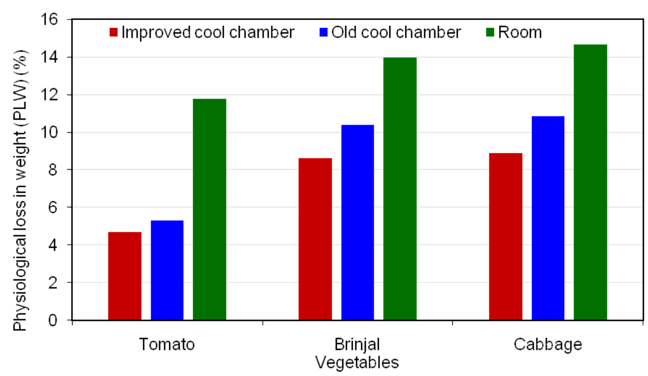

Fig. 6: Physiological loss in weight (%) of different vegetables under storage in cool chamber and room during summer, 2016

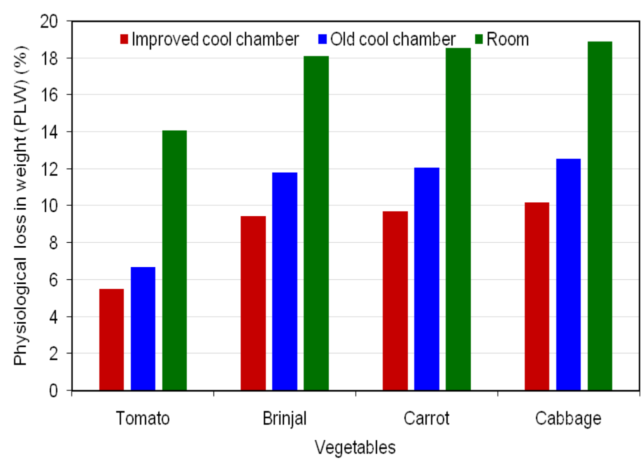

Fig. 7: Physiological loss in weight (%) of different vegetables under storage in cool chamber and room during winter, 2017

physiological stress when stored for long period. The physiological loss in weight of tomatoes was found to be 4.70% as compared to 5.30% in old cool chamber and 11.75% in room after 5 days of storage in improved ZEPCC (Fig. 6). Five per cent shrinkage for tomatoes was observed even after 5 days in improved cool chamber against 30% in room. The appearance of tomatoes stored in cool chamber looked fresh as compared to dull appearance of tomatoes stored in room. Similar results were found for other vegetables like brinjal and cabbage preserved in cool chamber. The physiological loss in weight of brinjal was found to be 8.60% as compared to 10.40% in old cool chamber and 13.98% in room and in cabbage it was found to be 8.95% compared to 10.85% in old cool chamber and 14.65% in room after 5 days of storage in in improved ZEPCC (Fig. 6). The Fig. 6 shows that weight loss of vegetables increased with interval of time but was always smaller in case of cool chamber as compared to room and consequently spoilage was reduced in cool chamber.

Trials were also conducted for preservation of vegetables for 7 days period in winter season during February, 2017. The tomatoes stored in cool chamber looked comparatively fresh as compared to room condition. The weight loss of tomatoes preserved in improved cool chamber was 5.50% as compared to 6.71% in old cool chamber and 14.10% stored in room after a period of 7 days (Fig. 7). Less shrinkage and better quality were observed in case of tomatoes preserved in the improved cool chamber compared to old cool chamber and room conditions. The red color of tomatoes almost remained the same in cool chamber whereas outer skin of tomatoes turned to dull color stored in room. The tomatoes off-loaded from the cool chamber were found edible even after 7 days storage but tomatoes preserved in the room for the same storage period were found unfit for human consumption as many vegetables suffered from fungal attack. The physiological loss in weight (PLW) of brinjal was found to be 9.45% compared to 11.80% in old cool chamber and 18.10% in room. In cabbage it was found to be 10.20% compared to 12.56% in old cool chamber and 18.91% in room and in carrot it was found to be 9.70% compared to 12.10% in old cool chamber and 18.55% in room after 7 days of storage in improved ZEPCC (Fig. 7). Weight loss and shrinkage were more pronounced in the vegetables preserved in room condition than in cool chamber. Fig. 7 shows relative daily weight loss of vegetables (tomatoes, brinjal, cabbage and carrot) stored in the cool chamber and room during a period of 8 days in the February (winter season), 2017.

In the cool chamber vegetables looked comparatively fresh with less weight loss and shrinkage. Again the spoilage of vegetables was heavily reduced as weight losses are less in cool chamber. The vegetables preserved in cool chambers were always found in good condition compared to vegetables stored in room condition.

CONCLUSION

The improved cool chamber was able to reduce the inside temperature by about 12-14°C during summer and 6-8°C during winter and maintained humidity more than 90%, to preserve vegetables for short term period. It can safely preserve vegetables for 7 days during winter and 4-5 days during summer. The improved zero energy passive cool chamber has wide utility for on-farm storage (in remote areas), vegetable markets (away from cities), retailers (vegetables vendors) and in rural areas of arid region. The cool chambers can be easily fabricated by an unskilled person with locally available materials in remote areas/villages/rural homes as per requirement ranging from domestic use (20 kg) to commercial level (1000 kg).

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