Performance evaluation of a low-cost evaporative cooling storage structure for citrus fruits in Sylhet Region of Bangladesh

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ABSTRACT

An experiment was conducted to evaluate the performance of low-cost evaporative cooling storage structures for extending the shelf life of citrus in comparison with ambient storage at the Sylhet Agricultural University, Bangladesh. A brick-walled cooler with wet river sand, clay, and zeolite mix pad material was used as a heat exchange material. The shelf life of citrus inside the structure was extended by 20–35 days relative to the ambient storage. During the summer season, the inside temperature was about 5–6°C lower than the outside temperature and relative humidity was about 10–15% higher than the normal condition. In contrast, the inside temperature was reduced to 10–11°C less than the ambient temperature in the winter season. Relative humidity was slightly increased to 20–23% at no-load condition but 16–17% in the presence of load condition. When the wind speed was high in the local area, the cooling capacity was varied from 1,176–3,461 W and the cooling efficiency was varied from 55–97% depending on these two climatic parameters. Daily data on physiological weight losses and citrus freshness were collected. Citruses such as lime (*C. aurantifolia*), lemon (*C. limon*), and citron (*C. medica*) were kept inside the structure for 44–45 days, with a 35-day increased shelf life. Average weight loss can be controlled inside the structure by 21–22%. However, pomelo (*C. maxima*) and mandarin orange can save 9–10% average weight loss, resulting in a 20–25-day shelf life when stored inside the cooler. This storage structure did not adversely affect the pH, total soluble sugar content, or titratable acidity of the juice. This structure, on the other hand, has the effectiveness of lowering the temperature and saving weight loss of citrus without the chilling injury in a cost-effective and environmentally friendly manner.

Keywords: Citrus, evaporative cooling, zeolite, cooling efficiency, storage system

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INTRODUCTION

Citrus fruits play an important role in the fruit world for their availability period, high nutritive content, and high market value. Sylhet, the northern east hilly territory of Bangladesh is one of the centers of origin of citrus and is suitable for citrus cultivation (Ahmed *et al*., 2020). This region is famous for some endemic fruit species like satkara (*C. hystrix*), orange (*C. aurantium*), lime (*C. aurantifolia*), lemon (*C. limon*), citron (*C. pennivesiculata*), malta (*C. sinensis*), and so on. Due to geo-climatic conditions, it favors the production of citrus all year-round except for some varieties such as orange and malta which grow abundantly in winter. People's efforts have been directed toward storage during the abundant availability of citrus.

Fruit loss is exacerbated further by a lack of sufficient cool storage space at the farm level and low-cost refrigerated storage at the market level (Lal Basediya *et al*., 2013). On the other hand, seasonal glut forces the farmers to sell their hard-earned produce at throw-away prices. However, extensive research is required to develop advanced postharvest treatment in order to maintain the high quality during the storage and marketing period. Postharvest decay is the major factor limiting the extension of the shelf life of many freshly harvested fruit. About 23% of postharvest losses of orange (*C. aurantium*) at Sylhet were observed in 2008 (Hassan, 2010). Furthermore, the high energy costs of storing fruits in refrigerators have increased the need for eco-friendly fruit management. In developing countries, the use of refrigerated storage is seldom economically feasible, as most citrus is produced and handled on a small scale and it is not profitable. Deterioration of fresh satkara, orange, lime, lemon, citron, malta, and so on during storage depends partly on temperature (Ajayi, 2011). Extreme cold temperatures can cause chilling injury to agricultural produce, and once the product leaves the temperature-controlled zone, deterioration resumes (Zakari *et al*., 2016). However, chilling for a prolonged duration in the refrigerator may damage the tissue to the level where it may become highly sensitive to fungal infections. Usually, the only means of keeping the fruit fresh at ambient conditions is by regular sprinkling with water.

Evaporative cooling is a gift of nature, and it is an environment-friendly cooling system (Mahmud *et al*., 2012). It is a well-known system to be an efficient and economical means for reducing the temperature and increasing the relative humidity in an enclosure and this effect has been extensively tried for increasing the shelf life of horticultural produce in some tropical and subtropical countries (Lal Basediya *et al*., 2013). Evaporative cooling storage structure is a double-wall structure having space between the walls which is filled with porous water-absorbing materials called pads (Roy, 1984). Different types of pad materials such as clay (Ndukwu, 2011), river sand (Singh and Yadav, 2012), zeolite (Ndyabawe *et al*., 2019), jute fiber (Al-Sulaiman, 2002), charcoal (Douglas *et al*., 2011), coconut coir (Kenghe *et al*., 2015), etc. were used for the exchange of heat in this system. These pads are kept constantly wet by applying water. When unsaturated air passes through a wet pad, transfer of mass and heat takes place and the energy for the evaporation process comes from the air stream. The best method of increasing relative humidity is to reduce temperature. In Bangladesh also, Jubayer *et al*. (2017) demonstrated a better outcome in shelf life and nutritional quality of potato with evaporative colling storage designed for farm households.

According to Lal Basediya *et al*. (2013), there are two common processes of evaporative cooling: direct and indirect cooling. Direct cooling is an adiabatic thermal process considering the change in dry bulb temperature while humidity increases in line with constant wet-bulb temperature. Direct cooling is 55–70% effective while indirect cooling has 75% effective without increasing the humidity. But indirect cooling runs on power supply while direct cooling needs a large amount of water. Therefore, this study considers direct cooling as of study area has a shortage of power supply. According to cooling medium evaporation cooling is also classified as air-mediated and water-mediated cooling (Yang *et al*., 2019). Air-mediated direct cooling can reduce the temperature up to 6.7°C and increase the humidity by 60–80%, making it suitable for dry and hot climates with rusting and waterborne bacterial problems in produce. Air-mediated indirect cooling has a distinct geometric design that ranges from metals such as aluminium to ceramic materials (Rey Martínez *et al*., 2004), which can eliminate rust and prevent waterborne bacteria but comes at a high cost and requires expert handling. Water-mediated direct cooling in contact with air stream needs more water (Kashani and Dobrego, 2016) 72, and 82 degrees to cool the system with the same limitations of air-mediated direct cooling. In contrast, water-mediated indirect cooling used multi-layer membrane evaporative cooling garment (Rothmaier *et al*., 2008) which is inapplicable for limited personal protective cloth. Liquid desiccants (Mohammad *et al*., 2016; Rafique *et al*., 2016) and solid desiccants (Hirunlabh *et al*., 2007; Jani *et al*., 2015; Rambhad *et al*., 2016; Zouaoui *et al*., 2016) are also used to enhance the energy effectivity in the cooling system. Two-stage evaporation cooling (El-Dessouky *et al*., 2004; Jain, 2007; Farmahini-Farahani and Heidarinejad, 2012; Mohammed, 2013; Uçkan *et al*., 2013) is also studied to improve the efficiency of evaporation cooling.

Anyanwu (2004) designed and developed a cuboid-shaped porous clay double-layer container to store fruits and vegetables with a performance of reducing ambient air temperature varied over 0.1–12°C. Singh and Satapathy (2006) evaluated the performance of zero energy cool chamber (ZECC) designed by the Indian Agricultural Research Institute (IARI) for storing fruits and vegetables in hilly areas and prolonged the shelf life of about 5–9 days with the decrease of ambient air temperature up to 5–6°C. Ndukwu (2011) developed an evaporative cooler that can reduce the temperature by up to 10°C. Most of the evaporative cooling systems concentrate on the storage of tomatoes (Getinet *et al*., 2011; Islam *et al*., 2013a; Arah *et al*., 2016; Dirpan *et al*., 2017; Tolesa and Workneh, 2017; Balogun *et al*., 2019; Ronoh *et al*., 2020). Molla *et al*. (2016) studied the performance of this type of structure for storing hyacinth beans at a reducing temperature from 8 to 6°C.

This type of storage structure was used for extending the shelf life of fruits such as orange (Umbarker *et al*., 1991), sapota (Reddy and Nagaraju, 1993), Kinnow mandarins (Pal *et al*., 1997), banana (Wasker and Roy, 2000), mandarin (Nagpur santra) (Bhardwaj and Sen, 2003), mango (Dhemre and Waskar, 2003), Kinnow (Jha, 2008), etc. in a different part of India. Marikar and Wijerathnam (2010) used a modified brick wall evaporative cooling chamber with a clay porous pad for extending the shelf life of limes (*Citrus aurantifolia*) about 5–20 days relative to ambient storage. The inside temperatures of the cooler were about 4–6°C less than the ambient temperatures, and humidity was about 10–20% higher than the ambient. Dasmohapatra *et al*. (2011) experimented with the storage of Malta fruits in a zero energy cool chamber with attached pedicel and enhanced the shelf-life could be to about 90 days. Ladaniya (2015) used evaporative cool chambers that extended the storage life of citrus 21–30 days in respect to 5–10 days at ambient conditions. Ishaque *et al*. (2019) developed a porous evaporative cooling structure which can preserve the freshness of citrus during storage.

The heat is transferred from the pad material during evaporation and the water is evaporated during this process. Different types of materials can be used as pads such as palm tree leaves, hessian cloths, jute, cotton, perforated clay blocks, etc. (Liberty *et al*., 2013). In a very recent work by Velasco-Gómez *et al*. (2020), cotton fabric has been used as an alternative to conventional colling pads. The water evaporation rate and volume of the pad determine the efficiency of the active evaporative cooler (Olosunde *et al*., 2009). Zeolites are minerals with a microporous structure that is uniform and has nearly identical properties. There are natural and synthetic zeolites available. Due to the sorption effect, zeolites can store energy in the form of heat. Mangnus (2007) developed a solar adsorption refrigeration system using zeolite and water. Tatlıer and Erdem-Şenatalar (1999) also used zeolite-water as working pair. Hu *et al*. (2009) tried to use zeolite composites to replace zeolite as an adsorbent. Trisupakitti *et al*. (2016) found a desirable effect in developing an adsorption cooling system using zeolite and Thai clay.

Islam *et al.* (2013b) developed a low-cost zero energy chamber to store fruits and vegetables and surveyed the opinion of farmers in different villages of Bangladesh regarding the dissemination of this technology. As most of the farmers, economic condition is poor, so the opinion of farmers about the adoption of this storage chamber is positive and potential to high acceptance toward household-based low-cost fruits and vegetable storage throughout the country. Joardder *et al.* (2020) stated that solar-driven evaporation cooling is economical, efficient, and avoids distress sale of plant-based foods in Bangladesh. As the farmers of Bangladesh are living below the poverty line, developing low-cost storage facilities at the farm household level for fruits and vegetables would be a convenient option for them (Jubayer *et al.,* 2017). This is where evaporative cooling comes in handy. Fruits and vegetables are essential human foods, but they are seasonal and highly perishable. As a result, properly storing these agricultural products in a low-temperature setting is important.

Evaporative cooling is a good way to meet this demand, particularly in a country like Bangladesh where the summer and spring temperatures are very hot (Alam *et al.*, 2017). The present research was therefore planned to establish and evaluate a low-cost evaporative cooling storage structure system at Sylhet Agricultural University (SAU) that could be used to extend the shelf life of citrus fruits. The implemented study compared the storage stability of various citrus under evaporative cooling storage structures and ambient temperature in this region in order to satisfy the farmers' economic return.

MATERIALS AND METHODS

Location

The low-cost evaporative cooling storage structure (ECSS) was constructed behind the Faculty of Agricultural Engineering and Technology, SAU, Sylhet, Bangladesh in April 2016. It lies between 24°3'' and 24°54'' north latitudes and between 90°54'' and 91°54''15' east longitudes respectively (Figure 1).

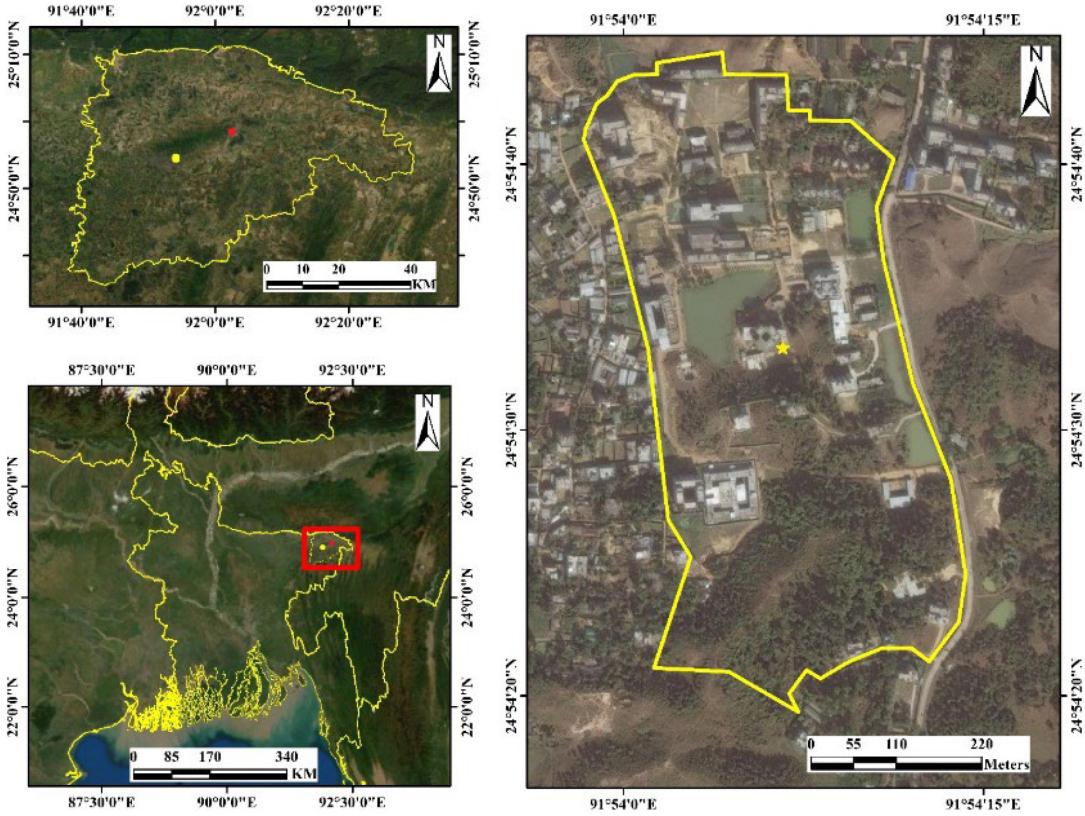

Figure 1 Map of the study area: Faculty of Agricultural Engineering and Technology, Sylhet Agricultural University, Sylhet, Bangladesh

The experiment was run for the ambient condition in the laboratory at room temperature located at the Department of Agricultural Construction and Environmental Engineering, SAU. All samples were collected from Jaintapur Upazilla which is located in between 24°5'' and 25°00'' north latitudes and between 91°40'' and 92°20'' east longitudes. The physiological quality tests were done in the laboratory of the Department of Food Engineering and Technology, SAU. The experiment was conducted in summer and winter seasons of 2016–2017. The seasonal variation of temperature and relative humidity of the year 2016–2017 collected from the Bangladesh Meteorological Department is shown in Figure 2.

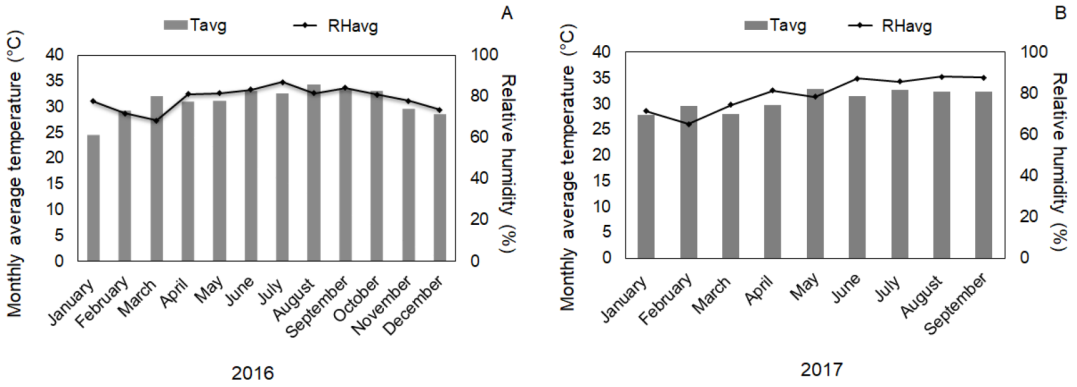

Figure 2 Seasonal variation of average temperature (Tavg) and average relative humidity (RHavg) in 2016 (A) and 2017 (B)

Establishment of Evaporative Cooling Storage Structure

Selection of structural material

According to Marikar and Wijerathnam (2010), Dasmohapatra *et al*. (2011), and Islam (2013b) designed for citrus storage, this study intends to evaluate the performance of evaporative cooling storage structure of porous brick, cement, and sand.

Selection of pad materials

Pad structure is an important part of ECSS. Used pad materials were sand, clay, zeolite, rice husk, and charcoal. However, after a thorough study of literature, firstly, river sand was used as pad material for both structures, but insignificant temperature drops of 1–2°C grew interested to other expeditions. Then, a mixture of river sand (50%) with clay (50%) was tried for a significant temperature drop. As Sylhet is a land of wetlands and most of the inhabitants have a fishing pond, due to the availability of zeolite in their household and according to Islam and Morimoto (2012) effectivity as pad material is known, this study test the mixture of river sand, clay, and zeolite as pad material. Later, a composite mixture of river sand, clay, and zeolite worked well to reduce the temperature to 5–6°C in summer and 10–11°C in winter. Whereas Jahun *et al.* (2013) found that the evaporative cooler can lessen the daily maximum ambient temperature, the average temperature inside the cooling chamber varied from 20–23.5°C while the ambient air temperature varied from 25–28°C for tomatoes and an average of 20.5–26.5°C inside the cabinet while the ambient air temperature was from 28–30.5°C for hot pepper. The mean relative humidity of the cabinet during the period of the experiment was about 51–93%, respectively, while the mean relative humidity of the ambient environment was from 47–58% for tomatoes, and the mean relative humidity for hot pepper was from 49–95% of the cabinet and the mean relative humidity of ambient was from 47–57%.

Description of evaporative cooling storage structure

The evaporative cooling storage structure was made of bricks, sand, and cement. This structure was designed to hold 30 kg of fruits at a time in three storage crates. The volume of each crate was calculated and the required storage volume was found at 30 ft^3. Accordingly, the length, width, and height of the structure were 8 ft, 3 ft, and 3 ft (244 cm × 92 cm × 92 cm) respectively. The spacing between the double brick wall was 3 inches (7.5 cm). The pad material was stored in a space of about 22 ft^3. A structure was erected to a certain height of 4 ft (122 cm) beside the double-wall to set up the water tank whose water holding capacity was 0.03 m^3. A shed was erected over the structure, which was made by using bamboo, straw, split bamboo, etc. The design of the structure was made by using software named Google SketchUp (Figure 3).

Construction of evaporative cooling storage structure

An upland area having a nearby source of water supply was selected whose floor space was made with brick 244 cm × 92 cm. The double-wall was erected to a height of 92 cm leaving a cavity of 7.5 cm. The chamber was drenched with water and soaked the fine riverbed sand with water. The 7.5 cm cavity between the double walls was filled with this wet sand and with a mixture of clay and zeolite (48% clay and 2% zeolite). A frame of the top cover was made with bamboo (244 cm × 92 cm) frame and straw or dry grass etc. Make attached/shed over the chamber to protect it from direct sun or rain. The cavity, brick walls, and top cover of the chamber were kept wet with water. Watering was done twice daily to achieve the desired temperature and relative humidity or a drip system was fixed with plastic pipes and microtubes connected to an overhead water source. The fruits were stored in this chamber by keeping in perforated plastic crates and these crates were covered with a thin polyethylene sheet. The construction procedure is shown in Figure 4.

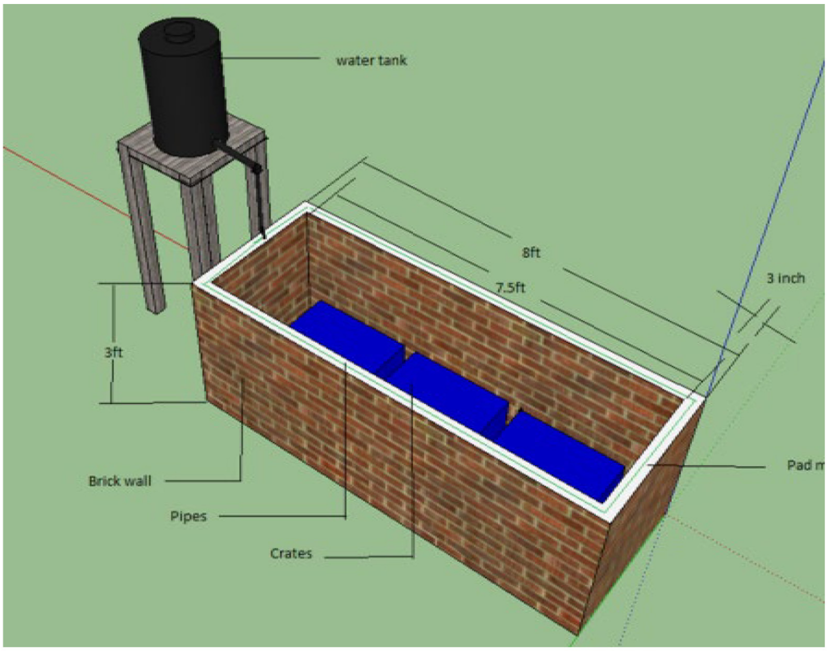

Figure 3 Designed evaporative cooling storage structure

Figure 4 Construction of evaporative cooling storage structure (ECSS): (A) levelling of the floor space, (B) watering of bricks, (C) building of ECSS, (D) levelling of the soil around the structure, (E) sheding for the whole structure, (F) fencing around the structure, (G) complete ECSS, (H) covering for the ECSS, (I) sample fruits in a crate

Methods of Storage at Evaporative Cooling Storage Structure

The fruits were kept in plastic baskets to avoid the absorption of moisture by the container. Fruits weighed separately into 3 kg each (average 30 lime fruits) crates and three storage crates which is equal to three crates of fruits for each treatment and replicated three times. Stored fruit crates inside the evaporative cooling storage structure and another three sets for ambient storage.

Experimental Procedure and Evaluation

The experimental evaporative storage structure was located behind the academic building and adjacent to slight hilly area, allowing it to be in an open-air flow condition with natural shedding from direct solar radiation. But the enclosed high speed of wind is the limitation of this area. The cooling pad was wetted three times a day, in the morning (10 a.m.), afternoon (2 p.m.), and night (10 p.m.) with an installed facility of the water tank as a sprinkler mode. The storage structure efficiency was conducted in no-load condition and load condition. The no-load test was carried out by comparing the climatic parameters temperature and relative humidity variations from ambient to cooling structure while taking into account the prevailing weather conditions prior to storage on a specific day. Load tests were conducted to determine the storage time of the citrus in the cooler before spoilage. Temperature and relative humidity were measured every 8 hours for all tests conducted between 6 and 22 hours local time. Digital thermometers permanently installed inside the cooling storage structure were used to monitor the wet-bulb temperatures. Ambient wet and dry bulb temperatures were measured with digital thermometers having a reading accuracy of ± 0.1°C. The relative humidity was also measured with a thermo-hygrometer with sensitive sensors and a ± 0.1% reading accuracy. The airflow rate, on the other hand, was determined by the current weather conditions. July to August of 2016 was accounted as summer for the no-load test and then the load test was done. Again, January to April of 2017 was accounted as winter for the no-load test, and April to May of 2017 was accounted as summer for the load test. The storage structure was evaluated based on the temperature differences between the ambient and the storage environment of the evaporative cooling storage structure, change in relative humidity between ambient and storage environment, cooling capacity, and efficiency. The parameters monitored or calculated were relative humidity and dry and wet-bulb temperatures. The cooling efficiency was calculated by using equation (1) (Lertsatitthanakorn *et al*., 2006). The cooling capacity of the direct evaporative cooler was calculated according to Yun (2008) as presented in equation (2).

$$\text{Cooling efficiency; } \eta = (TDB_a - TDB_c)/(TDB_a - TWB_a) \times 100 \qquad \text{------- (1)}$$

$$\text{Cooling capacity} = 1.08 \times Q \times [TDB_c - \eta(TDB_a - TWB_a)] \qquad \text{------- (2)}$$

where η *is* the evaporative effectiveness (%), TDB_a is the dry-bulb temperature of ambient air (°C), TWB_a is the wet-bulb temperature of the ambient air (°C), TDB_c is the temperature of cold air (°C), and Q is the airflow rate (m^3/s)

A control test in ambient conditions was also conducted in the open air at laboratory conditions. Following the stable result of temperature fluctuation, samples were collected from farmers in vinyl bags with the same size, color, disease, and damage-free appearance. After storing samples in ECSS and ambient conditions, the samples were weighed on the fifth day to determine the weight loss and the color was examined under full daylight to determine the color changes and presence of mold. Citrus quality was also determined through chemical analysis. Finally, analysis of variance (ANOVA) was used where $P < 0.05$ was considered significant. When ANOVA revealed that treatments had significant effects, a least significant difference (LSD) test was used to separate the mean.

Physiological Weight Loss (%) Determination

Every day, the weight loss of fruits was determined by weighing each sample with an electronic balance with an accuracy of 0.5 g, from the evaporative cooling storage structure and from ambient storage. Any fruits that showed signs of decay were recorded and removed from the sample under study. These balances accurately weigh objects with masses of up to 300 g to 2 or 3 decimal places; that is to 0.01 or 0.001 g (1 mg). This balance is extremely sensitive to air currents, with a sensitivity of 1 mg. As deterioration indicators, general cracks, bruise spots, over softening, and mold growth were used. Cumulative percent loss was determined until citrus fruits become pulpy, or their freshness was lost.

Chemical Analysis

All chemical analyses for juice content, juice pH, total soluble sugar content, citric acid content, and vitamin C content were done according to JBT FoodTech (2008).

Juice content

The juice contents were weighed and recorded in grams. The percentage of juice contents was calculated by using the following formula:

$$\text{Juice contents (\%)} = \frac{\text{Juice weight}}{\text{Fruit weight}} \times 100 \qquad \text{------- (3)}$$

The balance used in this experiment is capable of accurately weighing objects weighing up to 300 g to 2 or 3 decimal places, i.e., to 0.01 or 0.001 g (1 mg). This equilibrium is highly susceptible to air currents, with a sensitivity of one milligram.

Juice pH

pH concentrations in the juice were determined following extraction of juice in 50 mL flux at 27°C with a digital pH meter. Measurement of pH below about 2.5 (ca. 0.003 $moL\ dm^{-3}$ acid) and above about 10.5 (ca. 0.0003 $moL\ dm^{-3}$ alkaline) requires special procedures because the glass electrode used here will break down Nernst law under those conditions.

Total soluble sugar content

°Brix was determined by using the portable refractometer. One or two drops of juice were taken in the refractometer and then the reading was recorded.

Citric acid content

Citric acid content was determined following the titration method. At first, juice extraction was done by using a juice extractor. 100 g of the solution were made in a beaker (10 g of sample juice + 90 mL of water). After that, 5 mL of solution was taken in a conical flask, and phenolphthalein (2–3 drops) was added to that solution. Then the titration was done with NaOH (0.01 N) until the pink color appeared. The amount of NaOH needed for the titration was taken from a burette. For more accuracy, the titration was repeated 3 times for each sample. For the calculation of the amount of citric acid content in the sample, the average reading was calculated and then multiplied with the factor of 0.064.

Vitamin C content

Vitamin C content was determined following the titration method. The percentage of vitamin C content was measured according to the following procedure. At first, juice extraction was done by using a juice extractor. 20 g of the solution was made in a beaker (5 g of sample juice + 15 mL of water). After that, 5 mL of solution was taken in a conical flask. Then the titration was done with dye solution until the pink color appeared. The amount of dye solution needed for the titration was taken from a burette. For more accuracy, the titration was repeated 3 times for each sample. For the calculation of the amount of vitamin C content in the sample, the average reading was calculated and then compared with the standard (known) value. Vitamin C content was calculated.

Determination of the Gross Economic Benefit

Ignoring the fixed costs of the facilities, the calculation of the gross economic benefit using the storage was calculated using the following model presented by Jubayer *et al*. (2017).

$$B = p \times [(ps - plsp) \times (ldsp - plsk) \times ldsk] \text{ ------- } (4)$$

where B is the gross benefit in the developed storage in any month ($Tk.kg^{-1}$), p is the unit market price of the product ($Tk.kg^{-1}$), ps is the percentage of product saved, plsp is the price loss factor for the rotten product (fraction), ldsp is the percentage of loss difference due to rotten product, plsk is the price loss factor for weight loss/shrinkage (fraction), and ldsk is the percentage of loss difference due to weight loss/shrinkage.

Cost Analysis between Evaporative Cooling Storage Structure and Refrigerator

Fixed cost for the ECSS was calculated by using the information in Table 1. The depreciation (D) was estimated based on working life (L) for 5 years, salvage value (S) at 10% of the price (P) at Tk. 556 using the following formula: D = (P – S) / L; then D = Tk. 1,000. The pad material cost was considered as a maintenance cost thus the variable cost was Tk. 2,500. Fixed cost (Tk. 5,560) and variable cost (Tk. 2,500) were combined to calculate the total cost of ECSS which was Tk. 8,060.

For a refrigerator, the minimum purchase price of a refrigerator was the same capacity as ECSS (Tk. 25,000), and the costs of weir, plug, and electric switch were Tk. 1,000. Thus, the total fixed cost of the refrigerator was Tk. 26,000 with the depreciation cost of Tk. 4,680 (used the same formula as ECSS). Conventional refrigerators typically have a starting wattage of 800–1,200 Wh/day and a running wattage of around 150 Wh/day. Refrigerators are reactive devices that require additional power to start because they contain an electric motor, but significantly fewer watts to run as they remain on. According to the announcement, the retail power tariff has been increased from Tk. 6.77 to Tk. 7.13 per kilowatt-hour unit. The total electricity needed to run the refrigerator for at least 1 year was 1,296 kW/year (estimated from equation: (150 × 24 × 30 × 12) / 1,000). According to the unit price, the total maintenance cost which was considered as a variable cost was approximately Tk. 9,072 (estimated from equation: 1,296 × 7). Thus, the total cost of the refrigerator was Tk. 36,072. So, this is a convenient assessment of the amount and significance of an evaporative cooling storage structure based on the analysis above and proves to be cost-effective.

Table 1 Fixed cost for the low-cost evaporative cooling storage structure (ECSS)

Item	Amount (Tk.)
Brick (300 nos.)	2,200
Bamboo	520
Thatched shed	600
Water tank, pipes, tubes, poly sheet etc.	800
Plastic crate (3 nos.)	400
Labor	1,040
Total fixed cost	5,560

RESULTS AND DISCUSSION

Performance Evaluation of Evaporative Cooling Storage Structure

No-load test of ECSS

The ECSS was subjected to a no-load test to assess the effect of the evaporation that was expected to occur in the ECSS. The dry bulb temperature, wet bulb, and relative humidity data determined whether the process was effective or not. This was required to determine the structure's efficiency before it was loaded with the citrus fruits that will be stored within it. This was achieved by taking temperature difference and the relative humidity of the ECSS relative to the ambient condition. The average temperature was varied from 31–34°C and relative humidity was 71–78% in ambient conditions during summer. The inside temperature of the ECSS was 29–31°C and relative humidity was 77–83% when sand and clay was used as a pad material and after that temperature was varied from 28–30°C and relative humidity 81–87% when sand, clay, and zeolite was used as a pad material that was shown in Figure 5. So the average variation in temperature was 5–6°C and relative humidity was 10–15% which is comparable with Singh and Satapathy (2006), Marikar and Wijerathnam (2010), Islam and Morimoto (2015), etc. This study focused on the seasonal variations of temperature and relative humidity inside the structure. So, another trial of the no-load condition was repeated from 1st January 2017 to 26th February 2017. In addition, the ECSS cooler reduced its temperature of 10–11°C (Figure 6A) to the ambient conditions in winter. As the air is dry at winter more cooling was happened due to an increase of average relative humidity 20–23% (Figure 6B). The maximum temperature variation is found to be 6–22 hours, with morning temperatures of 11.35°C, noon temperatures of 11.7°C, and night temperatures of 4°C. The cooling efficiency of the ECSS was calculated and plotted in Figure 7A from 6 to 22 hours data of the dry-bulb and wet-bulb and relative humidity. Cooling efficiency varied from 55–94% in different day times depending on the relative humidity in the air which is in between the range of direct evaporation in the daytime (Yang *et al*., 2019) but for the night due to an increase of relative humidity and minimum fluctuation effectiveness was increased. If the wind speed is high in the local area, the cooling capacity varied from 1,176–3,461 W, and the cooling efficiency varied from 55–97%. A comparison study between effectiveness and cooling capacity has been shown (Figure 7B).

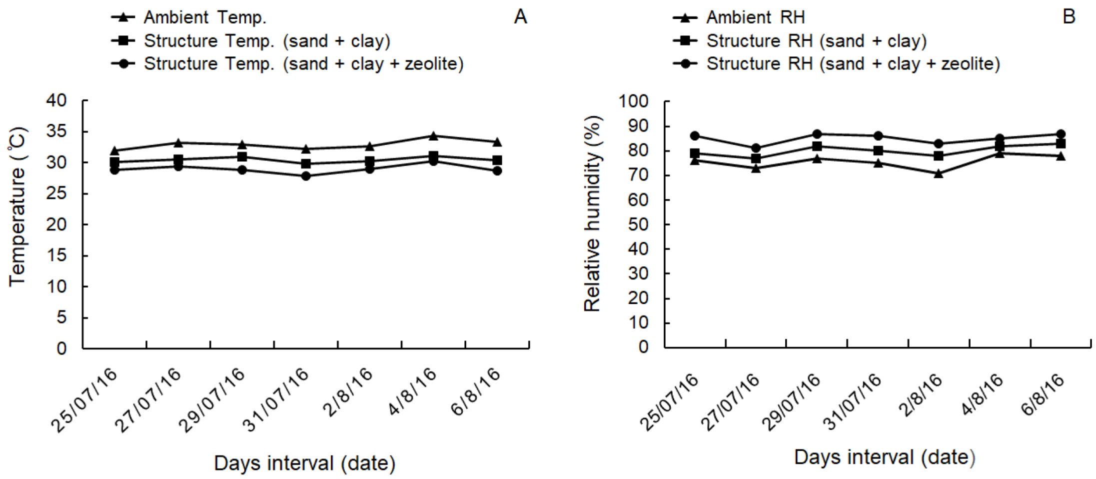

Figure 5 Comparison between ambient conditions and conditions inside the evaporative cooling storage structure for different pad materials: (A) temperature (Temp.), (B) relative humidity (RH)

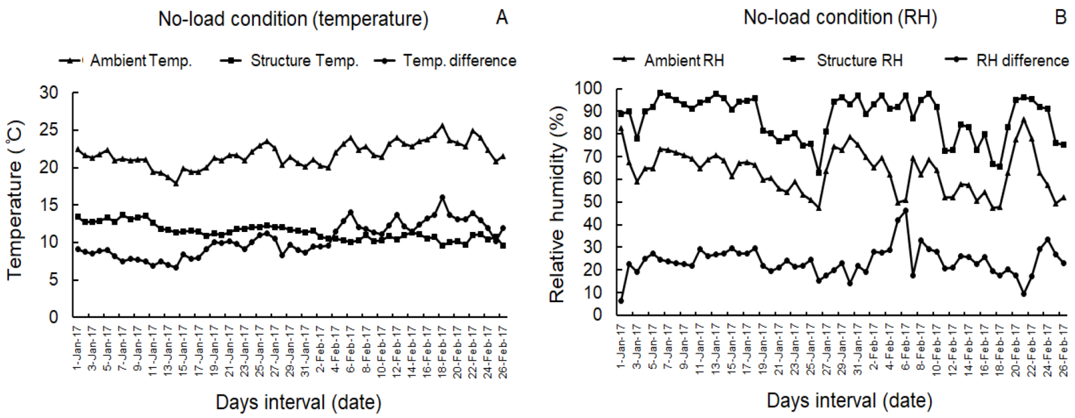

Figure 6 Comparison between ambient condition and conditions inside the evaporative cooling storage structure in winter in no-load condition: (A) temperature (Temp.), (B) relative humidity (RH)

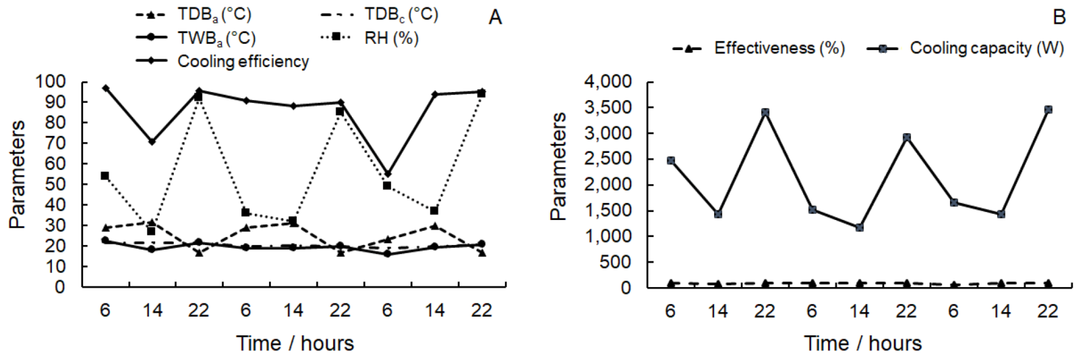

Figure 7 Periodic change in temperature, relative humidity with cooling efficiency (A) and comparison between cooling efficiency and cooling capacity (B) during the no-load test. TDB$_a$ = dry-bulb temperature of ambient air, TWB$_a$ = wet-bulb temperature of ambient air, TDB$_c$ = temperature of cold air, RH = relative humidity

Load test of ECSS

The performance of ECSS was evaluated from 7th August to 6th September 2016. Temperature swings were noticeable during these two months. The average temperature inside the structure varied from 25–29°C while the ambient air temperature varied from 30–35°C (Figure 8A). As a result, the ECSS temperatures were consistently lower than the ambient air temperatures during the hottest part of the day, when insulation was most effective, and cooling was most required. Because certain months, such as August and September, are extremely windy in the Sylhet Region, the inside of the evaporative cooling chamber is 85–86%, while the outside is 76% (Figure 8B). The relative humidity inside the structure remained about 10–15% higher than outside the structure. The above-mentioned transient responses of the evaporative cooler with load, with fresh citrus fruits during the months, are illustrated by a graph that shows relative humidity and average temperature. Low temperatures are required to keep the products fresh for a significantly longer period. These findings clearly show that the evaporative cooler can be used in our climate for short-term citrus fruit preservation without causing chilling injury, especially during the hottest times of the day when cooling is most needed. In the winter, another trial of this structure was done from January. Hence, an average temperature reduced to 10–11°C, and relative humidity increased to 16–17%. The average relative humidity fluctuation in a day was determined by recording the data from different days interval. The maximum and minimum variation of average relative humidity is shown in Figure 9.

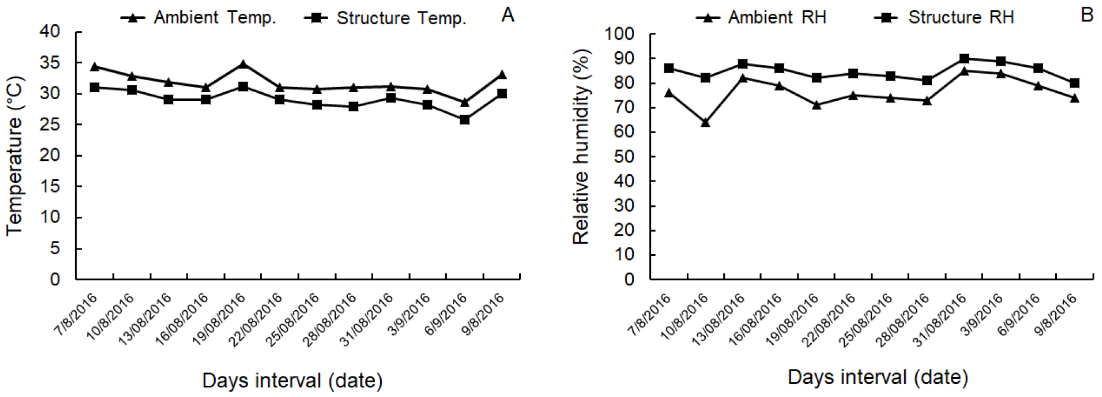

Figure 8 Comparison between ambient conditions and conditions inside the evaporative cooling storage structure in summer in load condition: (A) temperature (Temp.), (B) relative humidity (RH)

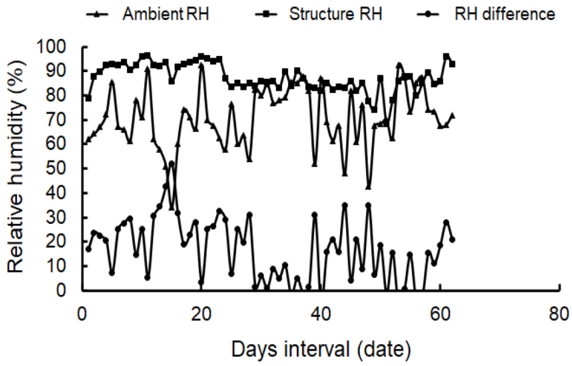

Figure 9 Comparison between ambient relative humidity and the relative humidity inside the evaporative cooling storage structure in winter in load condition

Physical and Chemical Quality Analysis

Weight loss during storage in ECSS

It was observed that when citrus fruits were stored in the modified ECSS, weight loss was minimal, whereas weight loss was highest in ambient storage. The weight of fresh citrus fruits in the modified ECSS and ambient storage significantly differed throughout the experiment during summer and winter as shown in Figures 10A–C and Figures 11A–B, respectively. The Figure 10A shows that in the summer, *Citrus maxima* (pomelo) reduced 3.5% weight inside the structure while 13.1% in ambient conditions. Therefore, *Citrus medica* (citron) decreased 6.9% inside the cooler while 29.32% in ambient conditions. In this regard, *Citrus aurantifolia* (lime) was 6.9% inside the ECSS and 23.6% outside. In short, ECSS can control 10–22% weight loss in the summer for pomelo and lime. In the case of *Citrus reticulate* (mandarin orange), it was 1% inside the structure and 10% in atmospheric condition. Correspondingly, *Citrus limon* (lemon) followed the same trend that was 3% in ECSS and 24% in ambient conditions. Thus, ECSS can control 9–21% weight loss in the winter for mandarin orange and lemon.

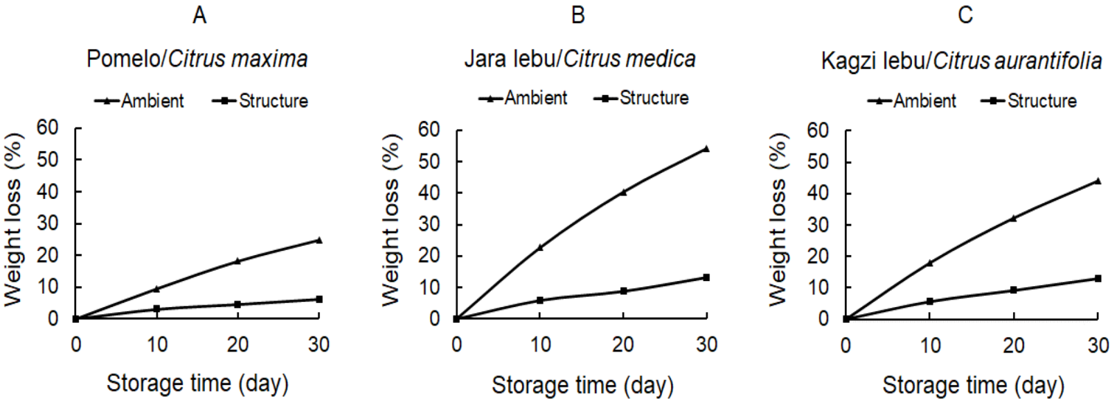

Figure 10 Graphical representation of weight loss percentage of (A) pomelo/*Citrus maxima,* (B) jara lebu/*Citrus medica*, and (C) kagzi lebu/*Citrus aurantifolia* during storage in summer

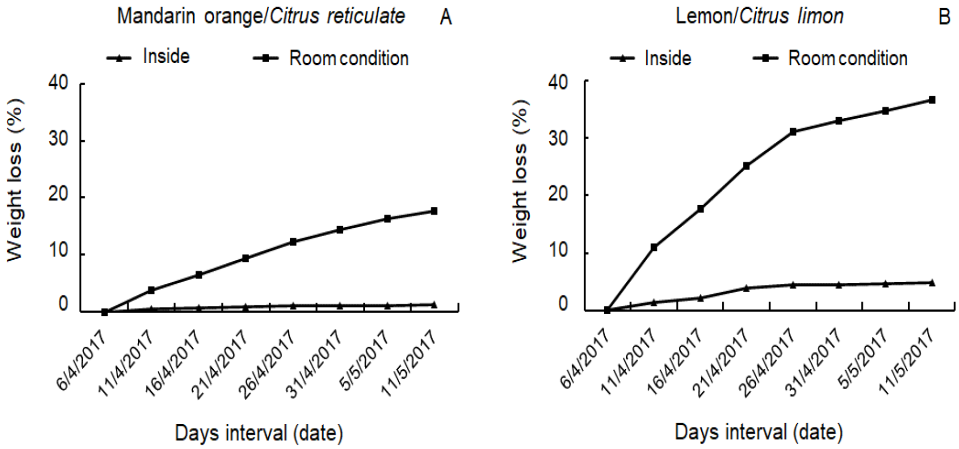

Figure 11 Graphical representation of weight loss percentage of (A) mandarin orange/*Citrus reticulate* and (B) lemon/*Citrus limon* in evaporative cooling storage structure during storage in winter

pH

There was a significant difference in the pH of citrus fruits in either the ECSS or ambient storage. An increase in pH value was observed in the ambient storage after 10 days and thereafter it increased at a gradual rate as well as in the ECSS in the summer (Figure 12). A similar trend was found in ECSS in the winter (Figure 13). During the summer, the pH of pomelo, jara lebu, and kagzi lebu in ambient storage increased from 3.45 to 3.60, 2.15 to 2.39, and 2.05 to 2.24, respectively. However, the pH for the same varieties in the ECSS increased as well, with values ranging from 3.45 to 3.49, 2.15 to 2.31, and 2.05 to 2.14, respectively. The difference in increased pH values between the two structures was found to be significant ($P < 0.05$). This trend, however, did not show any significant differences during the winter ($P > 0.05$).

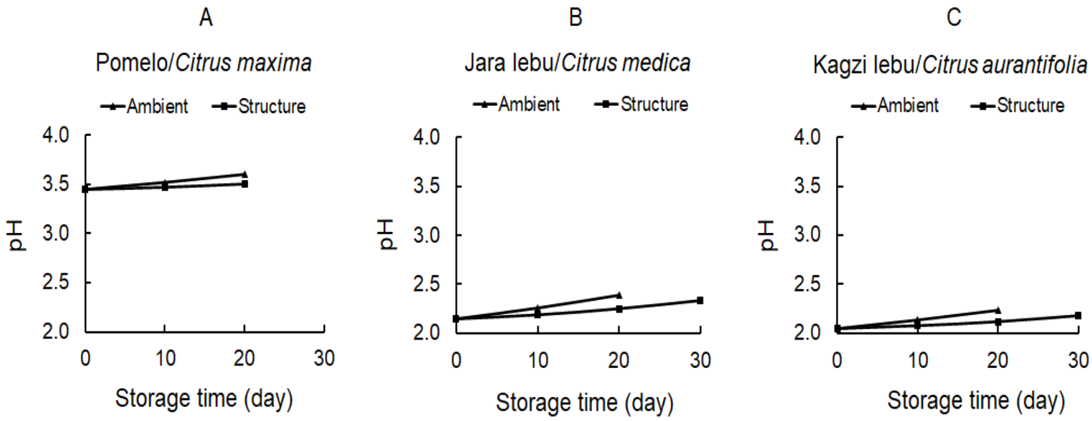

Figure 12 Graphical representation of pH variation of (A) pomelo/*Citrus maxima,* (B) jara lebu/*Citrus medica*, and (C) kagzi lebu/*Citrus aurantifolia* during storage in summer

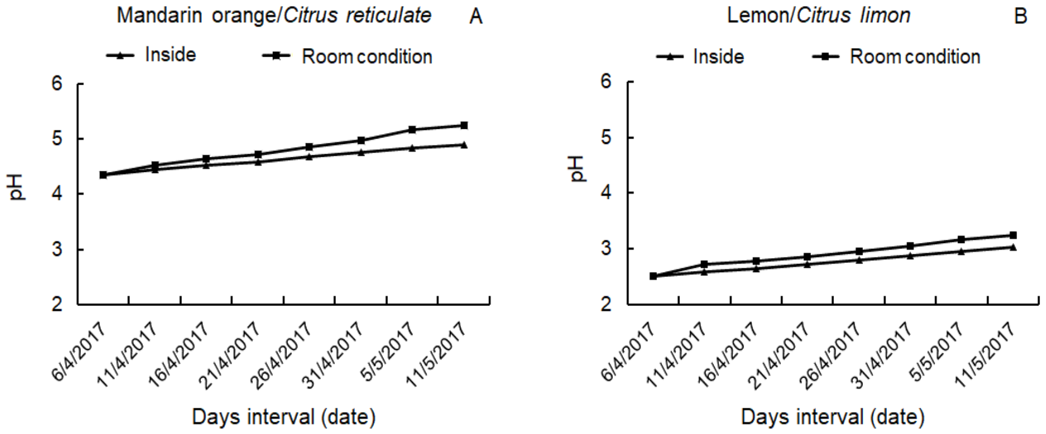

Figure 13 Graphical representation of pH variation of (A) mandarin orange/*Citrus reticulate* and (B) lemon/*Citrus limon* during storage in winter

Changes in total soluble sugar content (°Brix)

During storage, all samples showed a gradual increase in total soluble content. Figures 14A–E show changes in total soluble sugar content for various citrus fruits during the summer and winter. The higher amount of sugar gain was observed in the mandarin orange in the ambient storage (from 9.0 to 11.5), whereas in the ECSS the increase of sugar content ranged from 9.0 to 10.5. The sugar content got almost doubled (1.8–3.5) for lemon in the ambient storage during the winter. In the same case, the ECSS showed an increase in sugar from 1.8 to 2.6. However, the difference of final sugar content between the ambient storage and ECSS for pomelo, kagzi lebu, and jara lebu was not significant (P > 0.05). This change of sugar content for all varieties during storage may have been related to the persistent consumption of sugars and organic acids for lime tissue metabolism, rather than the solute concentration effects, during long-term storage. Ambient storage lime showed a significant difference in soluble sugar contents even in the initial stages which is similar to Marikar and Wijerathnam (2010).

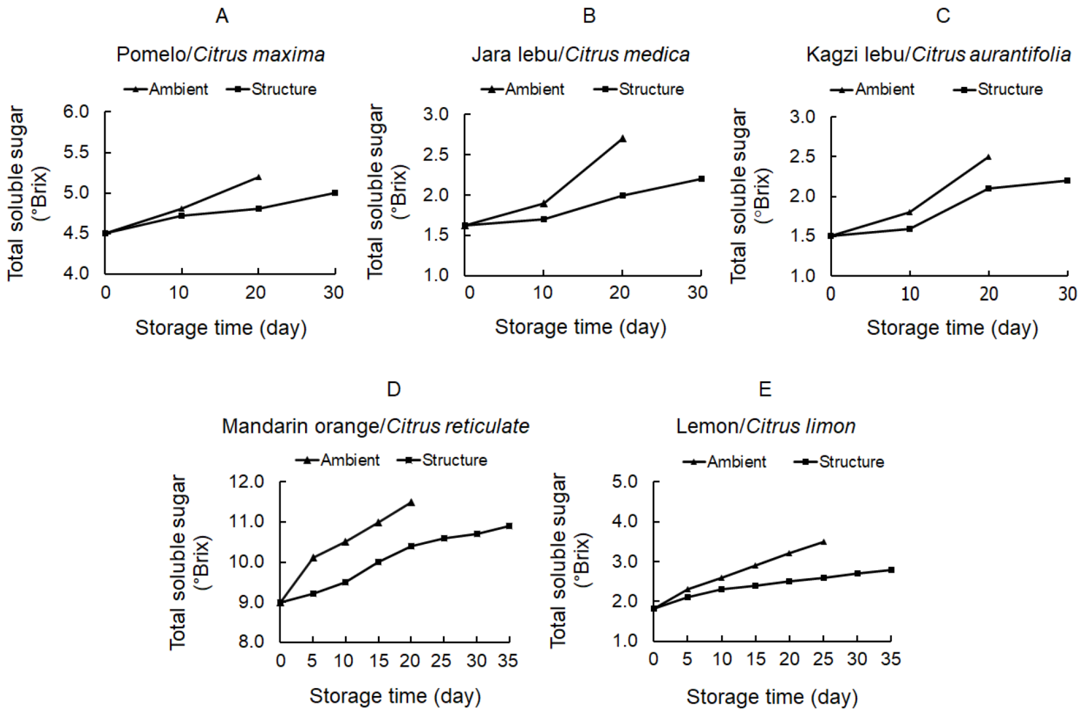

Figure 14 Graphical representation of total soluble sugar (°Brix) variation of (A) pomelo/*Citrus maxima,* (B) jara lebu/*Citrus medica* and (C) kagzi lebu/*Citrus aurantifolia* during storage in summer, and (D) mandarin orange/*Citrus reticulate* and (E) lemon/*Citrus limon* during storage in winter

Changes in citric acid content

A graphical representation of citric acid content in the different citrus fruits such as pomelo (*Citrus maxima*), kagzi lebu (*Citrus aurantifolia*), jara lebu (*Citrus medica*), mandarin orange, and citrus lemon was provided in Figures 15A–C and Figures 16A–B. They showed the comparison between ambient data and the structure data that was experimented in the summer. According to the laboratory test result in the ambient and ECSS, the final citric acid content of the aforementioned varieties was 1.5, 5.0, 2.4, 2.1, 2.3, and 1.8, 5.9, 2.7, 2.3, 3.5 mL/100mL, respectively. There were no significant differences (P > 0.05) in the decreasing rate of citric acid between ambient storage and ECSS.

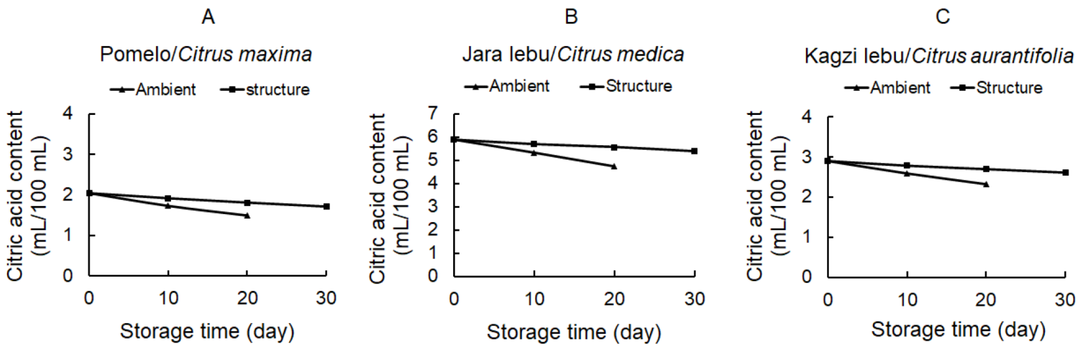

Figure 15 Graphical representation of citric acid content variation of (A) pomelo/*Citrus maxima,* (B) jara lebu/*Citrus medica*, and (C) kagzi lebu/*Citrus aurantifolia* during storage in summer

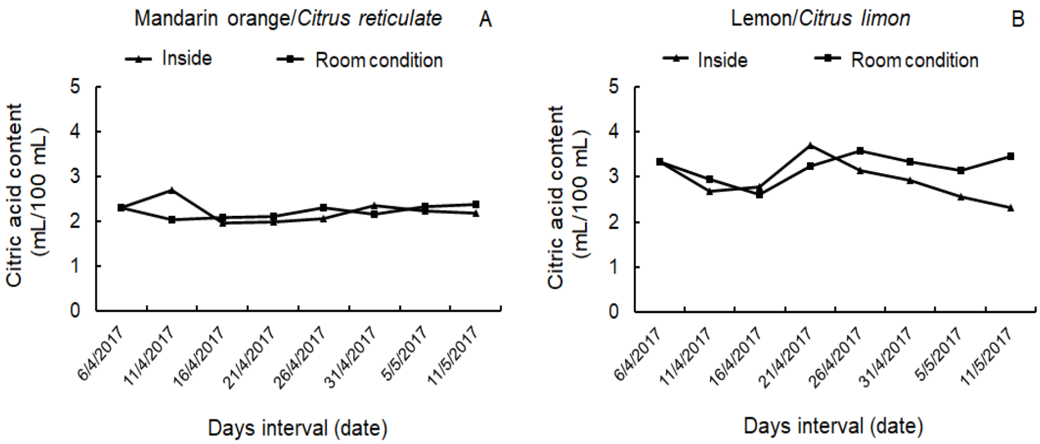

Figure 16 Changes in citric acid content of (A) mandarin orange/*Citrus reticulate* and (B) lemon/*Citrus limon* in evaporation cooling storage structure and ambient temperature during storage in winter

Changes in vitamin C content

The variation of ascorbic acid in the fruits was slightly substantial and it was observed in the different stages of the storage period. The amount of ascorbic acid was found to be decreased more in the ambient storage as compared to the storage structure shown in Figure 17A and Figure 17B, respectively. The vitamin C content of mandarin orange reduced from 59.6 to 38.0 mg/100 mg in ECSS and from 59.6 to 33.0 mg/100 mg at room temperature. The percentage of vitamin C lost in the ECSS and at room temperature did not differ significantly.

Changes in percentage of juice content

The change in percentage of juice content was significant at the ambient storage as well as in the cool chamber storage. Decreasing rate of juice content of limes at ambient storage is shown in Figures 18A–B. The juice content decreased much more in room conditions (from 46.0 to 14.5%) than the ECSS (from 46.0 to 26.0%) in case of mandarin orange. In lemon, the results showed the same type of significant ($P < 0.05$) outcome for room and ECSS.

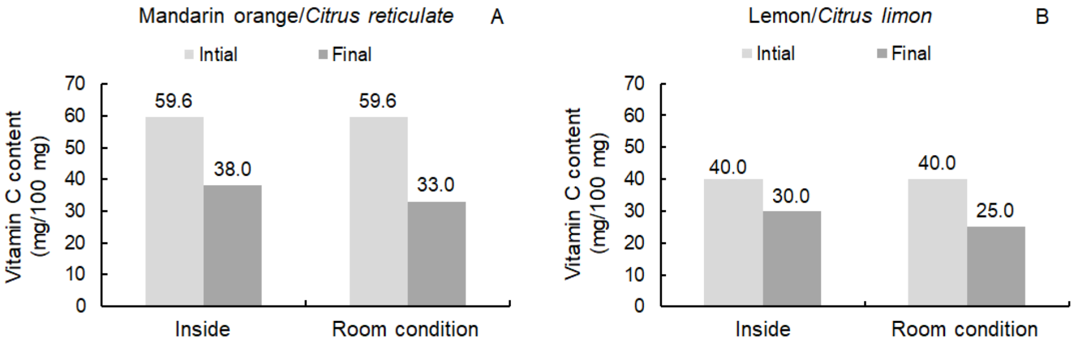

Figure 17 Changes in vitamin C content of (A) mandarin orange/*Citrus reticulate* and (B) lemon/*Citrus limon* in evaporation cooling storage structure and ambient temperature during storage

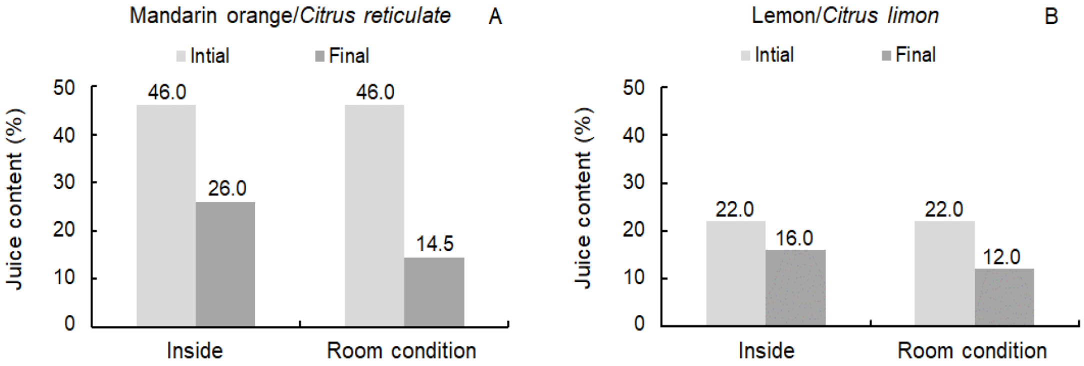

Figure 18 Changes in juice content (%) of (A) mandarin orange (*Citrus reticulate*) and (B) lemon (*Citrus limon*) in evaporation cooling storage structure and ambient temperature during storage

Increase of Shelf Life of Citrus

The ECSS increased the shelf life of citrus from 20–35 days. Table 2 illustrates the shelf life of different citrus by ECSS. Inside the ECSS, citrus shelf life increased 20–35 days which is comparable to Ladaniya (2015).

Table 2 Shelf life of different citrus inside the low-cost evaporative cooling storage structure (ECSS)

Citrus name	Shelf life (days)		Marketability (days)	Increase in days
	Ambient condition	ECSS		
Pomelo (*C. maxima*)	8–10	28	28	20
Jara lebu (*C. medica)*	10–15	44	44	34
Kagzi lebu (*C. aurantifolia)*	10–15	44	44	34
Mandarin orange (*C. reticulate)*	4–5	35	30	25
Pati lebu (*C. limon)*	10	45	45	35

Economic Return of Modified Evaporative Cooling Storage Structure

A cost analysis of the evaporative cooling storage structure was assessed. Most people are surprised by the economics of evaporative cooling storage structures. In general, it has lower upfront costs than refrigerated systems. An analysis was carried out to observe the economic feasibility of the evaporative cooling storage structure for the storage of citrus fruits. Two types of storage structures, one made with brick-sand-brick walls and the other refrigeration were considered for the analysis. It was discovered that the cost of storage in the evaporative cooling storage structure (30 kg capacity) was excessively low because there was no need for electricity to conduct the storage fruits. The initial cost of ECSS is given in Figure 19. The initial cost and variable cost of ECSS was Tk. 8,060 whereas the refrigerator of the same capacity was Tk. 36,072. As only water was supplied to keep fresh the fruits inside the structure it has no operational cost, but a continuous supply of electricity was required to keep the fruits fresh in a refrigerator which is highly expensive about Tk. 9,072 annually. Compared to mechanical refrigeration, the operating cost of heat evaporative exchanging are 90% less than air conditioning (Lal Basediya *et al*., 2013). This system can be used for pre-cooling and has less operational cost (Islam and Morimoto, 2015). So, this structure saved this amount of money as a benefit of ECSS. Farmers on-farm storage can save the loss of spoilage of fruits. Therefore, the economic return of ECSS for storing citrus for about 35 days is Tk. 60,000. Due to the above reason, the storage of citrus fruits through an evaporative cooling storage structure is most economical and more efficient than the conventional refrigeration system.

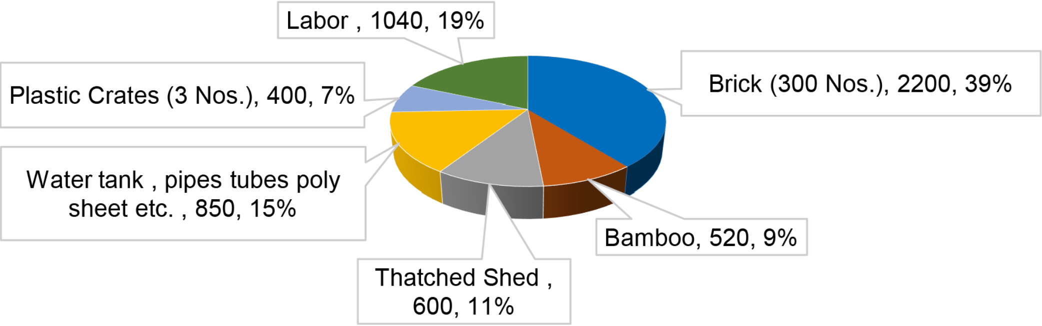

Figure 19 Initial cost of the low-cost evaporative cooling storage structure

CONCLUSIONS

According to the findings of this study, at the no-load test of ECSS, the average variation in temperature was reduced to 5–6°C, while relative humidity was increased to 10–15% inside the structure during the summer. In addition, the ECSS cooler reduced its temperature from 10–11°C to the ambient condition during the winter. As the air is dry in winter, more cooling occurs due to an increase of average relative humidity of 20–23%. At the load test of ECSS, the average temperature was reduced to 10–11°C and relative humidity was increased to 16–17% during the winter compared to the ambient conditions. The maximum variation in the morning was 11.35°C, which was slightly increased to noon at 11.7°C. Hence, the maximum difference between the ambient and structure temperature was 4°C. In terms of weight loss, ECSS can control 10–22% weight loss in the summer for citrus and about 9–21% weight loss in the winter. Inside the storage structure, the nutritional values were satisfactory.

The shelf life of pomelo (*C. maxima*) was increased to 20 days. In this circumstance, the shelf life of jara lebu (*Citrus medica)*, kagzi lebu (*Citrus aurantifolia)*, and pati lebu (*Citrus limon)* was extended to 35 days on average. However, mandarin orange (*Citrus reticulate)* showed 25 days increase in shelf life. The calculated cooling capacity of the ECSS was varied from 1,176–3,461 W and the cooling efficiency was varied from 55–97%. When compared to a refrigeration system, the economic return on ECSS is higher. As a result, ECSS is a profitable on-farm storage system that can ensure an economic return to farmers while also being environmentally friendly.

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