Progress and development in brick wall cooler storage system

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ABSTRACT

This paper carried out a review study into the brick wall cooler storage system (zero energy storage) in terms of its originality, current status, research and implementation achievement, benefit and possible barriers. The continuous progress in technology innovation, heat and mass exchanger of the brick wall cooler storage system now varied from sand-zeolite mixture, volcanic plate made wall, natural ventilation for releasing excess inside relative humidity, optimization of watering operation to save water and successful integration of the solar-driven adsorption cooling system with brick wall cooler storage system enhanced the cooling performance over those the decade ago by increasing the shelf-life of the stored fruit and vegetables. This review work indicated that the brick wall cooler storage system has potential to be an alternative to conventional electric powered expensive cooling storage for fruit and vegetables in the rural areas of the developing world. Future success on the dissemination of brick wall cooler storage system towards farmer's community may imply on more study on newer type of low cost heat exchanger material; further study on its economic, environment and social impacts; low cost postharvest treatment and packaging for brick wall cooler storage system; extensive farmers awareness and other dissemination measures; and public awareness and other dissemination measures.

Keywords: brick wall cooler storage system, evaporating medium, postharvest loss, shelf-life, solar adsorption, fruit and vegetables

Nomenclatures	Greek symbols
<p>q weight of vapor transmitted through a unit area in unit time</p> <p>P vapor pressure, KPa</p> <p>x distance along the flow path, mm</p> <p>W total weight of vapor transmitted, g</p> <p>A area of cross-section of flow path m^2</p> <p>ΔP partial pressure difference between ends flow path, KPa</p> <p>L thickness of the evaporative medium, m</p> <p>M permeance in $g \cdot hr^{-1} \cdot m^{-2}$ per vapor difference in KPa</p> <p>M_a mass of moist air, Kg</p> <p>V_a velocity of air, $m \cdot s^{-1}$</p> <p>W_o humidity ratio of the air, Kg of water $\cdot$ Kg of dry air^{-1}</p> <p>P_A effective evaporative medium surface area (m^2) expressed as $P_A = A_T \cdot P_E$</p> <p>A_T total evaporative medium surface area, m^2</p> <p>P_E evaporative medium efficiency (considered as the porosity of the material)</p> <p>P_s porosity of the evaporative medium, in decimal</p> <p>h_a enthalpy of moist air, $KJ \cdot Kg^{-1}$</p> <p>T_o outside air temperature, $^{\circ}C$</p> <p>C_v specific heat capacity of water vapor, $KJ \cdot Kg^{-1} \cdot ^{\circ}C$</p> <p>$h_c$ changes in enthalpy of the air with the respect to the change in evaporative medium thickness dP_T</p> <p>$\frac{dT}{dP_T}$ change in the temperature of the air passing through the evaporative medium thickness dP_T</p> <p>Q rate of heat transfer from the air the evaporative medium, $KJ \cdot s^{-1}$</p> <p>h' is the convective heat transfer coefficient, $Kj \cdot m^{-2} \cdot ^{\circ}C^{-1}$</p> <p>$T_s$ temperature of the air passing through the evaporative medium, $^{\circ}C$</p> <p>C_a specific heat capacity of the air, $KJ \cdot kg^{-1} \cdot ^{\circ}C^{-1}$</p> <p>$M_T$ mass of water evaporated by the air from the evaporated medium, $Kg \cdot s^{-1}$</p> <p>h_D mass transfer coefficient, $m \cdot s^{-1}$</p> <p>H_o concentration of water vapor in the outside free stream, $Kg \cdot m^{-3}$</p> <p>H_p concentration of water vapor in the boundary layer of the evaporative medium, $Kg \cdot m^{-3}$</p> <p>P_{vs} saturation vapor pressure at the wet-bulb temperature, $kg \cdot m^{-2}$</p> <p>P_{va} partial vapor pressure of the water vapor in the unsaturated air stream, $kg \cdot m^{-2}$</p>	<p>μ average permeability of material, $g \cdot mole \cdot m^{-2} \cdot hr^{-1} \cdot Kpa^{-1}$</p> <p>$\Theta$ time of transmission, hr</p> <p>ρ_a density of air, $Kg \cdot m^{-3}$</p>

<p>M_w molecular weight of water</p> <p>R_o universal gas constant, $8315 \text{ kJ} \cdot \text{kg}^{-1} \cdot ^\circ\text{K}^{-1} \text{ mole}$</p> <p>$T_{abs}$ absolute temperature, calculated as the average temperature between the dry bulb and wet bulb, $^\circ\text{K}$</p> <p>Q_w heat required to evaporate the water from the evaporation medium, kJ</p> <p>h_{fg} heat of vaporization, $\text{kJ} \cdot \text{kg}^{-1}$</p> <p>$T_{l(db)}$ dry-bulb of the ambient temperature, $^\circ\text{C}$</p> <p>$T_{2(db)}$ dry-bulb temperature of air inside the evaporative medium, $^\circ\text{C}$</p> <p>$T_{l(wb)}$ wet-bulb temperature of the ambient temperature, $^\circ\text{C}$</p> <p>Q_r respiration heat load of the stored fruit and vegetables, $\text{W} \cdot \text{hr}^{-1}$</p> <p>$M_p$ mass of fruit and vegetables, kg</p> <p>P_{re} rate of respiration heat production, $\text{W} \cdot \text{kg}^{-1} \cdot \text{hr}^{-1}$</p> <p>$Q_f$ field heat picked up by fruit and vegetables, W</p> <p>M_p mass of fruit and vegetables, kg</p> <p>C_p specific heat capacity, $\text{kJ} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}^{-1}$</p> <p>$t_c$ cooling time (seconds) for fruit, hr</p> <p>ΔT change in temperature, $^\circ\text{C}$</p> <p>Q_L heat transfer through cracks and opening of the storage cover, W</p> <p>Q_{A-B} heat supplied to heat activated carbon and methanol from point A to point B, $^\circ\text{C}$</p> <p>C_{ac} and C_r heat capacities of activated carbon and methanol</p> <p>M_{ac} and M_{rA} masses of activated carbon and methanol adsorbed ($M_{rA} = x_A \cdot M_{ac}$), Kg</p> <p>T_{con} and T_{gen} temperature of activated carbon and methanol-activated carbon temperature at points A and B, $^\circ\text{C}$</p> <p>Q_{B-C} heat supplied to heat activated carbon and methanol, leading to desorption, $^\circ\text{C}$</p> <p>$\overline{M}_r$ average mass of methanol, which can be calculated approximately using $\overline{M}_r = \frac{(\overline{M}_{rB} + \overline{M}_{rC})}{2}$</p> <p>$T_{gen}$ and T_{max} temperature of points B and C, $^\circ\text{C}$</p> <p>Δx concentrated variation that is calculated by $\Delta x = x_B - x_C$</p> <p>H_d desorption heat constant for a given pair, $\text{kJ} \cdot \text{Kg}^{-1}$</p> <p>$Q_{C-D}$ heat removed from the activated carbon and methanol by an external cooling source, $^\circ\text{C}$</p> <p>T_{max} and T_{ads} activated carbon temperature at points C and D, $^\circ\text{C}$</p>	
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Q_r cooling output, KJ L_o latent vaporization of methanol (treated as a constant in ideal case analysis), $\text{KJ} \cdot \text{Kg}^{-1}$ ΔM_r mass of liquid methanol that equates to $(M_{rB} - M_{rC})$ T_{con} and T_{ev} condensing and evaporating temperature, $^{\circ}\text{C}$ COP_s issolar coefficient of performance I total amount of heat input absorbed by the solar collector, MJ M_{ice} total amount of ice production, $\text{Kg} \cdot \text{cycle}^{-1}$ C_{pw} specific heat of water, $\text{KJ} \cdot \text{Kg}^{-1}$ L_{fus} , latent heat of ice fusion, $\text{KJ} \cdot \text{Kg}^{-1}$ C_{ice} specific heat of ice respectively, $\text{KJ} \cdot \text{Kg}^{-1} \cdot \text{K}^{-1}$	
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Contents

1. Introduction
2. A brief history
 - 2.1 State of the art – before 2000
 - 2.2 State of the art – after 2000
3. The evaporative cooling process
4. Development and evaluation of a brick wall cooler storage system with new postharvest treatment of fruit and vegetables
- 5, Dynamic optimization of inside temperature of brick wall cooler storage system for storing fruits and vegetables using neural networks and genetic algorithms
6. Design and development of a brick wall cooler storage system with a solar-driven adsorption refrigerator
7. Challenges Issues towards dissemination of brick wall cooler storage system
8. Conclusion
 - Acknowledgement
 - References

1. Introduction

Recent world energy consumption pattern showed that the inadequacy of fossil fuel and the increase demand of energy for industrial sector are the future energy security concerning issue around the world. As forecasted by International Energy Agency [1], the reserve of coal, oil and natural gas will be exhausted by 122, 42 and 60 years, respectively. Fruit and Vegetables grown in developing world are highly perishable in nature but rich in vitamins and minerals such as carotene, ascorbic acid, riboflavin, iron, iodine, calcium, etc [2]. However a report published by Gustavsson et al. [3], postharvest loss of 24% fruit and vegetables are caused by the lack of storage facility both in developed and developing countries. Deficiency of nutrients caused up to 2.7 million deaths worldwide and 1.8 percent of the total global disease which is directly related to inadequate consumption or availability of fruit and vegetables [4]. Main factors responsible for postharvest loss of fresh fruit and vegetables are environmental conditions (temperature, relative humidity, gaseous atmosphere); mechanical damage; spoilage by fungi, bacteria, insects, and other organisms, and physiological deterioration [5,6].

In developing countries, most agricultural areas do not have a grid electricity supply or electric-powered refrigeration systems to maintain the storage temperature constant at low level for fruit and vegetables. Even most farmers do not have the financial capability to purchase, maintain, and operate expensive cooling systems. This lack of refrigeration system causes decaying of the large quantities of fruit or vegetables. As a result, sharp differences in food supplies between the harvest and off harvest periods was observed in the affected areas. Therefore, prices of agricultural products are highest during the off-season and cheapest during the harvest season.

In this context some methods of preservation fruit and vegetables alternative to electric powered expensive refrigeration system like storage in ventilated shed, use of zero energy storage based on evaporative coolant system, waxing and hot water treatment has been found to be an efficient and economical means of reducing postharvest storage loss worldwide [7–12]. According to Dzivama [13], shelf life of fruit and vegetables are enhanced by minimizing deteriorative reactions and availability for longer periods would reduce fluctuation in market supply and prices.

The passive evaporative zero energy storage without using electricity is a low cost, rural area oriented on-farm simple storage system, and found very effective for increasing the shelf life of stored fruit [14–16]. Additionally, the cooling process of such storage is mainly depends on solar radiation, watering condition, ambient temperature and loading condition of stored fruit. The paper presents a short overview of the technological development of state-of-the-art of ecofriendly zero energy storage for storing fruit and vegetables in developing countries. The limitations and challenging issues towards implementation and dissemination of this technology is also discussed.

2. A brief history

The concept of using water for cooling air by evaporation gained popularity since ancient time. Evaporative cooling is a physical phenomenon in which evaporation of a liquid, typically into surrounding air, cools an object or a liquid in contact with it. The first known history of cooling food item was water in Egypt, in which Egyptian frescoes portraying large, porous jars of water being manually fanned to force evaporation and subsequent cooling have achieved [17]. Since then different complex evaporative cooling mechanisms and machines have been invented without changing any basic concept of evaporative cooling. An earlier example of tower cooled air cooling system

is invented in ancient Iran thousands years ago, which trapped the air at first and then passed over the water surface to reduce the air temperature. Later in 1800, the New England textiles factory began to use such evaporative cooling systems to cool their mills [18].

2.1 State of the art – before 2000

In developing world the much of postharvest loss of fruit and vegetables occur due to the lack of proper storage facilities. Increasing interest in low cost on farm level storage technology to extend the shelf life of fresh fruit and vegetables for increasing its marketability and availability throughout a year caused the development of different simple and low-cost storage system alternative to the electric powered expensive and complex storage system.

Roy and Khardi [19] built a simple cooling system with a storage capacity of 100kg developed by the Indian Agricultural Research Institute. The floor of the storage chamber is built from a single layer of bricks, and then a cavity wall constructed of brick around the outer edge of the floor and a gap of about 76.2 mm between the inner wall and outer wall. This cavity is then filled with sand. A covering for the chamber is made with canes covered in sacking all mounted in a bamboo frame to protect it from sun. After that, the walls, floor, sand in the cavity and cover are thoroughly saturated with water. Once the chamber is completely wet, a twice-daily sprinkling of water maintained 90% of humidity and 10 to 15°C lower temperature than ambient temperature inside storage chamber. Roy and Khardi [19] also proposed a simple automated drip watering system as shown in Figure 1:

Fig. 1. A static cooling system [19]

Roy and Pal [20] investigated performance of cool chambers at different locations of India and found satisfactory results for short term cool chamber storage of mangoes by extending 3 to 4 days more shelf life of mature green mangoes as compared to ambient condition storage. However, ripe mangoes when stored in cool chamber had 9 days shelf life as compared to 6 days under ambient condition and also scored high organoleptic values. Kumar and Nath [21] achieved slow rate of transpiration of highly perishable Aonla (*Emblia officinalis Gaertn*) fruit inside zero energy storage that caused increasing of shelf life upto 12 days than those stored at ambient temperature.

2.2 State of the art – after 2000

Ganesan et al. [14] standardized the quantity of water applied in zero energy storage. In his study, eggplants were stored in zero energy storage and at room temperature. Three different levels of watering operation (100, 75 and 50 liters per day) were added through drip irrigation system to moisten the sand in the cool chamber. The physiological loss in weight and rotting percentage increased at room temperature, but decreased with increasing water level up to 100 litres per day. As a result, the shelf-life of brinjal enhanced to 9 days with the addition of 100 liters of water per day.

Narayana et al. [22] studied quality of banana packed with low-density polyethylene bag with or without ventilation under different storage conditions, namely, ambient temperature, zero energy cool chamber (brick-sand evaporative cooler) and 13.5°C low temperature. Shelf-life of the fruit was highest at 13.5°C and minimum under ambient conditions in both vented and unvented polybags. Non-significant variation was observed for total soluble solids of fruit under all 3 storage conditions. The acidity increased gradually up to the end of green life and then either decreased (in unvented polybags) or remained unchanged (in ventilated polybags and unpacked control) till the end of life (yellow). Reducing sugars and total sugars increased gradually throughout the storage period and was highest in the control fruit and in fruit packed in ventilated polybags. Spoilage was maximum in unvented polybags under ambient and zero energy cool chamber conditions. Storing banana fruit in unvented polybags at low temperature could extend the shelf-life of the fruit up to 19.33 days.

Prabha et al. [23] conducted experiment to find out the changes in ascorbic acid content of lemon fruit stored in zero energy storage and under ambient atmosphere. He first freshly harvested disease free lemon fruit washed in plain and 100 ppm chlorinated water. The fruit from each lot were packaged in the 100 and 150 gauge thick polymeric film bags of varying ventilations (0.00, 0.50 and 1.00%). Unpacked fruit from each lot were kept as control. The treated fruit were stored in zero energy storage and under ambient conditions and then studied for changes in ascorbic acid contents after an interval of 15 days for storage duration of 45 days. Ascorbic acid contents in the stored fruit decreased in all the samples with the enhancement of storage duration but it decreased to a lesser extent in fruit treated in chlorine water and stored in zero energy storage. In the water washed fruit the minimum ascorbic acid (33.41 mg/100ml) was

recorded in the non-packaged fruit stored under ambient conditions, whereas the maximum ascorbic acid 41.49 mg/100ml was recorded in packaged of 150 gauge polyethylene film with 0.50% ventilation stored in zero energy storage. Thus zero energy storage was found to be very effective in relation to the retention of ascorbic acid during storage.

Dhumaland Karale [24] conducted an experiment with fully matured fruit of aonla (*Emblica officinalis Gaertn*) coated with wax emulsion and in combination with postharvest chemical and packed in different packaging which were stored in zero energy storage. The cool chamber was found effective in increasing the shelf life of aonla fruit up to 24 days without much deterioration in the physico-chemical parameters. It also retained the maximum marketability of the fruit. The physico-chemical changes were faster in untreated fruit than the chemically treated fruit and in nylon net bag packed fruit than in perforated polyethylene bags and in ventilated corrugated fiber board box packed fruit. 6% waxol + 400 ppm CCC (Cycocel, 2-chloroethyltrimethylammoniumchloride) treated fruit recorded lowest TSS and sugars, high ascorbic acid content at the end of storage period. The perforated polyethylene bags packaging was found to be the best, in retaining high acidity, ascorbic acid content, moisture percentage and low TSS and sugars in aonla fruit. The shelf-life of aonla fruit was extended up to 24 days in cool chamber when fruit were treated with 6% waxol + 400 ppm CCC and packed in perforated Polyethylene bags. This treatment combination recorded higher marketable preference with minimum deterioration of physico-chemical characteristics and can be recommended to extend the shelf-life of aonla fruit. Therefore, the zero energy storage could be a possible solution to the problem of storage of aonla fruit in glut season in India.

Singh et al. [25] mentioned a study carried out on zero energy storage along with post-harvest treatments (CaCl_2 , mustard oil and K_2SO_4) on fruit quality attributes of aonla (*Emblica officinalis Gaertn*) under semi-arid ecosystem of Gujarat. Fruit treated with 1.5% CaCl_2 and stored in zero energy storage recorded least PLW (16%), spoilage loss (16.5%), respiratory activity (83 mg CO_2 /kg/h) and exhibited 11 days of shelf-life, while untreated control had 6 days economic life. It was closely followed by 1% CaCl_2 + zero energy storage treatment. Fruit stored in zero energy storage recorded 9 days shelf-life. Highest respiration rate was in control (88.1 mg CO_2 /kg/h) on 13th day of storage. It may be concluded that 1.5% CaCl_2 and storage in zero energy storage treatment was found most efficient to retain the fruit quality attributes till 13th day of storage under semi-arid environment of western India. Kaushalya Foundation constructed 300 zero energy storage in Bihar, India caused an increasing the income of rural farmers through reduction of wastage upto 12-20% [26].

Cost effective analysis of on-farm storage of jamun fruit (*Syzygiumcumini*) with packaging on storability and fruit quality inside a zero energy cool chamber was done by Lata and Singh [27]. The fruit were examined for physiological loss in weight, spoilage loss, TSS, acidity, ascorbic acid, total sugar and marketable fruit on 1st, 3rd and 5th day of storage. The result revealed that fruit packed in perforated polythene bag and stored in zero energy cool chamber proved to be the best treatment and exhibited 4 days economic shelf-life, while control (under ambient condition) had 1 day economic shelf-life. Increase in physiological loss in weight (PLW), spoilage percentage, total soluble solids, total sugar and reduction in titratable acidity (TA), ascorbic acid with advancement of storage period were general phenomena in all the treatments. Minimum spoilage loss (12.50%) was recorded in perforated polythene bag and stored in zero

energy cool chamber on 5th day of storage. In terms of quality parameters, the same treatment was found to be the best. Percentage of marketable fruit was also found to be the highest (82.50%) on 5th day of storage in perforated polythene bag and stored in zero energy cool chamber, while it was only zero per cent under control (ambient temperature). It may be concluded that zero energy cool chamber along with perforated polythene bag is economically viable on farm storage for jamun fruit and may be followed for the benefits of both farmers and processors.

3. The evaporative cooling process

The working principle of zero energy storage (**Fig.2**) is as follows: when the dry surface of a heat exchanging outside wall is in contact with air, the opposite wet surface of the same heat exchanging wall absorbs heat from the dry side and then transfers it to the evaporative medium. As a result, the water molecules of the wet evaporative medium release this heat to the environment through evaporation, and therefore cool the dry side of the storage chamber. If storage chamber is load with fruit and vegetables, then due to respiration of fruit and vegetables inside storage temperature increased, then by increasing the frequency of watering, it is possible to decrease the storage chamber [28] This method has the advantage of maintaining a lower temperature without adding further moisture to the air. Experimental observations [29] show that under an ideal operating condition, heat flow from the product air (inside zero energy storage chamber) travels in a counter-flow manner to the working air (outside air) and the two airstreams have a good balance of heat flow rates over an contact area of outside wall, evaporative medium and inside wall of the passive evaporative cooler. As a result the product air temperature on the dry side of the inside wall reaches the wet bulb temperature of the incoming working air and the temperature of the working air on the wet-side of the

outside wall increases from its incoming dry bulb temperature to the inside product air dry bulb temperature and becomes saturated.

Fig.2. A schematic diagram of passive evaporative zero energy storage

3.1 Vapor transmission through materials

The rate of water vapor transmission is based on Frick's law [30], which is expressed as:

$$q = \frac{\mu \cdot dP}{dx} \quad (1.1)$$

By integrating Frick's equation (distance $x=0$ to L with time) and rearranging, the following is obtained:

$$q = \frac{W}{A} = \frac{\mu \cdot dP}{dx}$$

$$\therefore W = \mu \cdot A \cdot \theta \cdot \left(\frac{\Delta P}{L}\right) \quad (1.2)$$

For convenience in evaluating materials, μ can be expressed as a coefficient of transmission M , as:

$$\therefore W = M \cdot A \cdot \theta \cdot \Delta P \quad (1.3)$$

Permeance, like conductance is relative to any given materials. Perfectibility, like conductivity relates to the property of a substance and is numerically equal to the permeance for the unit thickness. As in a wall it is the sum of the resistances of the components. The overall permeance of a wall may be found in a way similar to the calculation of the overall coefficient of thermal resistance.

$$\therefore M_{total} = \left(\frac{1}{M_1} + \frac{1}{M_2} + \frac{1}{M_3} + \dots + \frac{1}{M_n} \right)^{-1} \quad (1.4)$$

3.2 Heat and mass balance at evaporative medium end

The heat and mass balance can be derived as follows:

3.2.1 Heat balance for the evaporative medium end

The mass of air is passing through the evaporative medium of volume $P_A P_T$ at any time dt is equals to:

$$M_a = (\rho_a \cdot V_a + \rho_a \cdot V_a \cdot W_o) \cdot P_A \cdot P_s dt \quad (1.5)$$

Where $P_A = A_T \cdot P_E$ [31];

dt is the time (s) takes for the air to pass through the evaporative medium thickness, expressed as $\frac{P_T}{V_a}$. The enthalpy of the air flowing through the evaporative medium at any time dt is equal to:

$$h_a = \frac{(\rho_a \cdot V_a + \rho_a \cdot V_a \cdot W_o \cdot C_v) \cdot T_o \cdot P_A \cdot P_s \cdot P_T}{V_A} \quad (1.6)$$

The change in the enthalpy of the air as it passes through the evaporative medium thickness due to the evaporative medium porosity in time dt , is equal to:

$$h_c = (\rho_a \cdot V_a + \rho_a \cdot V_a \cdot W_o \cdot C_v) \cdot \left(\frac{dT}{dT_T} \right) \cdot \left(\frac{P_A \cdot P_s \cdot P_T}{V_A} \right) \quad (1.7)$$

The change in the enthalpy of the air per unit evaporative medium thickness is due to the convective heat transfer from the air to the evaporative medium, required for the evaporation of the water from the evaporative medium .This can be represented by the

Newton's law of cooling in time dt , as :

$$Q = \frac{h^1(T_o - T_s) \cdot P_A \cdot P_s \cdot P_T}{T_A} \quad (1.8)$$

This change in the sensible heat is equal to the change in the enthalpy of the air after passing through the evaporative medium, therefore equating equations:

$$\frac{dP}{dP_T} = \frac{h^1(T_o - T_s)}{(\rho_a \cdot V_a \cdot C_a + \rho_a \cdot V_a \cdot w_o \cdot C_v)} \quad (1.9)$$

3.2.2 Mass balance for evaporative medium:

The mass transfer from the evaporative medium of a unit thickness, m , to the air, is due to the concentration difference or partial vapor pressure difference between the free air streams and the boundary layer of the evaporative medium. The rate of evaporation could be expressed as:

$$M_T = \frac{h_D \cdot \rho_a \cdot V_a \cdot (H_P - H_o) \cdot P_A \cdot P_s \cdot P_T}{V_A} = \frac{(h_D \cdot \rho_a \cdot V_a \cdot M_w)}{(R_o \cdot T_{abs})} \cdot \frac{(P_{vs} - P_{va}) \cdot P_A \cdot P_s \cdot P_T}{V_A} \quad (1.10)$$

3.3 The heat required to evaporate the water from the evaporating medium is dt is equal to:

$$Q_w = M_T \cdot h_{fg} = \frac{h_{fg} \cdot h_D \cdot M_w \cdot \rho_a \cdot V_a}{(R_o \cdot T_{abs})} \cdot \frac{(P_{vs} - P_{va}) \cdot P_A \cdot P_s \cdot P_T}{V_A} \quad (1.11)$$

Where $(h_{fg} = 2.503 \cdot 10^6 - 2.38 \cdot 10^3 | (T_{abs} - 273.16))$ for temperature equals to $273.16 < 338.723$ [20]

$(h_{fg} = 2.503 \cdot 10^6 - 2.38 \cdot 10^3 | (T_{abs} - 273.16))$ for temperature equals to $273.16 < 338.723$ [20];

At equilibrium, the total change in enthalpy of the air is equal to the heat required for the evaporation of the water from the evaporating medium, thus equating from equation 1.9 and 1.11 as:

$$\frac{h^1 \cdot (T_o - T_s)}{(\rho_a \cdot V_a \cdot C_a + \rho_a \cdot V_a \cdot w_o \cdot C_v)} = \frac{(h_{fg} \cdot h_D \cdot M_w \cdot \rho_a \cdot V_a)}{(R_o \cdot T_{abs})} \cdot \frac{(P_{vs} - P_{va}) \cdot P_P \cdot P_s \cdot P_T}{V_A} \quad (1.12)$$

We have,

$$T_s = T_o - \frac{(h_{fg} \cdot M_w (P_{vs} - P_{va}))}{R_o \cdot T_{abs} \cdot \rho_a \cdot C_a \cdot \left(\frac{Sc}{Pr}\right)^{\frac{2}{3}}} \rho_a^2 \cdot V_a^2 \cdot (C_a + W_o \cdot C_v) \cdot \frac{P_P \cdot P_s \cdot P_T}{V_A} \quad (1.13)$$

Where, the ratio of the convective heat transfer to that of the mass $\frac{h^1}{h_D} = \rho_a \cdot C_a \cdot \left(\frac{Sc}{Pr}\right)^{\frac{2}{3}}$ transfer coefficient; Sc is Schmidt number, defined as the ratio of momentum diffusivity (viscosity) and mass diffusivity, and is used to characterize fluid flows in which there are simultaneous momentum and mass diffusion convection processes; and Pr is Prandtl number, defined as the ratio of momentum diffusivity to thermal diffusivity.

The relative humidity passing through the evaporative medium could be predicted by representing the evaporative cooling on a psychometric chart (**Fig.3**); after calculating the temperature T_s . When the air passes through the evaporating medium, it is cooled adiabatically and it follows along with the wet- bulb temperature line on the psychometric chart. Effectiveness of indirect evaporative cooling is shown in equation 1.14.

Fig.3. A psychometric chart

Effectiveness of indirect evaporative cooling is:

$$\epsilon = \frac{T_{1(db)} - T_{2(db)}}{T_{1(db)} - T_{1(wb)}} \cdot 100 \quad (1.14)$$

3.4 Respiration heat load distribution inside the zero energy storage

Respiration heat load of the stored fruit and vegetables were calculated using the following equation [32]:

$$Q_r = M_p \times P_{re} \quad (1.15)$$

3.5 Heat accumulated by harvested fruit and vegetables

Heat accumulated by harvested fruit and vegetables from outside environment was calculated using Rastavoski's equation [33]:

$$Q_f = (M_p \cdot C_p) \frac{\Delta T}{t_c} \quad (1.16)$$

3.6 Infiltration of Air

The heat was estimated from 10 to 20% of the total heat load [33, 34]. Thus taking an average of 15%, infiltration was calculated as:

$$Q_L = \frac{(Q_c + Q_f + Q_r) \times 15}{100} \quad (1.17)$$

4. Development and evaluation of a brick wall cooler storage system with new postharvest treatment for stored fruit and vegetables

Islam and Morimoto [12] has been developed a brick wall cooler storage system consisting of a brick wall cooler and a combination of silver-ion coated container with antibacterial properties and hot water treatment techniques to prevent decay of stored fruit by the microbial activities. The brick wall cooler made of bricks with a mixture of moistened sand and zeolite allows low inside temperature and high relative humidity to be maintained based on the principles of a natural evaporative cooling mechanism.

4.1 Structure of the brick wall cooler storage system

Figure 4 shows the complete randomized block design of the brick wall cooler storage system. The dimensions of the outer and inner brick walls were $1510\text{ (L)} \times 1510\text{ (W)} \times 500\text{ (H)}$ mm and $1180\text{ (L)} \times 1180\text{ (W)} \times 500\text{ (H)}$ mm, respectively. The 75 mm gap left between the outer and inner wall was filled with a mixture of sand (60%) and zeolite (40%). Tap water was supplied to the sand area through drip irrigation using an electric valve. The cool chamber's storage area was $100\text{ (L)} \times 100\text{ (W)} \times 50\text{ cm (H)}$ in size. A shading curtain with dimensions of $2000\text{ (L)} \times 1500\text{ (W)}$ mm and capable of blocking out 60% of solar radiation was used.

Fig.4. A pictorial (top) and cross-sectional view (bottom) of the brick wall cooler storage system [12].

4.2. Storage container and post-harvest treatment

Two commercially available Passe Tight TW-100 silver ion coated containers measuring 356 (L) $\times$ 250 (W) $\times$ 165 (H) mm were used for the experiments. Hot water treated tomatoes and eggplants were stored inside each silver-ion-coated container in a process repeated three times. For comparison tomato and eggplant placed in a copper container and then buried with copper grains (1 mm $\varnothing$ $\times$ 0.5 mm). Two fully perforated crates measuring 45 (L) $\times$ 350 (W) $\times$ 250 (H) mm in size and made from fine grade high density polyethylene were used to store untreated eggplant and tomato.

4.3 Performance of the brick wall cooler storage system

The fundamental performance relative to temperature and relative humidity inside the brick wall cooler storage system was first investigated from the standpoints of both dynamic and static characteristics. **Figure 5** shows the typical diurnal changes in solar radiation, as well as the outside temperature, inside temperature, and inside relative humidity of the brick wall cooler storage system under no load, shading, and watering conditions. Solar radiation increased the outside temperature around the brick wall cooler storage system. An increase in outside temperature also increased the inside temperature of the brick wall cooler storage system. The shading curtain, however, protects the brick wall cooler storage system against direct exposure to solar radiation. For instance, under shading and watering conditions, the maximum values of the outside and inside brick wall cooler storage system temperatures were 35.4°C and 16.5°C, respectively. Conversely, the minimum values of the inside and outside brick wall cooler storage system temperatures were 9.6°C and 15°C, respectively. Under

shading and watering conditions, the average value of relative humidity was recorded at 90.6% inside the brick wall cooler storage system, but maximum relative humidity of 98.6% was achieved under the highest outside temperature. This is because a higher outside temperature increases the evaporation rate from the sand and wet bricks of the brick wall cooler storage system.

Fig.5. Fundamental performance of the brick wall cooler storage system [12].

Figure 6 shows the typical diurnal changes in inside temperature of the brick wall cooler storage system under watering, no watering, shading and no shading curtain conditions. The highest temperature (34.6°C) and lowest temperature (9.6°C) of the brick wall cooler storage system were recorded under no watering without the shading curtain and under watering with the shading curtain, respectively. Average inside temperatures of 12.7°C, 21.4°C, 23.8°C, and 26.8°C were recorded in the brick wall cooler storage system under watering with shading, watering without shading, no watering with shading, and no watering without shading, respectively. The inside temperature was thus found to be significantly affected by the shading curtain, outside

temperature, and watering. Therefore, the combined use of watering and the shading curtain was found to provide the lowest inside temperature of the brick wall cooler storage system. This is probably due to the effects of the evaporative cooling mechanism by water and the reduction of solar radiation by the shading curtain. Here, the outside temperature around the brick wall cooler storage system and the vapor pressure of the moist sand-zeolite mixture and surrounding air attempt to equalize. Liquid water molecules of the moist sand-zeolite mixture gasify under the influence of outside air through a process that uses energy to change the physical state. Heat transitions from the higher temperature of the air and brick walls to the lower temperature of water, due to convection and conduction. During this conversion process, there is a drop in ambient temperature. This cooling temperature caused by the effect of evaporation cools down the inside temperature of the brick wall cooler storage system below the dry-bulb temperature. This is the result of the combined effects of underground temperature, the moist inside walls, and watering. Consequently, the inside air temperature of the brick wall cooler storage system became cooler.

On the other hand, the shading curtain blocked 60% of the sun's infrared rays, thereby lowering both the temperature inside the brick wall cooler storage system and that surrounding it. Watering was also found to maintain a low inside temperature of the brick wall cooler storage system for a longer time. Under the shading condition, watering lowered the brick wall cooler storage system temperature for a longer duration, while under the no shading condition, watering slightly lowered the inside temperature of the brick wall cooler storage system for a shorter duration. This is because under the no shading condition, solar radiation directly striking the surface of the brick wall cooler storage system increased the inside temperature of the cool chamber. Under the

no shading condition, the maximum relative humidity and minimum temperature inside the brick wall cooler storage system were 68% and 19°C, respectively.

Fig.6. Diurnal changes in inside temperature of the brick wall cooler storage system [12].

Figure 7 shows the typical diurnal changes in the inside temperature and relative humidity of the brick wall cooler storage system, as affected by watering operation under no shading. Here, watering was performed four times. The responses of both inside temperature and relative humidity to the watering showed dynamic changes where a significant decrease in inside temperature and a marked increase in relative humidity were observed at watering. Therefore, the inside temperature and relative humidity can be modeled and controlled by the watering operation.

Fig. 7. Dynamic responses of inside temperature (a) and relative humidity (b) as affected by watering (c)

Figure 8 shows the daily changes in inside temperature and relative humidity of the brick wall cooler storage system over seven days [12]. **Figure 8**, (a) and (b) show daily average values of temperature and relative humidity at 13.8°C and 91.7%, respectively, under the shading curtain condition inside the cool chamber with watering, and at 25.4°C and 64.1%, respectively, without watering. The daily average values of temperature and relative humidity under the no shading condition inside the cool chamber were 27.8°C and 65.9%, respectively, with watering, and 29.4°C and 64.1% without watering. Outside average temperature of 30.2°C and relative humidity of 63.7% were recorded. From this experiment, we can see that the shading curtain can reduce the inside temperature of the brick wall cooler storage system, although its relative humidity remained virtually the same under both shading and no shading conditions.

Fig.8. Daily changes in the inside temperature and relative humidity of the brick wall cooler storage system [12].

4.4 Physiological loss in weight of stored fruit and vegetables inside the brick wall cooler storage system

Next, the physiological loss in the weight of tomatoes and eggplants stored in silver-ion-coated containers and placed in the brick wall cooler storage system after applying hot water treatment was investigated. In **Figure 9**, (a) and (b) show daily changes in PLW. In the experiment, significant differences were found in PLW (in percent) of tomato and eggplant stored in the brick wall cooler (at average temperature of 15°C) and at room temperature (average of 25°C). The brick wall cooler storage system reduced the percentage of PLW of tomato and eggplant in contrast to those stored outside the brick wall cooler storage system. Tomato stored outside the brick wall cooler storage system showed PLW of 5.4% after seven days, while tomato stored

inside the brick wall cooler storage system showed 5.35% after 16 days. Eggplant stored outside the brick wall cooler storage system showed PLW of 5.98% after four days, while eggplant stored inside the brick wall cooler storage system showed 5.01% after nine days. Thus, tomato and eggplant stored inside the brick wall cooler storage system showed lower PLW than those stored outside the brick wall cooler storage system.

In **Figures 9** (c), d), (e) and (f) show daily changes in PLW of tomatoes and eggplants stored in the silver-ion coated containers with copper grains after hot water treatment. Here, decay of the fruit was evaluated from an outside view. Hot water treatment at 45°C for one hour was applied to the tomatoes and eggplants.

Tomatoes treated in hot water and then stored in the silver-ion-coated container and copper grain lost only 1.01% of PLW after 12 days, 1.12% of PLW after nine days, and then decayed. Eggplants treated in hot water and then stored inside the silver-ion-coated container and copper grain lost 5.01% of PLW after 15 days, and 5.35% of PLW after 14 days without any decay. Tomatoes treated in hot water at 60°C for three minutes and then stored inside the silver-ion-coated container and copper grain lost 5.14% of PLW after 28 days, and 5.32% of PLW after 26 days without any decay. Eggplants treated in water at 60°C for three minutes and then stored inside the silver ion- coated container and copper grain lost only 1.98% of PLW after 10 days, lost 1.87% of PLW after eight days, and then decayed. This is because microorganisms easily affect tomato and eggplant not treated in hot water, and uncontrolled ethylene production causes the fruits to ripen faster. Hot water treatment slows down color development and the ripening process. Fruits subject to hot water treatment have lower levels of acidity and a higher content of soluble solids, glucose and sucrose, thereby achieving higher quality for consumption [31]. Epicuticular wax covering the eggplant is generally smoother than

that of tomato. This epicuticular wax is a very important factor in preventing the growth of harmful microorganisms after heat treatment. For instance, mild-temperature hot water treatment (at 45°C for one hour) of tomato with a longer duration, and high temperature hot water treatment (at 60°C for three minutes) of eggplant with a shorter duration damaged the layer of wax, but in both cases disinfected the surface. However, even such heat treatment in later stages could not prevent the growth of microorganisms that cause decay.

Fig.9. PLW of tomato and eggplant [12].

Where

TO: Tomato stored outside the brick wall cooler storage system in room temperature at 25°C;

TZ: Tomato stored inside the brick wall cooler storage system at average 15°C;

EO: Eggplant stored outside the brick wall cooler storage system in room temperature at 25°C;

EZ: Eggplant stored inside the brick wall cooler storage system at average 15°C;

CTT1Ag: Tomato treated with 45°C hot water for 1hr stored inside the silver ion coated container;

CTT1Cu: Tomato treated with 45°C hot water for 1hr stored inside the copper grain;

CET1Ag: Eggplant treated with 45°C hot water for 1hr stored inside the silver ion coated container;

CET1Cu: Eggplant treated with 45°C hot water for 1hr stored inside the copper grain;

CTT2Ag: Tomato treated with 60°C hot water for 3 min stored inside the silver ion coated container;

CTT2Cu: Tomato treated with 60°C hot water for 3 min stored inside the copper grain;

CET2Ag: Eggplant treated with 60°C hot water for 3 min stored inside the silver ion coated container;

CET2Cu: Eggplant treated with 60°C hot water for 3 min stored inside the copper grain.

At the same time, both high-temperature hot water treatment (at 60°C for three minutes) of tomato with a shorter duration and mild-temperature hot water treatment (at 45°C for one hour) of eggplant with a longer duration increase the thermo tolerance of plant cells and sterilize many types of bacteria. Many researchers have demonstrated that hot water treatment between 35°C and 63°C effectively inhibits ethylene production,

delays ripening [3, 32], and reduces the water loss of fruits during storage [6, 19]. Hot water treatment is also reportedly effective in preventing bacterial infection by activating the defense mechanism of cells [14, 21]. It is well known that exposing living organisms to heat stress produces several types of heat shock proteins (HSPs) in their cells, which acquire a transient thermotolerance [7, 28]. Therefore, acquiring thermo-tolerance and disinfection by heat treatment may reduce PLW and increase the shelf life for fruits during storage. It is thus logical to assume that hot water treatment reduces PLW.

Silver ions also have an antibacterial effect by emitting positively charged electric particles or ions. The silver ions penetrate the cell membrane and enter the body of bacteria. Silver ions (Ag^+) coming into contact with bacteria destroys the bacteria's proteins and interrupts the synthetic version of bacterial DNA. The bacteria loses the ability to divide and propagate, and thus eventually dies. Moreover, the higher redox potential of silver ions causes' faster dissociation after bacteria is destroyed. It will then continue to destroy other bacteria. Many researchers have described the obvious antibacterial effect of silver ions and how silver ions prevent the growth of microorganisms on the surfaces of tomato and eggplant [10, 15, 16, 19, 20, 28, 31]. Therefore, said antibacterial effect is probably due to the disinfection effect of silver ions. Together, copper grain can inhibit the growth of fungi [1, 4] that pose a great threat to fruits stored in moist and dark environments. The thermal conductivity of copper is greater than that of other materials, causes a faster decrease in fruit temperature, and reduces ethylene production. Table 1 shows the number of days until decay under different conditions.

Table 1. Number of days until decay of tomato and eggplant

Treatment		Storage	Normal room temperature (d)		brick wall cooler storage system (d)	
			Tomato	Eggplant	Tomato	Eggplant
No heat treatment		Outside the brick wall cooler storage system	7	4		
		Inside the brick wall cooler storage system			16	9
Treated 45°C	at	Silver-ion-coated container			12	15
		Copper			9	14
Treated 60°C	at	Silver-ion-coated container			28	10
		Copper			26	8

5. Dynamic optimization of inside temperature of the brick wall cooler storage system for storing fruits and vegetables using neural networks and genetic algorithms

Islam et al. [27] optimized the brick wall cooling system using artificial neural networks and genetic algorithms from the viewpoints of water savings. Because it is well known that intelligent approaches such as neural networks and searching technique using genetic algorithms are effective tools for imitating the skilled grower's thinking process. Neural networks mimic the human learning process and can identify nonlinear relationships between inputs and outputs of a system with their own high learning abilities [34]. Genetic algorithms mimic the biological evolutionary process and search for an optimal value in parallel with a multi-point search procedure, based on crossover and mutation in genetics [35, 36]. An intelligent control technique combining neural

networks with genetic algorithms has been used for realizing the optimization of cultivation and storage processes [33, 37, 38].

5.1 Design of a Control System

The conceptual diagram for an intelligent optimization technique is shown in **Figure 10 a**. It mainly consists of two steps. The first step is a “learning and modeling” process based on input data and dynamic changes of the input-output relationship. The second step is a “simulation (or prediction) and decision” process for selecting the best input values.

Figure 10 b shows the block diagram of an intelligent optimization technique mimicking a simple thinking process, which is applied for realizing the optimization control rate [33, 37, 38]. It consists of a decision system and a feedback control system. The decision system, consisting of neural networks and genetic algorithm, determines the optimal set point trajectory of the input factors. In the decision system, the rate of temperature reducing of the brick wall cooler storage system, as affected by the input factors such as outside temperature, watering and inside relative humidity, is first identified using the neural network, and then the optimal combination of the 1-step set points of the input factors that minimize the brick wall cooler storage system temperature is search for through simulation of the identified neural network model using the genetic algorithmic.

(a) A conceptual diagram of a decision procedure

(b) An intelligent optimization technique (IOT)

Fig.10. Diagram of a control system

5.2 Neural network for identification

A three-input (outside temperature, watering and inside RH) and one-output (inside temperature of the brick wall cooler storage system) system was used for identifying the dynamic response of the brick wall cooler storage system temperature and for creating a black-box model for simulation. **Figure 11** illustrates a NN time-delay for identifying the dynamic response of the inside temperature to outside temperature watering, and inside $RH(IH)$. It consisted of three layers and had arbitrary feedback loops that produce time histories of the input and output data for dynamic identification [39]. The input variables were the outside temperature $OT(k)$ and watering $W(k)$, $IH(k)$, and the output variable was the inside temperature of the brick wall cooler storage system $IT(k)$.

Fig.11. A three-layered neural network with time delay operator [27].

Training in the neural network is the process by which a neural network learns to recognize the underlying relationship between inputs and output, or just among the inputs (**Fig. 11**). During training, the weights and biases of the network are iteratively adjusted to minimize the network performance function [40]. This process requires computing the error derivative of the weights (EW); the process is repeated until the error sum falls below a preset level. For the learning of the NN, two $(n+1)$ th historical input data, $\{OT(k), \dots, OT(k-n)\}$ and $\{W(k), \dots, W(k-n)\}$, $\{IH(k), \dots, IH(k-n)\}$ and one n th historical output data, $\{IT(k-1), \dots, IT(k-n)\}$, are applied to the input layer, and one current output $IT(k)$ is applied to the output layer as training signals ($k=0, 1, \dots, N-n$, N : data number) [39]. The training method for neural computation is error back-propagation with two phases. In the forward pass, input signals flow from the network input to the output. In the reverse pass, the calculated error signals propagate backward through the network, where these update the network weights and biases in the direction of the negative gradient that indicated where network performance

function decreases most rapidly [41-43].

For the prediction, the current output, $IT(k)$, was estimated from two $(n+1)$ th historical input data, $\{OT(k), \dots, OT(k-n)\}$ and $\{W(k), \dots, W(k-n)\}$, $\{IH(k), \dots, IH(k-n)\}$ and one n th historical output data, $\{IT(k-1), \dots, IT(k-n)\}$, similar to an auto-regressive moving average (ARMA) model procedure [39].

A visual BASIC based program was developed for the NN. The well-known time delay neural-network model is:

$$IT(k) = f(OT(k), \dots, OT(k-n), W(k), \dots, W(k-n), IH(k), \dots, IH(k-n), IT(k-1), \dots, IT(k-n)) \quad 1.18$$

Where, n is the system parameter number and the unknown function $f(\square)$ can be approximated by the NN; $\{OT(k), \dots, OT(k-n)\}$, (watering) $\{W(k), \dots, W(k-n)\}$, and (relative humidity) $\{IH(k), \dots, IH(k-n)\}$ is present time series of the input; and $\{IT(k), \dots, IT(k-n)\}$ is the past time series of the output are (inside temperature).

Fig. 12. Flow chart for training of neural network model [modified from 27].

The data for identification are divided into two data sets, a training data set and a testing data set. The former is used for training the neural network, and the latter is used for evaluating the accuracy of the identified model. The testing data sets have to be independent of the training data sets. The most important task for determining the models structure is the choice of the system parameter number. Here, the system parameter number and the hidden neuron number of the neural network were determined based on cross validation [44].

5.3 Optimization method

In general, a lower temperature is desirable to maintain the freshness of fruits and vegetables during storage. The environmental factors (control inputs) that affect the inside temperature of the brick wall cooler storage system are mainly solar radiation, outside temperature, watering, inside RH and the quality of the wall material of the brick wall cooler storage system. The shade curtain was always used in this experiment because it is a low cost method that significantly reduces the solar power. Of these factors, watering and inside RH were selected as the control input for optimization because they were the only controllable variable. For identification, three factors, outside temperature, watering and inside RH, were used as the input variables. Thus, a three-input (outside temperature, watering and inside RH) and one-output (inside temperature of the brick wall cooler storage system) system was adopted for identification.

The inside temperature of the brick wall cooler storage system usually decreases as the water supply to the evaporative medium increases. An excessive amount of watering (e.g., continuous watering) was not very effective for lowering the inside temperature. This is probably due to the decrease in the evaporation area caused by excessive water in the evaporative medium. It may also due to the fact that the water is likely at ambient temperature. For this cause, circulating much water would create a warming effect since the energy required for evaporation would be supplied by the excess of water circulation. Thus, an optimal amount of watering (= optimal watering operation) does exist for minimization of the inside temperature. In this study, the amount of watering was controlled by establishing the optimal ON–OFF interval for watering process.

Let $IT(k)$ ($k = 1, 2, \dots, N$) be a time series of the inside temperature of the brick wall cooler storage system as affected by the outside temperature $OT(k)$, watering $W(k)$

and inside RH $IH(k)$ at time k . An objective function F (Eq. (1.19)) is given by the average value of the inside temperature for one day (Data number $N = 24 \text{ h} \times 60 \text{ min} = 1440$).

$$F = \sum_{k=1}^{k=N} \frac{IT(k)}{N} \quad 1.19$$

For optimization, the control process was divided into 8 steps. The sampling time is 60s. **Figure 13** shows the watering operation characterized by the 8-step ON–OFF intervals $W(k)$ which is a function of the ON–OFF intervals and given by the combination of 1(ON) and 0 (OFF).

$$\begin{aligned} W(k) &= f_{onoff}(\text{ON-OFF intervals}) \\ &= f_{onoff}(T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8, T_9, T_{10}, T_{11}, T_{12}, T_{13}, T_{14}, T_{15}, T_{16}) \end{aligned} \quad 1.20$$

Where

ON time : $T_1, T_3, T_5, T_7, T_9, T_{11}, T_{13}, T_{15}$

OFF time: $T_2, T_4, T_6, T_8, T_{10}, T_{12}, T_{14}, T_{16}$

Fig.13. The 8-step ON–OFF watering operation [27].

Therefore, the optimization problem here is to determine the 8-step ON–OFF intervals of watering which minimize the objective function F . For optimization, however, the watering duration was restricted to 3600 s in order to save water and fit the real system.

$$\text{Minimizing } F \quad 1.21$$

Subjected to $0 \leq T_1, T_2, \dots, T_{16} \leq 60 \text{ min}$

Figure 14 shows the flowchart for determining the optimal value. In this technique, the dynamic response (diurnal change) of the inside temperature of the brick wall cooler storage system as affected by the watering and the outside temperature is first identified using NN, and then the optimal 8-step ON–OFF intervals for watering process which minimize the objective function $F(W)$ are determined using simulation of the identified NN model and GA. Finally, the optimal value is applied to a real system.

Fig. 14. Flowchart for determining the optimal value [27].

In order to use the genetic algorithm, an ‘individual’ for evolution should be defined as the first step. Each individual represents a candidate for the optimal value. Since the optimal value is the 8- step ON–OFF intervals of watering, an individual can be given by the 8-step ON–OFF intervals of watering $\{T1, T2, \dots, T16\}$. They were all coded as 6-bit binary strings, which gives numerical values between $000000 (=2^0 - 1 = 0)$ and $111111 (=2^6 - 1 = 63 \text{ in decimal})$. The amount of watering as a value from 0 to

63 by using 6-bit binary strings. For optimization, however, the watering duration was restricted to 3600 s in order to save water and fit the real system (Eq. (1.18)). Individual $i = T_{i1}T_{i2}, \dots, T_{i16} = \{000000, 111000, \dots, 010101\}$.

A set of individuals is called a “population”. They evolve toward better solutions. GA work with a population involving many individuals. The population size varies according to the use of genetic operations with a smaller population size tending to converge to the local optima. Local optima mean local optimization, not a global one. When an objective function is characterized by a complex function, a poor search technique sometimes falls into the local optima. A local optima does not allow obtaining a global (true) optimal solution.

Fitness is an indicator for measuring an individual’s survival quality. All individuals are evaluated in terms of their performances, which is based on their fitness values. During the evolution process, individuals having a lower fitness reproduce, while individuals with a higher fitness die in each generation. An individual having the minimum fitness is regarded as the optimal solution. Fitness is similar to the objective function in conventional optimization problems. In this case, fitness can be defined as the objective function F given by Eq. (1.22).

$$\text{Fitness} = F = F(T_{i1}, T_{i2}, \dots, T_{i16}) \quad 1.22$$

Crossover and mutation were used as genetic operators. A single crossover was used. Two individuals (e.g., 000110 and 101101) are first mated at random. Next, these binary strings are cut at the 3-bit position along the strings and then two new individuals (000101 and 101110) are obtained by swapping all binary characters from the 1-bit to the 3-bit position. The mutation inverts one or more components of the binary strings from 0 to 1 or vice versa. Here, a two-point mutation was used. One individual (e.g.,

010110) is first selected at random, and then a new individual (0000010) is created by inverting two characters (genes), selected at random, from 0 to 1 or 1 to 0. The mutation operation increases the variability of the population and helps to avoid the possibility of falling into local optima in the evolution process [45]. The number of mutations depends on the mutation rate. The selection of individuals was carried out based on the elitist strategy by which an individual with a maximum fitness must remain in the next generation. However, the searching performance can easily fall into a local optimum because only the superior individuals with the higher fitness are picked in each generation. In this study, therefore, quite different individuals (=100) in another population were added to the original population in order to maintain the diversity and obtain a global optimal value.

Figure 15 shows the flow chart of the genetic algorithm. The procedure is as follows. (Step 1): The initial population consisting of ($N_i = 6$) types of individuals is generated at random. (Step 2): ($N_o = 100$) types of individuals are added to the original population from another population in order to maintain the diversity of the original population. (Step 3): Genetic operations, crossover and mutation, are applied to those individuals. Through the crossover, N_c sorts of individuals are newly created according to the crossover rate ($P_c = 0.8$), and N_m sorts of individuals are then newly generated according to the mutation rate ($P_m = 0.5$). From these operations, ($N = N_i + N_o + N_c + N_m$) types of individuals are obtained. (Step 4): The fitness (values of the objective function) of all individuals are calculated using the neural network model, and their performances are evaluated. (Step 5): Superior individuals, ($N_r = 200$) individuals with higher fitness, are selected and retained for the next generation based on elitist strategy selection. (Step 6): Step 2 to 5 are repeated until the fitness continues

to keep the same minimum value with increasing generation number. An optimal value is given by an individual with minimum fitness.

Fig.15. Search of optimal setpoint through Genetic algorithm [27].

5.4 Diurnal changes in the inside temperature of the brick wall cooler storage system for identification

Twenty-three types of data sets of the inputs and the output were obtained for identification. **Figure 16** shows that during a sunny day under the watering and shaded condition, the maximum average outside and inside temperature difference was 10.00°C, while during a rainy day, this difference was only 3.60 °C. This is because the outside temperature around the brick wall cooler storage system and the vapor pressure of the moist sand and zeolite mixtures and the surrounding air tend to equalize. Liquid water molecules in the moist sand and zeolite mixtures evaporate under the influence of the outside air through a process that uses energy to change the physical state. Heat moves from the higher temperature of the air and brick walls to the lower temperature of the

water due to convection and conduction. During this conversion process, the surrounding temperature decreased. Therefore, it was found that the combination of higher outside temperature, watering, inside RH and shade curtain provide the lowest inside temperature of the brick wall cooler storage system.

Fig.16. Optimization process of a zero energy storage [27].

5.5 Relationship between the amount of watering and the inside temperature

The effect of the amount of water used on the inside temperature was also investigated. **Figure 17** shows the fundamental relationship between the amount of

watering of the sand and the air temperature at 10 mm over the sand in a wind tunnel. A wind velocity of $4 \text{ mm}\cdot\text{s}^{-1}$ was used. The air temperature decreased with the increase of the amount of water used. **Figure 18** illustrates the actual relationship between the amount of watering and the inside temperature of the brick wall cooler storage system. In this case, we had three levels of watering (30, 45 and $60 \text{ L}\cdot\text{d}^{-1}$). The minimum inside temperature of 19.7°C was achieved by the intermediate watering of $45 \text{ L}\cdot\text{d}^{-1}$, not the 30 and $60 \text{ L}\cdot\text{d}^{-1}$ watering. From **Figures 17 and 18**, it was found that increasing too much the amount of water does not minimize the inside temperature, and the optimal amount of watering does exist for its minimization. This is because the presence of an excessive amount of water in the filler lowered the evaporation rate due to the decrease of the porous area inside it. The suitable moisture condition of the filler in the brick wall can more effectively minimize the inside temperature than the excessive moisture condition. Thus, it is necessary to optimize the amount of watering to improve the maximum cooling performance of the brick wall cooler storage system. We optimized the ON–OFF intervals of watering instead of the amount of watering for minimizing the inside temperature.

Fig.17. Fundamental relationship between the amount of watering and the air temperature at 10 mm over the sand in a wind tunnel test [27]..

Fig. 18. Relationship between the amount of watering (30, 45 and 60 L·d⁻¹) and the inside temperature of the brick wall cooler storage system [27].

5.6 Determination of system order and hidden neuron number

The system parameter number and the hidden neuron number of the neural network were determined based on the cross-validation. **Figure 19** shows that the root mean squared error (RMSE) value decreases as n increases. The 70th was selected as the effective system order because it gave the minimum RMSE value. The neuron number was changed between one and nine in **Fig. 20**. The minimum value of the RMSE was obtained when the neuron number was five. Therefore, from Figs. 18 and 19, it was concluded that the system order $n = 70$ and the neuron number in the hidden layer $N_h = 5$ are effective for identification.

Fig.19. Relationship between the system order and the RMSE [27].

Fig.20. Relationship between the neuron number in the hidden layer and the RMSE during fine day ($45 \text{ L}\cdot\text{d}^{-1}$) [27].

5.7 Identification results of the inside brick wall cooler storage system to outside temperature, watering and inside relative humidity

In order to confirm the model accuracy, the dynamic response (short-term diurnal change) of the inside temperature was compared between the estimated and real responses. **Figure 21** is a comparison of the dynamic response of the inside temperature as affected by the watering and the outside temperature of the brick wall cooler storage system on a fine day. These testing data were independent of the training data. The solid line shows the estimated response obtained from the NN model and the broken line shows the observed one. From the **Figure 21**, it was found that the estimated response was closely related to the observed one.

Fig. 21. Comparison of the estimated and observed responses of the inside temperature to watering process [27].

Next, the static relationship between the outside temperature, which depends on the solar radiation, and the inside temperature of the brick wall cooler storage system was investigated. **Figure 22** shows the comparison of the observed relationship (a) and the estimated relationship (b) between the outside temperature and the inside temperature of the brick wall cooler storage system. In this case, the other input variable, watering, was maintained at 0 (no watering). The estimated relationship was obtained from a simulation of the NN model. All the data in this graph were obtained from the calculation of the step responses of the inside temperature as affected by various levels of the step input of the outside temperature. It can be seen that the estimated relationship was closely related to the observed one. In general, it is well known that the relationship between the outside temperature and the net inside temperature show nonlinear

characteristics due to the thermo–physical properties of the cooling wall and environmental factors [46]. The nonlinear characteristics appear in both curves. This implies that the nonlinear identification of the net inside temperature was well attained using the NN method. These results suggest that a reliable computational model could be obtained for predicting the behavior of the inside temperature under any combination of watering.

Fig.22. Comparison of the static relationship between the outside temperature and the inside temperature of the brick wall cooler storage system on a fine day [27].

5.7 The search for an optimal value through model simulation

Figure 23 shows evolution curves in searching for an optimal value using the genetic algorithm. The crossover and mutation rates were 0.8 and 0.5, respectively. The selection technique was based on an elitist strategy which retains an individual with a maximum fitness for the next generation in each generation. From the curve, the fitness (the value of objective function) dramatically increased with the generation number and then reached the maximum value. The searching procedure is usually stopped when the

fitness continues to have the same maximum value with the increasing generation number, and an optimal value can be given by an individual with this maximum fitness. The optimal value was obtained at the 33rd generation. The searching performance can easily fall into a local optimum because only the superior individuals with the higher fitness are picked in each generation. In this case, a global optimal value could be successfully obtained by increasing the diversity of the original population by adding very different individuals from another population. The obtained optimal value was T1 = 35 min ON, T2 = 55 min OFF, T3 = 35 min ON, T4 = 55 min OFF, T5 = 35 min ON, T6 = 55 min OFF, T7 = 35 min ON, T8 = 55 min OFF, T9 = 35 min ON, T10 = 55 min OFF, T11 = 35 min ON, T12 = 55 min OFF, T13 = 35 min ON, T14 = 55 min OFF, T15 = 35 min ON, and T16 = 55 min OFF. The confirmation of the optimal value was carried out using a round-robin algorithm.

Fig.23. Evolution curve in searching for the optimal value using the genetic algorithm [27].

Fig. 24 illustrates the optimal control performance of the inside temperature of the brick wall cooler storage system as affected by the optimal watering, obtained from simulation for 12 h, under the shaded condition. The solid, broken and dash lines show

the cases of the optimal watering, continuous watering and no watering, respectively. The other input variable, solar radiation, was maintained constant at the adequate observed diurnal change during the simulation. The average values of the inside temperature were 18.7, 22.6 and 26.2 °C for the cases of the optimal watering, continuous watering and no watering. Thus, the inside temperature for the optimal watering was 4 °C lower than that for the continuous watering, and 7.5 °C lower than that for no watering. This is probably because the optimal watering provided a suitable balance of the gas and liquid phases for the active evaporation.

Fig. 24. The optimal control performance of the inside temperature of the brick wall cooler storage system by the control of the optimal watering based on optimal ON–OFF watering intervals [27].

5.8 Application of the optimal watering operation for real fruit storage

Next, the optimal value (optimal ON–OFF intervals of watering) was applied to a long-term real fruit storage. Controlling the watering using an intelligent optimization technique (IOT) combined with neural networks (NN) and genetic algorithms (GA) reduced the water requirement from 50 to 10 L·d⁻¹, as shown in Table 2. **Figure 25** illustrates the visual quality of the stored tomato during the optimal watering. In this figure, (a) is the tomatoes stored in the brick wall cooler storage system with optimal watering for 16 days and (b) are those stored at room temperature for 7 days. It is found that a significant decay was observed in the tomatoes stored at room temperature for 7 days, while the tomatoes stored in the brick wall cooler storage system with the optimal watering for 16 days appeared to have only a small decay on the fruit. Microorganisms easily infect the tomatoes and uncontrolled ethylene production causes the fruits to ripen faster. However, the brick wall cooler storage system with the optimal watering produced a lower inside temperature and then delayed the softening and decay of the fruit. Thus, it was determined that the brick wall cooler storage system with the optimal watering is useful to store fruit and vegetables with no electric energy.

Fig. 25. Visual appearances of tomatoes (a) after 16 days of storage inside the brick wall cooler storage system with optimal watering, and (b) after 7 days of storage at room temperature [27].

Table 2. Optimizing the water requirement of the brick wall cooler storage system

Brick wall cooler storage system	Optimization		Watering (L·d ⁻¹)	Temperature (°C)		Storage (day)	
	ANN	GA		Outside	Inside	Tomato	Eggplant
Conventional, Islam and Morimoto, 2012	-	-	50	30	18	16	9
Conventional, Islam and Morimoto, 2013	+	+	10	30	18	16	-

6. Design and development of a brick wall cooler storage system with a

solar-driven adsorption refrigerator

Solar energy is safe, environment friendly and abundant in nature. The solar-driven adsorption cooling system is receiving much attention for replacing the electric powered refrigeration system. The most promising method of producing ice by using solar energy is activated carbon (adsorbent) - methanol (adsorbate) pair, which could be driven by relatively low heat, near ambient temperatures and less expensive was developed by [47, 48]. However, Anyanwu and Ezekwe [49] designed an activated carbon-methanol adsorbent pair based refrigerator and then constructed and evaluated in the tropical climate of Nsukka, Nigeria. Their refrigerator chilled water of around 1°C, which is within the range of preservation temperature (4 to 16°C) of vegetables.

Later Islam and Morimoto [50] successfully designed, constructed and evaluated the performance of a new zero energy fruit storage chamber with a solar-driven adsorption refrigerator (**Fig.26 a, b**). During the night time, the solar-driven adsorption refrigerator produces ice inside the water tank of the evaporator by evaporation and adsorption of methanol on activated carbon fiber. During the daytime, this ice is stored inside the ice thermal storage in the storage chamber to achieve an average storage temperature of 12.07°C and higher humidity level of 87% for longer duration and increased the shelf life of stored tomato from 7 to 23 days. Meanwhile, evaporation from the wet filler between the double walls of the storage chamber prevents diffusion of higher ambient temperature inside the storage space and helps to maintain a lower storage temperature all day long. Therefore, such a new concept of energy storage and utilization might be an excellent means of sustainable low cost fruit storage development of the worldwide.

Fig.26. A new zero energy fruit storage system having two cooling systems, solar-driven adsorption refrigerator and an evaporative cooling system [50].

Figure 27 (a, b, c and d) shows a schematic diagram of the solar-driven adsorption refrigerator, which is similar to a conventional electric-driven vapor compression refrigeration system and in this system the adsorbent acts as a chemical compressor driven by solar heat. During the daytime, the activated carbon and methanol filled copper tube inside the solar collector was heated by solar radiation and this process continued until the activated carbon rose to temperature T_{gen} . As a result, at point B the vapor pressure of the desorbed methanol increased to P_{con} . During this process, both condenser and evaporator were isolated from activated carbon filled copper pipe of the solar collector by valves V_{ev1} , V_{ev2} , V_{ev3} and V_{con} . Once the methanol vapor pressure reached P_{con} , valve V_{ev1} was open and valves V_{ev2} , V_{ev3} and V_{con} were closed to equalize the activated carbon filled copper pipe inside pressure with the condenser pressure and

to allow the methanol vapor to flow towards the condenser. However, the temperature continued to increase but the amount of methanol inside the activated carbon continued to decrease as more adsorbate methanol vaporized from the activated carbon.

The condensed methanol was then stored inside the evaporator by opening valve $V_{con.}$, while valves V_{ev2} and V_{ev3} were closed to maintain the inside methanol pressure. During the night time period, at point C the solar radiation decreased to 0 and the activated carbon of the solar collector temperature fell due to convective and radiative heat transfer to the surrounding environment. Both temperature and pressure inside the activated carbon dropped until the pressure reached the evaporator pressure at point D. During this stage, valves V_{ev2} and V_{ev3} were opened and valves V_{ev1} and V_{con} were closed to allow the condensed methanol vaporized by absorbing heat from the water tank to flow towards the activated carbon of the solar collector. As a result, the temperature of the water in the water tank decreased to such a level that liquid water changed to solid ice. Later during the daytime, the produced ice stored inside the ice box, and then radiated the cold heat to the warm air in the chamber through radiation as the warm air contacted the ice box heat radiating fins. As a result the temperature inside the storage chamber decreased until the next ice producing cycle started. The valve-controlling method for phase scheduling of the thermodynamic cycles for producing ice is shown in **Table 3**.

Table 3. Controlling method for the thermodynamic cycles of the solar adsorption system [50]

Start time	Activity	Valve	Solar radiation (W/m ²)
(Sunrise: 5:00; Sunset 19:00)			
6:00	Isosteric heating (adsorbent heated)	V _{ev1} , V _{ev2} , V _{ev3} , V _{con} closed	0
9:00	Desorption (adsorbent heated and desorbing process)	V _{ev1} open, V _{ev2} , V _{ev3} , V _{con} closed	300 (peak 864.1)
18.00	Isosteric cooling (condensation and cooling of methanol)	V _{con} open, V _{ev1} , V _{ev2} , V _{ev3} closed	0
21.30	Adsorption (evaporation, refrigerant effect)	V _{ev1} , V _{con} closed, V _{ev2} , V _{ev3} open	0

In this section, the mathematical model is based on a steady state first law of thermodynamics which take place in all of the system components and all of the processes of the theoretical cycle. The adsorption refrigeration cycle consists of four cycles which was modified from a previous study by Akinbisoye and Odesola [51]:

(a) AB is the isosteric heating process of the adsorbent (pressurization; Fig. 27 a)

The adsorbent (activated carbon inside the copper tube) is heated up together with adsorbate (methanol) that was trapped in the micro pores of activated carbon particles. During this phase, the solar collector is not connected to the condenser and the pressure increases from P_{ev} to P_{con} . Concentration of methanol inside the activated carbon in this process remains changed. Energy input (energy losses are not taken into account) to heat activated carbon and methanol can be calculated by **Eq.1.23**, as shown below:

$$Q_{A-B} = (C_{ac} \cdot M_{ac} + C_r \cdot M_{rA})(T_{gen} - T_{con}) \quad (1.23)$$

(b) BC is the isobaric heating process of the fluid (decreasing the fluid concentration; Fig. 27 b)

The activated carbon releases the methanol to the condenser and decreases with heating; therefore, concentration of methanol (x) is no longer a constant in this process. Energy input for desorption of methanol from activated carbon is shown in Eq. 1.24:

$$Q_{B-C} = (C_{ac} \cdot M_{ac} + C_r \cdot \bar{M}_r)(T_{max} - T_{gen}) + \Delta x \cdot M_{ac} \cdot H_d \quad (1.24)$$

(c) CD is the isosteric cooling of the adsorbent (depressurization; Fig. 27 c)

In this process [Fig.27c], the sensible heat of activated carbon and methanol inside the condenser is removed by external cooling source air and energy balance can be expressed as:

$$Q_{C-D} = (C_{ac} \cdot M_{ac} + C_r \cdot M_{rc})(T_{max} - T_{ads}) \quad (1.25)$$

(d) DA is the isobaric cooling process of the fluid (evaporating the methanol and adsorbing the methanol vapor by activated carbon; Fig. 27d)

Once the pressure reached P_{ev} , the connection between evaporator and solar collector is established, and activated carbon started absorbing methanol from the evaporator. In the meantime, the evaporation of methanol results in useful effect of water cooling. At first temperature of water decreases to 0°C; then the liquid water started phase-change (ice) at constant temperature, and finally ice temperature is under-cooled until the methanol contained in the evaporator is completely evaporated.

Cooling output can be calculated approximately using **Eq. 1.26**:

$$Q_r = (\Delta M_r \cdot L_o + C_r \cdot \Delta M_r)(T_{con} - T_{ev}) \quad (1.26)$$

(a) Isosteric heating

(b) Isosteric desorption

(c) Isosteric cooling

(d) Isobaric adsorption

Fig. 27. Solar-driven adsorption refrigeration system [50].

Evaluation of cooling performance

The coefficient of performance of the solar adsorption refrigerator is defined as the amount of cooling produced by the refrigerant (methanol) divided by the net solar energy received from solar radiation, as shown in Eq. 1.27. The coefficient of cooling performance (COPs) was adopted from a previous study by Anyanwu and Ezekwe [49].

$$COP_s = \frac{\text{useful effect (refrigeration output)}}{\text{available solar energy}}$$

$$COP_s = \frac{Q_r}{(Q_{A \rightarrow B} + Q_{B \rightarrow C})} = \frac{\Delta M_r (L_0 - c_r (T_{con} - T_{ev}))}{I} \quad (1.27)$$

The total amount of ice production m_{ice} at a temperature of T_{ev} from initial temperature of T_w is given in Eq.6:

$$M_{ice} = \frac{Q_r}{C_w(T_w - 273) + L_{fus} + C_{ice}(273 - T_{ev})} \quad (1.28)$$

6.1. Storage environment of a solar-driven adsorption refrigerator

In **Figure 28**, the solid line is ambient temperature, the dotted line is adsorbent bed temperature and the semi-dotted line is evaporator temperature. As observed from the figure, adsorbent bed temperature increases gradually to its maximum of 105 °C which guarantees sufficient desorption of methanol [52]. At the end of the desorption process and before the beginning of any adsorption process, the cooling load of 3.5 L of water at ambient temperature was introduced into the water tank inside the evaporator. During evaporation of methanol inside the evaporator at the adsorption phase, the evaporator temperature decreased to -10 °C which triggered the transforming of liquid water to solid ice. The produced ice was then stored inside the ice box (**Fig. 26**) to reduce the storage temperature until the next cooling cycle started. The average cooling performance of the solar-driven adsorption refrigerator is shown in **Table 4**.

Fig.28. Changes in the operational temperatures of the solar-driven adsorption refrigerator [50].

Table 4. Performance of the solar-driven adsorption refrigerator [50]

Adsorption temperature (°C)	Desorption temperature (°C)	Condensation temperature (°C)	Evaporator temperature (°C)	^a COP _s
33	96.3	32	-10	0.071

^aCOP_s is calculated as described in Anyanwu and Ezekwe (ww)

6.2 Short- and long-term changes in inside temperature of the solar-driven adsorption refrigerator

Figure 29 a illustrates the dynamic changes in the inside temperature and relative humidity of the new brick wall cooler storage system to operations of watering and the solar-driven adsorption refrigerator (ice box). The on (35 min)-off (55 min) watering started at 5:00 and continued until the next cycle [27]. The ice box started melting at 5:00 and the ice completely melted by 17:00. Watering lowered the inside temperature

to 20.9°C and increased the relative humidity from 74 to 77% under an ambient temperature of 32.0°C. The inside temperature decreased further to 10.1°C and the inside relative humidity increased to 90% due to temperature decreasing . It was found that the combined use of watering and the ice box with heat radiating fin was effective in reducing the inside temperature. When the ice completely melted to water in the ice box, the inside temperature of the new brick wall cooler storage system increased to 12.1°C and relative humidity decreased to 86% by 2:00.

Figure 29 b shows the long-term changes in the inside temperature to watering and the ice box over twenty-three days. These data express the performance of the new brick wall cooler storage system as a fruit-storage chamber. From this experiment, the average inside temperature of the new brick wall cooler storage system was 12.07°C, while the average ambient temperature during the experiment period was 31.5°C.

(a) Short-term changes in inside temperature

(b) Long-term changes in outside and inside temperatures

Fig.29. Short-term and long-term changes in inside temperature of the new brick wall cooler storage system [50].

6.3 Evaluation of the stored tomato under different stored condition

Figure 30a shows that tomato stored at ambient temperature (control) and brick wall cooler storage system spoiled after 7 days with a physiological loss in weight (PLW) of 5.4%, and 17 days, respectively. However, the shelf life of tomato stored inside the solar-driven adsorption refrigerator based brick wall cooler storage system was prolonged to 27 days which is 10 days more than tomato stored in a brick wall cooler storage system [12, 53]. The continuous lower inside temperature of the prototype offers a unique advantage in lowering ethylene production and thus decreases physiological loss in weight (PLW) and other metabolic processes.

The development of firmness, that is, the softening of the fruit, was significantly affected by storage time and temperature. **Figure 30b** illustrates that the firmness of tomatoes (control) stored at ambient temperature was significantly lower than tomatoes stored inside the prototype. Fruit softened under both storage conditions during the storage period. Under the exposure of higher ambient temperature, the hemicelluloses and pectin of tomato become more soluble, which results in disruption and loosening of the cell walls [54]. As a result, the rate of loss of firmness of tomato stored inside the prototype decreased significantly compared with those stored at ambient temperature. The lower inside temperature of the integrated brick wall cooler storage system reduced the enzymatic activities of fruit, resulting in the lower loss of firmness [55, 56, 57, 58, 59].

(a) Physiological Loss of weight (PLW) of stored tomato

(b) Firmness of stored tomato

Fig.30. Changes in PLW and firmness of tomatoes stored at ambient temperature, brick wall cooler storage system and inside solar-driven adsorption refrigerator based brick wall cooler storage system [50].

7. Challenges Issues towards dissemination of brick wall cooler storage system

Agriculture in Bangladesh is the single largest producing sector of the national economy. More than 80% of the total population is engaged in agriculture, 57% of the labor force is engaged in the crop sector which represents about 78% of the value addition in the agricultural sector and more than 50% of the population depends on agriculture for their livelihoods. Bangladesh is blessed with about 90 kinds of vegetables and fruits almost throughout the country and grown all the year round. According to BBS [60], Bangladesh produced more than 6.279 million tons of fruits and

vegetables during 2010-2011. Mymensingh is the northern district of Bangladesh bordered on the north by India and lies between 24°02'03" and 25°25'56" north latitude and 89°39'00" and 91°15'35" east longitude. It has a total land area of about 1,243,900 acre, out of which 761,506 acres are under cultivation. The total irrigated area of Mymensingh district is about 69%. The maximum of annual average temperature is 33.3°C, and the minimum is 12°C and annual rainfall is 2,174 mm. The area is favorable for production of all major crops, fruits and vegetables. During 2009-2010, annual production of 24,003 tons of bananas, 13,745 tons of pineapples, 1,515 tons of wood apples, 18,936 tons of mangos, 60,566 t of jackfruit, 3,222 tons of papayas, 10,142 tons of green papayas, 6,000 tons of different types of vegetables, 3,392 tons of tomatoes, 6,281 tons of eggplant fruits were recorded in this part of the country.

The main disadvantages of these fruits and vegetables are vulnerability against high temperature. But, consumer preference greatly varies based on freshness, color, size and shape. The postharvest losses of fruits and vegetables are nearly 25% due to inadequate postharvest handling practices and non-availability of storage facilities [61]. There is a necessity to prevent the waste of fresh fruits and vegetables during storage by adopting newer storage techniques. For this purpose, an ecofriendly brick wall cooler storage system has been developed and then extended to the farmers' fields (**Fig.31**) to evaluate and assess the perceptions of fruit and vegetable farmer's about status, problems and prospects of brick wall cooler storage system.

Fig.31. Training and field trial response study.

Most of the fruit and vegetables grown in tropics and subtropics are perishable and bulky commodities during harvesting season. Islam et al. [62] conducted a case study within the farmer's community in Bangladesh from 2011 to 2012. They found that most of the farmers sell their fruit and vegetables to the middlemen just after the harvest and couldn't able to get the return of invested money for cultivating vegetables or fruit that caused higher percentage of poverty level in farmer's community. In this context, pre and post brick wall cooler storage system demonstration survey were conducted to find out problems in storage of fruits or vegetables and feasibility of brick wall cooler storage system, including their application, acceptability and profitability to the local market. Total 50 number of zero energy storage chambers was constructed for demonstration trial. About 100 respondents were selected randomly for and a

questionnaire was used to collect the primary data from the responded farmers by direct question, focus group discussion and individual face to face interview. The contents of the questionnaire are presented as follows. Main contents of the questionnaire for pre demonstration trial of the brick wall cooler storage system:

1. Which types of agricultural produces do you cultivate?
2. What storage method do you use for storing fruits and vegetables?
3. Explain the cause of deteriorations of fruits and vegetables.
4. What do you think about the brick wall cooler storage system?

Main contents of questionnaire for post demonstration trial of the brick wall cooler storage system:

1. Feelings about use - when asked what they liked to use brick wall cooler storage system?
2. Where do you want to use brick wall cooler storage system?
3. Are you satisfied with the brick wall cooler storage system?

If yes, reason for satisfaction?

If no, what are the problems?

4. What is your opinion about the design of brick wall cooler storage system?
5. Are you satisfied about the provided instructions and information during field trials?
6. What benefits you achieved during the exploitation of the brick wall cooler storage system?

7.1 Pre-demonstration trial perspective

Survey results revealed that farmers were growing a number of vegetables and fruits. However, a majority of them were inclined towards growing jackfruit (98%), followed by wood apple (70%), mango (50%), guava (42%), ber (35%), lichi (25%),

lemon (25%), banana (23%) and papaya (13%) fruit (**Fig. 32**). Similarly, major vegetables grown in the area were brinjal (98%), bottle gourd (64%), bitter gourd (60%), hyacinth bean (55%), tomato (45%), pumpkin (44%), cucumber (37%), cauliflower (33%), carrot (32%), and ladies finger (30%) as is shown in **Fig. 33**.

Fig.32. Percent of farmers cultivating fruits in sampled area [62].

Fig. 33. Percent of farmers cultivating vegetables in sampled area [62].

Due to unavailability and lack of technical know-how about storage methods, most of the farmers sell their fruits (60%) to the middleman just after harvest to avoid any deterioration and financial loss. However, among different methods practiced locally, sun drying is the most popular method by 75% of the contacted farmers (**Fig. 34**). Very few growers are also using bamboo or mud made structure for drying (10%) and

15% have no idea about any type of storage system for fruits.

Similar to vegetables, most of the farmers sell all their vegetables (80%) immediately after harvest due to unavailability of proper storage facilities (**Fig. 35**). However, only a small number of farmers (25%) opted for storage of vegetables by sun drying method, and followed by (5%) bamboo or mud made structure. A majority of the farmers (99%) of the sampled population had no access of storage facility.

Fig. 34. Percent of farmers using fruits storages methods in sampled area [62].

Fig. 35. Percent of farmers using vegetables storages methods in sampled area [62].

It has been observed from the data that the majority of growers mentioned deterioration in fruits and vegetables after harvesting (**Fig. 36**). The major factors quoted were lack of storage facility (93%), postharvest diseases (85%) that resulted in rotten, bad flavored and inferior quality of fruits and vegetables and lack of knowledge

of postharvest treatment (80%). The results were shown in the figure 36 as below.

Fig. 36. Percent of farmers cited types of deterioration of fruits and vegetables in sampled area [62].

When asked to profile their observation about the brick wall cooler storage system, most participants (95%) were not satisfied about the current storage methods (It was shown as **Table 5**). But when asked about the storage system which they like to use in the future, 75% considered that the storage system should be of low operating cost, followed by easy handling (65%) and low installation cost (65%).

Table 5. Perception about the brick wall cooler storage system before pre demonstration trial [62]

Participants	Value
Are satisfied with the storage system they currently used	5%
Consider the storage system they use to be 'low installation cost'	65%
Consider the storage system they use to be 'Low operating cost'	75%
Consider the storage system they use to be 'Easy handling'	70%
Consider the storage system they use to be 'Eco friendly'	30%
Feel dissatisfied, or worried about their current storage system	95%

7.2 Post demonstration trial perspective

The largest number of respondents (60%) indicated that they like to use brick wall cooler storage system in the back yard of their house (**Fig. 37**). Because backyard is unused and women can easily access there followed by the fact that it is attached to their house. About 20% of farmers like to operate it in their field followed by inside the kitchen (10%), in the local market (6%) and 4% others.

Fig. 37. Location of use [62].

About 75% of the contacted farmers were satisfied with the performance of the brick wall cooler storage system for storing fruits and vegetables (**Fig. 38**). It was because the prevalence of advantages in storage such as increasing shelf life of fruits and vegetables and quality [12]. Only 15% were dissatisfied because it was not able to store fruits and vegetables with bulk quantities.

Note: 1- Very satisfied; 2- Very unsatisfied; 3- Satisfied; 4-Dissatisfied; 5- To some extent; 6- Neutral.

Fig. 38. Satisfaction with the use of zero energy cool chamber [62].

The main reasons for satisfaction (**Fig. 39**) were easy handling and maintenance level of easy exploitation (84%) followed by no requirement of electricity (90%) and low installation cost (85%). Almost 60% of respondents exposed that increasing interest of gender participation in agriculture activities. In case of most farmer families, young and middle aged men were mostly engaged in agricultural works. The elderly men and both young and elderly women were mostly looked after the livestock and homestead activities. In rice based farming system, men had higher participation in farm related activities compared to women. Moreover, in case of the access and control over resources (both in household and agricultural production) young and elder men play a major role. The situation for women involvement in fruit and vegetable and livestock based farming systems was better than that of rice based. Women are partially engaged in postharvest operation which requires less labor. Involving women for maintaining brick wall cooler storage system based post-harvest farming system will improve the farmers' overall economic condition by reducing the loss of fruits and vegetables. It will also increase the daily uptake of fruits and vegetables which will reduce the

malnutrition problem in the rural areas of Bangladesh.

Note: 1- Handling and maintenance is comfortable; 2- Involvement of women; 3- No need of electricity; 4- Low installation cost; 6: Others.

Fig. 39. Reasons for satisfaction [62].

Participants had positive experiences using the brick wall cooler storage system (**Fig. 40**). Most indicated that it was comfortable to use (90%) and only 8% participants felt discomfort during the exploitation because of its size and shape, while only 2% refused to make any comments.

Fig. 40. Farmer's opinion about the design of brick wall cooler storage system [62].

Most participants were satisfied with the amount of information provided to them about know- how of the brick wall cooler storage system (**Fig 41**). About 95% stated that the information provided was sufficient followed by 82% who felt that the instruction for operating the brick wall cooler storage system was helpful, and some

(5%) recommendations included more comprehensive demonstrations.

Note: 1- Sufficient information; 2- Instruction was helpful; 3- Recommendation; 4- Others.

Fig. 41. Satisfaction over the information and instruction provided during demonstration trial [62].

A sizeable portion of the farmers (42%) were satisfied with the storage capability of unsold fruits and vegetables (**Fig. 42**). The other major factors quoted by farmers (38%) were the improvement of the bargaining capacity which is directly related with their financial benefits.

Note: 1- Capable to store unsold fruits and vegetables; 2- Improve the quality; 3- Food security improved; 4- Bargaining capacity improved; 5- Others.

Fig. 42. Benefits of the brick wall cooler storage system [62].

Most participants (75) would recommend the brick wall cooler storage system to others (**Fig. 43**). However, only 22% of respondents said they would think of the necessity of talking about the brick wall cooler storage system to others, and fewer (3%) refused to make any comments. Establishment of cold storage for the preservation of fruits and vegetables involves not only huge investment and infrastructure but also less feasible under many circumstances. Moreover, installation of brick wall cooler storage system requires less initial investment, no need of electricity and less skill to operate it.

Note: 1- Recommend others; 2-Feel necessity to recommend others; 3- Refused to make any comments.

Fig. 43. Benefits of the brick wall cooler storage system. [62].

Further post demonstration trial found that the 60% respondents like to use zero energy storage chamber in the back yard of their house. Because backyard is unused and women can easily access there followed by the fact that it is attached to their house. Moreover, about 75% of the contacted farmers were satisfied with the performance of the zero energy storage system for storing fruit and vegetables. They identify the main reasons for satisfaction which were easy handling and maintenance level of easy exploitation, no requirement of electricity and low installation cost and increasing interest of gender participation in agriculture activities. Involving women for

maintaining zero energy based post-harvest farming system will improve the farmers' overall economic condition by reducing the loss of fruit and vegetables. It will also increase the daily uptake of fruit and vegetables which will reduce the malnutrition problem in the rural areas of Bangladesh. The other major factors quoted by farmers were the improvement of the bargaining capacity which is directly related with their financial benefits. Therefore, a lot of extension effort is required on the dissemination of zero energy storage chamber technology in the developing countries. Further, Islam et al. [62] proposed a framework for dissemination and training of rural farmers is shown in

Fig. 44:

Fig.44. Participatory survey and framework for dissemination of the brick wall cooler storage system in the rural areas

7.3 The important advantages of the brick wall cooler storage system are as follows:

- a. Depending upon the performance of the system used, the operating cost gets

reduced by 20% - 60% below that of refrigerant air conditioning. The temperature achieved by evaporative cooling is higher and varying unlike air conditioned system;

b. Power consumption is less resulting in a sharp reduction in the running costs. Because of this reason, the indirect evaporative coolers can also be used where electricity is expensive or scarce; and

c. It can be used as a pre-cooler for refrigerant air conditioning systems.

8. Conclusion

This paper carried out a review study into the developing progress of the brick wall cooler storage system in terms of its originality, current status, research and implementation achievement, benefit and possible barriers. A brick wall cooler storage system doesn't require any electric energy; that is made from locally available materials. It is noiseless, simple in structure, easy to operate and maintenance cost is low. The brick wall cooler storage system can maintain relatively low inside temperature and high relative humidity as compared with outside temperature and relative humidity. Temperature inside the brick wall cooler storage system can be reduced through the process of an evaporative cooling mechanism and by using a shading curtain to protect the brick wall cooler storage system against direct exposure to solar radiation.

Under shading condition, temperature reduced from 27.8°C to 13.8°C, and increased humidity increased from 65.9% to 91.7%, respectively inside the brick wall cooler storage system. But under no watering and no shading conditions, the inside temperature and relative humidity were 29.4°C and 64.1%, respectively. However, there were few differences between the shelf life of tomato and eggplant as increased by the silver-ion-coated container and copper grain. Copper grain is very heavy in weight and might cause mechanical damage to fruits during the storage period. Therefore, a

combination of lower temperature and higher humidity inside the cool chamber, along with hot water treatment and the use of a silver-coated storage container could prevent the decay of tomato and eggplant, while increasing the shelf life of tomato and eggplant. The inside temperature of the brick wall cooler storage system as affected by climate factors is quite complex and uncertain. An intelligent optimization technique combined with neural networks and genetic algorithms was applied to minimize the inside temperature of the brick wall cooler storage system. The control input was watering which is supplied to the filler made from sand and zeolite between the brick walls. First, the inside temperature of the brick wall cooler storage system as affected by the outside temperature, watering and inside RH was identified using the neural network. A three-layered neural network with a time-delay operator was useful for identifying this dynamic system. Then, the genetic algorithm was used for searching for the optimal 8-step ON-OFF intervals of watering which minimize the inside temperature of the brick wall cooler storage system through simulation of the identified neural-network model. High diversity of the population by adding some individuals from another population and having high crossover and mutation rates shortened the searching time for the global optimal value. The optimal intervals obtained for the watering schedule were $T_1 = 35$ min ON, $T_2 = 55$ min OFF, $T_3 = 35$ min ON, $T_4 = 55$ min OFF, $T_5 = 35$ min ON, $T_6 = 55$ min OFF, $T_7 = 35$ min ON, $T_8 = 55$ min OFF, $T_9 = 35$ min ON, $T_{10} = 55$ min OFF, $T_{11} = 35$ min ON, $T_{12} = 55$ min OFF, $T_{13} = 35$ min ON, $T_{14} = 55$ min OFF, $T_{15} = 35$ min ON, and $T_{16} = 55$ min OFF. The average inside temperature for this optimal control was 4.0 °C lower than that for the continuous watering for 24 h, and was also 7.5 °C lower than that for no watering. Furthermore, the shelf-life of the tomatoes during storage in the optimized brick wall cooler storage system was extended

from 7 to 16 days. Thus, it is concluded that the brick wall cooler storage system optimized with an intelligent optimization technique combining with the neural network and genetic algorithm achieves a minimum inside temperature and is therefore effective for storing tomato from the viewpoints of low cost and energy saving.

Furthermore, a new brick wall cooler storage system with two types of cooling system, a solar-driven adsorption refrigerator and an evaporative cooling system, was developed. The solar-driven adsorption refrigerator produced about 3.5 kg of ice per day with a solar COP of 0.071. The ice was then stored in the ice box and cooled the storage space well throughout the following day. Both cooling systems allowed lowering of the inside temperature of the new brick wall cooler storage system without any electricity. The inside temperature during the diurnal change was lowered to 20.9 °C by watering and then further reduced to 10.1 °C by applying the solar-driven adsorption refrigerator, while the ambient outside temperature was 32.0 °C. The average inside temperature of the new brick wall cooler storage system for twenty-three days was 12.07 °C, while the average outside temperature was 31.5 °C, and the shelf life of tomatoes was extended from 7 to 23 days. Physiological loss in weight (PLW) of 5.4%, firmness of 0.3 kg·cm⁻², TSS of 5.1% and pH of 4.7 were obtained after storing tomatoes for 23 days. Thus, the new brick wall cooler storage system proposed here is very effective in lowering the storage temperature and expanding the shelf life of fruit and vegetables in an area without electricity. This system can help to store medicine and vaccine in the remote areas of the developing countries. The effectiveness of this new system could be improved by finding new light weight, low-cost, high heat conducting, and environmental friendly materials for collector, condenser and evaporator; it is necessary to conduct field trial in the farmer's level.

From the field study it has been observed that an appropriate low cost sustainable storage solution within the rural farmer's financial ability is to construct brick wall cooler storage system which has to be both operational friendly and environmentally sound. Brick wall cooler storage system can contribute to changing the rural agricultural based society as an effective approach to develop household-based low cost fruits and vegetables storage in this country. Farmer's community gave a positive respond about the use of brick wall cooler storage system. To disseminate this newer technology, training program was found very much effective, where participant learnt about the necessity and benefit of brick wall cooler storage system for their daily livelihood. From a gender perspective, this study also improved the social position of women. Consequently, the combined use of different postharvest treatment such as heat treatment, wax emulsion; perforated polythene bag, antibacterial storage box and integrating the solar vapor adsorption based cooling system with brick wall cooler storage system has become the potential perspective approach for the present and future trend of the zero energy storage development.

Acknowledgments

The authors would like to acknowledge the financial support provided for this research by the Toyota Foundation's Asian Neighbors Program on "Improving food security and farmers socioeconomic condition in Bangladesh through the dissemination of a zero energy cool chamber" (2010–2012); ESPEC Foundation, Japan, under its 15th Global Environment Research and Technology (2012–2013) fund; JST A-STEP FS stage Search-type Program (2012); the United Graduate School of Agricultural Sciences (UGAS), Ehime University, Japan, under its student research project support program

(2013–2015); and Grants-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (No.26450354, 2013–2016).

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