A techno-economic assessment for viability of some waste as cooling pads in evaporative cooling system

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Abstract: The viability of some waste as cooling pads for evaporative cooling application in South-Western Nigeria was experimentally assessed. This is to ascertain their effectiveness as a substitute for costly imported pads in a low income environment. Also presented was the feasibility of utilizing standalone evaporative coolers for storage and selling of fruits in South-Western Nigeria. Natural ambient air was forced through the various pads at three different fan speeds and constant cooling pad thickness of 30 mm. Performance characteristics were considered based on daily analysis using temperature and humidity data measured from morning to evening at location co-ordinates latitude 7°10′N and longitude 5°05′E for 6 weeks. The daily temperature T and humidity h ranged between $26°C \leq T \leq 45°C$ and $28\% \leq h_2 \leq 80\%$. Temperature difference ΔT and humidity difference Δh of $0.6°C \leq \Delta T \leq 18.3°C$ and $1.0\% \leq \Delta h \leq 53\%$ was achieved for the four cooling pad materials tested at three fan speeds. Highest ΔT and Δh was recorded at fan speed of 4 m/s with shredded latex foam and jute sack respectively. The cooling efficiency (η) calculated for all the pads under the three speeds ranged from $17.3\% \leq \eta \leq 98.8\%$. Payback period (PBP) analysis indicated the considered EVC is economically feasible and investors will break even in 1.75 years.

Keywords: evaporative cooling, agricultural residues, passive cooling, cooling effectiveness, cooling pads

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1 Introduction

The full deregulation of the power sector in Nigeria in 2013-2014 presented new challenges to the electricity consumers in terms of increased energy cost. This is as a result of the removal of government subsidy on electricity consumption. The analogue electricity billing method is being replaced with pay as you consume metering systems in many states especially in western parts of the country. Households are seeking for alternative ways to conserve energy and reduce cost. One of the major areas of interest should be the use of energy efficient appliances with lower power consumption. In Nigeria house cooling and cold storage consumes a lot of energy and globally it can range between 40% to 70% of the total energy consumption of a country[1]. Northern Nigeria experiences long spell of dry or harmattan weather with temperatures sometimes in the upper forties and humidity as low as 20% while the southern part can experience the same weather though at a shorter time especially around December to February. Therefore air conditioning is required to support daily living. Generally the most common methods used to accomplish room cooling and cold storage is the utilization of mechanical vapour compression cooling or

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refrigeration. Most of these systems have low energy efficiency ratio and the electric power required to power them is generated from power stations that employ the burning of fossil fuels to generate their power. The by-products of the burning of the fuel like CO_2, sulphides, soot and hydrocarbons are hazardous to the environment and contribute to the increase in greenhouse gas emission which depletes the ozone layer. Various chloro-fluorocarbon refrigerants used by these systems contribute also to the environmental problem when they are released to the atmosphere. This adds up to the increased taxation of the electricity company in terms of environmental tax and the burden is usually transferred to electricity consumers in the form of increased billing.

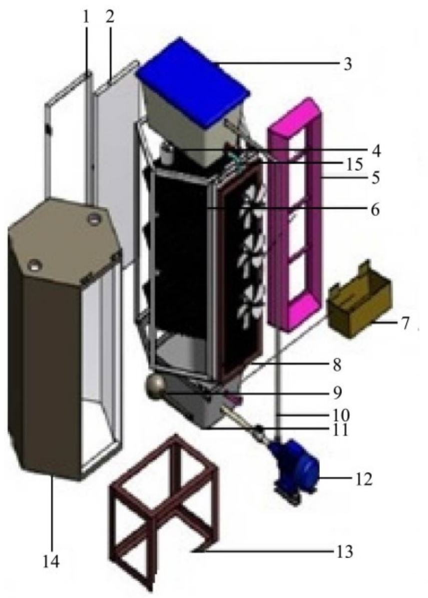
However various attempts has been made in Nigeria to replace the stand alone mechanical vapour compression systems with standalone evaporative coolers (EVC) which is environmental friendly and energy efficient[2-5]. These efforts are hampered by (1) the unpredictability of the weather condition where there are frequent period of hot weather with high humidity which does not support evaporative cooling[2]; (2) lack of quantitative data on effective cooling pad; and (3) lack of investments and utilization due to lack off detailed economic assessment. The first problem makes generalization of results over days or months in EVC difficult and the conclusion very subjective because each day can presents variable weather conditions[6]. Therefore the use of hourly temperature and humidity difference is a common way of evaluating EVC performance[2-8] and the same method is adopted in this research to tackle the second and third problem mentioned above. Therefore this research focused on the feasibility of using palm fruit fiber, wood charcoal, jute fiber and shredded latex foam as cooling pads. These materials represent waste material from palm fruit processing, cooking at homes and in furniture making. The aim of this research is to investigate the viability of each kind of these materials in real time to provide a room cooling condition for home or fruit, water or vegetable, and also analyze the profitability of EVC utilization in South Western Nigeria. The success of the research will expand the choice of pad materials available in the country and provide a cheaper alternative from costly and scarce pads from abroad and also convert these wastes to wealth. Palm fruit producing countries can involve companies with better equipped technology to process and package the palm fruit fiber into cooling pads which add to their GDP.

2 Methods and analysis

This study was conducted from December 2012 to February 2013 at a location in Akure, Nigeria (7°10′N and 5°05′E). A standalone EVC locally developed at the agricultural engineering workshop of Federal University of Technology Akure for preservation of fruits and vegetables and presented in literature [9] was used for the experimental analysis. Four materials, palm fruit fibers, wood charcoal, jute fiber and shredded latex foam were tested for their viability as cooling pad in EVC. These materials were sourced as waste from palm oil processing, burning of firewood and fabrics and padding in furniture productions. The palm fruit and jute fibers were washed, dried and weaved into strands and weaved into 300 mm×400 mm×60 mm dimension with a packing density of about 20-22 kg/m^3 while the latex foam and charcoal were shredded. Following is the discussion of the entire procedure.

2.1 Experimental procedure

Figure 1a and 1b illustrates the operation of the EVC. The figures shows the arrangements of the various components of the system which includes the fan, water pump, water tank, the cooling pad and the positions of the thermocouples. The water sprays over the top edges of the pad from the upper water tank through pinhole perforations overlaying the top of the pads. The water distributes through the pad by gravity and capillary action and percolates into the bottom water tank. The electric water pump controlled by a water level thermostat intermittently pumps the water back to the upper tank and the above process repeated. The three fans suck in warm air across the pads and most of its heat is absorbed by the water which it uses to evaporate and the temperature of the air drops. The cooled air passes through the horizontal path to provide the supply air into the room. The speed of the fan is controlled through a variable speed regulator. Three fan speeds of 3.0, 4.0 and 4.5 m/s was used throughout the research. Each experiment lasted for a week. However, because the weather data (inlet ambient temperature and relative humidity) kept on varying between days and only one cooler was used for all the experiments, it will be difficult to compare performance for all the pads for days or months based on replications and statistical data. This has been corroborated by researchers[2,6,7]; therefore a typical day data has always been used in presenting results and this method is followed in this research. Measuring was carried out using thermocouples reading at 4-points centralized on a data logger system (omega data logger, HH1147) and a laptop computer (HP 650) and averaged out on a one hour time scale before being processed. A hand-held vane digital anemometer (microprocessor, AM-4826) in front of the pads was used to measure the airflow rate travelling through the pad at three points. The experiment started at 6:00-9:00 and ended at 17:00-18:00 local time (t). Pad thickness and water flow rate were constant while the air flow rate was established through the adjustment of the speed regulator.



Components of the evaporative cooling system		
S/N	Description	Qty
1	Door frame	1
2	Door	1
3	Upper water tank	1
4	Air vent	1
5	Air channel	1
6	Fruit and vegetable tray	1
7	Water collector	1
8	Cooling pad holder	1
9	Water control switch	1
10	Water return pipe	1
11	Sump	1
12	Water pump	1
13	Stand	1
14	Cooler housing	1
15	Water distribution header	1

Figure 1a Exploded form of the EVC showing the arrangements of the components to form the EVC

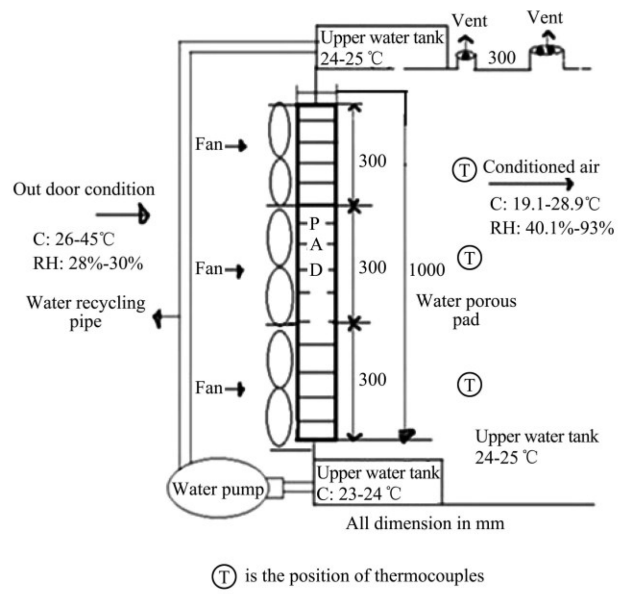


Figure 1 b Schematic representation of EVC

2.2 Performance evaluation

Performance evaluation of the pads was based on change in temperature ($\Delta T = T - T_C$), change in relative humidity ($\Delta h = h_c - h_2$), where T is the temperature of warm air at inlet (ºC); T_c is the temperature of the air after passing the cooling pad into the room (ºC); h_2 is the ambient relative humidity (%) and h_1 is the room relative humidity (%) and the cooling efficiency of the EVC calculated as Equations (1)[2-8] as follows:

$$\text{cooling efficiency } (\eta\%) = \frac{T - T_s}{T - T_w} \times 100 \tag{1}$$

where, T is the dry bulb temperature (ºC); T_w is the wet bulb temperature (ºC) and T_s is the temperature of cooler storage space.

2.3 Statistical analysis

Mean temperature data T_m and humidity data h_m and their variance σ^2 were determined by Equations (2) to (5)[10]:

$$T_m = \frac{1}{n}\sum_{i=1}^{n} T_i \tag{2}$$

$$h_m = \frac{1}{n}\sum_{i=1}^{n} h_i \tag{3}$$

where, T_i and h_i is the temperature and relative humidity at time t.

$$\sigma_T^2 = \frac{1}{n-1}\sum_{i=1}^{n} (T_i - T_m)^2 \tag{4}$$

$$\sigma_h^2 = \frac{1}{n-1}\sum_{i=1}^{n} (h_i - h_m)^2 \tag{5}$$

2.4 Cost analysis of the cooling pads as integral component of the evaporative cooler

The cost of the evaporative cooling pads is analyzed as an integral part of the standalone EVC which is primarily designed for storage of fruits and vegetables. The cost is calculated using the present value Cost (PVC) expressed in Equation (6)[11].

$$PVC = \left[I + Com\left(\frac{1+r}{r-i}\right) \times \left[\left(1 - \frac{1+i}{1+r}\right)^n\right] - S\left(\frac{1+r}{1+i}\right)^n \right] \quad (6)$$

where, I is total investment, Com is operational and maintenance cost, n is useful life of the evaporative cooler, r is interest rate, S is salvage value and i is the inflation rate. The following assumptions were made in calculating the cost: (i) lifetime of the evaporative cooler was considered to be 10 years; (ii) Interest and inflation rates were taken to be 20%and 16%, respectively (based on the countries current value); (iii) 5% of the system cost was assigned for annual repair and maintenance; and (iv) Investment cost being the total cost of all cost involved for the fabrication and installation of the evaporative cooler. This involves the cost of mild steel sheet, cooling pads (cost involved is for gathering, transportation, washing and preparation into installation shapes) water pump, plastic tank, PVC pipes elbow joints ball and socket valves aluminum sheets, fiber glass, three suction fans, floating valves, angle iron, switch and sockets, electric cables, variable speed regulator and labour. Therefore the total cost of initial investment for the 0.24 m^3 EVC was estimated at ₦70 000 ($353.54; 1$≈₦198). The salvage value (v) was put at 10%.

2.4.1 Evaluation of payback period

The payback period (PBP) is a critical economic decision making tool. PBP is the expected number of years required to recover the original investment. Investors will like to get back their money quickly and payback period becomes an important cost analysis tool. It is the ratio of the initial investment to the estimated equivalent uniform annual benefit (E)[12]. Also literature[13] stated that shorter payback period means greater project's liquidity and makes the project less risky. The PBP is the value at the point when the accumulated PVC equals the present value benefit (PVB)[12]. The PVB is calculated using Equation (7) as follows:

$$PVB = E\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \quad (7)$$

The estimated equivalent uniform annual benefit (E) or net annual cash flow in a particular year j is given as[13]:

$$\begin{aligned} E &= (Cash\ input)j - (Cash\ output)j \\ &= Pr\ from\ sales - (com\ and\ op - crcp) \end{aligned} \quad (8)$$

where, Pr is gain from selling fruits or vegetable using EVC; $com\ and\ op$ is the cost of maintenance and operation and $crcp$ is the cost of replacing the cooling pads every month.

To determine the estimated equivalent uniform annual benefit (E) or net annual cash flow, the following decisions were made: (i) the stand alone evaporative cooler is used for storing tropical fruits and vegetables; (ii) the 100% shelf life of most of the tropical fruits is 15 d and they are available around a period of 4 months in a year[14]; (iii) the evaporative cooler is also available around 4 months in a year (i.e November-February when the weather conditions favours its operation which translates to 100% availability in a year; however in South Western Nigeria, the major available fruit is orange, banana, paw-paw and cashew to a lesser extent while tomato is available in the north within this period; (iv) there is no risk of losses in fruit; (v) on a conservative estimate, the cooler can handle 500 kg of fruits in a month, however based on 4 months availability of the cooler and fruits, this will translate to 2 000 kg/a; (vi) in 2014 during December period 1 kg of orange is purchased at between ₦120–₦150 ($0.6–$0.76) and sold around ₦150–₦200 ($0.76–$1.01) depending on locality which translates to a profit of ₦30–₦50 ($0.15–$0.25) per kilogram (this is based on real time market assessment from fruit sellers) i.e average of ₦40 per kg ($0.2 per kg); (vii) the EVC utilizes 20 L of water in a week at a cost of ₦5 per 20 L which translates to 320 L/a based on 4 months availability of the EVC and fruits; (viii) the cooling pad is proposed to be replaced once per month at a cost of ₦360 ($1.82) each (ix) it is assumed that the electric fan runs continuously for the whole day while the water pumps intermittently throughout the day; (x) the maximum total power utilized is calculated as the sum of the rated power of each electrical components (fan -0.02 kW and pump -0.35 kW) and if they are used for 24 hours a day , the total energy consumed by the EVC is given as 8.88 kW·h/d and 1 065.6 kW·h/a based on

4 months availability of fruits and the EVC; (xi) present market cost of electricity in Nigeria, is ₦24/kW·h ($0.120) as at December, 2014[15]; (xii) Maintenance and repair is taking as 5% per annum i.e ₦3500 ($17.68); and (xiii) assuming no subsidy was obtained from government based on the above assumption and analysis, the complete iteration of the estimated equivalent uniform annual benefit (E) or net annual cash flow is shown in Table 1.

Table 1 Net cash flow calculation

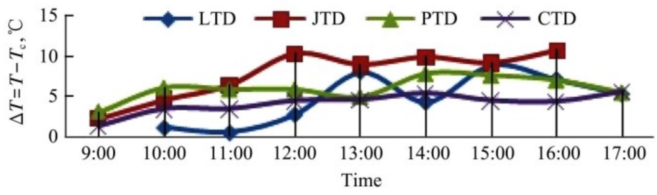
Total cash input	₦80000 ($404.04)
Total cash output	₦30594.4 ($154.52)
Annual net cash flow	₦49404.96 ($249.52)

3 Results and discussion

This study present a comprehensive techno – economic evaluation of shredded latex foam, jute fiber, palm fruit fiber and wood charcoal sourced as agro waste as cooling pads using a standalone EVC over a 6 weeks period from late December 2012 to early February 2014. Calculations were made to determine the EVC cooling efficiency (η), ΔT, Δh and cost of investing on the said EVC. The following is the presentation of the key results obtained.

3.1 Temperature and relative humidity

Figure 2, 3 depict a typical daily temperature variation while Figure 4-6 depict a typical daily relative humidity variation between the ambient (inlet) value and storage room value for the four pads at 3.0, 4.0 and 4.5 m/s fan speed. The daily trends of the four pads are somehow comparable as greater value of ΔT and Δh were achieved between 11:00-15:00 local time with few exceptions partly due to the unpredictability of the weather conditions. The mean daily ambient data for the four pads lies between (27.2-32.85)ºC ± (0.725-4.29)ºC for the ambient temperature, (21.96-28.25)ºC ± (0.38-2.07)ºC for the storage room temperature, (31.9%-64.7%) ± (2.02%-18.49%) for the ambient relative humidity and (57.42%-91.06%) ± (0.202%-16.59%) for the storage room as show in Table 2. However as depicted in the schematic presentation of EVC in Figure 1b, the daily temperature T and humidity h ranged between $26^{\circ}C \leq T \leq 45^{o}C$ and $28\% \leq h_2 \leq 80\%$. Temperature difference ΔT and humidity difference Δh of $0.6°C \leq \Delta T \leq 18.3°C$ and $1.0\% \leq \Delta h \leq 53\%$ was achieved for the four cooling pad materials tested at three fan speeds as shown in Figure 2-6. Highest value of ΔT and Δh was obtained at fan speed of 4 m/s with shredded latex foam and jute sack respectively.



Note: LTD=ΔT for latex foam; JTD=ΔT for jute fiber; PTD=ΔT for palm; CTD=ΔT wood charcoal

Figure 2 Periodic ΔT for the EVC at 3 m/s for the four cooling pads

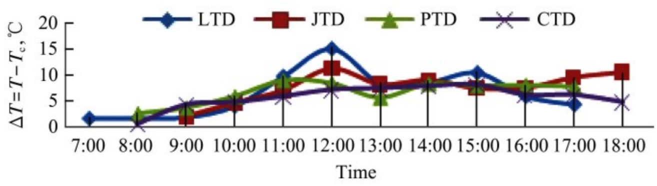


Figure 3 Periodic ΔT for the EVC at 4 m/s for the four cooling pads

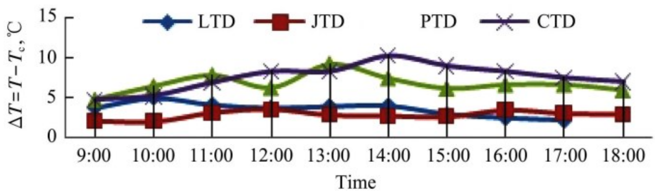
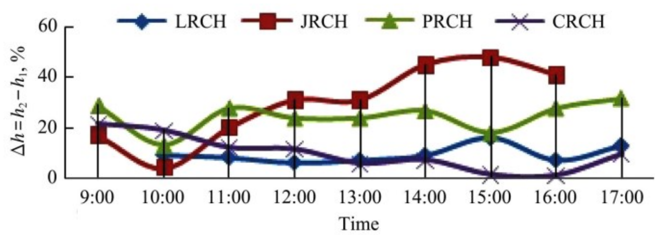


Figure 4 Periodic ΔT for the EVC at 4.5 m/s for the four cooling pads



Note: LRCH=Δh for latex foam; JRCH=Δh for jute fiber; PRCH=Δh for palm fiber; CRCH=Δh for charcoal

Figure 5 Periodic Δh for the EVC at 3 m/s for the four cooling pads

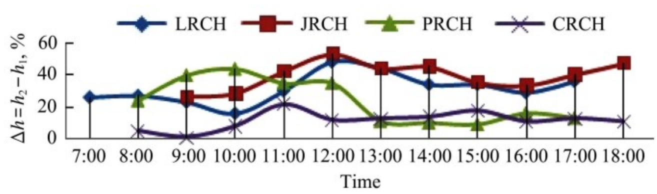


Figure 6 Periodic Δh for the EVC at 4 m/s for the four cooling pads

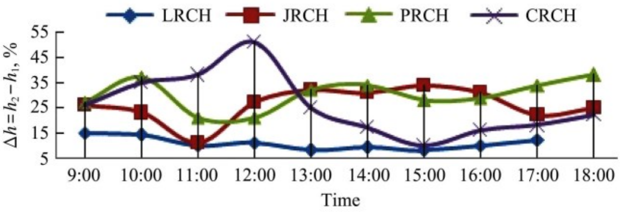


Figure 7 Periodic Δh for the EVC at 4.5 m/s for the four cooling pads

Despite the wide variation of the mean cooler temperature of 21.96-28.25°C the daily variation for each pad is very small as shown in the standard deviation (σ_{Tc}) of the storage room temperature of each cooling pads in Table 2. Therefore there was no significant difference in T_c at $t_{\alpha = 0.05}$ as show in Table 2. However wider variation (p>0.05) was obtained in most ambient (inlet) temperature and relative humidity and slightly in relative humidity of the storage rooms except wood charcoal as also show in Table 2. Generally jute fiber and shredded latex foam provided a higher ΔT at lower air speed of 3 m/s and 4 m/s while wood charcoal provided a higher ΔT in the afternoon at 4.5 m/s. Comparatively for most cooling pads higher ΔT was recorded at 4 m/s, however 4.0 m/s also presented wider variation in storage room temperature values and 4.5 m/s less variation for latex foam and jute fibers as show by σ_{Tc} in Table 2. Also the relative humidity of the storage room was better improved at 4 m/s compared to 3.0 m/s and 4.5 m/s for most of the cooling pads; however the variation in h_c was inconsistent with fan speeds.

Table 2 A typical day EVC characteristics for the four pads

Item	Shredded latex foam			Jute fiber			Palm fruit fiber			Wood charcoal		
	Fan speed/m·s^{-1}											
	4.5	4.0	3.0	4.5	4.0	3.0	4.5	4.0	3.0	4.5	4.0	3.0
T_{am}	29.68	32.26	32.85	27.2**	31.79	32.43	29.76	28.73	28.68	32.87	31.55	30.77
h_{am}	58.42	54.72	55.65	64.7	45.7	39.34	39	31.9**	31.67	33.5	48.09	61.11
σ_{Tam}	1.108	4.29	3.90	0.725	2.94	3.15	2.8	3.93	2.12**	2.90	3.79	2.54
σ_{ham}	3.61	12.67	7.86	4.62	11.83	12.06	3.77	2.02	2.55	4.11	18.49	10.01
T_{cm}	26.5**	25.22**	28.25**	24.4**	23.15**	24.74**	23.37**	21.96**	22.6**	25.22**	25.77**	26.61**
h_{cm}	70**	90	64.2	91.06	84.81	70	71	70	57.42	63.36	59.66	61.5
σ_{Tc}	1.04	1.15	1.08	0.38	1.01	0.54	2.07	2.49	1.44	1.59	1.98	1.49
σ_{hc}	0.202	9.45	5.46	6.63	8.03	9.26	9.88	14.32	4.94	19.53	15.41	16.59

Note: T_{am}- mean inlet air temperature, h_{am} - mean inlet air relative humidity, σ_{Tam}- - inlet air temperature standard deviation, σ_{ham} - inlet air relative humidity standard deviation, T_{cm}- mean storage room air temperature, h_{cm} - mean storage room air relative humidity, σ_{Tc} – storage room air temperature standard deviation, σ_{hc} storage room air temperature standard deviation, ** p < 0.05.

3.2 Cooling performance of the EVC

The hourly cooling efficiency at the three different speeds for the four cooling pads was presented in Table 3. From the results the maximum cooling efficiency of 98.8% was obtained using palm fruit fiber at 4 m/s and the lowest of 17.3 was obtained for shredded latex foam at 3.0 m/s. Cooling efficiency takes into account the wet bulb temperature of the inlet air[16-20]. Because the cooling fluid in EVC is water, therefore the minimum temperature that can be achieved in EVC is the wet bulb temperature. This implies the closer the T_c is to the wet bulb temperature the higher the cooling efficiency (η). For the four cooling pads the cooling efficiency obtained was 17.3% ≤ η ≤ 98.8%. Mostly lower η was obtained from 6:00-11:00 and 16:00-18:00 local time with few exceptions which is a function of the inconsistency of weather behavior pattern. Also higher η was obtained at 4.0 m/s with also few variations for all the cooling pads.

3.3 Cost of utilizing the EVC for commercial purpose and the payback period.

The cost of the cooling pads was analyzed as an integral component of the EVC because the benefit that can be achieved in EVC is as a result of using the entire system not only cooling pad. What the cooling pad does is to lower the initial cost of investment. The cost of the cooling pads was summed as the total cost of transportation, washing and labour. Therefore the cost of cooling pads only was predicted at ₦360 ($1.82) which is a cost component of the whole EVC. The accumulated present value cost (PVC) and accumulated present value benefit (PVB) is shown in Figure 8. The PVC equals PVB at 1.75 years which is the payback period (PBP) which shows that the EVC is highly economical feasible to be used in South-Western Nigeria. The result by extension shows that EVC will be highly suitable in northern Nigeria because of more and longer favourable feather weather.

Table 3 Calculated cooling efficiency for the four cooling pads

Time	Fan speed/m·s^{-1}											
	4.5				4.0				3.0			
	Shredded latex foam	Jute fiber	Palm fruit fiber	Wood charcoal	Shredded latex foam	Jute fiber	Palm fruit fiber	Wood charcoal	Shredded latex foam	Jute fiber	Palm fruit fiber	Wood charcoal
6:00	50.9	-	-	-	-	-	-	-	-	-	-	-
7:00	54.6	-	-		41.7	-	-	-	-	-	-	-
8:00	57.7	-	87.7	62	40.2	-	46.1	31.3	-	-	-	-
9:00	63	93.8	89	65.7	46.3	83.3	69.4	85	-	-	49	51.85
10:00	70.9	89.3	85.9	77	79.8	74	96.7	77	34.3	53.5	88	90.4
11:00	64.5	92.6	83.11	83.6	82.9	81	96	91	17.3	17.4	86	77.95
12:00	57.5	85.7	87.6	70	87.7	92.6	98.8	65	73.5	71.9	84	77.98
13:00	57	84.3	75	83	84.9	79.61	75.5	65	90.9	91.1	-	74.31
14:00	55.6	78.3	69	76	85.0	73	90	64	81.8	78.8	66	68.61
15:00	40	75.4	68	65	95.4	84	85.74	63	92.7	79.7	85	52.69
16:00	31.9	83.7	74	70	61.3	83	88.62	55	94.7	74	81	55.69
17:00	28.5	91	67	61	49.1	83.4	85.25	55	90.3	72.3	96	67.8
18:00	-	80	-	-	-	95	-	46	-	-	81	-

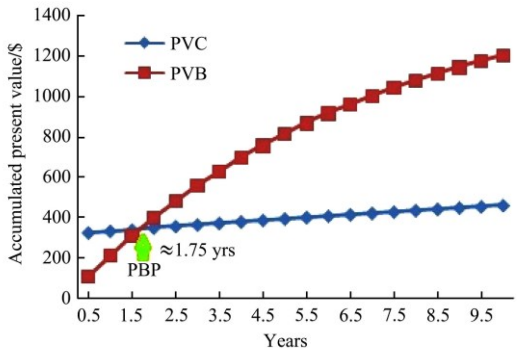


Figure 8 Accumulated PVC and PVB for 10 years

4 Conclusions

Evaporative cooling utilization in fruit and vegetable preservation or in homes to cool houses is one of the methods to overcome the effect of fossil fuels and hydrocarbons to the environment. Also with the increased tariff on electricity utilization in Nigeria diversification to more environmental friendly and energy conserving equipment has become necessary. For this reason, closer assessment of equipment and various ways to channel resource to achieve the above objective is important for investment. Therefore the following conclusions are drawn from the study of techno-economic viability of some waste utilization in EVC which are affordable and also the feasibility of EVC application in South Western Nigeria:

1) With the daily temperature T and humidity h ranged between 26ºC $\leq T \leq$ 45ºC and 28%$\leq h_2 \leq$ 80% around December 2013 and February in South Western Nigeria, temperature drop ΔT and humidity increase Δh of 0.6ºC $\leq \Delta T \leq$ 18.3ºC and 1.0% $\leq \Delta h \leq$ 53% is achievable using active EVC with shredded latex foam, jute fiber, palm fruit fiber and wood charcoal around December and February in South Western Nigeria.

2) Performance ranged of 17.3%$\leq \eta \leq$ 98.8% can be achieved in using EVC in South Western Nigeria.

3) Operating the EVC at 4.0 m/s fan speed gave a higher ΔT and daily T_c for all the pads are not significant at p<0.05.

4) Lower efficiency was obtained around 6:00-11:00 and 16:00-18:00 local time with few exceptions.

5) All the cooling pads can lower the inlet air temperature and improves its relative humidity to some extent though this can vary based on the prevailing weather conditions.

6) Investment on EVC for selling of fruits is economically feasible around December to February with a payback period of investing in EVC in South Western Nigeria as 1.75 years.

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