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Development and Performance Evaluation of an Evaporative Charcoal Cooler for the Conservation of Biological Material

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Abstract:

In tropical regions, post-harvest losses of fruits and vegetables caused by high temperatures is a major challenge in agriculture, especially in places with poor or no power supply for the functioning of very efficient cooling systems. Vegetables and fruits are highly perishable due to their high moisture and heat content. Given their nutritive and economic importance, they need to be conserved fresh, though famers in rural zones can't afford sophisticated cooling technology. This study presents an evaporative charcoal cooler as an alternative cooling technology to refrigeration that could be used to store fresh fruits and vegetables. Tomato (*Solanum lycopersicum*) was chosen to be the main vegetable to be freshly conserved; a survey revealed that fruit firmness was the main attribute used by tomatoes retailers to appraise tomato quality, followed by juicy secretions from the fruit, in the main market of Dschang. The charcoal cooler was constructed with local materials to have a storage capacity of 0.33m³ for fruits and vegetables. The charcoal evaporative cooler was able to extend the shelf life of stored tomatoes by 6 days, as it maintained at least an average temperature drop of 4.80°C and 3.76°C with a corresponding increase in relative humidity of 22.61% and 18.17% in the dry and wet seasons respectively compared to ambient condition. This resulted to a maintained storage temperature and relative humidity of 20.85°C and 87.94% against an ambient temperature and relative humidity of 24.57°C and 69.33% respectively with an average cooling efficiency of 81.02%, making the stored fruit to lose 2.76% and 4.65% weight in the cooling room and ambient condition respectively.

Keywords — **Temperature drop, Charcoal evaporative cooler, Cooling efficiency, Fruits and vegetables.**

I. INTRODUCTION

The increase in global population, together with the increased purchasing power of the middle-class population in developing countries with emerging markets will result in a projected increase in food demand of 50–70 % by mid-century [1], [2]. In contrast, to this background of rising global demand in food, it is estimated that about one billion people are chronically under-nourished and suffer from nutritional deficiencies [2]. Furthermore, future food security; which is the ability of the world to provide enough safe and nutritious food for its entire population, is deeply threatened by emerging environmental constraints such as stringent climate change, land degradation, and water scarcity [3], [4]. The issue of food loss prevention has recently achieved high importance as part of worldwide efforts to combat global hunger and improve food security, since reducing food losses will increase food availability and security, and promote environmental sustainability [5], [6]. Studies indicated that in low-income countries, food losses result largely from managerial and technical limitations in harvesting techniques, storage, transportation, and processing activities, because of lack of proper cooling facilities, infrastructure, and packaging and marketing systems [7]. More to these, fruits and vegetables generally harvested with very high moisture contents of over 90%, which makes them very perishable [8]. A significant portion of tomato fruits is lost because of poor handling and marketing conditions, especially in Sub-Saharan Africa (SSA). In Cameroon, both exotic and indigenous vegetables are mainly cultivated during the rainy seasons, with high productivity leading to huge post-harvest losses [9]. According to [10], for post-harvest losses to be reduced, affordable storage and processing technologies need to be identified and developed to prolong the shelf life and marketability of fruits and vegetables for longer periods after harvest.

Vegetables and fruits are highly perishable agricultural goods due to their high water content and their metabolic activities which are even more accelerated when harvested [8]. These products when harvested are still living and are at high temperatures due to the heat accumulated throughout their growing and developmental stages; this heat is due to transpiration, respiration and ripening even after harvest; must be rapidly removed to avoid rapid deterioration of the product. This heat can be removed through cooling, but the average small scale farmer can't afford the sophisticated cooling technologies available such as refrigerator, hydro cooling and vacuum cooling due to their high purchasing and running cost. Because of these, farmers of vegetables and fruits are experiencing post-harvest losses which globally in developed and less developed countries ranges from 7-53% and 7-70% respectively, making the famers not able to maximize profit on their produces, forcing to sell at giveaway prices in order to avoid them getting bad and being of no economic value [11]. The availability of an alternative cheap cooling technology will be of great benefit to them. Evaporative charcoal cooler is a cooling technology that works on the principles of evaporation to lower temperature by about 10°C while increasing relative humidity; similar conditions that are necessary for the fresh preservation of fruits and vegetables [12]. Evaporative cooling is a cooling technology used in food preservation, which the world bank and the food and agricultural organisation (FAO) advocate for rural zones not connected to the grid [13], [14].

The aim of this study is to characterize the suitability of a charcoal evaporative cooler in the town of Dschang during the raining and dry season with respect to the preservation of tomatoes. This aim was archived by identifying the deterioration criteria of tomatoes from producers, designing and constructing the charcoal cooler and lastly evaluating the performance of the cooler.

II. MATERIALS AND METHODS

A. *Presentation of the study zone*

The current study was carried out, in the agricultural engineering research unit of the University of Dschang. Dschang is the head quarter of the Menoua division in the West region of Cameroon. More precisely, the study practice is carried out in “cite la prudence” on the 3rd floor of its building which is at an altitude of 1355m. Dschang, is situated between longitude 10° and 10°5 East of the Prime meridian and between latitude 5°25’ and 5°30’ North of the Equator. It belonging to the western highlands gives it a mountainous relief with an average altitude of 1400m and covering an area of 228km² [15], [16].

Dschang has a sub equatorial climate which gives a dry season that last averagely for four months going from mid-November to mid-March, and a rainy season which runs from mid-March to mid-November, with an annual average rainfall between 1200-1800mm. The average daily temperature is 20.9℃ and an average daily humidity ranging from 33% to 98% [17], [18], [15].

Solar radiation or the sun intensity is more important during the dry season, where it represents 8.5hours per day, while in the rainy season it drops to 2.2 hours per day. Dschang, throughout the year has a total sunshine of 1,864 hours per year. The recorded average monthly insolation is 155.3 hours.

B. *Designing and construction of the cooler*

The choice of the evaporative cooler is that of a passive direct evaporative cooler which has a soaked media or pad charcoal. The cooler was passive, because in many rural areas or zones in Cameroon and precisely in the study site, the access to a reliable source of energy (electricity) is very limited and many producers can't also afford it. Also, the choice of making it a direct evaporative cooling system, is attributed to its high performance ranging between 55 to 70%.as mentioned by [19], [20]. Furthermore, using charcoal as the soaked media or pad is due to its relative abundance in markets and also because of its very good porous nature to retain water and in the same like allow air pass through. Lastly, the choice of making the evaporative cooler as a temporal storage of fruits and vegetables, is also due to its relative cheap cost of affordability owing to that the material used in its realisation are local materials and readily available.

The cooler is basically a small room with charcoal walls. Two wooden frames are constructed with woods of 5cm thickness (Fig. 1). The first (inner) frame is made by cutting the woods with a sowing machine to have woods of 0.75m which are then joint and nailed with a harmer. The second (outer) frame is made to have dimensions of 1mx1mx1m. With the help of joining woods, the inner frame was being inserted into the outer frame, with a spacing of 8cm being ensured between. With the help of mesh wires surrounding both the inner and outer frame to hold and maintain charcoal that is being loaded into the 8cm spacing to make the wall, this is done on all four walls including the security door. The roof is made of plywood with a vent on it to allow more air circulation and preventing condensation within the cooling box (chamber). The floor alongside the shelves is lined with mesh wires, so as to allow for water that could result from the tomatoes spoilage or condensation to drain to the ground. The inner cooler was lined with shelves on which the biomaterial will be kept on inside the cooler.

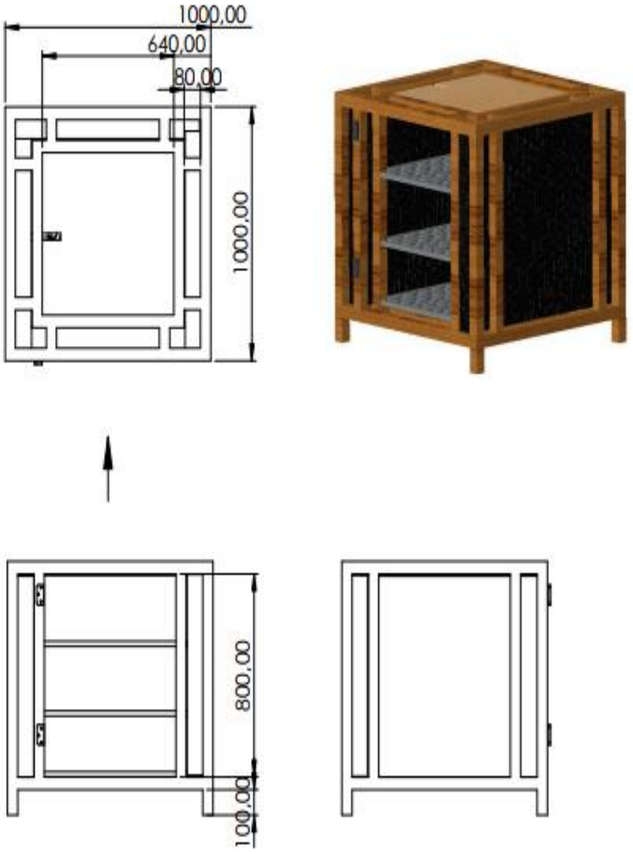

Fig. 1 Designing of the charcoal evaporative cooler

C. Evaluating the performance of the cooler

The evaporative charcoal cooler was being tested during the dry and rain season for a total of 32 days, for which 5 days in the dry season and 27days of the rain season.

- **Technical material**

The temperature and relative humidity both within the cooling box or chamber and the external environment were measured using a DHT 11 temperature and humidity sensor for 32 days, DHT11 sensor belongs to the arduino tool. This sensor was chosen owing to its dual functionality and its compatibility to the arduino cart. Equally a thermocouple of mark Hti (HT-9815) was used to ensure the validity of the temperature read by the DHT sensor.

Fig. 2 Thermocouple and Surface pro connected to Arduino DHT11

A surface pro tablet machine (Fig. 2) was used as a power source to power the arduino cart and also to display the readings from the sensor on the monitor with the help of the arduino coding software (version 1.85), this is so because the machine could ensure a continuous reading while going for a battery could not. Also, the readings of the temperature and relative humidity were recorded after every one hour from 8am in the morning to 4pm in the evening using a single DHT 11 sensor, which was inserted into the cool box via a vent on the top and allowed for two to three minutes for the sensor to sense the right temperature as indicated by the thermocouple and consequently the corresponding relative humidity. The readings were taking from 8am to 4pm, because towards the evening and very early in the morning, the temperature and relative humidity are very low and high respectively and there is very little or no evaporation taking place at those hours. The data collected were transferred to an excel spreadsheet using Excel software 2010 of the office package.

Fig. 3 Mass of tomatoes being measured

An electronic precision balance 0.01 (Silver Crest) was used to measure the masses of the biomaterial (Fig. 3) every evening and morning when the ambient conditions and that within the cooling box are almost similar. The mass read was always recorded on an excel spreadsheet in the Excel software of the 2010 office package.

- **Biological material**

Tomato (*Solanum lycopersicum*), was used as the test biomaterial. These vegetables and fruits, is a product of the season (climaceric), was chosen because of its abundance on the market and the difficulty producers, retailers and consumers are facing in its fresh conservation. Indeed, the municipality of Dschang is a cosmopolitan centre and a production basin of tomato. Due to problems of lack of effective means of conservation we are witnessing significant post-harvest losses. In addition, the abundance of these products causes a drastic drop in market prices in such a way that they are not means of preserving the freshness of the product to meet up with the period of scarcity of the produce; and this contributes to the reduction of farmers' incomes. The fruit was harvested directly from the farm and the temperature at harvest was equally recorded.

The fruit was harvested at two different maturity stages for the second trial, that is ripe (red) and half ripe (yellowish green). While, the tomatoes for the first trial was harvested when it was ripe. However, the tomatoes for the trials came from different farms. The tomatoes were first washed to remove any traces of chemical that was used to protect the plant against pest and disease and which are liable in accelerating the deterioration of the product after being harvested. For the experimental test, the biomaterial was then weighed and placed in the cooler and also allowed in ambient condition (control test) under shade.

The cooler after construction was put to test under conditions of load and non-load in the dry and rainy seasons. For the dry season, only data for the non-loading conditions were recorded and consequently, comparison will be made only on the bases of non-loading between both rainy and dry season.

- **Calculating the cooling efficiency**

The cooling efficiency of the charcoal cooler was determined using the ASHARE 1997 model which was equally used by [21], can be written as follows:

$$\eta_{cooling} = \left(\frac{T_{ent} - T_i}{T_a - T_{wb}}\right) \qquad 1$$

Where:

$\eta_{cooling}$ = cooling efficiency (%)
T_{ent} = ambient dry bulb temperature (°C)
T_i = internal dry bulb temperature (°C)
T_{wb} = ambient wet bulb temperature gotten from ASHARE approved calculator

- **Calculating the loss in weight**

The average mass of the tomatoes was calculated in order to have a representative of the masses of each of the tomatoes using equation (2) and the change in mass was then determine using equation (3) daily till when the vegetables under conservation were declared bad.

$$M = \frac{m}{n} \qquad (2)$$

$$\Delta M = \left(\frac{M_i - M_f}{M_i}\right) * 100 \qquad (3)$$

Where:

M = Average mass of a tomatoes (g)
M_i = Initial average mass of tomatoes (g)
M_f = Final average mass of tomatoes (g)

ΔM = Change in average mass of tomatoes (%)
m = Total bulk mass as read (g)
n = Number of tomatoes in a bulk

III. RESULTS AND DISCUSSIONS

A. *Physical appreciation of deteriorated tomatoes*

The survey conducted shows that each retailer has a different degree of appreciating the physical degrading parameters of freshly harvested tomatoes with respect to their purchasing cliental (Fig. 4). It was found that firmness (37%) was the most outstanding criteria used by the retailers followed closely by juicy secretions 33%, to indicate that a given fruit isn't fit for selling and hence consumption. While 23% and 7% of the retailers make use of the presence of fruit fly and mould as physical indicators of a degrading tomato fruit (all other parameters kept constant). Equally, these attributes determine the attractiveness of a consumer towards a given fruit.

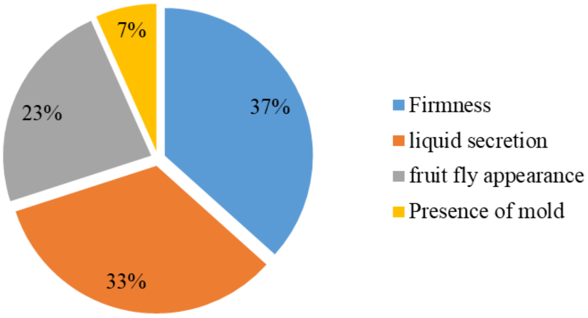

Fig. 4 Parameters checked by retailers to determine a bad fruit

These retailers due to their bulk purchase from producers, conserve their fruit under ambient conditions that is, in open air under the suns and cover them with polyethylene bags during times of rains and in the night. Based on the above degradation criteria, the retailers are able to record averagely 14 days and 7days shelf life for a well on-farm treated fruit during the dry and rainy season respectively. Equally, averagely 7 days and less than 3 days for a poorly on-farm treated tomato fruit during the dry and rainy season respectively.

B. *Designed and constructed charcoal cooler*

The 0.33m³ capacity evaporative charcoal cooler (Fig. 5) for the storage of fruits and vegetables was constructed to have a charcoal wall of thickness 8cm. the cooler is made up of three storage shelves and a vent at its top for more air circulation. The mounting up of the entire frame was done in wood.

Fig. 5 Evaporative charcoal cooler put to use

C. *Performance values*

- **Cooler efficiency**

The average cooler efficiencies for a 9hours period reveals that the cooler efficiency ranged between 71.15% and 95.68%. It is seen that the variation of the cooling efficiency doesn't fallow a linear pattern as in the 8th, 11th, 15th and 16th hours of the day; the cooling efficiency is above 80%. At the 15th and 16th hour, the efficiency is highest, that is above 90%. This coincided to a period where cooling of fresh produce is much needed [22]. The average cooling efficiency was 81.02%, which is less than the cooling efficiency of charcoal when use as the wet media for evaporation as gotten by [23].

A maximum cooling efficiency of 95.68% was attained at a high temperature difference of 5.17℃. At a low outside air (ambient) temperature, the interior cooled temperature is marginally lowered and, hence, has a small temperature drop. It implies, therefore, that a higher evaporative efficiency has the potential to significantly increase the cooling capacity of the cooler.

- **Ambient and cooler air properties**

The ambient temperature and relative humidity were always lower and greater than that in the cooling box (Fig. 6). In the dry season, the average ambient temperature and relative humidity were

27.88℃ and 40.37% and the evaporative cooler was able to maintain an average storage temperature of 23.12℃ and a relative humidity of 62.98%, thus a temperature drop and relative humidity increase of 4.80℃ and 22.61% respectively during the 5 days of dry season in which the cooler was tested. Peak average temperature drop was 6.80 ℃ and a corresponding 32.3% increase in relative humidity in the dry season, on the 10th hour.

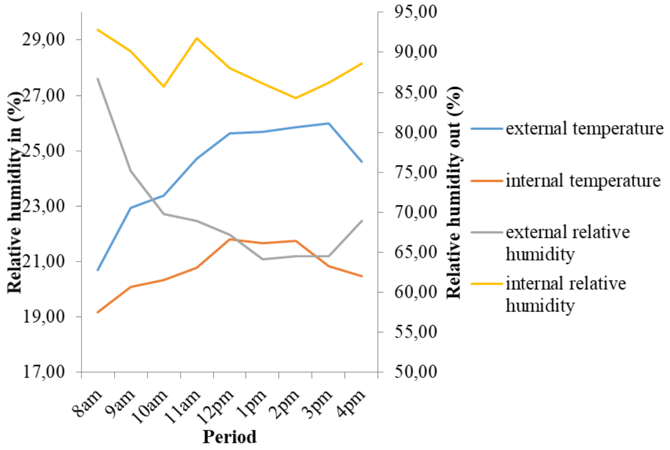

Fig. 6 Conditions in and out of the cooling box

During the rainy season, the average peak temperature drop was 5.20℃ in the 15th hour and an increased in relative humidity of 22.8% on the 11th hour. The average ambient temperature and relative humidity out of the box were 24.57℃ and 69.33% respectively against an in cooler temperature and relative humidity of the storage box of 20.85 ℃ and 87.94% respectively. The evaporative cooler during its 28 days of testing in the rainy season maintained an average temperature drop of 3.73℃ and relative humidity increase of 18.17%.

These conditions maintained in the rainy season made the evaporative cooler extend the shelf life of the fruit by 6days after the fruits that were stored under ambient conditions lasted for 15days and a majority of them had already be diagnosed with the physical criteria of deterioration as indicated by the retailers. The tomatoes in the storage box lasted for 6 more days before the effective pronouncement of senescence because, the rate of metabolic activities, respiration and transpiration were greatly reduced compared to the ambiently stored fruits. This is in accordance with the Q10 law, which states that; For every 10 ℃ (18℉) increase in temperature, the rate of deterioration increases by two to three folds [13]. Respiration rate of commodities is directly related to product temperature, the higher the temperature, the higher the respiration rate. Low temperature reduces the respiratory activity and prolongs perishable commodities' shelf life because respiration, ethylene production and water loss are minimized which result in delay of ripening and senescence of produce.

- **Physiological weight loss**

From an initial averaged weight of 90.36g and 99.29g, in both ambient and cooler storage conditions respectively, it was found out that, there was a rapid increase in weight loss for the tomatoes kept under ambient conditions than the tomatoes kept in the charcoal cooler (Fig. 7). Throughout the 15days, for which the fruits stored under ambient conditions took to get bad; the average physiological weight loss was 4.84% (4.37g) and 2.74% (2.72g) of weight loss for ambient and cooler storage respectively, this implies that; the evaporative cooler microclimate increased the shelf-life of the selected produce.

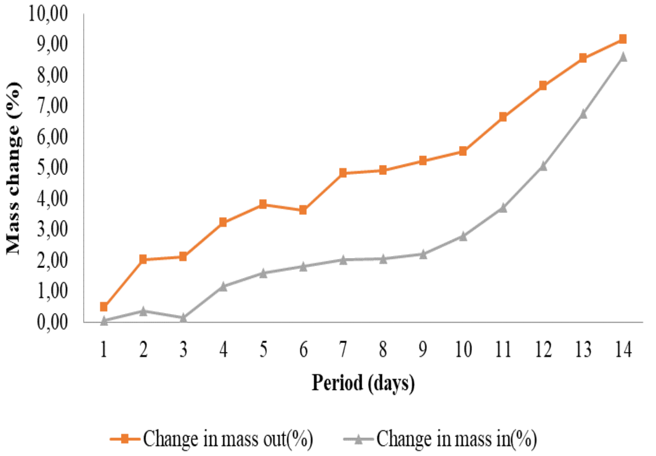

Fig. 7 Physiological weight loss variation

- **Colour change and firmness**

The whole (Fig. 7-1) and cut section (Fig. 7-2) of both tomatoes stores in ambient and cooler storage conditions, due to the excessive loss of water from the ambient tomatoes as a results of excessive respiration and transpiration the tomatoes after 28 days became twisted and consequently softer (Fig. 7-1A) than the corresponding tomatoes stored in the evaporative cooler (Fig. 7-1B) which because of the high relative humidity and low temperature to which it was subjected to made it to respire and transpire less and hence making it to loss less water, and by so making the tomatoes in the cooler more smooth and firm (looking more fresh for consumption).

The cut section (2), revealed that the content of the tomatoes stored in ambient condition (Fig. 7-2A) was more liquefied than that stored in the cooler (Fig. 7-2B) this can be because, the metabolic activities going on in the fruits stored in the ambient condition was more than that of the cooling box due to its higher temperatures. When relative humidity is high as it was in the cooling box, the tomatoes maintained its saleable weight, appearance, nutritional quality and flavour, while wilting, softening and juiciness are reduced.

Tomato deterioration with respect to retailers and consumer's appreciation is very subjective, but this study shows that fruit firmness is the most indicative attribute used by these tomatoes dealer to judge the quality of a tomato fruit as being good or bad. This results corroborates with the findings of [24], [25], [26]. Equally, as a results of the packaging methods adopted by the surveyed tomatoes retailers during the nights of the dry and rainy seasons (covering the fruits with polyethylene papers), the shelf life of the fruits found were not in accordance to the findings of [27], this is probably due to the fact that tomatoes are a climacteric fruit and the climates where [27] did the search are different and owing to the different in tomatoes variety.

The variation of cooling efficiency within the day as results of constant changes in weather conditions is in line with the findings of [28]. However, the average cooling efficiency obtained is less than that found by [29] for charcoal when used as the wet media. The variation in cooling efficiency showed a proportionate relationship existing between temperature drops and cooling efficiency which is in accordance with the findings of [29] as predicted by equation (1).

It could also be seen that the relative humidity and temperature of ambient air was always low and high respectively when compared to air relative humidity and temperature within the storage box as reported equally by [37], [20], [30]. The average temperature drops and relative humidity increase recorded corroborates with that found by [13], [31].

The difference in average temperature drop and relative humidity change, in the cooler between the dry and the rainy season can be due to the difference in the air relative humidity and temperature. In the dry season, air moisture content or relative humidity and temperature were very low and high respectively, giving the air to have a very high evaporative rate compared to the air of the rainy season. High evaporative rate means greater wet bulb temperature depression being achieved for evaporative cooler [32].

The tomatoes fruit were able to have a shelf life extension of 6 days, which is very short when compared to the shelf life extension of 18 days reported by [23]. However, the shelf life under ambient condition reported by [23] is very short (2days) when compared to the 15 days shelf life obtained by this present work. These differences could be attributed to a difference in weather conditions, a difference in variety of fruit, a difference in pre and post-harvest handling. Most of the tomatoes that were placed in the cooling box, went bad though still very firm as a result of mould apparition; this deterioration could be attributed to chilling injury caused by extreme low temperatures at nights and condensation of water on the tomatoes (dew point temperature was often reached on rainy days and at night) which led to the growth of mould, which are one of the consequences of using an evaporative cooler as reported by [23], [33].

The overall decrease in weight of the fresh fruit observed is in agreement with the findings of [19], [34], [36], [37]. Ambient weight loss was greater than the weight loss of tomatoes kept in the cooling chamber, a similar result was gotten by [23], [30], [33], [35]. Equally, the results gotten by [19] is in accordance with the findings of this work, that is; fresh horticultural produce should generally be stored at lower temperatures because of their highly perishable nature, was verified as the stored fruit under these conditions had its shelf life increased. The lengthening of the shelf-life is adequate for ensuring that the produce takes a significantly longer time to get to the markets (for producers transporting their produce far markets), for a favourable price fluctuation and making consumption at a later day before it goes bad [19], [31]. The high relative humidity and low temperatures in the evaporative cooling system discouraged microorganism actions on the selected produce (tomatoes) leading to a lengthened shelf-life. The outdoor conditions, on the other hand, provided an optimum environment for the microorganisms' respiration and metabolism of the fresh produce [23]. In this way, the produce is subjected to a hastened structural decay when compared to that stored in the evaporative cooler. It means then that, under the outdoor conditions, the produce will lose most or all of their nutritive capacities and, hence, negatively affect their marketability. Weight loss of fresh tomato has been reported by [8] to be primarily due to transpiration and respiration which are higher in ambient condition due to its high temperatures and low relative humidity which causes a higher rate of metabolic reactions.

- **Degradation of local material use for construction**

During the course of using the evaporative cooler, it was observed that the local material used such as the iron mesh wire and charcoal became rusted and suffered from the accumulation of minerals respectively (Fig. 8). Charcoal that was initially black became grey-whitish.

Fig. 8 Rusting and mineral deposition effect

The observation made about the low resistance of the local material used for the construction of the cooler, was one of the disadvantage highlighted by [36], [37] which was equally the case in this study.

IV. CONCLUSIONS

This study was carried out in an agricultural engineering research unit at the university of Dschang in order to provide an alternative accessible storage facility for fruits and vegetables. An evaporative charcoal cooler was designed, constructed and tested with tomatoes. The charcoal cooler was constructed with the cooling chamber (inner box) having a storage capacity of $0.33m^3$ making it capable of storing 304kg tomatoes. At the end of this study, tomatoes firmness was the most predominant attributes (37%) used to tell if a tomatoes fruit was bad or not, followed by juicy secretions (33%), presence of fruit fly and mold development as reported by large tomatoes retailers. The evaporative cooler maintained an average temperature drop of 4.80℃ and 3.73℃ in the dry and rainy season respectively. While there was an average increase in relative humidity by 22.61% and 18.17% for the dry and rainy season respectively. This led to an increase in shelf life by 6 days. Averagely the cooling or saturation efficiency of the cooler was 81.02%. There was a 2.74% and 4.84% fruit weight loss in the cooler and in ambient conditions respectively. The material uses to make the charcoal cooler are not resistant.

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