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Development and Performance Evaluation of a Solar Powered Tomatoes Storage Chamber

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Abstract. Fresh vegetables and fruits, most of which are perishable, are known to be good sources of nutrients supplements with health benefits. Tomatoes fruits fall into this category of food supplements. However, the post-harvest losses associated with tomatoes fruits have greatly reduced the profitability of its farming and have even scared some farmers away from producing it. To reduce the losses and encourage tomatoes farming, this study designed, constructed, and evaluated the performance of a solar-powered electronic storage chamber for tomatoes fruits. In the performance evaluation, the weight, firmness, ripening index, and rate of spoilage of tomatoes fruits stored, within six weeks, at room temperature and atmospheric humidity and in the storage chamber were analyzed and compared per week. The results showed that the weight and firmness of the test experiment deteriorated by 24.87% and 20.83% respectively while that of the control experiment deteriorated by 50.59% and 79.68% respectively. Also, the percentage of cumulative spoilage for the test and control experiment was estimated to be 23.32 and 68.84 respectively showing a significant reduction in the rate of spoilage when the tomatoes were stored in the chamber.

Keywords: Tomatoes, Farming, Solar system, Electronic Storage Chamber, Post-harvest Losses

1. Introduction

Vegetables and fruits are known to be good sources of many traditional nutrients and are consumed worldwide due to their health benefits[1] [2]. Tomatoes are one such fruit that is available and consumed everywhere in the world today as a result of their high bioactive phytochemical contents [2] [3]. Tomato is a delicate fleshy fruit comprising distinct tissues including the pericarp (made up of the endocarp, mesocarp, and exocarp), placenta, septum, and locular tissue that contains seeds [4]. The fruit volume increases as a result of biophysical constraints by epidermal flaccidity and the development of pericarp tissue which forms the largest proportion of the fruit weight [5] [6]. Two activities in the pericarp, namely, cell division and expansion are determinants for tomato growth. Cell division in the epidermis is a continuous process that lasts throughout the development of the fruit while the cell division process in the pericarp lasts for only a short period. After cell division might have ceased, the fruit size continues to increase through cell expansion.

Tomato fruits have attractive colors and can be processed for consumption in the forms of peeled tomato (diced or whole), ketchup, sauce, and juices as a good source of carotenoids, and ascorbic acid and phenols [1] [7] [8]. Though tomatoes are consumed everywhere in the world, they are not produced everywhere. While they are available in excess in some regions, they are scantly available in other regions. Consequently, transportation over long distances may be required to get the excess produced in one region to meet the demand of the people in those other regions where tomatoes are scantly available. Also, tomatoes are climacteric in nature and thus continue ripening after harvest and have high water content and soft-thin-easy to damage and rot fruit skin resulting in short shelf life [9] [7]. The above makes tomatoes to be subject to large post-harvest losses [10].

In addition, tomato production is seasonal, and as such the fruits are available in excess in a particular season of the year at which time the market price is normally very low [11] [12]. To ensure the continuous availability of tomatoes all through the year and also help the farmer to obtain better returns, there is a need to preserve the excesses gathered during the harvest period [13].

Furthermore, harvested tomato fruits are exposed to several external factors capable of causing product deterioration [14]. These include chilling injury, (which is a postharvest physiological disorder initiated by abnormal storage temperature that could lead to inhibition of color development, surface pitting and disease susceptibility [15]), microbial contamination (especially Salmonella enterica serovar Typhimurium), and poor handling such as improper packaging after harvest [8].

The post-harvest losses associated with most perishable fruits (tomatoes inclusive) have adverse effects on food security, consumers' tastes, and income generation via Agriculture. Post-harvest losses have discouraged many from farming which would have helped to reduce the unemployment rate of the present time to the barest minimum. Farmers, both in the rural and urban areas are compelled to sell their perishable fruits, especially tomatoes at give-away prices immediately after harvest for the fear of decay, rot, loss of original flavor, taste, color, and nutritional value. The above and consumers' growing concern for product quality have made research into fruit storage and preservation attractive in the last decades [16].

Traditionally, low-temperature storage is used to preserve tomato fruits with sensory and nutritional value retention [17]. However, at low temperatures (< 10^0C), tomatoes are prone to chilling injury [18] [19] which is capable of shortening the shelf life of the fruits. High temperatures above 30^0 C are also not ideal for tomato fruits storage as the same tends to increase fruit softening which could result in increased wastage [20]. Thus, this study evaluates the performance of a solar-powered temperature-regulated electronic system for tomato storage. The power supply to this unit is from a solar PV system since the system is targeted for use by rural dwellers where there is electricity supply from the utility company to preserve their farm produce and as well improve carbon footprint in the environment.

2. Key indicating parameters for determining stored tomatoes quality

2.1. Theoretical Model for Tomatoes weight analysis

The weight and composition of any fruit are depended mostly on the balance between the outward and inward flow of water and carbon to/from the fruit, which involves several processes. One of such processes is transpiration, which leads to water loss from the fruit leaving a concentration of soluble compounds thereby decreasing the weight of the fresh fruit. Cell division and expansion are the determinants of the final size of the fruit [21]. However, in this study, the following parameters were used for the theoretical model for the weight analysis: $\mathbf{A\ =Surface\ area\ of\ tomato}$, ($m^2$), $\mathbf{D\ =\ Diameter\ of\ tomato}$,Re = Reynolds number, Sc = Schmidt number, W = Weight of tomato, (kg), $\boldsymbol{\rho\ =\ }\mathbf{Density\ of\ tomato}$, ($kg/m^3$), ρa = Density of air, (kg/m^3), p = Absolute viscosity in kg/ (ms), v = Kinematic viscosity,(m/s^2).

For a spherical body like tomatoes, with airflow rate at Reynolds number between 25 and 100,000, the heat transfer co-efficient is given as,

$$hc\ =\ (0.37)\ (Re)0.6/D \qquad 1$$

Also, weight loss per area can be evaluated as this

$$A = \pi d^2 \quad (2)$$

and internal weight loss is given as:

$$W_L = \pi/6 \rho D^3 \quad (3)$$

Diving equation (4) by (3) will give

$$Internal\ weight\ loss\ per\ area = W_L/A \quad (4)$$

2.2. Physiological Weight Loss

The methodology described by Workneh et al in [22] and Haile in [23] was adopted in the physiological weight loss of the specimen. Equations (5) and (6) were used to calculate the physiological weight loss and successive weight loss of the fruits expressed as a percentage of the initial weight respectively.

$$Weight\ loss = W_i - W_t \quad (5)$$

$$Percentage\ loss\ in\ weight = \frac{W_i - W_t}{W_i} \times 100\% \quad (6)$$

Where;
$W_i = initial\ weight$, and
$W_t = weight\ at\ current\ storage\ time.$
After the storage process, the storage-ability of the chamber was measured as a percentage cumulative total loss in weight of tomatoes during the storage period of six weeks.

2.3. Firmness

Firmness is one of the key determinants of tomatoes quality. Its measurement is critical for quality control reasons, as well as for post-harvest studies in order to develop a procedure for handling and preservation of fresh tomatoes. The firmness, F, consists of a fixed part and a first-order mechanism as the variable part. For this study, equation (7) was used to estimate the firmness of the tomatoes' fruits.

$$F = (f_{\circ} - f_{fix})\, e^{-kt} + f_{fix} \quad (7)$$

Where
F *is the* firmness at current storage time *t* (measured in Newton);
f_0 is the initial firmness (measured in Newton);
f_{fix} is the fixed part of the firmness (measured in Newton);
$\boldsymbol{k\ is}$ **the** $\boldsymbol{reaction\ rate\ constant\ at\ temperature\ t}$;
t is the time (in weeks)

The magnitudes of both the invariable and the variable parts of firmness depending on the perimeter and surface area of the puncture probe. To accommodate the differences in the magnitudes of firmness between the puncture probes, equation (7) was multiplied by a factor called the correction factor (*corr*). Thus the equation becomes:

$$F = (f_{\circ} - f_{fix})\, e^{-kt} + f_{fix}\ .corr \quad (8)$$

Where;

$$Corr = \frac{(1 - f_{cs}).A}{A_{ref}} + \frac{f_{cs}.P}{P_{ref}} \quad (9)$$

Where;
A is the surface area (obtained from the diameter of the probe
P is the perimeter (also obtained from the diameter of the probe)
f_{cs} and 1 - f_{cs} represent the relative influence of shear force and compression force on firmness.

The referee area and perimeter could be obtained using any chosen diameter for the probe. The reference diameter chosen for this study is 1.5 mm. The inclusion of reference points in the correction factor is to ensure that the dimension factor is dimensionless.

2.4. Ripening Index
One of the most complex attributes of the qualities of fruit is its color. Colour is the most important visible characteristic for assessing the ripeness and post-harvest life of tomatoes fruits. It also influences the purchase decision of consumers. Normally, the degree of ripening of fruits is represented using color charts. The presence of diverse carotenoid pigment which is subject to both genetic and environmental regulation in tomatoes fruit makes the color of ripening tomatoes to be very complex [24]. The Red coloration of ripening tomatoes fruit is the result of the abasement of chlorophyll and the fusion of lycopene and other carotenoids, which results in the conversion of chloroplasts into chromoplasts [25]. Based on the external color, six ripening phases reflecting human propensity to differentiate ripeness were established by the United States Department of Agriculture (USDA). These stages include: green, 100% green; breaker, a noticeable break in color with lesser than 10% of other colors other than green; turning, between 10 and 30% of the surface, in the aggregate, of red(ish) color; pink, between 30 and 60% of red(ish) color; light red, between 60 and 90% and red, more than 90% red [26].

The ripening index denoted as RI was calculated using equation (10):

$$\boldsymbol{RI} = \frac{\boldsymbol{A+B+C+D+E+F}}{\boldsymbol{Y\ x\ Z}} \times \mathbf{100} \qquad \mathbf{10}$$

Where;
$\boldsymbol{A}$, B, C, D E, and $\boldsymbol{F}$ represent the production of the number of fruits and the assigned scores at each stage of ripening.
Y is the total number of fruits in the determination A − $\boldsymbol{F}$
Z is the number of ripening stages in the replicate.

3. Methodology

3.1. Design of the Storage Chamber
For better thermal insulation and firm support, the chamber was made with metallic material that is lagged internally. The volumetric capacity was calculated with the following dimensions

$$\boldsymbol{Chamber\ Length, L_C = 40cm = 0.4m}$$

$$\boldsymbol{Chamber\ Width, \quad W_C = 65cm = 0.65m}$$

$$\boldsymbol{Chamber\ Height, H_C = 80cm = 0.8m}$$

But volume of the chamber, V_C is given by:

$$\boldsymbol{V_C = L_C \times W_C \times H_C} \qquad \mathbf{11}$$

$$\therefore \boldsymbol{V_C = 0.4 \times 0.65 \times 0.8 = 0.208m^3}$$

The chamber has two sections: the refrigerating and the electronic controller section. The chamber uses a compressor of 0.125hp as the electrical load. Solar PV-charged battery storage provides the power supply. The electronic section comprises an electronic circuitry to monitor the two parameters (temperature and humidity) using appropriate sensors as shown in the block diagram of Figure 1.

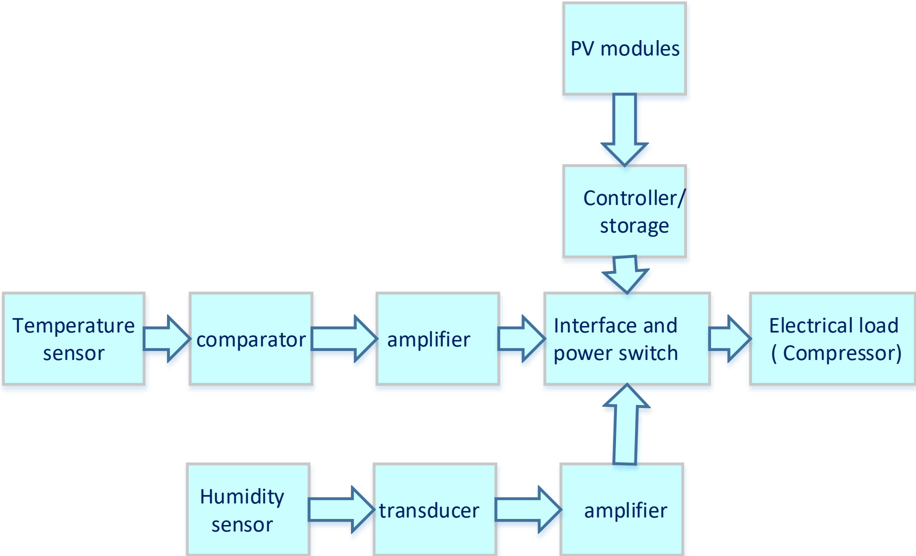

Figure 1. Block diagram of the system

3.1.1. The Temperature Control Unit. The sensor used for temperature was a negative temperature coefficient (NTC) thermistor whose resistance varies with the temperature. The resistance of the thermistor decreases when heated up. The changes in the resistance were sensed by biasing the thermistor and comparing the voltage across it to another voltage representing the sample temperature. The device produced voltage levels related to a temperature difference and sent the various voltage levels to the input of the input port of a peripheral interface controller (LM339). This was used to measure the system's temperature and the output was used to regulate the cooling of the chamber.

3.1.2. The Humidity Monitoring Unit. A capacitive relative humidity sensor which uses a thin strip of metal oxide between two electrodes for relative humidity measurement was used to determine the storage chamber's humidity level. The capacitance of the metal oxide changes with the atmospheric relative humidity. This type of sensor offers various voltage levels to the input of a transistor which acts as an amplifier. The sensor output relative humidity range between 0.5 and 1.

3.2. Design of the Solar Power Unit

The loads that were used for the sizing of the solar PV system used to power the unit are shown in Table 1. The basic component required for a solar power system includes: PV panels, charge controller, batteries for energy storage, and other control interfaces as some level of automation is required. The solar panels were installed on the rooftop of the laboratory due to space constraints and the fact that it is shade-free. 12VDC was used as the system voltage. The solar panels were installed at a tilt angle of 10 degrees facing south [27]. The size of the solar PV was determined using equation (12)

The laboratory used has a flattened concrete roof that could support the photovoltaic power system. It is located at a latitude of 6.677° North (approximately) and a longitude of 3.2334° East. The mean solar irradiation received at the location of the laboratory is 5.43$kW/m^2/day$ [NASA data for Lagos, Nigeria].

Table 1. The Storage Chamber Loads

Load Name	Heater	Compressor	Indicators/Control Units	Total
Load Size (kW)	0.2	0.1	0.005	0.305
Average daily time of use (Hours)	2	4	24	-
Daily energy usage (Watt-hour)	400	400	120	920

The size of the solar panel required was estimated using [28]:

$$W_{SPV} = \frac{E_P}{G * \eta_{sys}} \quad 12$$

Where
W_{SPV} is the Peak wattage of the panels (Watts)
E_P is the peak energy required per day (Watt-hours)
G = number of peak hours per day = $5.43 kW/m^2/day$
η_{sys} = total system efficiency

Using a tolerance of 25%, the daily energy required, E, was estimated to be 1150 Wh
$E_P = 1150Wh$

$$\eta_{sys} = \eta_{PV} \times \eta_{c1} \times \eta_{cc} \times \eta_{Batt} \times \eta_{c2} \quad 13$$

Where
η_{PV} = Efficiency of PV modules taken as 80%
η_{c1} = Efficiency of cables connecting PV array to battery taken as 98%
η_{cc} = Charge controller efficiency taken as 98%
η_{Batt} = Battery efficiency taken as 90%
η_{c2} = Efficiency of the connecting cables between the PV battery to the loads taken as 0.98
Therefore,

$$\boldsymbol{\eta_{sys} = 0.8 \times 0.98 \times 0.98 \times 0.90 \times 0.98 = 0.68}$$

$$\therefore \mathbf{W_{SPV}} = \frac{\mathbf{1150}}{\mathbf{5.43 \times 0.68}} = \mathbf{311.45\ W}$$

For this work, 200W and 130W crystalline modules rated at 12V DC were chosen and connected in parallel to generate the required energy.

Considering the Battery Sizing using equation (14)

$$Q = \frac{E_P \times A}{V \times D \times \eta_{c2}} \quad 14$$

Where:
Q is the minimum capacity of battery required (Ah)
E_P is the daily energy required in (Watt-hour)
A is the number of days of autonomy
V is the system DC voltage (V)
D is the allowable depth of discharge of the battery

Using system data,
E_P = 1150 W-h
A = 1 day
V = 12V
D = 50% = 0.5
$\boldsymbol{\eta_{c2}}$ = 0.98

$$\mathbf{Q = \frac{1150 \times 1}{12 \times 0.5 \times 0.98} = 195.58Ah}$$

From the obtained result, it can be seen that a battery with 195.58Ah capacity is required. The nearest available capacity 200Ah battery was used in this study.

The charge controller regulates the charging of the batteries from the solar PV panels and discharging to the load in order to prevent overcharging and over-discharging to prolong the life span of the battery. A Pulse Width Modulated (PWM) charge controller was used in this design. The chosen controller was built with circuitries that measure and display parameters like charging current from the panel, battery temperature, available stored energy, cut-off voltages (maximum and minimum), operation status, state of charge, and battery voltage. The controller was sized using equation (15) as given by the authors in [29].

$$\boldsymbol{CCS = I_s \times n \times 1.25} \qquad \textbf{15}$$

Where:
CCS is charge controller size,
$\mathbf{I_s}$ is the short circuit current of the panel
n is the number of panels in parallel if panel sizes are the same
1.25 is the safety factor
Now, for the 230 and 100 W panels used, have, $\mathbf{I_s = 8.12 + 5A = 13.12\ A}$
Substituting the values of $\mathbf{I_s}$ and n into equation (15) will give;
$\mathbf{CCS = 13.12 \times 1.25 = 16.40\ A}$
The nearest available charge controller size (50 A) was used in this design.

3.3. Performance Evaluation of the Storage Chamber
The method used for the performance evaluation of the electronic storage chamber comprises the control experiment and test experiment.

3.3.1. Control Experiment

The control experiment consists of 12 kg of tomato placed in a tray in an open space at room temperature and weighed on a spring balance at the end of every week for six successive weeks. The weekly measurements were used to observe and record the changes in weight, firmness, and the ripening index. The results for the control experiment were recorded as presented in Tables 2-5.

3.3.2. Test Experiment
The test experiment consists of 12kg of tomatoes which were also weighed using a spring balance and arranged inside the storage chamber with a pre-set value of 15°C temperature and 97% humidity. The weight of the tomatoes was measured simultaneous with the ones in the control experiment for six successive weeks and the weekly weight, firmness, and ripening index were recorded as shown in Tables 2-5.

4. Methodology

Tables 2 to 5 show the behavioral characteristics of the storage chamber and the response of the tomatoes based on the pre-set value of 15^{0}C temperature and 93% humidity.

The complete assembly of the system (chamber and solar PV) is shown in figure 2. The measurement was taken weekly up till the eighth week. The values observed were shown in the Tables 2 to table 5, the observed changes for the weight, ripening index, and firmness were interpreted in graphical form; The deterioration rate in the weight and firmness of the control tomato was faster than the test tomato, also there was a sharp increase in the ripening index and a large difference in the percentage cumulative spoilage of the control tomato compared to the test tomato.

Figure 2. The complete chamber and solar PV module

4.1. Weight of Tomatoes

Weekly measurement using a spring balance was used to determine the weight of the tomatoes. The results obtained for six (6) successive weeks are shown in Table 2 and figure 3. From the table, the percentage deterioration of the test and control experiment was estimated to be 24.87% and 50.59% respectively.

Table 2. Weekly weight of the tomatoes

Period (Week)	Test Experiment (kg)	Control Experiment (kg)
0	12.00	12.00
1	11.82	10.20
2	11.40	9.12
3	10.56	7.68
4	10.20	6.24
5	9.84	5.88
6	8.88	5.04

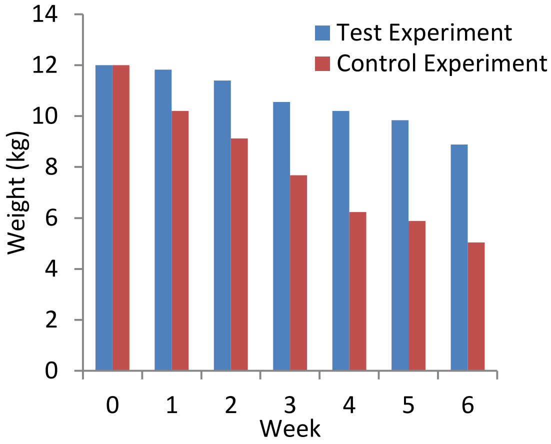

Figure 3. Weekly Weight Chart for the tomatoes

4.2. Firmness

The firmness of the tomatoes in the test and control experiments was determined using a penetrometer. The standard value of firmness for a ripe tomato was reported to be 6.90 ± 2.22 N [30]. However, the readings from the penetrometer scale representing the rate at which the firmness of the tomatoes deteriorates per week are shown in Table 3 and figure 4. From the table, the percentage deterioration in the firmness of the tomatoes in the test and control experiment was estimated to be 20.83% and 79.68% respectively.

Table 3. Weekly firmness of the tomatoes

Period (Week)	Test(N)	Control(N)
0	6.30	6.30
1	5.36	4.32
2	5.28	4.06
3	5.21	3.82
4	5.13	3.01
5	5.06	2.41
6	5.00	1.28

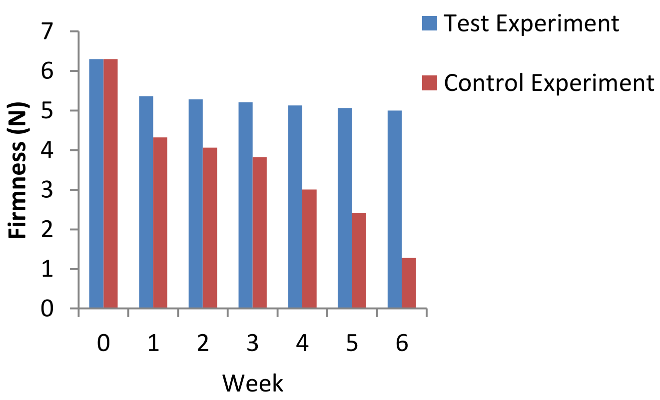

Figure 4. Weekly Firmness Chart for the Tomatoes

4.3. Ripening Index

Equation (10) was used to calculate the ripening index based on observation of the rate of ripening of the tomatoes in the test and control experiment and the results were tabulated as shown in Table 4 and figure 5. The result showed 62% and 152% ripening indices for the test and control experiments respectively at the end of the 6th week

Table 4. Ripening Index for the Tomatoes

Period(Week)	Test (%)	Control (%)
1	0	0
2	6	50
3	19	83
4	30	108
5	45	129
6	62	157

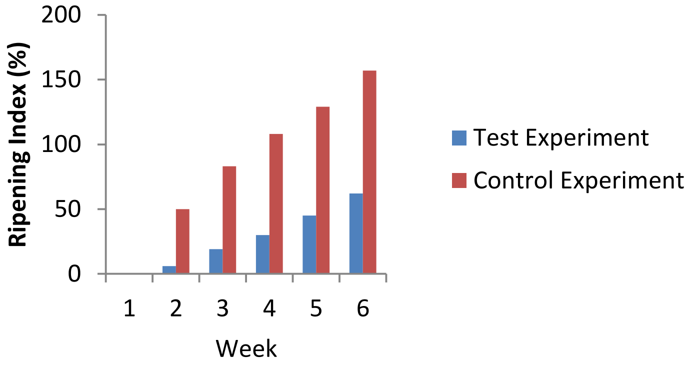

Figure 5. Ripening Index Chart for the Tomatoes

4.4. Percentage Cumulative Spoilage

The percentage of cumulative spoilage per week was analyzed using the mean values of the percentage weekly weight and firmness with respect to the initial weight and firmness respectively. The results of the analysis are presented in Table 5 and figure 6. The results showed that only 23.32% of the initial 12kg of the tomatoes in the chamber got spoilt at the end of the 6th week while 68.84% of the control experiment got spoilt.

Table 5. Percentage Cumulative Spoilage of the Tomatoes

Period (Week)	Test	Control
0	0.00	0.00
1	8.21	23.21
2	10.60	29.78
3	14.65	37.68
4	16.79	50.11
5	18.84	56.37
6	23.32	68.84

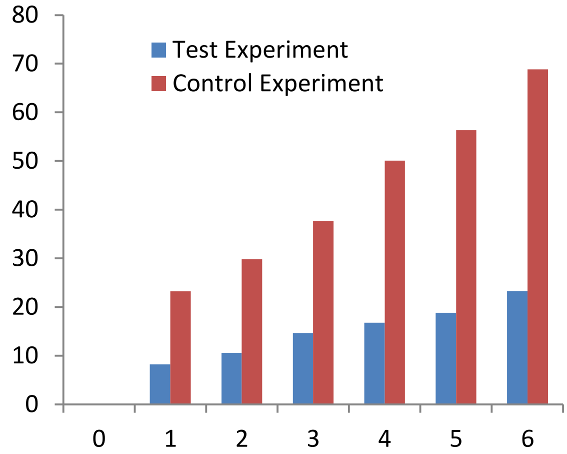

Figure 6. Percentage Cumulative Spoilage Chart for the tomatoes

5. Conclusion

In this paper, the design and performance evaluation of a solar power electronic storage chamber for tomatoes fruit was presented. The chamber was designed with electronic sensors and controllers to regulate the Chamber's temperature and humidity level at 15°C and 93% respectively. The performance of the chamber was evaluated simultaneously with a control experiment in order to ascertain its effectiveness in extending the shelf life of tomatoes fruits.

The results showed that the weight and firmness of the test experiment deteriorated by 24.87% and 20.83% respectively while that of the control experiment deteriorated by 50.59% and 79.68% respectively. In addition, the percentage of cumulative spoilage for the test and control experiment was estimated to be 23.32 and 68.84% respectively showing a significant reduction in the rate of spoilage when the tomatoes were stored in the chamber.

Further works shall consider the electronic storage for other perishable food items like carrots, leafy vegetables, okra, etc., to help farmers reduce postharvest losses and increase profit.

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