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Performance of an Integrated Solar-Greenhouse Photovoltaic Ventilated Dryer with Clay-$CaCl_2$ Energy Storage Desiccants for Tomato Drying

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Abstract: The use of solar energy in drying of perishable crops such as tomatoes is a good alternative to the problem of post-harvest processing in tropical eastern African countries. A review of the literature revealed that most of the solar crop drying systems developed during the last five decades have small loading capacity and cannot operate during the night. Therefore, an integrated solar greenhouse dryer system [SGDS] with Clay-$CaCl_2$ desiccant energy storage system was designed and tested. Such SGDS have the advantage over other solar systems of high loading capacity and structural simplicity. In addition, they have relatively good thermal crop drying performance compared to most solar dryers. However, their main limitation, like most solar dryers, is their inability to dry at night. Therefore, to enhance night-time drying capacity, a prototype SGDS integrated with a low-cost Clay-$CaCl_2$ desiccant energy storage system was designed, fabricated, and tested. The drying performance of this prototype was evaluated using loads of fresh tomatoes during October – December 2019 at Nairobi, Kenya. The dryer was able to dry fresh tomatoes from 93.9% (mcwb) to 8.3% (mcwb) within 27hours with solar greenhouse drying efficiency of 23% during daytime and desiccant drying efficiency of 19.9% during nighttime. The drying rate for the two-day light drying was 0.985kg/h and 0.875kg/h respectively and that in night drying using desiccants was 0.34kg/h. Based on these results, it was concluded that prototype solar greenhouse dryer with Clay-$CaCl_2$ energy storage has great potential for drying perishable produce such as tomatoes in tropical countries.

Keywords: Clay-$CaCl_2$ Solid Desiccants, Desiccant Energy Storage, Drying Efficiency, Drying Time, Solar Greenhouse Drying, Tomatoes

1. Introduction

The global tomato production is currently around 130 million tons, and occupies the second place after the potato [7]. Tomato crop is one of the most consumed agricultural products in the world. While developed countries process 32% of their tomatoes, in East Africa tomatoes are consumed mostly fresh in food preparation leaving up to 45% post-harvest losses, or half of what is grown [15]. This loss is attributed mainly to number of factors including lack of on farm tomato processing industries, inefficient sun drying method, poor road networks infrastructure resulting in mechanical injury during transportation to the local market centers. Other factors for widespread post-harvest loss are attributed to competition from the Common Market for Eastern and Southern Africa (COMESA) imports into the local market [6]. Therefore, it is necessary to reduce post-harvest losses using appropriate post-harvest technology for increased agricultural production in East Africa.

Open sun drying of agricultural crops is widely practiced in East African countries because of its simplicity and low cost. Open sun drying method is labor intensive, produces poor quality dried products and dried products are susceptible to fungal attack and insect infestation. Crop drying extends agricultural products shelf life. Drying of fruits and vegetables requires the right combination of warm temperatures, low humidity, and airflow. Optimum temperature for drying food is 60°C [29]. Higher drying temperatures lead to drying crops being cooked and enhanced microbial spoilage activities [8].

Freshly harvested tomatoes delivered to the market normally fetch good price. However, with time tomato price drops because of loss in freshness accompanied by shrinkage, water loss and rapid deterioration [20]. Also, fully ripe tomatoes are susceptible to injuries especially during harvesting and transportation. Storage life of tomatoes is greatly influenced by the respiration process as well as water loss [23]. For short term storage up to one week, tomato fruits can be stored at ambient conditions [33] with enough ventilation to lower the heat from respiration. For longer storage time, ripe tomatoes can be stored at about 10-14°C and 85-95% relative humidity. At these temperatures, ripening and chilling injuries are reduced to the minimum levels. However, at higher temperature and humidity the quality of tomato is greatly compromised [22]. On the contrary, at very low temperatures the tomatoes can be disadvantageous. For instance, refrigerating tomato will reduce its flavor, the quality trait that is being determined by total soluble solids (TSS) and the pH. In tropical East African Countries, it is also difficult to obtain these conditions and therefore substantial losses of harvested tomatoes have been reported [22 & 14].

Research shows that very small amounts of lycopene are found in other fruits including watermelon, guava, and pink grapefruits as compared to tomatoes [3]. Particularly, solar dried tomatoes are reported to have huge amount of lycopene content as compared to fresh ones [12]. Again, most local industries have not invested in the efficient crop drying technologies in East Africa despite the high nutritive value reported on the processed tomato products. In view of these many post-harvest challenges, this research was carried out to investigate the performance of day-night low-cost solar greenhouse drying system with Clay-$CaCl_2$ desiccant energy storage for use at farm level in East Africa.

Literature review shows that various crop drying technologies available for small scale rural farmers in East Africa are expensive in terms of initial capital as well as operational cost, design complexity and high energy requirements. Under adverse weather conditions especially during harvesting seasons, most farmers experience post-harvest and storage losses amounting to almost 45% of the total output because of a number of factors including lack of crop processing facilities, poor power access and poor transportation infrastructure. Also, the use of expensive fossil fuel has negative effect on the environment and agricultural production. Therefore, this research, developed solar greenhouse drying system with desiccant energy storage for drying tomatoes during the day, followed by desiccant drying process during the night.

Solar drying is a low-cost effective technology especially in sunny tropical countries. Literature review shows that most agricultural crops can be satisfactory sun dried under clear weather conditions. Various designs of small-scale solar crop dryers have been tested in developing countries with positive benefits. Despite these efforts, certain problems remain: extending the drying process overnight times and dangers of aflatoxin formation due to prolonged drying [19 & 25]. The inclusion of desiccants enhances continuation of the drying process into the night period [28] thereby reducing the overall drying time. Desiccant drying involves forcing air through a packed bed of solar regenerated desiccant to absorb moisture from the wet crop.

Therefore, the objective of this paper was to develop solar greenhouse drying system with desiccant energy storage for tomato drying to enable continuous drying operations during day and night time. Further, this study reported on the performance evaluation of the solar greenhouse drying system with desiccant energy storage for tomato drying during day time and night time by calculating the drying efficiency and drying rate of tomato.

2. Materials and Methods

The experiment was carried out at Kenyatta University (KU), Nairobi County (Kenya) with geographical coordinates 1°10'50.0"S, 36°55'41.0"E (Latitude: -1.180568; Longitude: 36.928042) from October to December 2019.

2.1. Experimental Setup

The experimental greenhouse solar dryer with solid Clay-$CaCl_2$ desiccant energy storage system used in this study shown in Figures 1 & 2 was designed and constructed at Kenyatta University (Nairobi, Kenya). It was constructed using locally available materials and equipment. For a maximum passage of solar radiation, the system was covered with transparent greenhouse plastic with transmittance value of 80%. The system was specifically designed to dry fresh tomatoes during day time using solar thermal energy and night-time using solid Clay-$CaCl_2$ desiccants.

The solar greenhouse dryer system was positioned with its longest side on North-South direction to capture maximum solar radiation. Four 25W, 12 Volts DC solar photovoltaic powered fans with speed regulator were installed in the system as shown in Figures 3 & 4. The extractive fans were mounted on both solar greenhouse chamber and desiccant chamber to extract moist air out and enhance the drying process. One fan was positioned in between greenhouse dryer and desiccant chamber to enable moisture removal during the night time using desiccant energy storage system. All fans were powered by two solar modules Polycrystalline 50-Watt solar panel Victron 50W 12V the make of China to charge battery of capacity 200Ah to be used during night.

Figure 1. *Experimental solar greenhouse dryer incorporated with Solid Clay-$CaCl_2$ desiccant energy storage system.*

Ambient temperature, greenhouse dryer air temperature, relative humidity of the inlet and outlet air conditions were recorded, and as well solar radiation. A preliminary experiment was conducted under no load condition to establish the optimal operating conditions of the system and the best one was used to conduct this experiment. Airflow rate were set at three levels for both drying and desiccant chamber. A $0.19 m^3/s$, $0.28 m^3/s$ and $0.45 m^3/s$; and $0.07 m^3/s$ $0.17 m^3/s$ and $0.36 m^3/s$ as independent variables termed as low, medium and high flow rates, for dryer and desiccant chamber respectively. The data was collected for set of three rates at different times to establish the optimum parameters. The best rate selected for this study was $0.28 m^3/s$ and $0.07 m^3/s$ for tomato and desiccant chamber respectively.

Moisture content of the dried tomatoes was determined using standard oven drying method and recorded as dependent variable. The greenhouse shield facilitated the heating of air within the system to create hot air to dry sliced tomatoes. The sliced tomatoes were spread in eight trays in two layers vis upper and lower layer each carry four trays. The drying process was observed until the product was completely dried under the greenhouse dryer. Lastly under each trays the weight loss of the product was measured and the overall drying performance of the system was estimated.

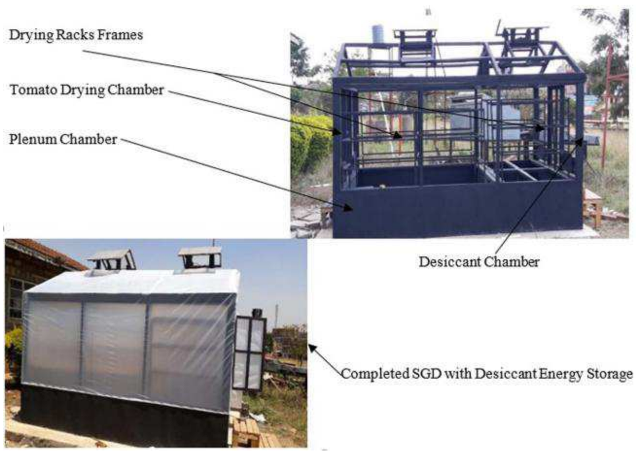

Figure 2. *Constructed SGD with Solid $CaCl_2$ - Clay Desiccant energy storage system Photo.*

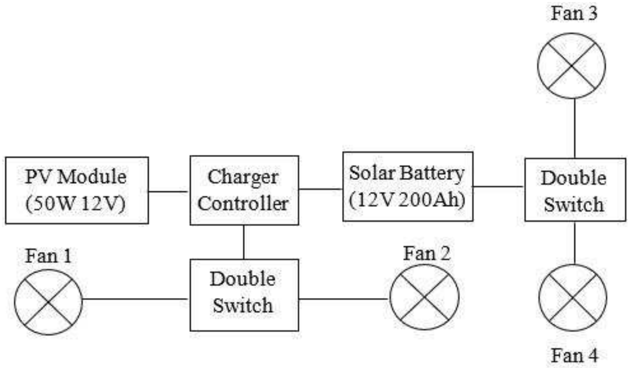

Figure 3. *Photovoltaic powered fans Circuit for the drying system.*

Figures 5 & 6 shows solar photovoltaic powered fans with battery energy storage air flow mode during day and night time. During the day solar energy enters the greenhouse and is converted into heat and exhaust fans move the moisture from both tomato crop and desiccants (Figure 6). During the night desiccant energy storage adsorbs the moisture from the tomatoes via desiccant air dehumidification process thereby continuing the overall tomato drying process. Figures 7 & 8 represents flow diagrams during both day and night times.

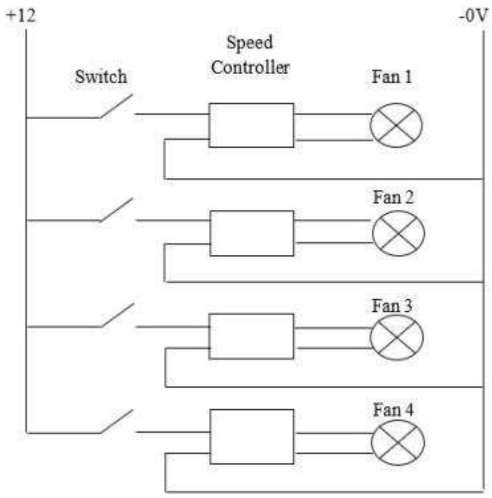

Figure 4. *Circuit diagram of the fans.*

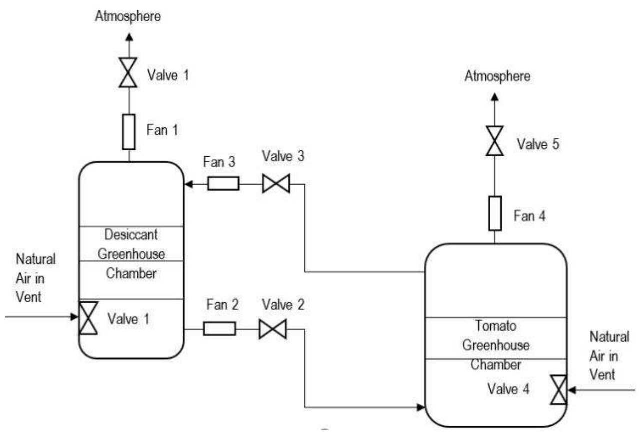

Figure 5. *Experimental layout of the Solar Greenhouse Dryer incorporated with Desiccant Energy Storage.*

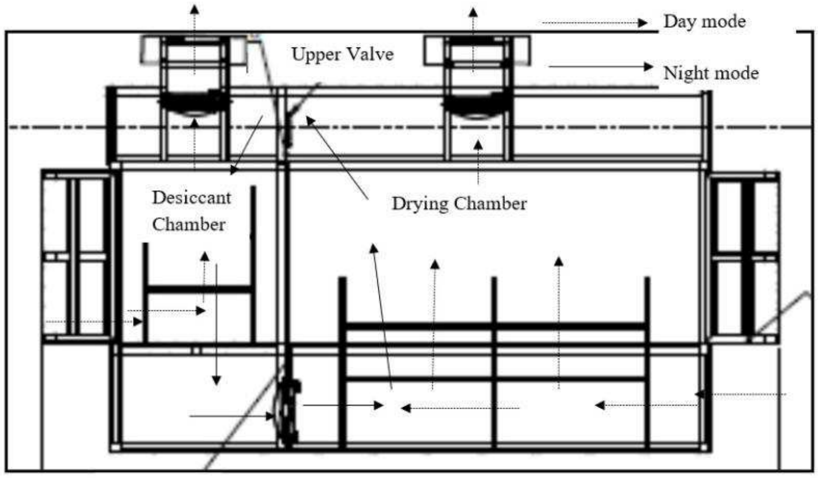

Figure 6. *Principle of Operation of Solar Greenhouse-Desiccant Drying System (Day and Night Mode).*

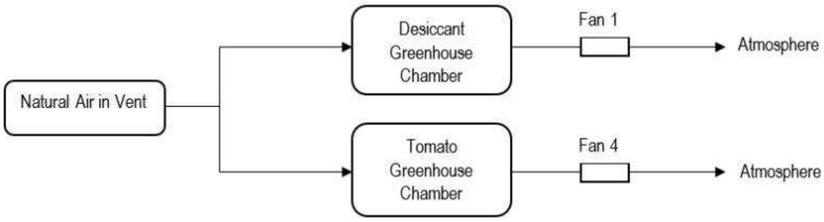

Figure 7. *Flow diagram during day time.*

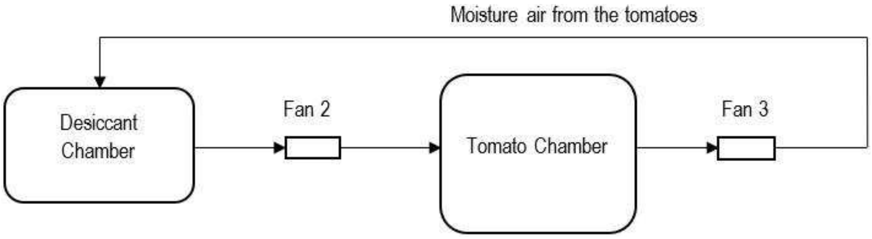

Figure 8. *Flow diagram during night time.*

2.2. Tomato Sample Preparation

In this study, tomatoes were purchased from the Githurai market located 4km from Kenyatta University, Kiambu County along Thika Road superhighway, Kenya. Sixteen kilograms of tomatoes were sorted and only firm, ripe and unstained tomatoes with uniform size were selected, then washed and dried with clean cloth, and sliced into 5mm thick round [26]. The sliced tomatoes were spread on the drying trays with a spacing distance less than 1cm and placed in double layers within the system as shown in Figure 9.

Figure 9. *Photo of Sliced and tray loaded with uniformly spread tomatoes in the Solar Greenhouse Dryer.*

2.3. Solid $CaCl_2$ - Clay Desiccant Preparation

Solid Clay - $CaCl_2$ desiccants were prepared by mixing clay with $CaCl_2$ as recommended by Thoruwa *et al.* [27]. A total of 32.3 kg solid Clay-$CaCl_2$ desiccants were spread uniformly onto desiccant trays and loaded into the chamber as shown in Figure 10.

Figure 10. *Loaded Solid Clay-$CaCl_2$ desiccants in the greenhouse desiccant.*

2.4. Performance Evaluation of the Solar Greenhouse Dryer with Desiccant Energy Storage

In this study, we investigated tomato drying performance using an integrated greenhouse solar dryer with $CaCl_2$-Clay desiccant energy storage as shown in Figure 1. A total of 10 experimental tests were conducted during October and November 2019 under average tropical weather conditions at Kenyatta University, Nairobi. Kenya. The best test was chosen and reported on this study.

2.5. Instrumentation and Data Collection Procedure

Temperature measurements were done using Thermocouple type K (with an optimum range of -270°C to 1372°C and temperature coefficient of ± (0.015% +1mV)/°C). Solar radiation was measured using Australian Kipp and Zenon pyranometer (CN27-277) with sensitivity of 91.68 W/m² per mV mounted on the rooftop adjacent building to the solar greenhouse dryer. Both Solar radiation and temperature measurements were monitored and recorded at 15 minutes intervals via Chinese data logger Model RIGOL's M300 Series.

Ambient relative humidity and exit conditions of the greenhouse drying system with desiccant energy storage were calculated using equation 1 as presented by Australian Government Bureau of Meteorology and the other researchers [11]. The equation considered Dry Bulb Temperature, Wet Bulb Temperature and the atmospheric pressure of the field-testing site. The atmospheric pressure was taken at an altitude of Nairobi which is 1500m as shown on Table 1 [11].

$$R.H = \frac{100\left[expexp\left[1.8096+\left(\frac{17.2694Tw}{237.3+Tw}\right)\right]-7.866*10^{-4}*P(T-Tw)\left(1+\frac{Tw}{610}\right)\right]}{expexp\left[1.8096+\left(\frac{17.2694T}{237.3+T}\right)\right]} \quad (1)$$

Where $R.H$ is Relative Humidity (%), Tw is Wet Bulb Temperature (°C), T is Dry Bulb Temperature (°C), P is Station Level Pressure (kPa)

The equation was applicable because the air temperature was greater than or equal to 0°C [32]. The inside relative humidity for both greenhouse chamber and desiccant chamber was obtained on hourly basis by using a digital psychrometer model 5105 (UK) and counter checked with humidity meter model 5070 (UK) with range 20% - 90% RH and temperature range 0 - 60°C).

Table 1. *Standard Pressures if the pressure is not known.*

Station Altitudes (m)	Pressure (kPa)
0 – 250	998.3
251 – 500	969.0
501 – 750	940.4
1001 – 1250	912.5
1251 – 1500	885.2

Air flow rate (m^3s^{-1}), Air velocity (ms^{-1}) and weight (kg) of the wet and dried tomatoes were measured manually at an hour interval. The weight (kg) of the wet and dried tomatoes was measured by the digital platform balance model 14191 – 461F (China). The air flow rates through drying systems were measured using VELOCICALC portable air flow meter model 8357 manufactured by TSI, USA.

Moisture content of tomato samples were monitored on hourly basis via manual weighing via a digital platform balance model 14191 – 461F (China). The moisture content of tomato samples was determined using standard an electric air convection oven drying method (200±1°C) at 105°C until the constant mass was achieved [31 & 2].

2.6. Experimental Testing Conditions

The experiments were carried out during the sunny months of October and November of the year 2019. The reason to spread these experiments was because of unpredictable weather conditions during the testing period. The solar greenhouse tomato and desiccant Chamber flowrates were maintained at $0.28m^3/s$ and $0.07m^3/s$ respectively. Solar radiation, ambient temperatures, greenhouse drying temperature, inlet and exit relative humidity air conditions was recorded.

2.6.1. Tomato Drying Performance

Moisture content of the dried tomatoes was monitored and recorded as dependent variables as a function of time for tomato crop. The greenhouse shield facilitated the heating of air within the system to create hot air to dry sliced tomatoes. The drying process was observed until the product was completely dried under the greenhouse dryer. The moisture content of tomato samples was determined using equation 2 [31]. For each tray the weight loss of the product was measured and the overall solar drying performance of the system was estimated.

$$Mt = \frac{Wt-Wd}{Wt} \quad (2)$$

Where t is a subscript representing time, Mt is Moisture content of tomato slices on wet bases, Wt is the weight of the sample at time t and Wd is the weight of the dried sample

2.6.2. Performance Evaluation of the Dryer System

Drying Efficiency

Drying Efficiency, ηd is the ratio of the energy needed to evaporate moisture from the product to the heat supplied to the dryer. It was calculated with respect to. It was calculated with respect to the factors prevailing the drying process of the product such as the materials to be dried, air temperature within the dryer and air flow of the dryer [5]. For the dryer assisted with exhaust fan equation 3 was used:

$$Drying\ efficiency, \eta d = \frac{MwL}{IcAct+Pf} \times 100\% \quad (3)$$

Where; Mw – weight of water to be removed, kg, L – Latent heat of vaporization of water at a drying temperature, $kJkg^{-1}$, Ic – Solar Radiation of the Collector, Wm^{-2}, Ac– Area of the collector, m², t – Drying time, s, Pf – Power of the fan, Watt

Drying Rate

Drying rate is the amount of evaporated moisture over time [5]. It was determined using equation 4:

$$D.R = \frac{mi - md}{t} \quad (4)$$

Where, mi – Mass of sample before drying, kg, md – Mass of sample after drying, kg, t – Drying duration time, s

3. Results and Discussion

3.1. Performance of a Loaded Solar Greenhouse Dryer Under Field Conditions

3.1.1. Drying with Solar Energy During Daytime 1 Conditions

Figure 11 shows typical variation of Greenhouse Temperature and Solar Radiation profiles of loaded system with time on 16th October 2019. The graph trends depicted are actual measurements recorded during the experiment. It can be seen that the solar radiation increased from morning time reaching maximum 940.7 W/m^2 at 13:15 and decreased in the afternoon. The ambient temperature increased with solar radiation intensity up to 15:30 hours and decreased slowly towards the end of the day. The average greenhouse temperature attained was 42.2°C ± 6.5%. It was observed that the maximum and the minimum temperature, inside and outside the greenhouse dryer were 45.3°C and 33.8°C, and 31.7°C and 21.3°C, respectively. The average solar radiation on the testing date was 559.2W/m^2 while the minimum was 18.2 W/m^2 at 18:00 end of the day. The drying temperatures of the present-day study was 33.8°C – 45.3°C and conforms with results of Yokeshwaraperumal *et al.* [30].

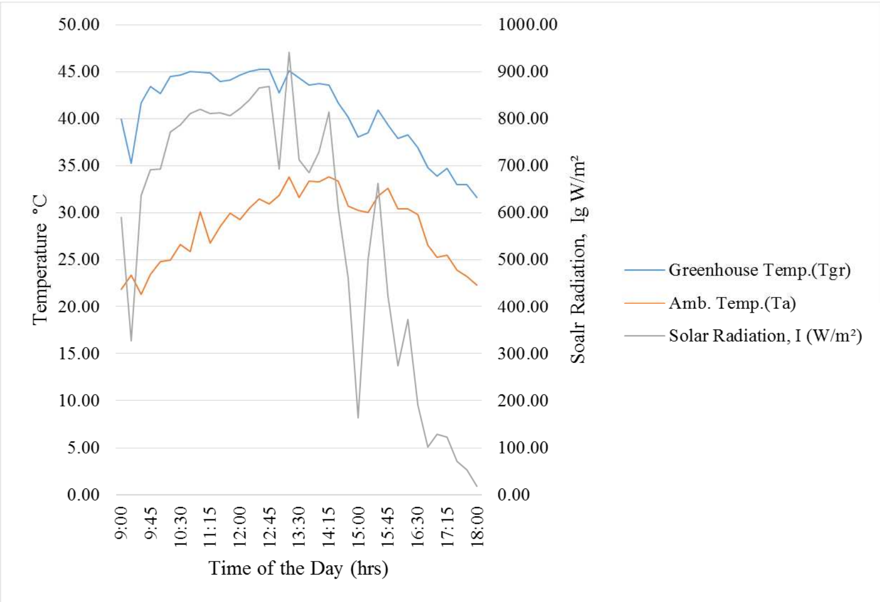

Figure 11. *Typical Temperature and Solar radiation profiles for the Loaded System.*

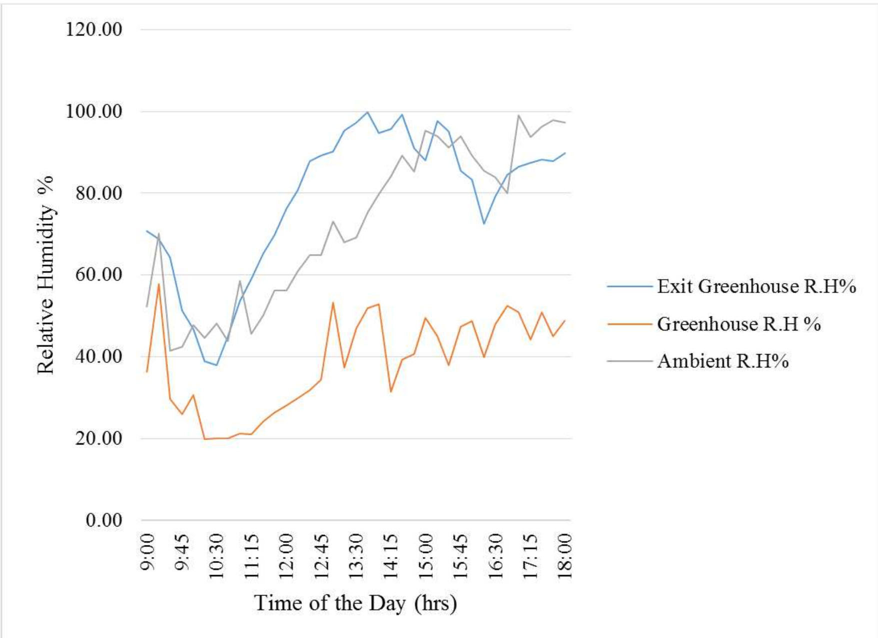

Figure 12. *Typical Relative Humidity profiles of the loaded system.*

Figure 12 shows relative humidity profiles of the loaded solar greenhouse drying system. An ambient air with 72.2% RH entered the system and heated to an average temperature of 42.2°C ± 6.5% was lowered to 38.4% RH but leaving drying chamber with higher RH by 6% compared to the ambient relative humidity of 72.2%. It is seen that the RH within the greenhouse is comparatively low compared to the ambient air, and the air leaving the chamber. The air leaving the drying chamber is highly humid due to addition of moisture from drying fresh sliced tomatoes. Thus, the lower the relative humidity the high chance to keep the favorable temperatures within the system for moisture uptake. Water holding capacity of the greenhouse air increases with low relative humidity within the system hence more moisture uptake as described by Ahmad & Prakash, [1] and Madhava & Smith, [17]. Therefore, from figures 11 & 12 we can see that temperatures within the greenhouse chamber rises as relative humidity falls and conforms with the findings of Prakash *et al.* [24].

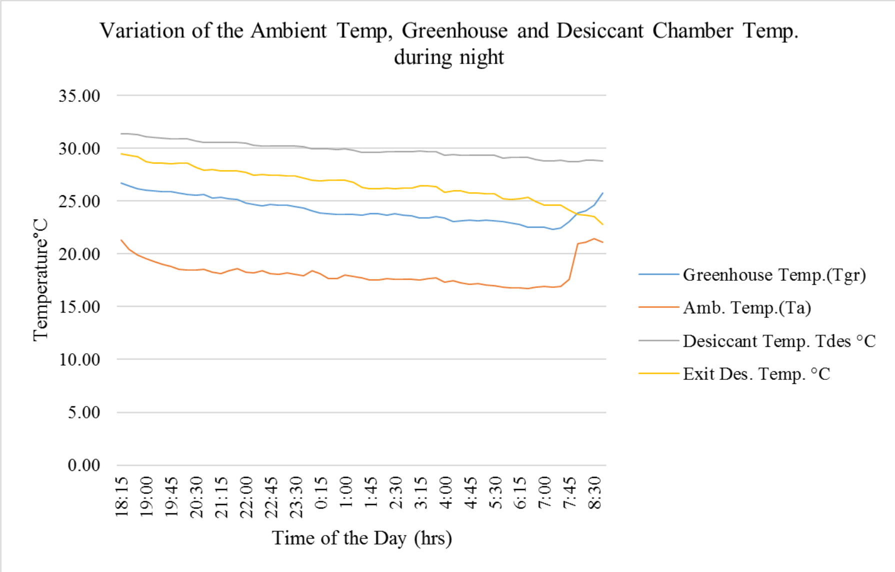

Figure 13. *Greenhouse and Desiccant Chamber Typical Temperature profile during night time on 17th October 2019.*

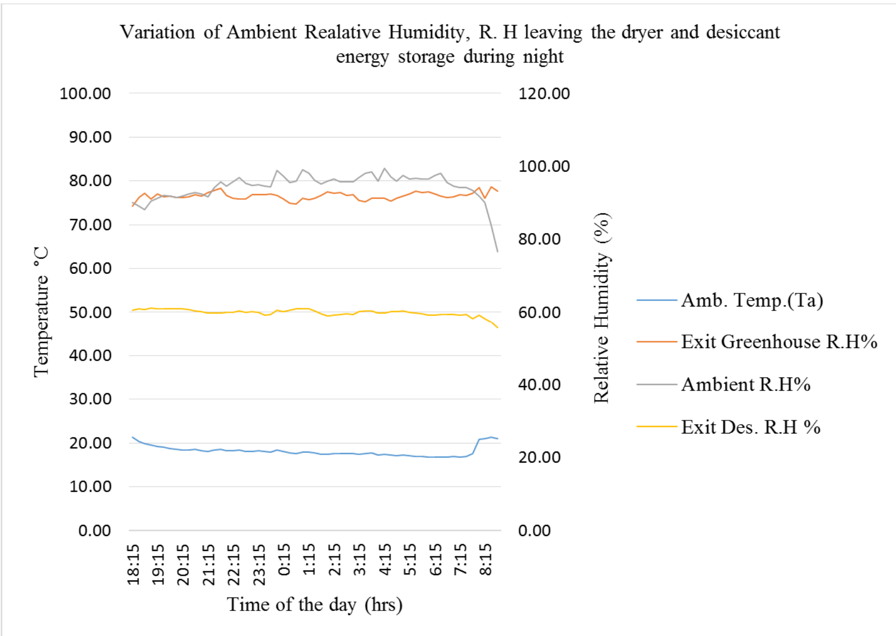

Figure 14. *Greenhouse and Desiccant chamber Typical Relative Humidity Profile during night time on 17th October 2019.*

3.1.2. Night Drying using Desiccant Energy Storage System

Night drying of tomato was achieved via desiccant energy storage system through circulation of the dehumidified air using an axial fan placed between the desiccant energy storage system and tomato drying chamber. The airflow rates were set constant at 0.07 m^3/s and 0.28 m^3/s for greenhouse desiccant and tomato dryer chamber respectively. The operating environment was at an average ambient temperature and relative humidity of 18.2°C and 94.4% respectively. Figures 13 & 14 shows typical temperature and relative humidity profiles of the drying chamber and desiccant energy system with time. It was observed that the desiccant energy storage exits air temperature varied from 22.5°C to 29.5°C giving an average of 26.6°C ± 5.8% temperature while maintaining an average RH of 59.9% during the off-shine duration between 18:15 hours to 08:45 hours. The values were in good agreement with the data presented by other researchers [9 & 19]. The moisture adsorption rate was driven mainly by dehumidified air from the desiccant energy storage which was higher temperature by 8.4°C above ambient and 34.5% relative humidity below ambient RH respectively. The condition favors energy transfer for moisture uptake from the fresh sliced tomatoes during the night period.

Figure 14 illustrates the moisture air out of the dryer was at an average RH of 91.9% ± 1.1%. The highest humidity of the air leaving the dryer was 94.3% and the lowest was 89.1% respectively. This shows that there is moisture transfer from tomatoes being dried during night process. During this time desiccant material were able to adsorb 5.44kg (37.3% of the total moisture to be removed from 16kg of fresh sliced tomatoes) of water, from 8.92kg of the fresh sliced tomatoes left during solar drying of on the day time. The study confirms that with $CaCl_2$ salt impregnated in composite desiccant can be used to retain water uptake during night period to extend the drying process as reported by Malan *et al.* [18].

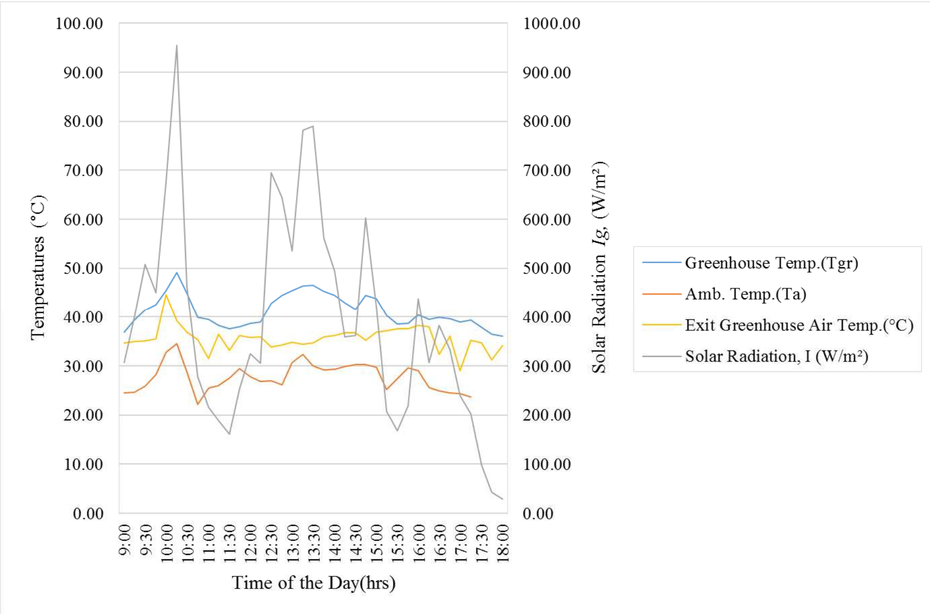

Figure 15. *Greenhouse Chamber Typical Temperature and Solar Radiation profile with time During Day 2 on 17th October 2019.*

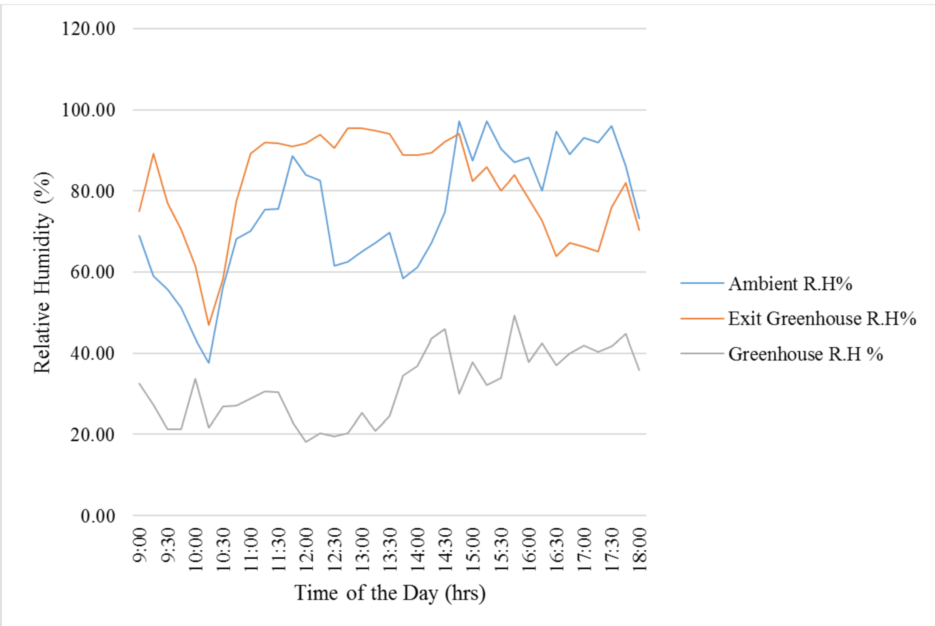

Figure 16. *Greenhouse Drying and Desiccant Chambers Relative Humidity Profiles of with time During Day 2 on 17th October 2019.*

3.1.3. Tomato Drying Performance Using Solar Energy During Daytime in Day 2

Figures 15 & 16 illustrate the trend of the greenhouse dryer temperature and relative humidity during day 2 drying condition on 17th October 2019. Tomato solar drying process continued during the second day at an average 27.8°C ± 8.3% ambient temperature and 389W/m² solar radiation. From the trend it was observed that high temperatures were obtained in the drying system while relative humidity remained low most of the time. The average greenhouse temperature and relative humidity obtained were 41.2°C ± 5.6% and 31.9% ± 9.2% respectively, and conforms with results of Odhiambo, [21] and Janjai, [13].

3.2. Determination of Initial Moisture Content of Fresh Sliced Tomatoes

In this study, moisture content of tomato sample was determined using the standard oven drying method at 105°C until there was no further change in dry weight [2]. Table 2 shows the average initial moisture content of the fresh sliced tomatoes to be 93.9% (dwb) and varied along the layers of trays from 92.9% to 94.8% (dwb). This is compatible with other researcher's findings which showed that fresh tomatoes moisture content varied from 92% to 95% (dwb) [16 & 4].

Table 2. *Average Initial Moisture content of fresh sliced tomatoes.*

Layers	Tray Labels	Initial weight of tomatoes in kg	Final weight of Oven dried tomatoes in kg	Initial Moisture Content (%)
Lower Layer Trays	H1	2.1	0.14	93.3
	H3	2.1	0.15	92.9
	H5	2.1	0.14	93.3
	H7	2.1	0.13	93.8
Upper Layer Trays	H2	2.1	0.11	94.8
	H4	2.1	0.12	94.3
	H6	2.1	0.11	94.8
	H8	2.1	0.12	94.3
		16.8	1.02	93.9

3.3. Tomatoes Drying Rate During Solar Drying and Desiccant Phase

Figure 17 shows the changes of moisture content of the fresh sliced tomatoes during the drying process in the greenhouse dryer with desiccant energy storage system. From the graph we see that the moisture content of the fresh tomatoes was reduced from 94.3% (dwb) to 25.5% (dwb) during the solar drying phase, then followed by desiccant phase to 16.4% (dwb) and finally was solar drying phase to 8.3% (dwb). The graph shows that the moisture content remained constant after 25 hours; this means the weight of the dried product remained constant.

On the basis of these results, it was concluded that the prototype solar greenhouse dryer with desiccant energy storage system was capable of drying the fresh sliced tomatoes from 94.5% (dwb) to 8.3% (dwb) within 27 hours. The results have huge implications in commercialization of solar greenhouse dryers with energy storage system for various drying operations.

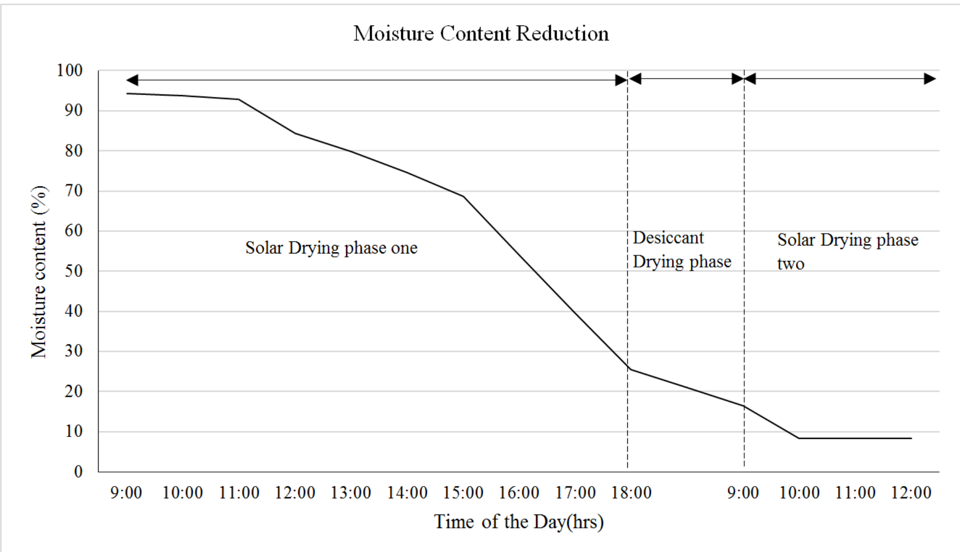

Figure 17. *Moisture Content Reduction of tomato samples with respect to time.*

4. Conclusion

The following were drawn conclusion from the experimental study of the solar greenhouse dryer with the desiccant storage:

1) The Solar Greenhouse Dryer with Clay-$CaCl_2$ Desiccant Energy storage powered by a photovoltaic solar panel to power the fans was designed and constructed using locally available materials [sized 2m×3.5m×2.1m (width, length and height)]. The dryer demonstrated capability of drying tomatoes continuously from 94.3% (dwb) to 8.3% (dwb) within 27 hours.
2) The prototype solar greenhouse dryer with desiccant energy storage system demonstrated typical tomato drying efficiency of 23.72% and 22.56% during day 1 and 2 respectively while operating with an average solar radiation of 559.2W/m^2 and 389W/m^2 respectively.
3) The average drying rate of solar greenhouse dryer with desiccant energy storage system during the two-day operation was 0.985kg/h and 0.875kg/h (during solar drying mode) while night drying using desiccant energy storage system demonstrated an average drying rate of 0.34kg/h.
4) On the basis of results the developed dryer has a great potential for drying high moisture agricultural crops.

5. Recommendation

In order to improve the performance of the solar greenhouse dryer with Clay-$CaCl_2$ desiccant energy storage, air flow needs further evaluation to improve on the desiccant moisture uptake especially during night drying operation.

Conflicts of Interest

The Authors has no conflicts of interest

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