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Drying Performance and Economic Analysis of a Greenhouse Solar Dryer for Tomatoes

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Abstract

Purpose: The purpose of this study was to assess the drying performance and economic feasibility of a Greenhouse Solar Dryer for Tomatoes. With a focus on small-scale tomato drying, the study aimed to evaluate the effectiveness of the greenhouse in comparison to traditional sun drying methods. Additionally, the economic analysis sought to determine the investment attractiveness of the greenhouse dryer by considering the initial investment, operational costs, and potential revenue generation.

Methodology: The methodology involved conducting drying experiments using the Greenhouse Solar Dryer for Tomatoes under existing weather conditions. The dryer's components include the steel frame, greenhouse plastic cover, and concrete floor. The temperature and relative humidity contributed to the environment inside the greenhouse that facilitated the drying process. Moisture content measurements were taken at regular intervals to assess the drying kinetics and effectiveness of the greenhouse. Economic analysis was conducted to evaluate the project's financial viability, considering initial investment, revenue generation, and operational costs.

Findings: The findings revealed that the Greenhouse Solar Dryer outperformed sun drying methods, achieving higher temperatures and faster drying times for tomatoes. Specifically, the greenhouse reached maximum temperatures of 38.4 °C and 45.5 °C on the first and second days, respectively, leading to a moisture content of 14.9% wet basis within 11 hours on the second day. In contrast, sun drying resulted in a significantly higher moisture content of 37.9% at the same time, highlighting the effectiveness of the greenhouse. Economic analysis demonstrated that the project had a payback period of 1.6 years, indicating its attractiveness as an investment opportunity for farmers.

Unique Contribution to theory, practice and policy: This study makes a unique contribution to knowledge by providing empirical evidence of the drying performance and economic viability of a Greenhouse Solar Dryer for Tomatoes. By demonstrating the effectiveness of the greenhouse in achieving faster drying times and lower moisture content compared to sun drying methods, the study underscores the potential of solar drying technologies in small-scale agricultural settings. Additionally, the economic analysis offers valuable insights into the financial feasibility of adopting greenhouse dryers, particularly for farmers seeking to enhance their income through value-added tomato products.

Keywords: *Drying Performance, Economic Analysis, Greenhouse Solar Dryer, Tomatoes*

1. INTRODUCTION

Although there are many methods of preserving fruits and vegetables, drying is particularly well-suited for developing nations with inadequately developed low-temperature storage infrastructure. Drying reduces weight and volume significantly, which is beneficial for developing nations since it reduces packaging, storage, and shipping expenses. Additionally, the dried product can be stored at room temperature (Simate and Ahrné, 2006). Tomatoes have a high-water content, making them susceptible to microbial growth and rapid spoilage. Drying removes a significant portion of the moisture content, reducing the water activity level and inhibiting microbial growth, thereby enhancing their shelf stability (Zhang *et al*., 2017).

Technological breakthroughs and innovations have resulted in improved drying techniques that are more energy-efficient and allow for better preservation of nutritional and organoleptic properties. Drying holds a major position in the food processing sectors due to its versatility in handling a wide range of foods, including fruits and vegetables, with different properties (Guiné, 2018). Conventional dryers can be costly to run and require grid electricity. As a result, the market for affordable solar-powered agricultural dryers that are suitable for small-scale farmers is expanding. Modern electrical-powered dryers are still superior to solar dryers in terms of performance, but solar dryers are more sustainable, have reduced operating costs, and can be utilized almost in any place where there is a plentiful supply of solar energy (Rizalman *et al*., 2023).

With the ability to function in forced or natural convection modes, solar dryers can be broadly categorized into three groups. These are direct solar dryers, indirect solar dryers, and mixed-mode solar dryers. Compared to other types of solar dryers, the mixed mode solar dryer has been proven to have a higher drying rate, a dried food with more consistent moisture content, and a better temperature distribution for drying food (Simate, 1999; Simate, 2020). Janjai (2012) describes a greenhouse type of solar dryer that has a concrete floor and a parabolic roof structure that is covered with polycarbonate sheets. The operation is such that the air within the dryer is heated by the solar radiation that enters through the roof. Photo Voltaic powered fans located at the top of the dryer's back side extract air from the dryer, causing ambient air to enter the dryer through a small aperture at the bottom of the dryer. The air is then heated by the floor as it enters the greenhouse. The moisture of the drying products is absorbed by the hot air as it passes over and through the drying products resulting in a high drying rate. The products are dried more quickly because they are exposed to both direct sunlight and warm drying air.

Due to their extreme perishability, tomatoes lose quality quickly after being harvested. Maintaining the quality after harvest also requires using the best physical and postharvest handling techniques, as well as elements including the ideal temperature, relative humidity, storage gases, postharvest calcium chloride application, and the best handling procedures (Arah *et al*., 2015). The extreme perishability of tomatoes is a big challenge to farmers and traders of fresh tomatoes in Zambia as evidenced by the high postharvest losses of these fruits during transportation to the markets and during handling at the farms and markets. According to Phiri

(2010), transportation of fresh produce to the market is often the most important factor that contributes to the price of the farm produce. The poor road infrastructure from production areas to the markets, especially during the rainy seasons when the feeder roads are almost impassable, exacerbates the price of tomatoes. A study done by Tschirley and Hichaambwa (2010) on the structure and behavior of vegetable markets serving Lusaka city in Zambia, found that production interruption is one of the reasons for the volatility in the quantity of tomatoes that reach the market. However, the underlying cause of quantity fluctuations is the system's extremely restricted capacity to coordinate across levels in order to facilitate the flow of tomatoes to the market. The system uses shipments outside of Lusaka, as well as short-term storage at retail and in customers' homes to lessen the impact of these quantity changes. But even with these safeguards in place, tomato wholesale prices are still somewhat erratic.

The implication of volatility in the quantity of tomatoes supplied to the market is that sometimes there is glut of tomato on the market which results in wastage of the tomatoes as they cannot be stored in their fresh form for a long time before they start rotting. To mitigate this problem, a greenhouse solar dryer is proposed which farmers and traders can use to dry excess tomato and add value to it. In addition to addressing the problem of glut, farmers can dry their fresh tomatoes right at their farms, with the objective of adding value so that they can get higher returns.

Carrying out an economic analysis of a project before its adoption is crucial for making informed decisions regarding resource allocation, risk assessment, and long-term sustainability. Economic analysis provides valuable insights into the financial feasibility, potential returns, and overall economic impact of a project, guiding stakeholders in determining its viability and alignment with organizational goals. By evaluating costs, benefits, and risks associated with the project, economic analysis helps in identifying potential challenges, minimizing uncertainties, and optimizing resource utilization. Moreover, it facilitates comparisons between alternative projects or investment opportunities, enabling decision-makers to prioritize investments based on their potential economic returns. Without a comprehensive economic analysis, projects may be implemented without a clear understanding of their financial implications, leading to inefficiencies, cost overruns, and missed opportunities for value creation. Therefore, conducting an economic analysis is essential for ensuring prudent decision-making and maximizing the likelihood of project success (Belessiotis and Delyannis, 2011; Chaudhari *et al*., 2018; El Hage *et al*., 2018).

The objective of this study is to determine the drying performance and to carry out an economic analysis of a Greenhouse Solar Dryer for Tomatoes. By addressing these key sections, a study on the drying performance and economic analysis of a greenhouse solar dryer for tomatoes aims to provide a comprehensive understanding of the technology's effectiveness and economic feasibility.

2. METHODOLOGY

2.1 Greenhouse Solar Dryer

The Greenhouse solar dryer used in the experiment is shown in Figure 1.

Figure 1. Greenhouse Solar Dryer

The major parts of the dryer are the steel frame, greenhouse plastic cover, and the floor. The dryer has floor dimensions of 5m long by 3m wide, and is built on a 0.1m thick concrete floor and, has a height of 2m. Other components of the dryer are the extractor fans mounted on a flat galvanised iron sheet, and solar panels mounted on a 4m high 100mm*100mm square pipe. A gable type of roof was selected for this greenhouse dryer as it has been reported by Kassem, (2011) to give higher drying rates due to its ability to capture more solar radiation than other shapes. Simate and Simukonda (2022) also built a greenhouse solar dryer with a gable roof and dried mango slices from a moisture content of 88.2% to 13.7 % wet basis in 7.5 hours, showing the effectiveness of this type of dryer. To hold the drying tomatoes, trays each measuring 4 m long by 0.8 m wide and 0.9 m high, were used. The trays were fabricated from 20mm-by-20mm steel square tubes. The top sides of the trays were covered with plastic nets for holding the drying tomatoes.

2.2 Experimental Setup

The tomato solar drying experiment was performed at the Department of Agricultural Engineering of the University of Zambia, Lusaka, Zambia. The experiment was done over a period of two consecutive days from 09:00 hours to 16:00 hours, each day. Fresh and washed tomatoes were sliced 4 mm thick and then loaded on the drying trays inside the greenhouse (Figure 2). To monitor the drying process, small samples of tomato were weighed every hour using a digital weighing scale (model: PE 3000, Mettler Instruments BV, Switzerland; maximum weighing capacity: 3,100 g; accuracy: ±0.1 g) in order to track the weight loss of the tomatoes as they dried. For open sun drying, sliced tomatoes were put on a tray outside the greenhouse (Figure 3) from which small samples were also weighed every hour.

The air temperatures were measured using thermocouple type temperature probes (Campbell Scientific Inc., model: 108–L accuracy ±0.01 °C, which can measure temperatures between -5 and +95 °C) at entry to the greenhouse (T_Ambient), and on top of the drying trays inside the greenhouse (T_Greenhouse). The relative humidity of the air was measured using relative humidity probes (Campbell Scientific Inc., model: HMP35D; accuracy at +20 °C is ±2% RH (0–90% RH) and ±3% RH (90–100% RH)) at the entry point to the greenhouse (RH_Ambient) and, on top of the drying tray inside the greenhouse (RH_Greenhouse). Solar radiation was measured using a pyranometer (Kipp & Zonen Delft BV, model: CM11, irradiance range: 0–1,400 W/m^2, sensitivity: between 4 and 6 μV/Wm^2) that was set up on a level horizontal ground surface close to the greenhouse solar dryer. A multiprobe data logger (Campbell Scientific Inc., model: CR 1000) that recorded the air temperatures, relative humidity, and sun radiation every minute was linked to all the probes. Figure 4 shows the computer, data logger and instruments for recording drying data.

The ambient wind speed outside the greenhouse and the airflow at the exhaust fans of the greenhouse were measured with a KUSAM-MECO DIGITAL THERMO ANEMOMETER Model KM-909, INDIA, with Wind Velocity measurement: Resolution = 0.01m/s; Threshold: 0.3m/s; Range: 0.0 - 30.0m/s. The airflow at the exhaust fans was then multiplied with the flow areas of the fans to obtain the volume flowrate. Based on the continuity equation, the volume flowrate of air at the exhaust fans was considered to be equal to the volume flowrate of air through the dryer.

Figure 2. The inside of the Greenhouse Solar Dryer showing the sliced tomato on drying trays

Figure 3 Open Sun drying, with tray of sliced tomatoes put outside the Greenhouse Solar Dryer

Figure 4. Computer, data logger and instruments for recording drying data

2.3 Economic Analysis Framework

Due to their capital-intensive nature, solar dryers typically require strong financial viability in order to compete with traditional commercial dryers. The dryer's fixed cost, running costs, and payback are typically included in the financial analysis. They are only feasible if fuel savings can be offset by the annual cost of the additional investment in the solar dryer, or if equipment costs can be decreased (Tiwari, 2016).

In this work the economic analyses done are the Annualized Cost and the Payback Period. An annualised cost method for working out the yearly cost of owning a machine developed by Audsley and Wheeler (1978) was used. This method has also been used by Aymen *et al*., (2019) and, Elbanna and Al -Gaadi (2002). The process is predicated on four different forms of cash flows: the initial cost of purchasing the machine, the yearly recurring maintenance and repair costs, the machine's resale value, and the interest paid on borrowed funds. In the current study, we incorporated the operational cost of the solar dryer in the Audsley and Wheeler formular to calculate the annual cost C_a, as given by Equation (1).

$$C_a = \frac{(C_{M\&L} + \sum_{n=1}^{N}(C_{m,n} + C_{o,n})W^n - S_N W^N)(W-1)}{W(W^N - 1)} \quad (1)$$

Where:

$W=(1+i)/(1+r)$

$C_{M\&L}$ = cost of material and labour to build the solar dryer, ZMW

$C_{m,n}$ = maintenance cost during year *n*, ZMW

$C_{o,n}$ = operational cost during year *n*, ZMW

S_N = current resale value of the *N* years old solar dryer, ZMW

N = number of years the solar dryer is owned

i = inflation rate

r = interest rate

The Payback period is the amount of time needed to recoup the cost of the solar dryer, taking inflation and interest rates into account (Shrivastava and Kumar, 2017). The Payback period can also be defined as the time required for the total initial investment to be equalled by the cumulative savings (Sreekumar *et al*., 2008). The Payback period *(PBP)* is calculated using equation (2) as given by Aymen *et al*., (2019).

$$PBP = \frac{C_{M\&L}}{S_{DT} - C_{FT} - C_a} \quad (2)$$

Where:

S_{DT} = annual sale of dried tomato, ZMW

C_{FT} = annual cost of fresh tomato, ZMW

C_a = annual cost, ZMW

3. RESULTS AND DISCUSSION

3.1 Drying Performance Analysis

Figure 5 shows the variation of solar radiation and temperature in the ambient and inside the greenhouse solar dryer with time of the day during the two-days of the drying experiment. The solar radiation reached a peak of 845 W/m^2 and 866 W/m^2 on the first and second day of drying, respectively, with an average of 628 W/m^2 for the two days. The ambient temperature reached a peak of 28.5°C and 29°C for the first and second day, respectively, with an average of 25.4°C for the two days. Under these conditions, the temperature inside the greenhouse reached an average of 37.2°C during the two days of drying. The maximum temperatures inside the greenhouse were 38.4°C and 45.5°C for first and second day, respectively. The temperature inside the greenhouse is the temperature at which the tomato dries and has a bearing on the quality of the dried tomato. In a study by Obadina *et al*., (2018), the quality changes of tomatoes (cherry and plum) dried at temperatures of 60, 65 and 70°C was investigated. They found that the redness and chroma of the stored powder from the dried tomato decreased, while lightness, yellowness, and hue increased with increased drying temperature. They concluded that 60°C temperature gave the best quality dried tomato powder. Even though our current study did not consider the quality of the dried tomato, the 45.5°C maximum temperature recorded in the greenhouse is an indication that the greenhouse can produce good quality dried tomatoes.

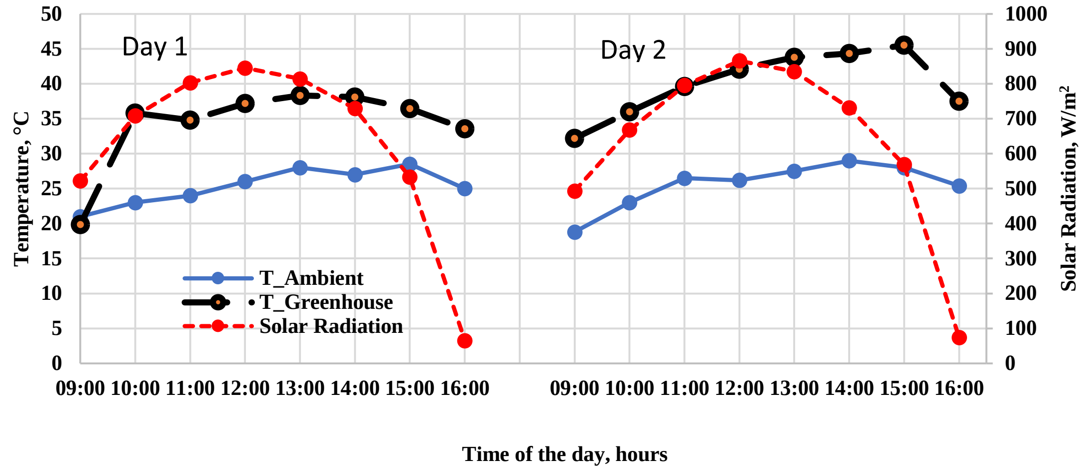

Figure 5. Variation of solar radiation, temperature in the ambient and inside the greenhouse solar dryer with time of the day

Figure 6 shows the variation of relative humidity in the ambient and inside the greenhouse. On the first day of drying, the relative humidity of air inside the greenhouse is lower than that in the ambient by 1.2%. This difference in the relative humidity is small considering the difference between the temperature of air inside the greenhouse and that in the ambient, shown in Figure 5. The higher-than-expected relative humidity inside the greenhouse is due to high evaporation of water from the fresh tomato slices. On the second day however, the relative humidity inside the greenhouse is lower than that in the ambient by 18.2% due to reduced evaporation from the tomatoes.

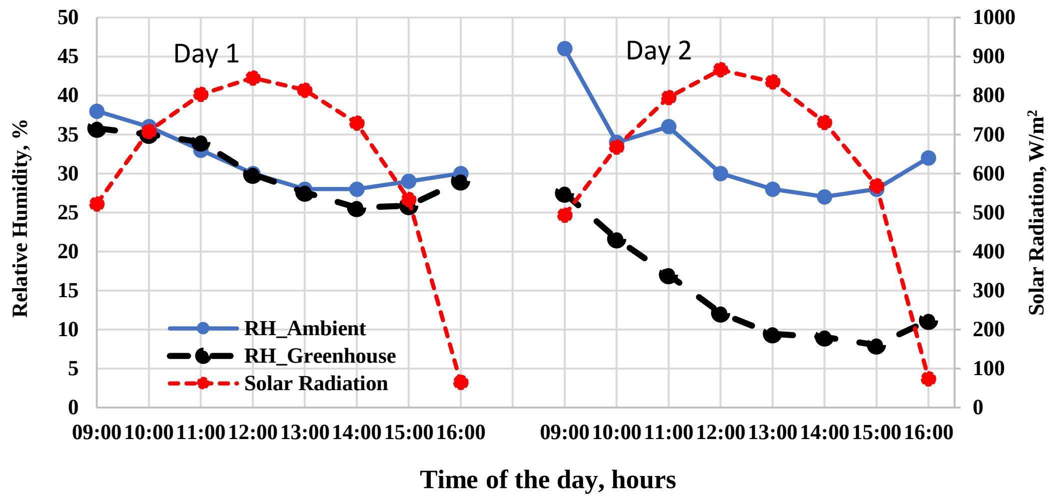

Figure 6. Variation of solar radiation, relative humidity in the ambient and inside the greenhouse dryer with time of the day

The changes in the volume flowrate of air through the greenhouse dryer with respect to time of the day is shown in Figure 7. The flowrate typically follows the pattern of the solar radiation. This is because the fans are DC and are powered directly by the Solar PV panels whose electrical power output depends on the intensity of the sun. Airflow in solar drying is an important factor in the drying rate of foods. Hanif et al., (2013) investigated the impact of air mass flowrate on the drying rate of apricots using a drying chamber connected to a Parabolic Trough Solar Collector. They found that the drying rate increased at higher mass airflow rates, and recommended the use of high airflow to produce good quality dried apricots. The rate of drying increases as air temperature and flow velocity rise. However, according to Chandramohan (2018), higher airflow velocities such as 4 and 6 m/s, do not significantly alter the drying rate, though, because of the nearly constant diffusion coefficient that is seen at these higher velocities. At greater moisture content levels, the diffusion coefficient is larger; at lower moisture content levels, it decreases and stays nearly constant.

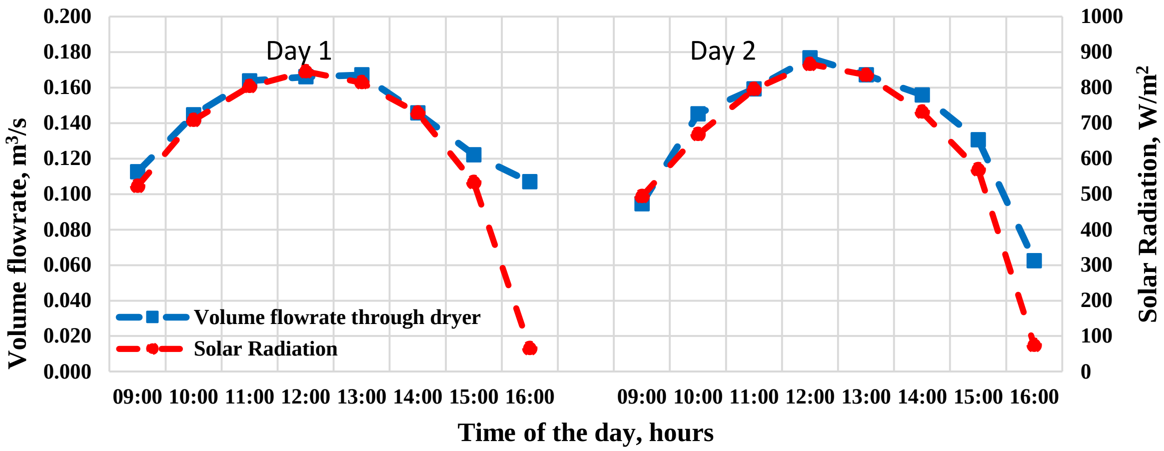

Figure 7. Volume flowrate through the Greenhouse dryer with time of the day

The tomato that was put outside the greenhouse to dry under the sun was exposed to the ambient conditions which include the solar radiation, ambient air temperature and humidity and, wind. Figure 8 shows the wind speed with respect to the time of the day. The wind speed is very erratic with big fluctuations, reaching an average of 3.05 m/s over the two-day drying period. Wind speed in sun drying affects the drying rate, and as Hanif et al., (2013) reported in the drying of apricots, the drying rate increased at higher mass airflow.

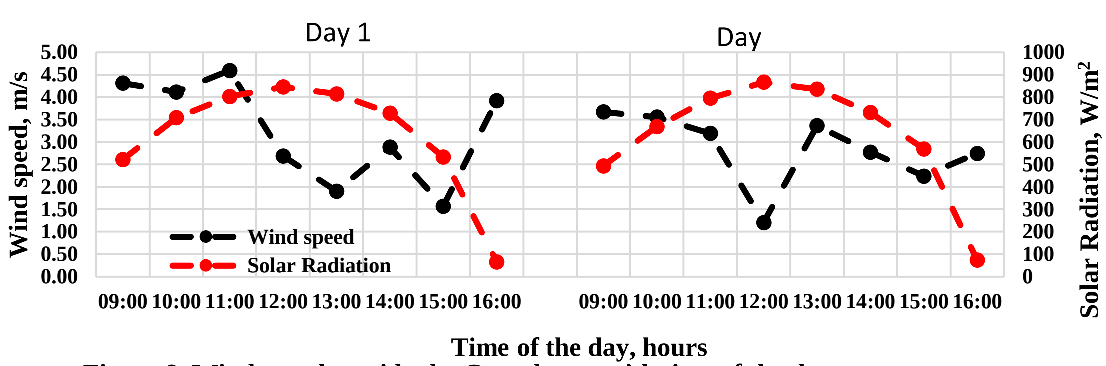

Figure 8. Wind speed outside the Greenhouse with time of the day

The variation of moisture content (MC) with drying time is shown in Figure 9 for the tomato in the greenhouse and that outside under sun drying. The tomato in the greenhouse reached a moisture content of 14.9% wet basis at 12:00 hours of the second day, while that under sun drying reached only 37.9% wet basis; thus, the effectiveness of the greenhouse in drying tomato is quite evident. It is noted that between the end of data recording on the first day and the beginning of data recording on the second day, drying continued, as evidenced by the reduction in the moisture content. This can be attributed to the air temperature and humidity still supporting the drying process during this time. In addition, the drying of tomatoes continued due to the heat absorbed and stored by the concrete floor. The concrete floor served as thermal energy storage system.

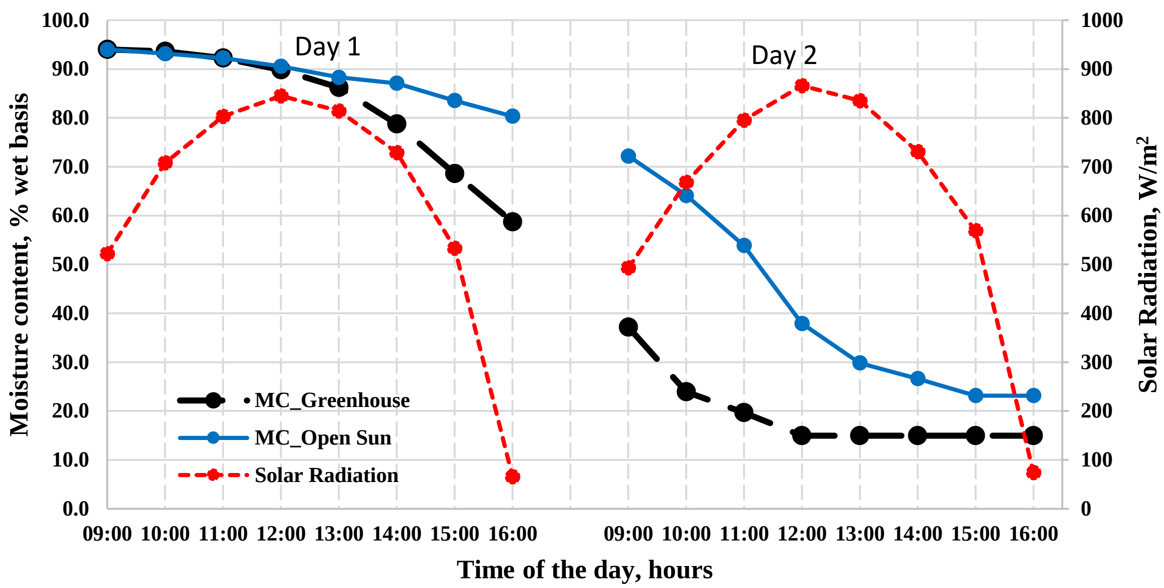

Figure 9. Moisture content variation with time of the day

3.2 Economic analysis

The initial investment in the project is the cost of materials and labour to build the greenhouse dryer ($C_{M\&L}$). The main parts of the dryer are the concrete floor, steel frame, greenhouse plastic cover, DC fans, solar panels, and the trays, giving an initial investment of ZMW29,640.35. It is projected that maintenance expenses will account for 2% of the total investment, which gives an amount of ZMW592.81. The fresh sliced tomato per batch was 29 kg and this took about two days to dry (see Figure 7) giving 2.04 kg of dried tomato per batch. With two batches of fresh tomato per week, 3,016 kg of fresh tomato (moisture content = 94% wet basis) is processed in a year, giving 212.64 kg of dried tomato (moisture content = 14.9% wet basis) in a year. The price of fresh tomato and the workers' remuneration for processing them are included in the operational cost which comes to ZMW39,699.29. The selling price of dried tomato is estimated to be ZMW300/kg, based on the price from a local supermarket, and after taking into consideration the cost of packaging and transportation by the farmer/trader supplying the dried tomato. An inflation

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rate of 13.2% for Zambia in January 2024 (Trading Economics, 2024), and interest rate of 12% for loans borrowed from the Citizens' Economic Empowerment Commission, Zambia (CEEC, 2024), are used in the calculation of the annual cost. The amounts are given in ZMW, or Zambian Kwacha (1 United States Dollar = 22.95 Zambian Kwacha, as of 24 February 2024).

The economic parameters in Table 1 give an annual cost of ZMW42,037.45; and with a revenue of ZMW63,792.00, a Payback period of 1.6 years is realised. Mukanema and Simate (2024), in their economic analysis of a natural convection solar tunnel dryer for banana slices, found a payback period of 2 years. In a study by Akowuah et al. (2021), a maize solar dryer's payback period was found to be influenced by both the initial capital expenditure and the drying charge. They determined that a $2.11 drying price per bag had a 2.7-year payback period. In yet another study, Philip et al. (2022) investigated a greenhouse solar drier with a 100 kg capacity that was intended to yield premium dried goods. They found that the dryer had a payback period ranging from 1.5 to 2.1 years. The payback periods found in these studies are comparable to what the current study has found.

Table 1. Parameters used in the economic analyses

No.	Parameter	Amount	Remarks
1	Fresh tomato processed/year (kg)	3,016	2 batches are processed every week for 52 weeks
2	Dried tomato produced/year (kg)	212.64	
3	Investment, ZMW	29,640.35	Materials and labour to build the dryer
4	Revenue from sale of dried tomato, ZMW/year	63,792.00	Price of dried tomato estimated to be ZMW300/kg
5	Operations and Maintenance ZMW/year	39,699.29	Cost of fresh tomatoes, overhead & maintenance, and remuneration
6	Interest rate, %	12	
7	Inflation rate, %	13.2	
8	Years of ownership	10	
9	Annual Cost, ZMW	42,037.45	
10	Payback Period, years	1.6	

There are uncertainties in the estimates of solar dryer performance, and a sensitivity analysis is the most effective way to handle the uncertainty around the estimate of solar dryer performance metrics (Hasan and Langrish, 2016). The Interest Rate, *r*, in the equation for determining the Annual Cost of the solar dryer was taken into consideration to be 12.0% in the base scenario. Consequently, the Annual Cost has a great influence on the Pay Back Period. Therefore, a sensitivity study incorporating modifications to the Interest Rate employed in the general methodology suggested here has been conducted. Together with the base results, the sensitivity test results for the 2.0 % and 22.0% Interest Rates are provided in Table 2. Both the Annual Cost and Pay Back Period decrease and increase with decrease and increase of the Interest Rate, respectively. It is also noted that for the 10% increase in Interest Rate, the percentage change in the Pay Back Period of 9.49% is more than the 5.06% increase in the Annual Cost, showing how sensitive the Pay Back Period is to changes in Interest Rate. Barnwal and Tiwari (2008) found that the interest rate for a hybrid photovoltaic/thermal greenhouse dryer had significant effect on the payback period at low annual cash flows while at higher annual cash flows the effect was not significant.

Table 2. Effect of Interest Rate on the Annual Cost and Pay Back Period

Interest Rate		**Annual Cost**		**Pay Back Period**	
%		**(ZMW)**	**(% change)**	**(years)**	**(% change)**
2.0	10% Lower	36,662.72	-4.37	1.27	-7.30
12.0	Base value	38,338.16	0	1.37	0
22.0	10% Higher	40,267.40	5.06	1.50	9.49

4. CONCLUSION

This study presented an evaluation of the drying performance and economic viability of a Greenhouse Solar Dryer for Tomatoes aimed at addressing the high postharvest losses of this important vegetable. With a capacity of 29 kg of fresh sliced tomatoes in each batch, this greenhouse solar dryer for tomatoes was evaluated for drying and economic performance. For the first and second days of drying, the maximum temperatures generated within the greenhouse were 38.4 °C and 45.5 °C, respectively, under average solar radiation of 628 W/m^2 and average ambient temperature of 25.4 °C. After 11 hours of drying, the tomatoes' wet basis moisture content dropped from 94% to 14.9%, while the sample under open sun drying reached only 37.9% wet basis, thus showing the effectiveness of the greenhouse dryer.

After deducting the ZMW39,699.29 operations and maintenance costs, an annual revenue of ZMW63,792.00 is obtained for an initial investment of ZMW29,640.35. The project is a desirable investment because of its 1.6-year payback period.

Farmers who cultivate tomatoes can find that adopting this greenhouse dryer has a significant impact on food security by lowering the current post-harvest losses of tomatoes. Additionally, by selling the dried tomatoes that would otherwise go to waste owing to a lack of preservation facilities, farmers would be able to get some income.

5. RECOMMENDATIONS

The research study carried out in this paper proposes the following recommendations:

a) Farmers and other stakeholders need to be sensitised about this technology of greenhouse solar dryer to enhance its fast adoption.
b) This study should be extended to fruits and vegetables that also have high postharvest losses, e.g., mangoes.
c) The potential reduction in postharvest losses that can be realised if this technology is adopted should be assessed.

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