

Research Article

Development of a Dryer Coupled to a Solar Concentrator for Drying Food (Vegetables and Fruits) as a Sustainable Alternative to Reduce Post-Harvest Losses in Manica Province

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Abstract

The prevalence of problems related to food waste has gained significant global visibility today, with around 30% of food produced being wasted annually, compromising the sustainability of our planet in some way. In Mozambique, it is estimated that between 30% and 50% of food produced, mainly vegetables and fruits, decomposes in warehouses, with the aim of minimizing food waste, this article was developed, whose main objective is to develop a dryer coupled with a solar concentrator for drying food as a sustainable alternative for reducing post-harvest losses. This is an experimental study; however, thermometers and scales, both calibrated to monitor temperature variation and food mass during the drying process, were used to collect data, ensuring compliance with food safety standards. In addition, with the help of NASA data, values for weather conditions such as solar radiation, relative humidity, and wind speed were obtained from the point where the device was tested. Microsoft Excel was used for statistical data processing with the help of SigmaPlot software version 15.0. The results obtained reveal that the dryer coupled to the solar concentrator for drying foods such as okra, kale, tomatoes, bananas, and mangoes demonstrated compliance with expected standards, presenting good visual quality and moisture content in accordance with established recommendations, below 25% for dried fruits and 12% for dried vegetables. In terms of mass efficiency, the solar dryer ranged from 86.2% to 99.7% for different foods, demonstrating its viability in both rural and urban areas. This makes it an effective solution to combat food waste without relying on electricity, thus contributing to food security and reducing environmental impacts. The efficiency of the dryer, together with the solar concentrator, reached 61.0%, highlighting solar concentrators as a promising option for improving the efficiency of food drying using solar energy.

Keywords

Food Waste, Sustainability, Solar Energy, Food Security

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Received: 5 August 2025; **Accepted:** 25 August 2025; **Published:** 19 September 2025



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1. Introduction

Throughout human history, food production, consumption, and sustainability have always played a central role in the lives of communities. The sustainability of our planet is compromised when billions of tons of food are wasted each year. It is estimated that 1.3 billion tons of food produced on the planet each year are wasted [8]. However, food waste contributes to global warming because it causes greenhouse gases to accumulate in the atmosphere through the decomposition of food waste, which releases methane (CH_4), a powerful greenhouse gas. In addition, conventional food drying methods often use fossil fuels, which release carbon dioxide (CO_2) into the atmosphere, also contributing to global warming. Therefore, taking into account one of the United Nations Sustainable Development Goals, urgent measures must be taken to combat climate change and its impacts, substantially increasing the share of renewable energies in the energy matrix [16].

The development of a dryer coupled with a solar concentrator for drying food harnesses the renewable energy of the sun, which has proven to be a viable alternative because it is renewable and sustainable, environmentally friendly, and reduces dependence on fossil fuels.

Increasing cultivation areas, seed quality, and crop monitoring is essential to combat hunger, but there is a major challenge in reducing food waste [4], since 30% of the food produced on the planet is wasted, compromising sustainability in a way [8]. In the specific case of Mozambique, it is estimated that around 30% to 50% of the food produced rots in warehouses, especially vegetables and fruit [15]. On the other hand, according to a study by the Technical Secretariat for Food and Nutritional Security (SETSAN) in 2013 and 2014, 27.5% of households in Mozambique were in a situation of chronic and acute food insecurity [3].

The province of Manica is considered one of the most productive and has favorable agro-meteorological conditions to continue increasing production, but suffers heavy losses after harvesting these foods. For example, since 2018, Mozambican mangoes have been prevented from being exported due to the presence of a type of fruit fly (*Bactrocera invadens*) [3]. Therefore, if there is a sustainable alternative close to the communities that complies with all food processing standards, most fruits and vegetables can be preserved and sent to other national and international markets.

For example, bananas produced in Manica province are wasted every year due to limited processing capacity, so with solar drying technology they can be processed into dried bananas or banana flour for better preservation [3], not to mention tomatoes, which are another food that is easily lost.

Food waste¹ directly affects the three domains of sustainability. From an environmental perspective, wasted food often

ends up in landfills, where its decomposition releases methane, a greenhouse gas that contributes to climate change. From a social perspective, food waste exacerbates food shortages, while millions of people suffer from hunger and food insecurity, and this wasted food could be redistributed to help those who need it most. From an economic perspective, both consumers and businesses suffer financial losses when food rots.

One of the alternatives that the population of Manica province uses to preserve food is freezing, but most do not have access to electricity in their homes, and even in homes that do have electricity, it is unstable. In addition to this alternative, natural drying is also used, which generally requires more time and, during the drying process, food is exposed to the external environment, making it susceptible to contamination by insects, dust, microorganisms, and environmental pollution, which can compromise food safety and quality.

To address this issue, a dryer was developed and attached to the solar concentrator to dry food, as a practical solution to reduce food waste, allowing food to be processed for longer preservation using solar energy as a renewable energy source. It is a sustainable alternative that uses the abundant solar radiation in the region without emitting greenhouse gases.

The research is fully aligned with the UN Sustainable Development Goals, as the solar dryer can be used to preserve food, reducing post-harvest waste and ensuring food security (Zero Hunger and Sustainable Agriculture). The solar dryer uses solar energy, a renewable and clean energy source, contributing to more sustainable energy access (Affordable and Clean Energy). By enabling food to be preserved in a sustainable manner, the solar dryer can promote more responsible consumption and production practices (Responsible Consumption and Production), and the use of solar dryers can help reduce greenhouse gas emissions associated with conventional food preservation methods, which often involve the use of fossil fuels (Action Against Global Climate Change).

Objectives

In general, the objective of the research is to develop a dryer coupled to a solar concentrator for food drying as a sustainable alternative for reducing post-harvest losses in Manica Province. Specifically, the aim is to:

- 1) Design the dryer coupled to the solar concentrator for drying food;
- 2) Describe the process of building a dryer coupled to a solar concentrator for drying food;
- 3) Build and test the solar concentrator dryer in the food drying process;
- 4) Determine the thermal and mass efficiency of the solar dryer in drying food;
- 5) Compare the results obtained in food drying with those of other authors.

¹Food waste is considered to be the reduction in food available for consumption that occurs in the final stages of the food supply chain, i.e., when food is already available to retailers and consumers.

2. Literature Review

2.1. Solar Dryer

Drying is a physical process that consists of removing water through evaporation in order to improve food preservation. In other words, this process consists of reducing moisture content in order to prevent the growth of microorganisms and undesirable chemical reactions that can spoil food, rendering it unfit for consumption [24]. There are several methods of drying food, but the most common are natural drying, solar drying, and artificial drying, the main difference between them being how the drying air is heated [17].

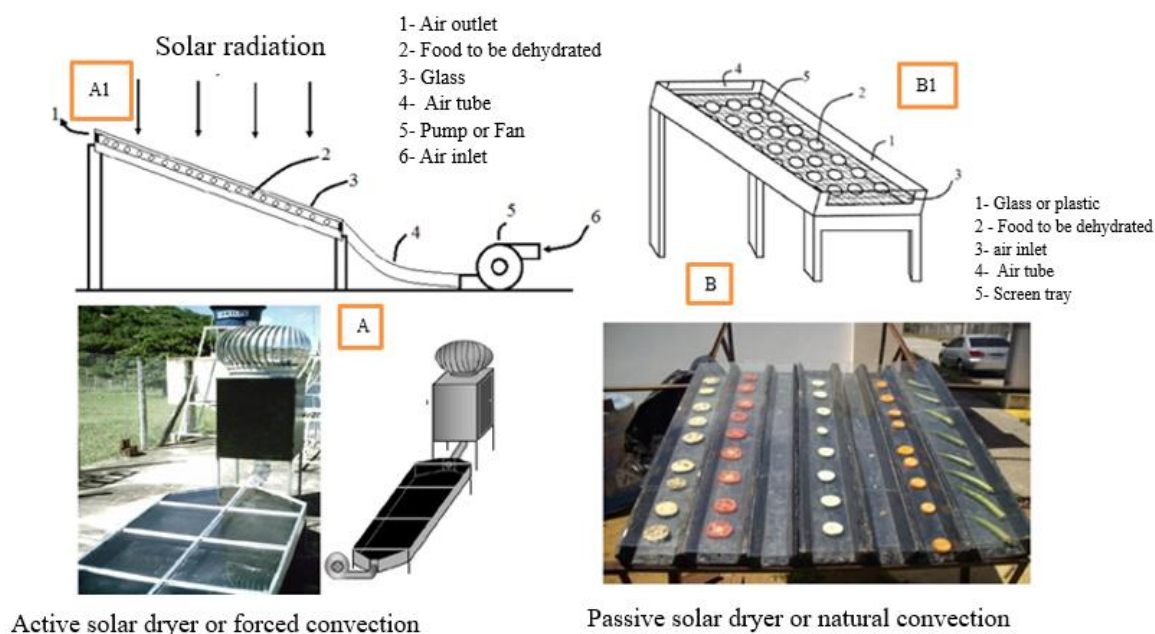
Natural drying is the oldest method among the others. It involves low investment, but the food is exposed to wind, rain, and solar radiation without any device. However, the food can dry out too much, making this method less effective [14], a concrete example: when food is scattered on the ground, there is a risk that insects will land on it and cause contamination, which can be harmful to human health, and natural drying is much slower than solar and artificial drying.

In an artificial dryer, air conducts heat to the food, evaporating the water from it and transporting the moist vapor away from the food. This can be done using energy sources such as burning fossil fuels or electricity, among others. However, this dryer is more efficient in terms of drying time, since the drying conditions are artificially controlled, such as

humidity control, which is one of the reasons why drying is faster and more efficient, but involves higher costs [14].

A solar dryer is a device that uses solar thermal energy, obtained by converting solar radiation into heat that warms the air and evaporates the moisture present in food. Thus, solar dryers are a sustainable and clean alternative to other drying methods, as they protect the food being dried [14]. Solar dryers have three main components: a drying chamber in which food is dried, protecting it from animals, insects, dust, and rain. In this case, the chamber is always insulated to increase its efficiency, and the trays inside the drying chamber must be made of materials suitable for food use. a plastic cover to prevent harmful residues from entering the food, a solar collector, which is usually a black-painted box with a transparent cover that heats the air, increasing the air temperature between 10 and 30 °C above the ambient temperature, and some type of air flow system [21].

Its operation is based on the principle of mass and heat transfer, known as convection, in which solar energy is captured by the collector, which transfers the heat to the drying chamber. The drying chamber is a closed space with a transparent cover that allows solar radiation to enter, through which water is forced to evaporate and this vapor is removed naturally or by forced convection [24]. In other words, during the drying process, two phenomena occur at the same time: the transfer of heat from the heat source to the food and the transfer of mass from inside the food to the environment.



Source: Adapted from [23]

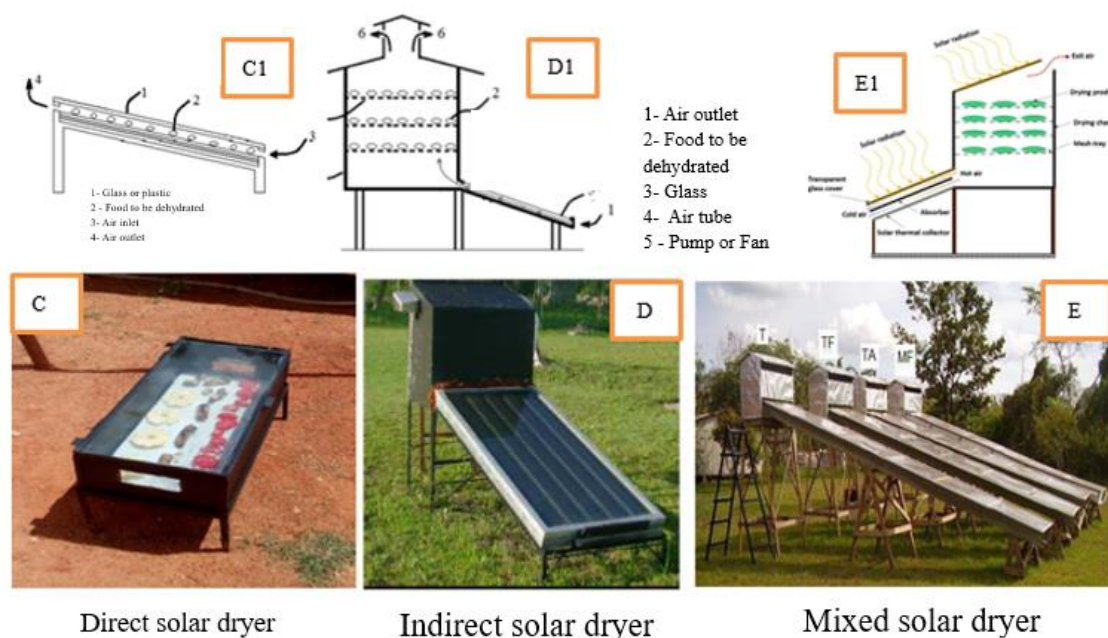
Figure 1. Passive and active solar dryer.

Solar dryers are divided into two groups: passive and active solar dryers, and are further subdivided into three categories: direct, indirect, and mixed dryers. The specifications for

classifying dryers vary greatly and meet the different requirements of the drying process [27], however, the passive solar dryer is a fairly simple device in which food is exposed

to solar radiation through a transparent cover. However, hot air circulates inside the dryer by natural convection and uses renewable energy sources, so it can be installed in places where there is no electricity grid, while the active solar dryer is a complex device compared to the passive one, because hot

air circulates inside the dryer by forced convection, which requires a fan to circulate the air inside the dryer [27]. As shown in Figure 1, A1 represents the active solar dryer design, A represents the dryer itself, while B1 represents the passive solar dryer design and B represents the dryer itself.



Source: Adapted from [23]
Figure 2. Direct solar dryer, indirect solar dryer, and mixed solar dryer.

2.2. Solar Collector

There are two types of solar collectors: non-concentrating and concentrating. Non-concentrating solar collectors are flat, designed for applications that require low temperatures, and have a coverage area equivalent to the size of the collector [12], for example, flat plate solar collectors and vacuum tube solar collectors. While, concentrating solar collectors are designed for applications that require high temperatures. They have a reflective surface that directs direct radiation to a point where there is a receiver through which the heat-absorbing fluid flows [12], for example, a parabolic dish, central tower or concentration tower, Fresnel collector, and cylindrical parabolic solar concentrator.

However, the cylindrical parabolic solar concentrator is a cylindrical parabolic collector covered with a parabolic-shaped reflective material. Along the focal line of the parabolic reflector is a black metal tube called a receiver. Thus, when the parabola points toward the sun, the sun's direct rays are reflected by the reflective surface and concentrated on the receiver, whereby the concentrated radiation heats the fluid circulating inside the tube [12], as illustrated in Figure 4.

Cylindrical parabolic collectors are usually built with a single-axis sun tracking system, which can be oriented in an

east-west direction, following the sun from north to south, or in a north-south direction, following the sun from east to west. For example, in an east-west direction, these move little throughout the day and are always facing directly towards the sun at midday, but this is reduced at the beginning of the day and in the late afternoon, due to the greater angles of incidence of the sun's rays on the collector surface. In the north-south direction, for example, there are greater angles of incidence during midday and, consequently, greater heat losses at this time of day, while it points more directly towards the sun at the beginning of the day and in the late afternoon [11].

Over the course of a year, a north-south facing collector absorbs more energy than an east-west facing one, so a north-south collector collects more heat in summer and less in winter than an east-west facing collector, which produces more energy evenly throughout the year. so the choice of orientation also depends on the application and when the energy is most needed, i.e., whether demand varies significantly depending on the season, winter or summer, or whether it varies more during the day [12, 13].

Since the cylindrical parabolic solar concentrator has the shape of a parabola and a reflective surface, it has the same optical properties as concave spherical mirrors, as shown in Figure 3, which are capable of increasing the intensity of radiation before the rays reach the absorbing surface [10].

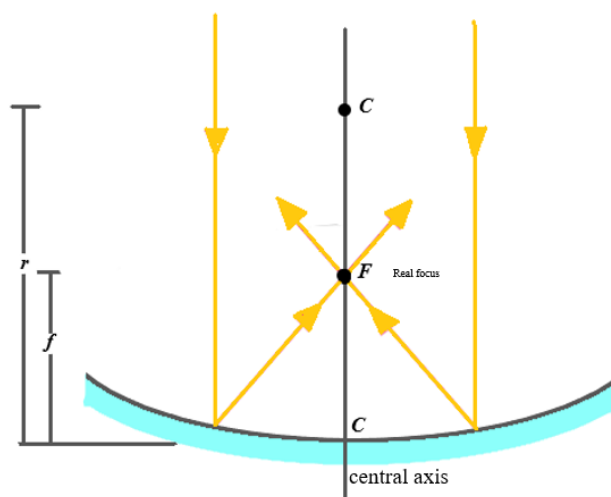


Figure 3. Concave mirror with parallel incident rays.



Source: [11]

Figure 4. Parabolic trough solar concentrator.

However, the relevant parameters for the use of a cylindrical parabolic solar concentrator are the determination of the radius to be used, with the absorber tube located at its focus, as well as the opening angle of the cylindrical trough [13].

When the Sun emits light at a great distance from the mirror, the rays are parallel to the central axis of the mirror, so when these rays are reflected by a concave mirror, they converge at a common point called the focal point, located at a specific distance from the mirror, called the focal length [28], as shown in Figure 3. The focal length of the mirror f , based on the radius of curvature r , is determined by equation (1) [28]:

$$f = \frac{r}{2} \quad (1)$$

As shown in Figure 3, the center of curvature (C) is located at the center point of the parabolic mirror, while the focus is located at a distance equal to half the radius of the parabolic mirror from the center of curvature. As for the opening angle

of the cylindrical trough, it is estimated that an angle of around 70° is suitable for prototypes, mainly because it significantly reduces the effects of wind on the collector, and the maximum concentration of a two-dimensional concentrator is given by an angle of 90° [13], therefore, there are several materials that can be used to reflect radiation in solar concentrators. Each material has different optical properties that can affect the efficiency and performance of the concentrator. Table 1 compares the reflectance values of some materials.

Table 1. Comparison of reflection values for some materials.

Reflective surface	Reflection Factor [%]
Silver	92-97
Vaporized aluminum	90-95
Gold	60-92
Mirrors	80-85
Light green	70-80
Copper	35-80
Polished Aluminum	67-72
Nickel Polished	60-65
Polished Chrome	60-65
Light blue	45-55
Light gray	40-50
Light red	30-50
Black	3-4

Source: Adapted from [6]

The greater the reflective capacity of a given material, the better its performance in conserving solar energy for various purposes. Generally, the materials most commonly used to harness solar energy are those that are most efficient at reflecting or absorbing solar radiation, such as mirrors, vaporized aluminum, silver, light green, among others [6].

2.3. Factors Influencing Food Drying in Solar Dryers

In the food drying process, there are three external factors that make control difficult due to constant variations in climatic conditions throughout the day and night. For example, an increase in the flow of air entering from outside has the effect of lowering the temperature inside the dryer and slightly increasing the relative humidity of the air. However, these factors are temperature, air humidity, and air velocity [22].

The minimum temperature required to dry food is approximately 35°C , and the maximum is approximately 82°C ,

at which point the drying speed increases. However, the most common range is between 43 °C and 60 °C, but between 57 °C and 82 °C, bacteria and enzymes are eliminated, so when food is exposed to a temperature of 57 °C for 1 hour or 80 °C for 10 to 15 minutes at the beginning of the drying process [1, 22].

In the case of air speed, this is a factor that generally depends on mechanical actions, such as opening or closing the air inlets, but its adjustment depends on the air inlet area, which is easily adjustable, and the wind speed, which is highly variable, making it difficult to manage the dryer inlet area. Therefore, a decrease in the air flow at the dryer inlet causes an increase in the air temperature inside the dryer and a slight decrease in the air humidity inside the dryer [1, 22].

In the case of humidity, this is possibly the most difficult factor to control, because the higher the percentage of moisture in the air, the greater the air flow required and the higher the temperature required to increase the air's capacity to retain water. For example, for every 15 °C increase in temperature, the air's capacity to retain moisture doubles [1].

2.4. Advantages and Disadvantages of Dry Foods

The use of drying for food preservation has advantages, such as increasing the shelf life of food. Dried foods are nutritious because their nutritional value is concentrated due to water loss, despite the possible loss of some nutrients. They are also easy to transport and market, as dried foods are light, compact, and their qualities remain unchanged for long periods, and the cost associated with the packaging and storage process is lower for dried foods than for canned and frozen foods [8, 18].

2.5. Determination of Moisture Content

Moisture content can be determined in several ways, however, the choice of method depends on factors such as the form in which water is present in food, the nature of the food, and the desired speed. Water can be present in food in two forms: free water, which is water adsorbed by food, which is the most abundant form and is easily lost to the environment at temperatures close to boiling; and bound water, which is water that is bound to the structure of food. Free water, which is the most abundant, is easily lost to the environment at temperatures close to boiling, and bound water, which is water bound to the food structure, is bound to soluble food components such as proteins, sugars, minerals, amino acids, and adsorbed on the surface of colloidal particles. This water cannot be removed through normal drying, requires high temperatures for its removal, and in some cases is not eliminated even at temperatures that partially char the food [19].

Moisture content determinations are classified into direct and indirect methods. However, in the direct method, water is usually removed from food through a heating process and

the determination is made by weighing, with the moisture content calculated by the difference in food mass at the beginning and end of the drying process. In indirect methods, determinations are made by measuring the physical characteristics of the material related to the water content of the food, the moisture content is estimated based on the electrical properties of the food under a given condition [7, 19].

The amount of water removed during the drying process is calculated according to the initial and final moisture content of the food to be dried and the total mass of the food before the start of the process. This content can be expressed as the ratio between the mass of water contained in the food and its total mass [19], as shown in equation (2).

$$X_{bm} = \frac{m_{H_2O}}{m_t} \quad (2)$$

Where: X_{bm} is the moisture content on a wet basis, which indicates the amount of moisture in the food after drying, which can indicate whether the food has been dried sufficiently [%]; m_t is the total mass of the food, which corresponds to the sum of the mass of water and the mass of dry matter ($m_t = m_{H_2O} + m_{m_d}$), [kg];

In order to ensure public health and food quality, the Codex Alimentarius Commission has established food standards, which include standards for all major foods: processed, semi-processed, or raw, for distribution to consumers or as raw materials [2]. For example, processed or dried foods must have a maximum final moisture content, on a wet basis, of 25% for dried fruits and 12% for dried vegetables [9], which will prevent the food from spoiling and allow it to be stored for longer.

2.6. Calculation of Drying System Efficiency

The efficiency of the drying system is obtained by calculating the performance of the drying process and the thermal efficiency of the equipment. However, this performance must evaluate two characteristics: the equipment itself and the process for which it is intended. Thus, the efficiency of the solar dryer is related to its thermal efficiency, while the efficiency of the drying process can be evaluated by the difference between the initial mass and the final mass of the food, in relation to the initial mass of water present in the food [22].

Thus, to calculate the thermal efficiency of the equipment, we start from the basic concept of thermodynamic efficiency, which is the ratio between the power supplied by the system and the power available in it. In this case, the efficiency of a solar dryer can be determined by equation (3) [26].

$$\eta_t = \frac{P_u}{A_c \cdot G} \cdot 100\% \quad (3)$$

Where: η_t is the solar dryer efficiency [%]; P_u is the power transferred to the working fluid [W]; A_c is the trans-

parent coverage area [m^2]; $\bar{G}$ is the average incident solar radiation [W/m^2].

The power transferred to the working fluid is also referred to as useful power and represents the amount of energy transferred to the working fluid, which is air [19], and is determined using equation (4):

$$P_u = \dot{m} \cdot C_p \cdot \Delta T \quad (4)$$

Where: $\dot{m}$ is the mass flow rate of the working fluid [kg/s], which can be determined using the specific density (ρ) of the air, the fluid flow velocity [m/s], and the cross-sectional area through which the fluid flows [m^2], thus $\dot{m} = \rho \cdot v \cdot A$; C_p is the specific heat of the working fluid [J/kgK]; ΔT is the temperature difference between the outlet and inlet air of the dryer [K]. The mass efficiency of the drying process can also be obtained by measuring the variation in the masses of the dried food [5], so:

$$\eta_p = \frac{mass_i - mass_f}{mass_{TH_2O}} \cdot 100\% \quad (5)$$

Where: η_p is the mass efficiency of the process (%); $mass_i$ is the initial mass of the food (kg); $mass_f$ is the final mass of the food (kg); $mass_{TH_2O}$ is the total mass of water present in the food to be dried (kg), however, this mass is given by $mass_{TH_2O} = mass_i \times w$, where w corresponds to the moisture content present in the food or initial moisture.

3. Methodology

The study was conducted at the headquarters of the University of Púnguê in the Heróis Moçambicanos neighborhood, in Chimoio, capital of Manica province, as illustrated in Figure 5 with the coordinates of the location where the experiment was tested.



Figure 5. Location of the study (Púnguê University campus).

In terms of methods, this research used bibliographic, experimental, and statistical methods. However, before proceeding with the experimental part, a series of bibliographic consultations was carried out.

With regard to the experimental method, it is important to note that it focused on the operation of the device developed, with the aim of observing the results of the variables during the experiment. Therefore, food drying tests were carried out using laboratory techniques, which allowed the use of instruments such as thermometers and scales. These instruments were used to measure the temperature at various points, namely at the test site, at the focal point of the solar concentrator, inside the solar dryer, at the inlet and outlet of the solar dryer, as well as to measure the mass of the food to be dried.

In turn, statistics were used, after the food masses remained constant, indicating that they were completely dry, to determine the amount of water removed from the food (moisture content, on a wet basis) and the mass efficiency of the food

drying process, using equations (2) and (5), respectively, and the efficiency of the solar dryer using equation (3), enabling the calculation of various statistical parameters, such as the average temperature values at the inlet and outlet of the solar dryer.

For data processing, Microsoft Office Excel and SigmaPlot v15.0 were used to construct graphs representing solar radiation, ambient temperature, relative humidity, and wind speed, as well as graphs of the temperature behavior inside the solar dryers during the drying process and the behavior of the food masses to be dried.

Experimental Procedures

The experimental part was divided into two distinct phases:

Construction of the solar concentrator and dryer: The solar concentrator was constructed using a recycled 200-liter polyethylene drum, angle brackets, metal bars, mirrors, rivets, and silicone. To build it, two supports were first made using angle brackets and metal bars to secure the other elements of

the prototype in place. Next, a longitudinal cut was made in two equal parts of the polyethylene drum, each of which was fixed to each support with rivets, as shown in Figure 6.

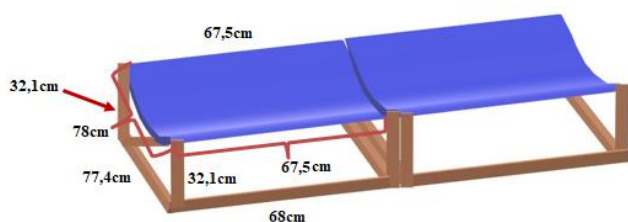


Figure 6. Parts of the drum attached to the supports.

Once the solar concentrator was completed, the objective was to ensure that the radiation, upon reaching the mirrors, would be reflected to a receiver, which is the solar dryer, as shown in Figure 7.

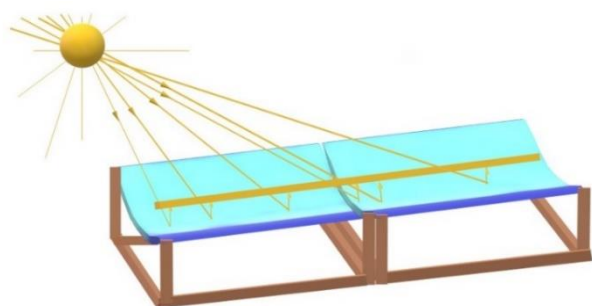


Figure 7. Solar concentrator.

After constructing the solar concentrator, a support was made, where the receiver or solar dryer is located, using angle iron, containing a screw to allow the solar dryer to be raised or lowered, so that the radiation reaches the dryer with greater intensity (when in focus) or less intensity (when moved up or down from the focus).

Finally, the solar dryer was built using glass, wood, metal mesh, and nails. The solar dryer was made in the shape of a box, with wood on the sides, a drawer at the back where the food is placed, and a metal mesh with holes at the front to allow air to enter and exit. Three solar dryers were built, two on the sides and one in the middle, as shown in Figure 8.

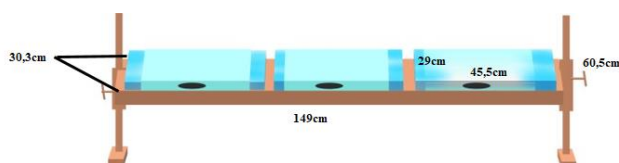


Figure 8. Solar dryer installed on top of the dryer base.

Thus, the final structure of the dryer coupled to the solar concentrator for food drying is shown in Figure 8 already in operation, where the solar concentrator has an area of $4556,25\text{cm}^2$ and the solar dryer has a transparent coverage area of 2639cm^2 .



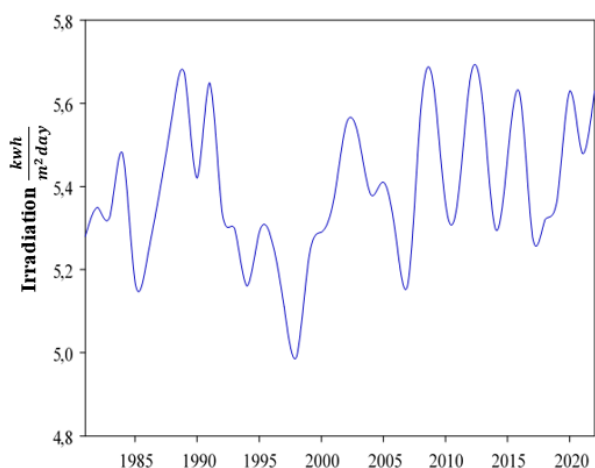
Figure 9. Dryer connected to the solar concentrator in operation.

This involved testing the operation of the experiment and collecting data: During this stage, temperatures were recorded at different points, including at the test site, at the focal point of the solar concentrator, inside the solar dryer, at the inlet and outlet of the solar dryer. However, the temperatures at the inlet, outlet, and inside the solar dryer were recorded every 5 minutes with the aid of a thermometer, with the aim of observing the behavior of the solar dryers or monitoring temperature changes. However, measuring the temperature of the drying air inside the dryer is extremely important for observing its variation throughout the day and better controlling conditions in order to optimize the drying process, as highlighted by [19].

The mass of the food to be dried was measured every 45 minutes using a scale to monitor mass loss until it stabilized, as this not only helps determine the ideal time to stop the drying process, but also allows the moisture content of the food to be calculated, thus ensuring its compliance with regulatory food safety standards. The variables measured were influenced by weather conditions, so the average daily solar radiation, ambient temperature, average relative humidity, and wind speed were taken into account in the measurement and processing of the data, and the values of these parameters were extracted via satellite (Power Data Access Viewer v2.0.0) from the NASA database at the point where the device was tested.

4. Presentation and Discussion of Results

Initially, an analysis was made of the meteorological conditions at the point where the dryer coupled to the solar concentrator for drying food was tested.

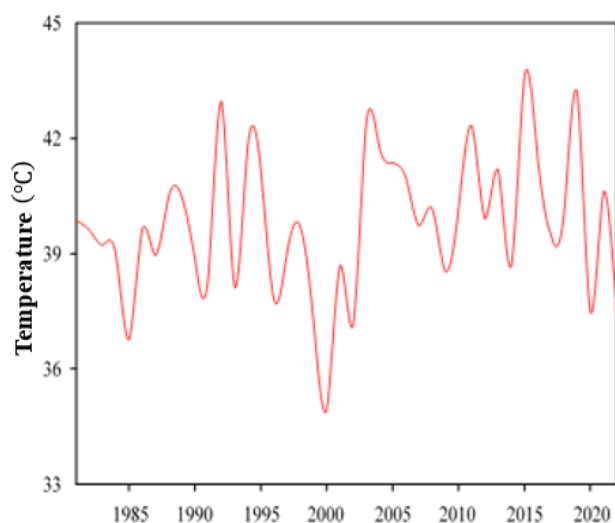


Source: elaborate by the author using data from [20] (1984–2024)

Figure 10. Solar radiation from 1984 to 2022.

Solar radiation is not constant, it varies continuously, as evidenced by Figure 10, which shows solar radiation over time from 1984 to 2022. Figure 10 shows that the irradiation value increased from 1988, reaching its peak in 1992, corresponding to $5,67 \text{ kWh/m}^2$. Between 1994 and 2000, there was a decrease in solar radiation, reaching its minimum value in 2000, of $4,99 \text{ kWh/m}^2$, due to atypical weather conditions. During the rainy season, cloud concentration is higher, which reduces solar radiation due to the absorption, dispersion, and reflection of light by raindrops and cloud particles. Therefore, the variation in solar radiation depends on how it is influenced by the atmosphere and the Earth's surface.

From 2001 onwards, there was a gradual increase in radiation until 2005, and from then until 2022, the variations were not as significant as those that occurred in the 1980s.



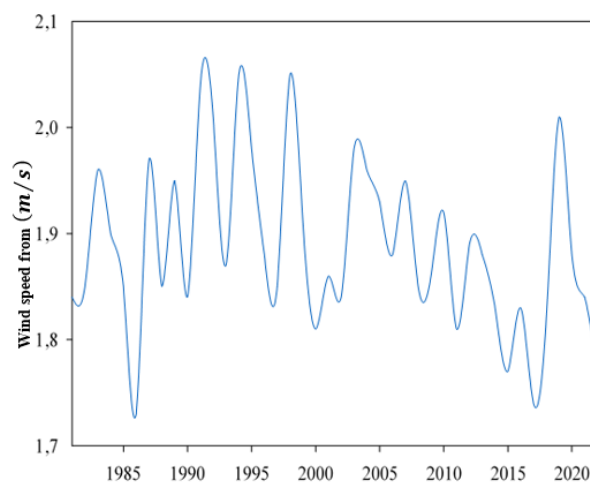
Source: elaborate by the author using data from [20] (1984–2024)

Figure 11. Temperature from 1981 to 2022.

Temperature and solar radiation are two directly proportional quantities. According to Figure 11, which shows the temperature over time from 1981 to 2022, there was an increase in temperature values between 1985 and 1992, with the maximum temperature reaching 44.24°C in 1992. For example, an analysis conducted [32] on temperatures in Mozambique during the period from 1960 to 2005 found significant increases in all regions of Mozambique, especially from the 1990s onwards, considered the hottest decade.

The value of 44.24°C is consistent with the relationship between solar radiation and temperature, since in Figure 10, solar radiation peaked in 1992, and in Figure 11, the temperature peaked in the same year. Then, from 1994 to 2002, there was a decrease in temperature, with the minimum being reached in 2000, corresponding to 34.94°C , as can be seen in Figure 10, which shows that in that same year, 2000, radiation was minimal and, therefore, temperature was also minimal, as verified by [32].

From 2002 onwards, there was an increase in temperature until 2005, and after that, until 2022, fluctuations were normal compared to the 1980s, as was the case with solar radiation. Therefore, the reasons for temperature fluctuations over the years are the same as those explained for solar radiation.

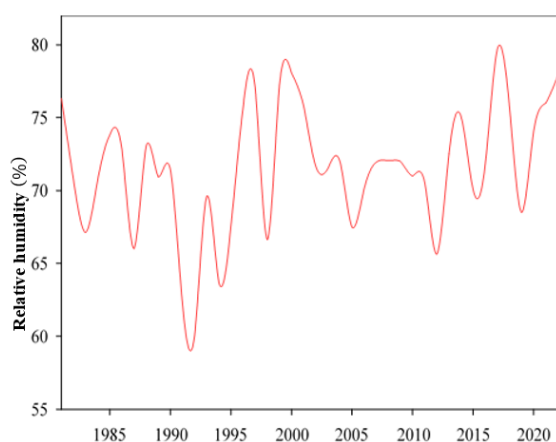


Source: elaborate by the author using data from [20] (1984–2024)

Figure 12. Wind speed from 1981 to 2022.

Wind is the movement of air from one place to another due to differences in temperature and atmospheric pressure. When warm air rises, it creates areas of low pressure, and air moves from areas of high pressure to areas of low pressure, filling the empty space [25]. Figure 12 shows that from 1983 to 1986, there was a decrease in wind speed, with the minimum speed of 1.73 m/s being reached in 1986. In the following years, there was an increase in wind speed until 1998, with maximum speeds reached between 1994 and 1998, corresponding to 2.05 m/s . There was then a decrease in wind speed from 2000 to 2017, with a variation of 0.07 m/s . These fluctuations occur due to temperature variations that influence at-

atmospheric pressure, interfering with wind behavior.



Source: elaborate by the author using data from [20] (1984–2024)

Figure 13. Relative humidity from 1981 to 2022.

Relative humidity is directly related to the amount of water vapor present in the atmosphere and can influence temperature variation. Figure 13 shows that from 1990 to 1994, there was a decrease in relative humidity, reaching a minimum of 60.06% in 1992. Subsequently, from 1994 to 1997, there was a gradual increase, followed by a sharp drop in 1998. From that year until 2000, there was an upward trend, followed by normal fluctuations from 2000 to 2022.

These variations are related to the behavior of solar radiation and temperature, since solar radiation is inversely proportional to relative humidity, and temperature is also inversely proportional to relative humidity. This can be easily observed in Figure 10 or Figure 11. For example, in 1992, solar radiation and temperature values are at their maximum, while relative humidity is at a minimum. In 2000, however, solar radiation and temperature values are at a minimum, while relative humidity reaches a maximum value, as observed by [31].

4.1. Energy Optimization Parameters of the Solar Concentrator

One of the first analyses to be performed on the solar concentrator is to find the focus, which is half the radius of curvature. The diameter of the concentrator is 134.4 cm, so the focus is at a distance of 33.6 cm. Figure 14 shows the focus analysis.

According to Figure 14, the thermometer in the center is at a distance of 33.6 cm, it is at the focal point, so the concentrator can reach up to 65.8°C. The thermometer above the focus is at a distance of 50.9 cm and reaches a temperature of up to 48.5°C, and the thermometer below the focus is at a distance of 17.3 cm and can reach up to 56.7°C. Therefore, the temperature is higher at the focus compared to any other point. For example, when the distance is varied, increasing or

decreasing in relation to the focus, the temperature decreases, and this is extremely important because the temperature can be varied according to the food to be dried.

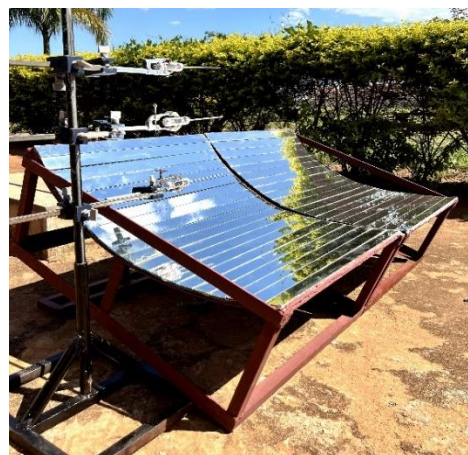


Figure 14. Focal length analysis.

4.2. Drying Food (Okra, Kale, and Pumpkin Leaves)

The drying of these foods took a total of 6.75 hours (six hours and forty-five minutes), spread over two days. On the first day, as well as on the following days of drying, the predicted temperatures for the city of Chimoio were consulted, which were $T_{min} = 14^{\circ}\text{C}$ and $T_{max} = 29^{\circ}\text{C}$. Next, the temperature of the test site was measured with a thermometer, resulting in $T = 25.68^{\circ}\text{C}$. In addition, the temperature at the focal point was also measured, resulting in $T_{focus} = 55^{\circ}\text{C}$. An increase in temperature was observed at the focal point in relation to the ambient temperature. Figure 15 illustrates the temperature behavior inside each solar dryer.

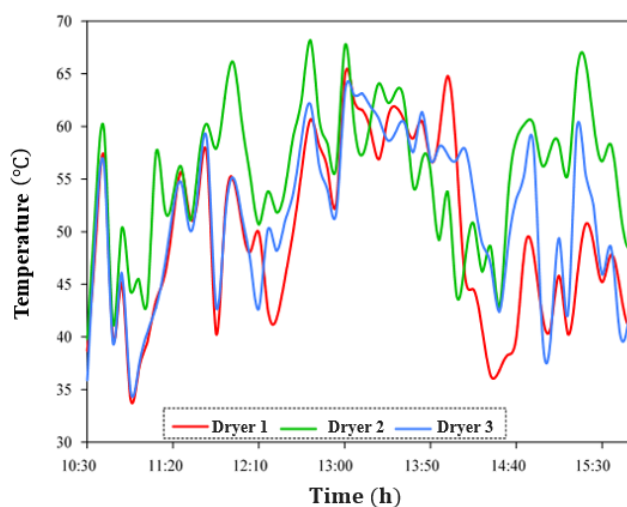


Figure 15. Temperature behavior inside solar dryers (January 22, 2024).

During the observation period, the lowest temperatures were recorded between 10:30 a.m. and 11:05 a.m., reaching a minimum temperature of 34.3°C , while the highest temperatures were recorded during the middle of the day, between 12:00 p.m. and 1:35 p.m., reaching a maximum temperature of 67.7°C on the 22nd. These temperatures were measured while the food was being dried inside the dryers. For example, in dryer 1, there was okra, in dryer 2, there was kale, and in dryer 3, there was pumpkin greens. Figure 16 illustrates the temperature behavior at the beginning and end of the drying process for these foods during the two days of drying.

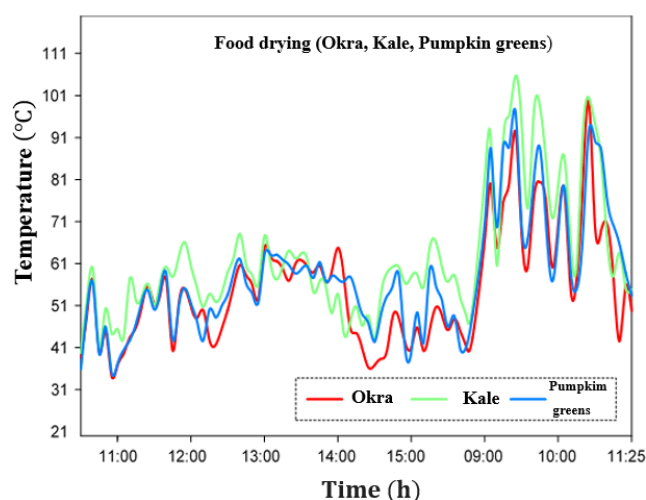


Figure 16. Temperature behavior inside solar dryers during the drying of okra, kale, and pumpkin vegetables.

Part of the moisture was removed on the 22nd and another part on the 23rd, as shown in Figure 16, resulting in temperature peaks due to the weather conditions on each day. For example, on the 22nd, the average solar radiation was $8230 \text{ Wm}^{-2}\text{h}$, with an average temperature of 27.58°C , at the test site, an average relative humidity of 48%, an average air speed of 3.46 m/s , and the sky was cloudy, hindering the passage of sunlight, as the presence of clouds has a direct impact on the temperature inside the solar dryer, since they block solar radiation, reducing the energy transferred from the concentrator to the solar dryer.

While on the 23rd, the average solar radiation was $7560 \text{ Wm}^{-2}\text{h}$, with an average temperature of 26.94°C and

average relative humidity of 51.16%, an average air speed of 6.27 m/s , and clear skies, providing high temperatures inside the dryers, these data were obtained from [20].

Also in Figure 16, it can be seen that dryer 2 (containing the kale) reaches higher temperatures than those on the sides, as it is less influenced by wind speed and relative humidity than the other two dryers located on the sides. Figure 17 shows the behavior of okra, kale, and pumpkin vegetable masses.

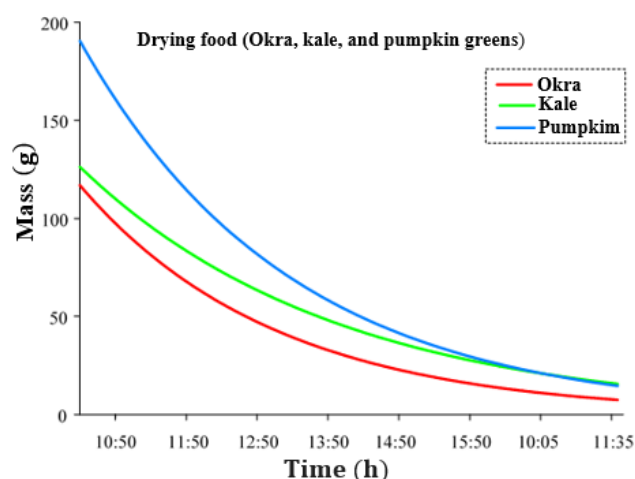


Figure 17. Behavior of food masses during drying (okra, kale, and pumpkin greens).

Figure 17 shows that the highest rate of mass loss occurs at the beginning of drying, due to the presence of free water in the food, which is easily removed during the drying process. Thus, on the first day (10:30 a.m. to 3:50 p.m.), most of the water was removed from the three foods by evaporation. On the second day (10:05 a.m. to 11:35 a.m.), the remaining water or part of the bound water was removed, which requires high temperatures and, even so, may not be completely removed. This led to the conclusion that these foods dried at the same time, as evidenced by the stabilization of the food masses.

With regard to the mass efficiency of the drying process and the moisture content on a final wet basis, equations (5) and (2) are used, respectively. For example, Table 2 shows the values of mass efficiency and moisture content on a wet basis for okra, kale, and pumpkin greens.

Table 2. Mass parameters and mass efficiency of okra, kale, and pumpkin vegetables.

Food	m_t [g]	m_f [g]	$m_{\text{H}_2\text{O}}$ [g]	X_{bmi} [%]	X_{bmf} [%]	η_p [%]
Okra	117	16	105,3	86,3	11,1	95,9
Kale	127	24	109,22	81,1	4,0	94,3
Pumpkin vegetables	190	19	174,8	90	17	97,8

The efficiency of the drying process for okra, kale, and pumpkin vegetables in relation to the total load tested was 95.9%, 94.3%, and 97.8%, respectively, meaning that dryers 1, 2, and 3 achieved significant efficiency during the drying of these foods, resulting in a relatively short drying time.

As for the initial moisture content of okra, kale, and pumpkin, it was 86.3%, 81.1%, and 90.0%, respectively, after six hours and forty-five minutes (6.75 hours), the final moisture content was 11.1% for okra, 4.0% for kale, and 17.0% for pumpkin. However, it can be said that the okra and kale dried sufficiently, as they are within the recommended range for dried vegetables, they meet quality standards, since the moisture content on a wet basis does not exceed 12%. Pumpkin vegetables, on the other hand, do not meet quality standards, as they have a moisture content above the recommended level, exceeding 12%. This is due to the initial moisture content, which is much higher than that of other foods, which can lead to deterioration due to the growth of microorganisms and a reduction in the shelf life of the food.

The temperatures inside the dryers varied. For example, okra was dried at temperatures of $T_{min} = 34,3^{\circ}\text{C}$ and $T_{max} = 99,7^{\circ}\text{C}$, kale at $T_{min} = 39,8^{\circ}\text{C}$ and $T_{max} = 105,7^{\circ}\text{C}$, and pumpkin vegetables at $T_{min} = 35,9^{\circ}\text{C}$ and $T_{max} = 97,4^{\circ}\text{C}$. Figure 18 shows the foods before and after the drying process.

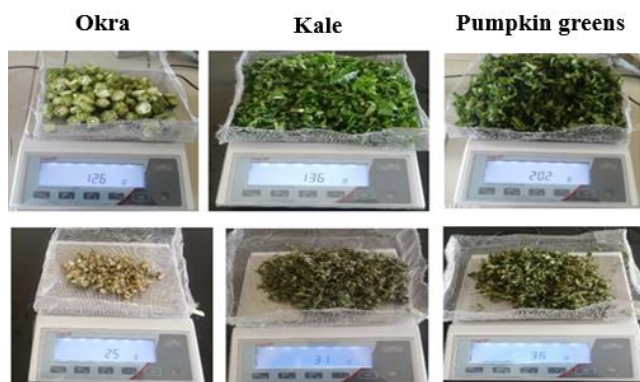


Figure 18. Food before and after the drying process.

4.3. Food Drying (Tomatoes, Bananas, and Mangoes)

The removal of moisture from these foods occurred over an irregular period of time, requiring 6 hours and 45 minutes to dry mangoes, 7 hours and 30 minutes for tomatoes, and 13 hours and 30 minutes for bananas, reflecting temperature variations inside the dryers, as shown in Figure 19. However, the drying time for these foods was spread over three days (January 23, 24, and 25). The mangoes and tomatoes were dried in two days (23 and 24), and the bananas were dried in three days (23, 24, and 25).

To analyze the temperature inside the solar dryers, first the

predicted temperatures for the city of Chimoio were considered, with $T_{min} = 17,5^{\circ}\text{C}$ and $T_{max} = 28,9^{\circ}\text{C}$. Next, the temperature of the test site was measured using a thermometer, which recorded $26,6^{\circ}\text{C}$. In addition, the temperature at the focus was measured and resulted in $T_{focus} = 59^{\circ}\text{C}$. Thus, Figure 19 illustrates the temperature behavior inside the solar dryers.

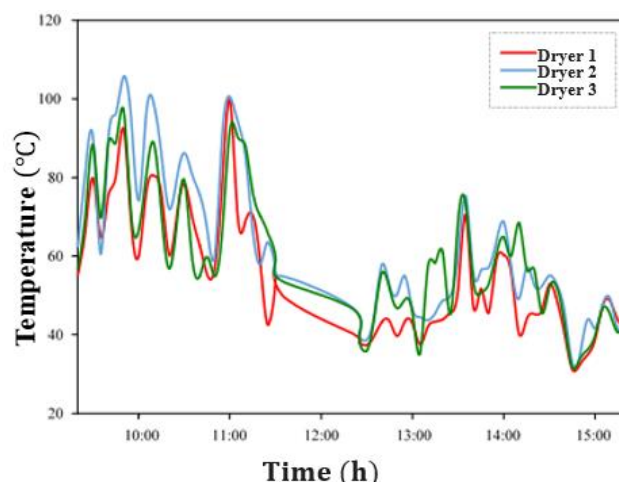


Figure 19. Temperature behavior inside solar dryers (January 23, 2024).

According to Figure 19, the lowest temperatures were recorded between 2:40 p.m. and 3:25 p.m., with a minimum temperature of $31,2^{\circ}\text{C}$, while the highest temperatures occurred in the early hours of the day (9:25 a.m. to 11:25 a.m.), reaching a maximum temperature of $105,7^{\circ}\text{C}$. During the recording of temperatures in the solar dryers, tomatoes were in dryer 1, bananas were in dryer 2, and mangoes were in dryer 3, as illustrated in Figure 20, which shows the temperature behavior at the beginning and end of the drying process for these foods.

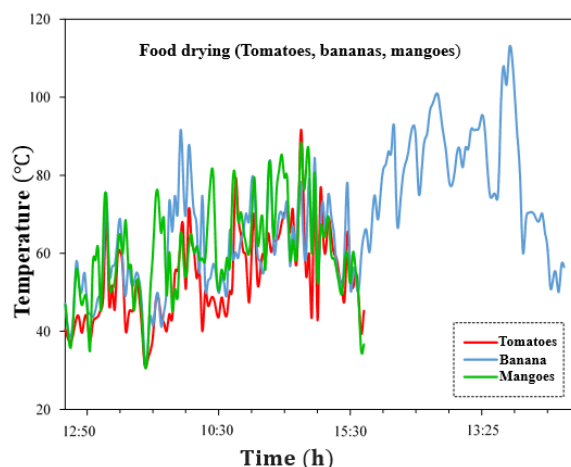


Figure 20. Temperature behavior inside solar dryers during the drying of tomatoes, bananas, and mangoes.

The temperature fluctuations are attributed to the weather conditions on the days when the food was dried. For example, on the 23rd, the drying hours were from 12:20 to 15:25, and the weather conditions for that day were discussed earlier.

The following day, the 24th, drying took place from 10:00 to 15:30, under the following weather conditions: average solar radiation of $7280 \text{ Wm}^{-2}\text{h}$, average temperature at the test site of 26.02°C , an average relative humidity of 60.67%, an average air speed of 6.25 m/s [20]. However, before starting the drying process, the predicted temperatures for the city of Chimoio were considered, with $T_{\min} = 17^\circ\text{C}$ and $T_{\max} = 27^\circ\text{C}$. Next, the temperature of the test site was measured with a thermometer, recording 27.2°C , and the temperature at the focus was measured, resulting in $T_{\text{focus}} = 60.5^\circ\text{C}$.

On the last day, the 25th, drying hours were from 9:50 a.m. to 3:25 p.m., and the weather conditions were as follows: average solar radiation of $8080 \text{ Wm}^{-2}\text{h}$, average temperature at the test site of 25.95°C , average relative humidity of 49.79%, average air speed of 5.85 m/s , and clear skies, these data were obtained from [20]. Before the drying process, the forecast temperatures for the city of Chimoio were consulted, with $T_{\min} = 19^\circ\text{C}$ and $T_{\max} = 28^\circ\text{C}$. Next, the temperature at the test site was measured using a thermometer, recording 25.4°C , and the temperature at the focus was also measured, resulting in $T_{\text{focus}} = 60^\circ\text{C}$.

During the drying of these foods, it was observed that dryer 2 (containing bananas) reaches higher temperatures than the side dryers, as seen during the drying of kale. In addition, it is notable that temperatures on day 25 are higher, which is attributed to greater solar radiation on that day compared to days 23 and 24. Figure 21 illustrates the behavior of food masses during the drying process.

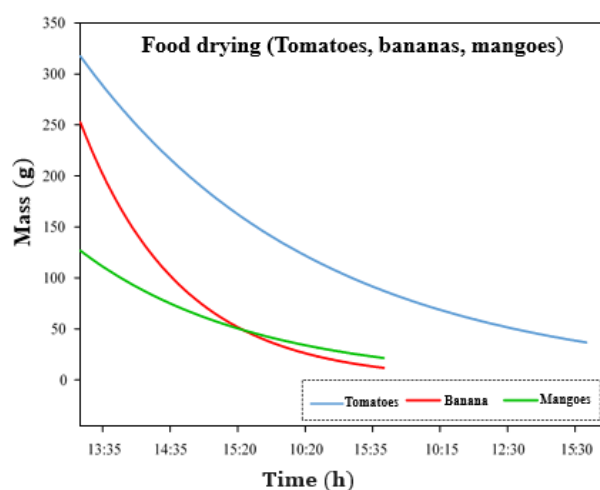


Figure 21. Behavior of food masses during drying (tomatoes, bananas, and mangoes).

Figure 21 shows that the greatest loss of mass occurs at the beginning of the drying process, due to the removal of free water from the food. Thus, most of the water was removed by evaporation on the first day (12:20 to 15:20) for tomatoes and mangoes, and on the second day, the bound water was removed until the food masses remained constant. In the case of bananas, most of the free water was eliminated on the first day (12:20 to 15:20), and an additional portion on the second day (11:05 to 13:20). On the same day, a portion of the bound water was removed, however, the remaining portion of bound water was removed on the third day, as the mass of this food stabilized.

Table 3 shows the values of mass efficiency and moisture content on a wet basis for tomatoes, bananas, and mangoes after the drying process. These parameters are calculated using equations (5) and (2), respectively, considering the variations in the initial and final masses of the products to be dried.

Table 3. Mass parameters and mass efficiency of tomatoes, bananas, and mangoes.

Food	m_t [g]	m_f [g]	$m_{\text{H}_2\text{O}}$ [g]	X_{bmi} [%]	X_{bmf} [%]	η_p [%]
Tomatoes	238	15	223,72	93,7	11,8	99,7
Bananas	322	70	289,8	78,3	5,4	87,0
Mangoes	137	39	113,71	71,5	2,5	86,2

The efficiency of the tomato drying process was remarkable, reaching 99.7% of the total load tested, which is why the drying time was a considerable 7.5 hours, compared to a previous study on natural tomato drying by Manuel (2014), where the tomatoes were left in a greenhouse exposed to the open air, which took 7 days to dry.

The efficiency of the banana drying process reached

87.0%, revealing significant efficiency in dryer 2. This result is in line with previous studies, such as that of [23], who obtained an efficiency of 84.4% in his banana drying process using a direct exposure dryer with natural convection. Other studies, such as those by [14, 19] achieved efficiencies of 89.9% and 86.6%, respectively, using different drying methods and technologies.

The final moisture contents obtained on a wet basis are 11.8% for tomatoes, 5.4% for bananas, and 2.5% for mangoes. These values indicate that the foods have dried sufficiently and are within the quality standards established for dried foods. Although all foods reached adequate moisture levels, it is important to note that they were dried at different times and at varying temperatures within the dryers. For example, tomatoes were dried at temperatures ranging from $T_{min} = 31,2^{\circ}\text{C}$ to $T_{max} = 91,7^{\circ}\text{C}$, bananas between $T_{min} = 32,9^{\circ}\text{C}$ to $T_{max} = 112,3^{\circ}\text{C}$ and mangoes between $T_{min} = 35,1^{\circ}\text{C}$ e $T_{max} = 88,4^{\circ}\text{C}$. Figure 22 illustrates the appearance of the foods before and after the drying process, showing the significant reduction in moisture and the desired final appearance for each food.



Figure 22. Food before and after the drying process.

4.4. Solar Dryer Efficiency

To determine the efficiency of the solar dryer using equation (3), it is first necessary to determine the power transferred to the working fluid, or the useful power, using equation (4).

Therefore, the dryer coupled to the solar concentrator has a maximum efficiency of 61.0% in converting solar radiation into heat, a value approximately two or three times higher than the yields obtained in previous studies by [19, 29, 30], which were 20.0%, 29.0%, and 29.27%, respectively.

This high thermal efficiency of the solar dryer is attributed to the use of the solar concentrator and the structure of the dryer, which consists of two glass panels. One of these panels, located at the bottom, absorbs solar radiation reflected by the solar concentrator, while the other, at the top, absorbs direct solar radiation.

5. Conclusions and Suggestions

Based on the results obtained, it can be concluded that the dryer coupled to the solar concentrator for food drying, de-

veloped and tested at the Unip úngu é university campus, in the drying process of okra, cabbage, tomato, banana, and mango, proved to be compatible with quality standards. The dried foods were of good quality in terms of visual appearance, with a moisture content of less than 25% for dried fruits and 12% for dried vegetables, in accordance with established recommendations.

With the mass efficiency achieved by the solar dryer, which ranges from 86.2% to 99.7% for different foods such as okra, kale, pumpkin, tomatoes, bananas, and mangoes, its viability in both rural and urban areas is evident. This high efficiency makes the dryer coupled with the solar concentrator a sustainable alternative for reducing post-harvest waste and losses without relying on electricity, contributing to food security and reducing environmental impact.

The efficiency of the dryer coupled with the solar concentrator reached 61.0%, which explains the drying time of the tested foods, which was adequate: 6.75 hours for mango, kale, okra, and pumpkin vegetables, 7.5 hours for tomatoes, and 13.5 hours for bananas. This shows that solar concentrators are a promising option for improving the efficiency of food drying using solar energy.

A significant limitation observed is that solar energy is an irregular source, which makes it difficult to carry out the drying process during periods of rain and at night. It is concluded that this limitation can only be overcome by using a dryer that runs on electricity.

Suggestions

- 1) Implement a thermal storage system to capture and store heat generated during the day for use during the rainy season and at night;
- 2) Conduct a nutritional analysis of dried foods;
- 3) Hold lectures in communities to teach the population how to use the food dryer developed;

Abbreviations

Unip úngu é	P úngu è University
$^{\circ}\text{C}$	Degrees Celsius
Kg	Kilogram
m/s	Meter Per Second
η_t	Solar Dryer Efficiency
P_u	Power Transferred to the Working Fluid
η_p	Mass Efficiency of the Process

Conflicts of Interest

The authors declare no conflicts of interest.

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