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ORIGINAL ARTICLE

# Experimental evaluation of a passive indirect solar dryer for agricultural products in Central Mozambique

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## Abstract

Post-harvest losses are one of the major livelihood challenges for farmers in the Global South. The use of drying technologies to preserve agricultural products has been promoted as a particular solution to address this challenge. In this regard, we designed and tested a passive indirect solar dryer for drying agricultural products as an alternative to open sun drying (OSD) in Gurue district, Central Mozambique, using amaranth leaves and maize. In addition, a sensorial analysis was conducted by randomly selecting a group of 60 adults who evaluated the texture, aroma and color of dried amaranth and maize grains. Compared to OSD, the passive indirect solar dryer reduced drying time and increased the thermal efficiency. Evaluation of sensory quality attributes showed that passive indirect solar drying outperforms OSD.

## Practical applications

This study evaluates the performance of a passive indirect solar dryer, a sustainable alternative to conventional food preservation technologies (e.g., refrigeration) that are not affordable to resource-constrained communities. The use of passive solar dryers, if carried out correctly, creates the possibility for poor rural households to safely store and increase shelf life of food. In addition, the acceptability of products dried in the passive indirect solar dryer is evaluated. Thus, the study also provides insights on passive solar dryer potential for preserving the quality of the final product.

## 1 | INTRODUCTION

Post-harvest losses (PHL) are significant threats to food security in the global South (Affognon et al., 2015; Hodges et al., 2011), and their reduction is an important factor in achieving the sustainable development goals (SDG), particularly, SDG 2 (Zero Hunger) and SDG 12 (ensure sustainable consumption and production patterns) (FAO, 2019). In addition, the African Union has committed to halving PHL by 2025 under the Malabo Declaration (AUC, 2014). These targets are particularly important to smallholder farmers in Sub-Saharan Africa (SSA) as they are among the poorest populations in the world (WB, 2016) and rely largely on food production for their livelihoods (Sheahan & Barrett, 2017). Indeed, more than 80% of rural households in many SSA countries depend to some extent on agriculture (Davis et al., 2017), even though agricultural production in SSA faces major challenges due to climate change. Moreover, reliance on traditional food processing and preservation techniques exacerbates their vulnerability to food insecurity (FI) (Adeyeye, 2017). As reported by FAO, in 2016, about 14% of food produced in SSA was lost from post-harvest to distribution. In addition, SSA has the highest caloric losses globally due to PHL and presents the highest levels of malnutrition (FAO, 2019; FAO et al., 2020), which is likely to worsen for several reasons, including the growing food needs of the increasing population (Gerland et al., 2014; Valin et al., 2014), poor dietary habits (Afshin et al., 2019), potential impacts of Covid-19 (Saccone, 2021), and challenging global economic conditions (FAO & ECA, 2018). Therefore, finding solutions to minimize PHL is crucial to address FI in SSA.

A particular solution to this challenge is the adoption and application of more efficient drying methods for the preservation of agricultural products. Drying—defined as the removal of moisture from food to prevent the growth of molds, yeasts, fungi, and bacteria—can be accomplished using various energy sources such as fossil fuels, electricity, natural gas, biomass, and solar energy (Lingayat, Chandramohan, Raju, et al., 2020; Prakash & Kumar, 2017). However, energy sources such as fossil fuels, electricity, and natural gas are in generally comparatively expensive, and their access is often unreliable for rural households in developing countries. Therefore, given the abundant and freely available solar radiation in tropics and subtropics (Mustapha et al., 2014; Mustayen et al., 2014), the use of solar energy, one of the oldest methods of food preservation (Janjai & Bala, 2012), takes a leading role in the sustainable drying of agricultural products for smallholder farmers in the Global South (Esper & Mühlbauer, 1998; Lamidi et al., 2019).

Smallholder farmers in SSA use solar energy to dry their produce after harvest as an attempt to ensure safe storage of food until the next harvest (Stathers et al., 2013). However, the use of traditional open solar drying (OSD) to dry agricultural produce (Karekezi, 2002; Ndukwu et al., 2018) results in significant losses such as contamination from dust, rain, spoilage, insects and other pests (Affognon et al., 2015; Kaminski & Christiaensen, 2014; Kumar et al., 2016; Udomkun et al., 2020). Therefore, the advances in solar energy research and especially the corresponding applications in agriculture have led to the design and development of a variety of solar dryers to overcome the limitations of OSD (Mustayen et al., 2014; Ssemwanga et al., 2020).

Solar dryers need to supply more heat to the product than is available under ambient conditions to promote evaporation of moisture from inside the crop (Kalogirou, 2014). They are generally classified into direct, indirect or mixed mode, based on how heat is transferred to the food and passive or active, based on differences in the circulation of air used for drying (Chavan et al., 2020; Fudholi et al., 2010; Mohana et al., 2020; Visavale, 2012). In addition, solar dryers can also be classified as hybrid solar dryers, if they are designed with an additional heat sources—such as solar assisted auxiliary thermal storage system, wood, gas or electricity—to enable a higher crop drying rate and consequently a higher product quality (Khaing Hnin et al., 2019; Reyes et al., 2014; Udomkun et al., 2020).

In direct solar dryers (DSD), food is directly exposed to solar radiation that penetrates through a transparent cover (Islam et al., 2018; Kumar et al., 2016). This cover reduces heat losses, and minimizes the product contamination by rain, dust and insects (Sandali et al., 2019). However, sensory properties, such as color and certain vitamins, may be affected by direct sunlight (Al-Juamily et al., 2007; Mustayen et al., 2014). The use of indirect type solar dryers (ISD) leads to improved product quality compared to DSD (Mohana et al., 2020) as they minimize color changes and loss of specific vitamins (Tomar et al., 2017). They consist of a separate solar air heater in which solar energy is collected. The heated air circulates through trays in a drying chamber where the agricultural products are placed (El-Sebaii et al., 2002). An intermediate solution are mixed solar dryers (MSD), where the product is heated by both transparent drying chamber and also separate air heater (Shalaby et al., 2014).

In passive solar dryers (PSD), the heated air is circulated through the food products by buoyancy forces or as a result of pressure differences (Basunia & Abe, 2001; Ekechukwu & Norton, 1999). They are completely dependent on solar energy, while in active solar dryers (ASD), the circulation of heated air is done externally with the help of electric fans or pumps, which increases the drying rates (Lingayat, Chandramohan, Raju, et al., 2020). PSD play an important role in the drying sector because many rural areas in SSA have poor access to the electricity grid (Duran et al., 2015) and because of their low cost (Mustayen et al., 2014) compared to ASD. In fact, the requirements of ASD are not affordable to many rural households in developing countries due to the additional costs of the external energy source (Bala & Janjai, 2012; Veremachi et al., 2015).

Therefore, the performance of PSD needs to be further improved and evaluated. Erick César et al. (2020) designed and evaluated a PSD with the option operate as an ISD or MSD for drying tomato slices and found an overall efficiency of 8.8% and 10.7% for the ISD and MSD, respectively. Mahapatra and Tripathy (2019) tested the thermal performance of PSD under no load conditions and found efficiency of 31.4%, 27.6%, and 41.4% for DSD, ISD, and MSD, respectively. Musembi et al. (2016) designed and tested a passive indirect solar dryer (PISD) for drying fresh apples and found an overall dryer efficiency of 17.9%. Several other studies have also shown high performance of PSD as compared to OSD (Arunsandeep et al., 2018; Dasin et al., 2015; Ghaffari & Mehdipour, 2015; Irtwange & Adebayo, 2009; Mohammed, Fatumah, et al., 2020; Tedesco et al., 2018; Yadav et al., 2018).

Notably, solar dryers exhibit variations in their overall performance, attributed to factors such as the solar dryer's design (Nabnean et al., 2016), unstable ambient temperature, relative humidity, hours of sunshine, available solar radiation, frequency and duration of rain, and wind speed (Shahi et al., 2011). Therefore, research efforts aimed at adapting solar dryers to specific site conditions are critical for more effective use of solar drying systems. In addition, to avoid underutilization of a new technology, it is crucial to consider the preferences of potential users (Foster & Rosenzweig, 2010), especially the sensory characteristics of food (Leng et al., 2017). Attributes such as taste, texture, smell or appearance often tend to be less negotiable than other values (Furst et al., 1996). Thus, in this study we first constructed and tested a PISD for drying agricultural products as an alternative to OSD in Guruè district, Central Mozambique—where there is a limited access to costly modern food processing technologies—and secondly analyzed the acceptability of food dried with PISD using consumers' preference analysis.

## 2 | MATERIAL AND METHODS

### 2.1 | Description of the solar dryer

Since the constructed dryer is to be used in a rural area with limited access to fossil fuels, electricity and natural gas, a passive solar dryer design suitable for this environment was chosen (Figure 1). It was made of wood and consisted of a solar collector and a separate drying chamber with five drying trays. The dimensions of the solar collector are 0.3 × 0.75 × 1.90 m and the volume of the drying chamber is 1 $m^3$.

The solar collector was tilted (22°) so that its surface is perpendicular to the solar radiation, which ensures that more solar energy is collected and allows the hot air to rise naturally into the drying chamber (Forson et al., 2007; Handoyo et al., 2013). The base of the collector was vented to allow the entry of air that needs to be heated for drying. The venting was evenly distributed across the entire width of the collector base to prevent individual areas in the collector from overheating. The top of the collector was completely open to the bottom of the drying chamber. The absorber plate was suspended between the top clear cover and the base plate, providing two channels through which air flowed in the same direction on both sides of the absorber plate, thus, creating twice the surface area for heat transfer to the air (Forson et al., 2007). There were doors on the drying chamber that allowed access to the crop. At the top of the drying chamber was an exit air vent to allow natural air circulation throughout the solar dryer.

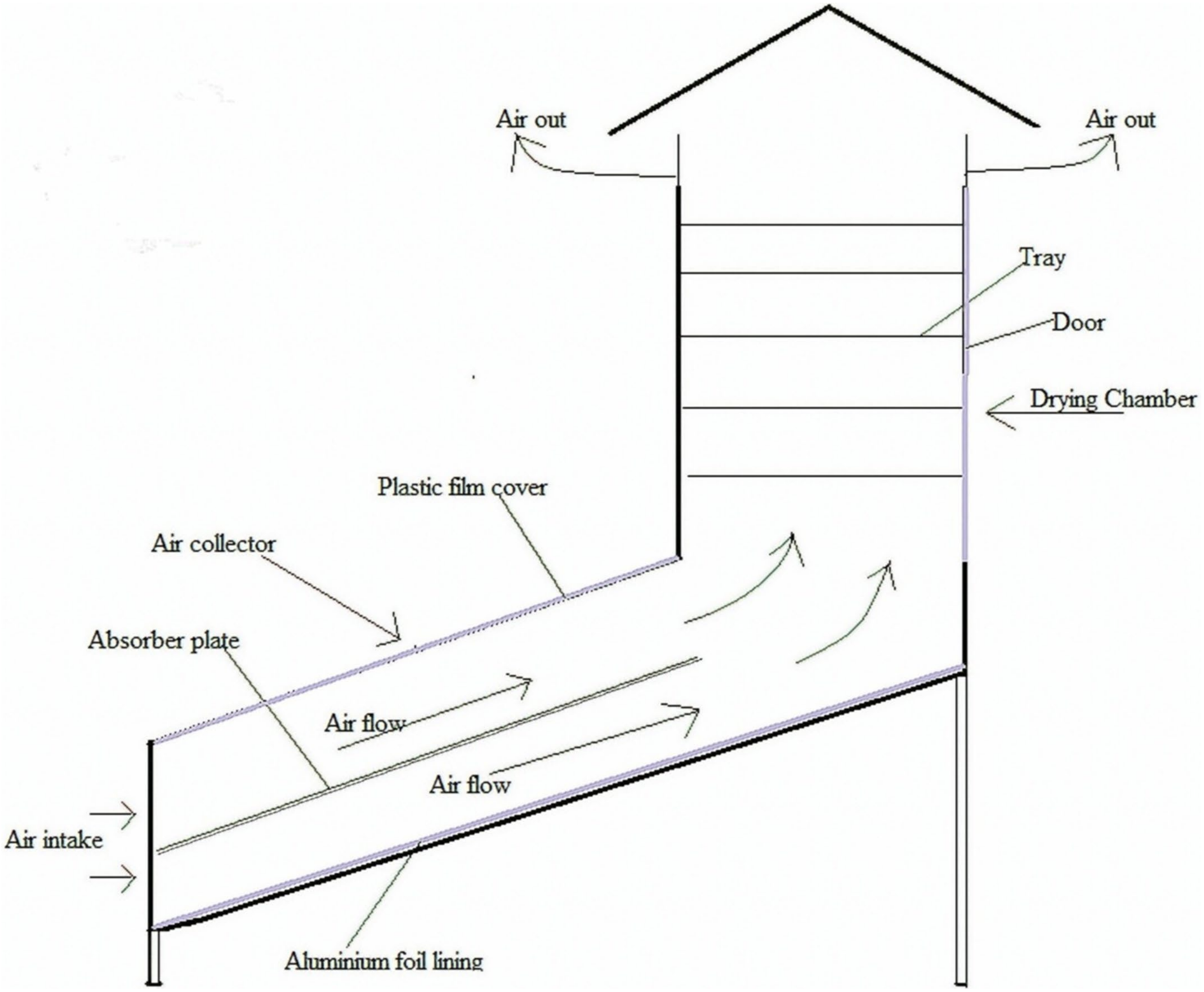

**FIGURE 1** Schematic view of passive indirect solar dryer

## 2.2 | Experimental procedure

Six solar dryers were constructed and tested simultaneously with the OSD for drying amaranth leaves (*Amaranthus gangeticus*) and maize (*Zea mays*) in August and September 2020, respectively. Maize was selected because it is the main food crop grown in the region (Chichongue et al., 2016) and amaranth was selected among other most commonly consumed green leafy vegetables in collaboration with local farmers. The experiments were conducted in Guruè district (latitude: 15°10′46.9″S; longitude: 36°48′32.6″E), Central Mozambique, one of the study sites embedded in the "Vegi-Leg project" (Vegi-Leg, 2019).

### 2.2.1 | Drying of amaranth leaves

Fresh amaranth leaves were obtained from the local market in Guruè, washed in clean water, blanched in water at 90°C for two minutes as described by Traoré et al. (2017), and cooled on an open stand for five minutes. Then, on the first day, about 7 kg were evenly divided and layered in the five drying trays. To avoid the voids in the trays caused by product shrinkage, we performed semi-continuous drying according to Singh et al. (2021). Thus, a total of 21.2 kg of fresh leaves were loaded in each solar dryer during the 7 days of the experiment. The amount of fresh leaves loaded on different days of the experiment is shown in Table 1. Observations were made at 5:00 p.m. each day and the leaves that were already dried were removed. As a control, a tray with an area of 1 $m^2$ was placed in the ground as practiced by the local residents for OSD.

### 2.2.2 | Drying of maize

Freshly harvested maize grains were loaded and stored in the PISD until they reach ≤14% of moisture according to Bern et al. (2013). The loading per unit aperture area was 13.5 $kg/m^2$. The grains were periodically mixed at two-hour intervals. No voids were observed in the trays during the maize experiment; hence, the semi-continuous mode of drying was not followed. Similar to amaranth leaves, OSD was carried out as a control and 13.5 kg of maize was placed in a 1 $m^2$ tray.

### 2.2.3 | Data collection and analysis

Ambient relative humidity and temperature, relative humidity and temperature inside the drying chamber were recorded during the experiment using the EL-USB-2-LCD Temperature and Relative Humidity Data Logger. Solar radiation on the aperture was measured hourly using a solar power meter (Tenmar TM 207). An electronic balance (±0.1 g accuracy) was used to measure the weight of dried products in each tray at start and end of each day. The standard oven method (Aoac, 1990) was used to determine the moisture content (M) of the amaranth leaves. An Agratronix MT-16 Grain Moisture Tester was used to determine the moisture content of maize.

Equations 1 and 2 were used to calculate thermal efficiency of the dryer ($\eta$) and the solar energy ($S$) required for 1 kg of moisture removal, respectively. The overall thermal efficiency was obtain by calculating the average of all daily efficiencies (Singh et al., 2021).

$$\eta = \frac{\mathrm{ml}}{I_{av}At} \times 100 \tag{1}$$

$$S = \frac{I_{av}\,(A)\,t}{m} \times \frac{1}{1000} \tag{2}$$

where $m$ is the mass of water evaporated (kg), $I_{av}$ is daily average solar radiation intensity ($W/m^2$), $L$ is the latent heat of water (kJ/kg K), $A$ is the area of solar collector ($m^2$), and $t$ is the time during drying day (s).

### 2.2.4 | Product acceptance

One day after the end of the drying experiment, a sensorial analysis was performed. We randomly selected a group of 60 adult people (43% female and 57% male) from six different communities who individually evaluated the texture, aroma, and color of dried amaranth and maize grains from both PISD and OSD following the ASTM standard guide for two-sample acceptance and preference testing with consumers (ASTM-International, 2015). People did not have prior knowledge of the method used to dry the product so as not to influence their choices. The evaluators specified their level of acceptance using a five points Likert scale (1 = very bad to 5 = very good). Each subject evaluated four samples in total, two from each dryer, with blinded codes. The frequency distribution of the scale categories was calculated and the Wilcoxon signed-rank test was used in order to examine the differences between the acceptances of the products dried using the PISD and the OSD.

# 3 | RESULTS

## 3.1 | Drying of amaranth leaves

The values of temperature and relative humidity variation for the ambient air, temperature and relative humidity in the drying chamber and intensity of solar radiation over time were recorded and their mean values are shown in Figure 2. The ambient temperature ranged from 20 to 27°C, while the temperature in the drying chamber varied from 27 to 38°C. The relative humidity for the ambient air and inside the drying chamber during drying ranged from 41% to 61% and 27% to 37%, respectively. The solar radiation varied from an average of 254 to 765 $W/m^2$. At end of 3rd, 4th, 5th, 6th, and 7th drying days, an average of 137, 356, 317, 319, and 297 g of dried leaves were removed, respectively (Table 1). Thus, an average of 1,430 g of dried amaranth leaves were obtained from each of the six solar dryers in 7 drying days.

The thermal efficiency from day 1 to 7 was 13%, 18%, 19%, 23%, 27%, 18%, and 16% (Figure 3). Thus, the overall thermal efficiency was 19%. Initial moisture content of the fresh leaves was 83.4%

**TABLE 1** Fresh leaves loaded during successive drying days

| Experiment day | Weight of fresh leaves loaded (g) | Weight at 8:00 a.m. (g) | Weight at 17:00 (g) | Weight of dried leaves removed (g) |
|---|---|---|---|---|
| 1st | 7,000 | 7,000 | 5,600 | 0 |
| 2nd | 50 | 5,460 | 3,696 | 0 |
| 3rd | 900 | 4,925 | 3,004 | 137 |
| 4th | 2,250 | 5,326 | 2,856 | 356 |
| 5th | 4,200 | 5,934 | 3,256 | 317 |
| 6th | 2,671 | 5,134 | 2,967 | 319 |
| 7th | 4,200 | 5,324 | 3,467 | 297 |

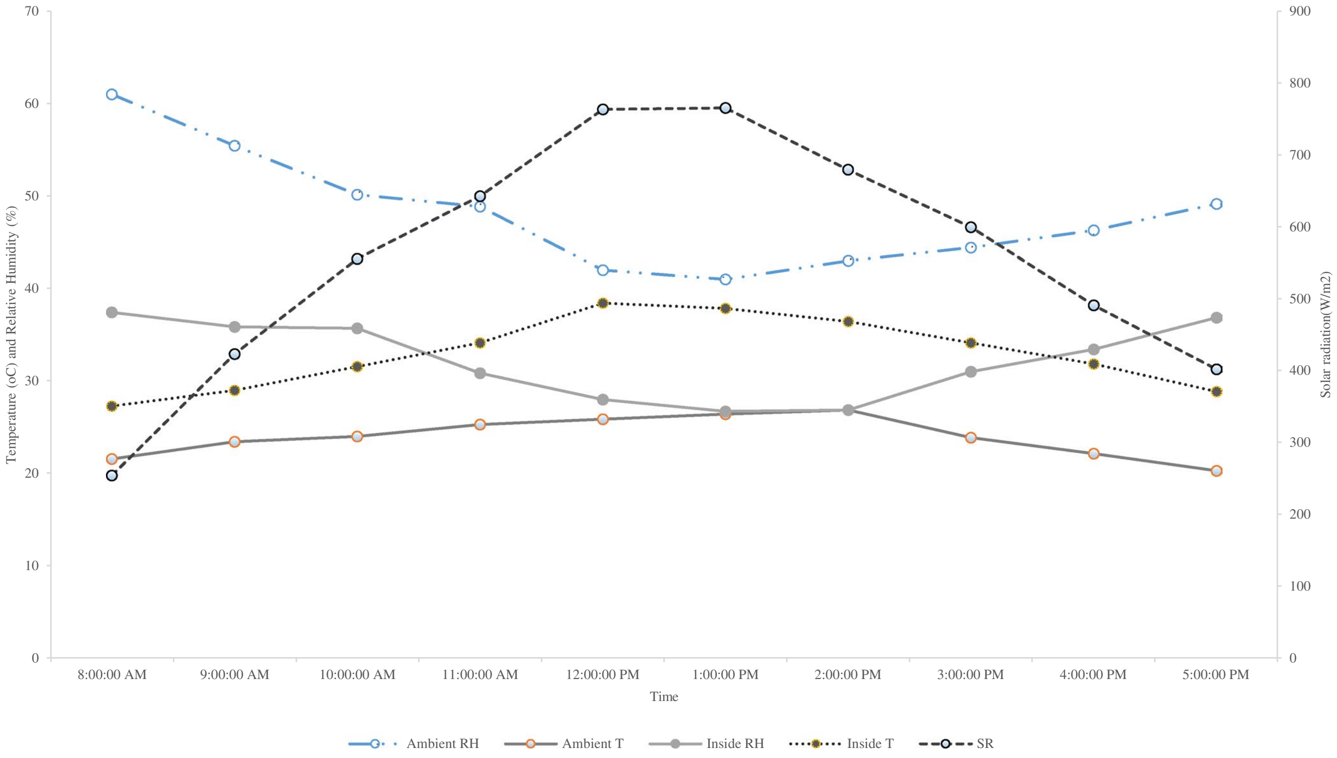

**FIGURE 2** Variation of the temperature and relative humidity at the ambient and inside the drying chamber and solar radiation intensity for amaranth leaves

and final moisture content after drying was 10.5%. In OSD, the first dried leaves (126 g) were obtained only on the 5th day. This is 58.7% more drying time compared to PISD. The average thermal efficiency for OSD was 7%, and the total dried amaranth leaves obtained by the end of the drying experiment was 850 g. The average solar energy input per unit water removal was 12.53 MJ/kg for PISD and 24.1 MJ/kg for OSD (Figure 3).

## 3.2 | Drying of maize

The drying of maize took 5 consecutive days to reduce the grain moisture from 26% to 14%. The variations in ambient air temperature and relative humidity, drying chamber temperature and relative humidity, and solar radiation were recorded, and their mean values plotted as shown in Figure 4. The ambient and indoor temperatures during drying ranged from 16.8 to 26.8°C and 27.6 to 48.2°C, respectively. The ambient relative humidity ranged from 40.8% to 59.4% and the drying chamber relative humidity ranged from 26.8% to 38%. The average solar radiation during different drying days ranged from 225.0 to 724.6 W/m$^2$.

Figure 5 shows the daily average solar energy input per unit water removal (S) and the thermal efficiency of the PSID. The values of *S* varied from 12.99 MJ/kg in the first day of drying to 28.65 MJ/kg in the 5th day. Thermal performance at the 1st, 2nd, 3rd, 4th, and 5th days were 17%, 18%, 15%, 14% and 8%, respectively. Thus the average thermal efficiency was 14%. For OSD, it took 7 days to reach the desired moisture content of ≤14%. Therefore, compared to OSD, PISD reduced drying time by 29%. The overall thermal efficiency of OSD was 4.6%.

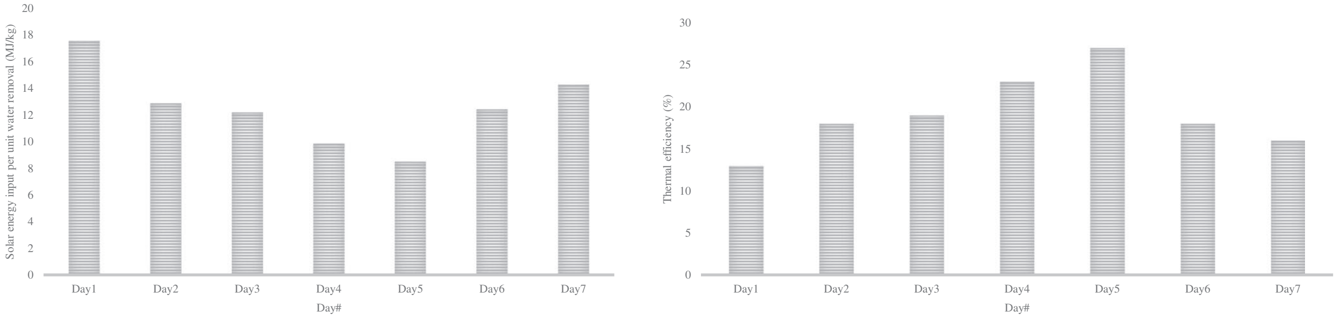

**FIGURE 3** Average solar energy input per unit water removal and thermal efficiency for amaranth leaves in passive indirect solar dryer

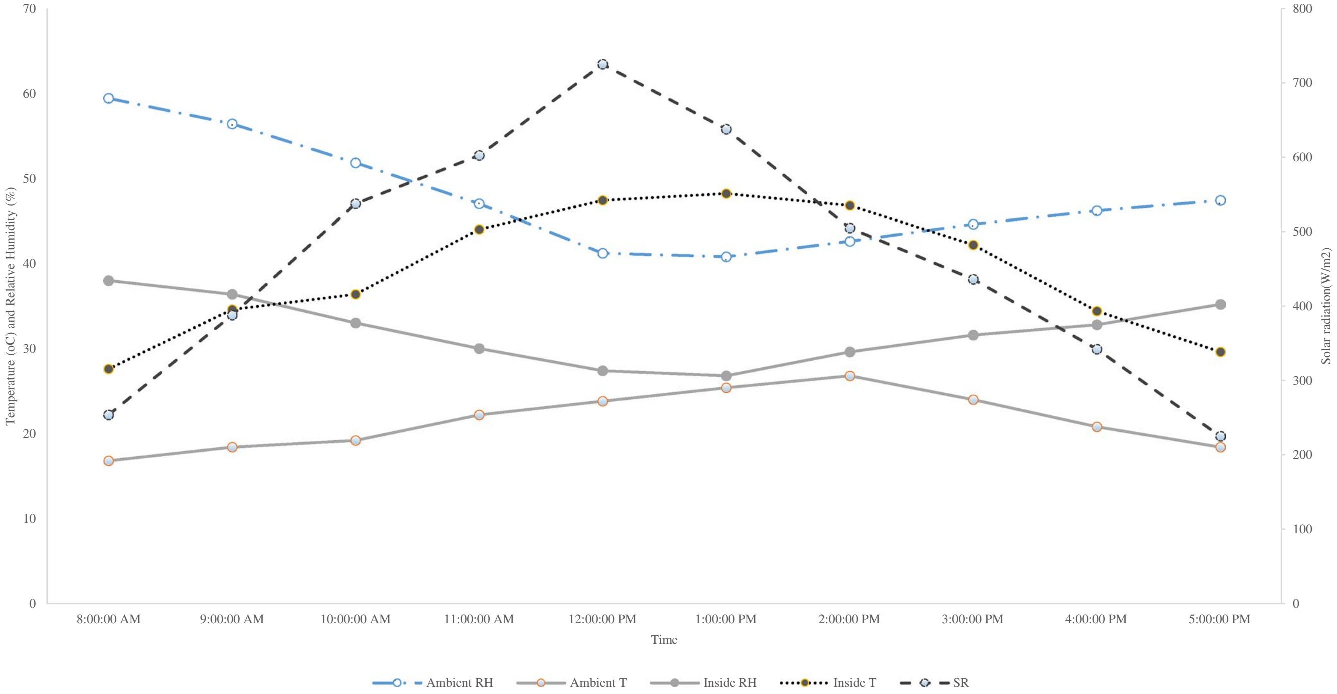

**FIGURE 4** Variation of the temperature and relative humidity at the ambient and inside the drying chamber and solar radiation intensity for maize

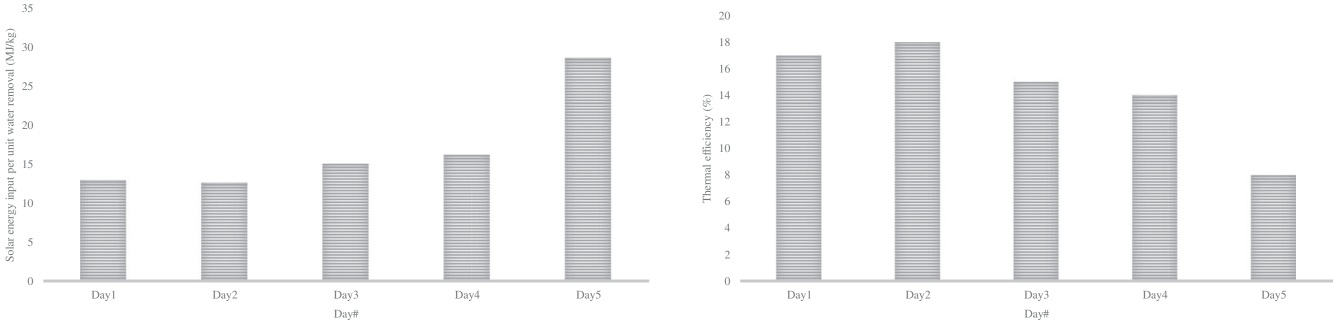

**FIGURE 5** Average solar energy input per unit water removal and thermal efficiency for maize in passive indirect solar dryer

## 3.3 | Product acceptance

We found that 40%, 27%, and 23% of the evaluators consider that the OSD had poor texture, aroma and color, respectively (Figure 6). None of the evaluators considered the sensory attributes of amaranth dried in the PISD to be bad or very bad. Most of them (more than 68%) indicated that the sensory properties were good or very good. In terms of overall acceptability, 40% of the people rated the amaranth leaves dried in the PISD as very good and 30% as good.

None of the evaluators found the dried amaranth from the OSD very good and only 23% found it good. The Wilcoxon signed-rank test was significant ($p_{\text{value}} < 0.01$) for all sensory attributes tested, indicating that most people preferred the dried amaranth leaves from the PISD.

With regards to dried maize, the evaluators also found the sensory attributes of maize dried in PISD better than that dried via OSD ($p_{\text{value}} < .01$). The percentage distribution of the evaluators by score category is shown in Figure 7. In general, the percentage of people who assign values 4 (good) and 5 (very good) for maize dried in PISD varies between 65% and 75%, depending on the sensory attribute. As in the evaluation of amaranth, none of the evaluators found the sensory attributes of maize dried in PISD bad or very bad, while 28%, 32%, and 33% of the evaluators found the texture, aroma, and color of the maize dried in the OSD bad, respectively. Furthermore, none of the evaluators found the sensory attributes of maize dried in the OSD to be very good.

## 4 | DISCUSSION

In this study, six solar dryers were constructed and tested simultaneously and their performance was evaluated. They were tested for drying amaranth leaves and maize grains. In general, the ambient and internal temperature of the drying chamber and the solar radiation increased to a peak in the afternoon and decreased in the evening (cf. Figures 2 and 3). This is in agreement with the results of Ayua et al. (2017) and Ssemwanga et al. (2020). Similar to Nimrotham et al. (2017), the relative humidity decreased to its minimum value during the afternoons. The relative humidity values observed inside PSD's drying chamber during the experiments were below 40%, which is a range in which most fungal species cannot grow as they require relative humidity above 60% (Arundel et al., 1986). In OSD, the observed relative humidity during the experiments was around 60%, making the crop more susceptible to attack by fungi. The comparatively lower relative humidity in the drying chamber of PSD allows for greater removal of moisture from the products being dried, as the reduction in humidity increases the diffusion of moisture from the product into the air, which accelerates the drying process (Aravindan et al., 2017). The drying temperatures in the drying chamber ranged from 27.6 to 48.2°C. These values are similar to those observed in other studies on PISD (Jain & Tewari, 2015; Ssemwanga et al., 2020; Vijayan et al., 2016). However, a very wide variation was observed. For example, Jain and Tewari (2015) found values that varied between 40 and 45°C and A. Lingayat et al. (2017) observed drying air temperature that ranged between 44 and 55°C. Nevertheless, Ahmad Fudholi et al. (2014) found Drying chamber air temperature ranging from 28 to 55°C. This variation is due to changes in the intensity of solar radiation and can be even higher depending on the position of the tray in the drying chamber (Lingayat, Chandramohan, & Raju, 2020). In addition, factors such as the design of the dryer and the season in which the analysis was carried out can also influence the temperature variation in the drying chamber.

The average thermal efficiency of PISD was higher than the efficiency of the OSD. Compared to the results of other studies, it was lower than that of Lingayat, Chandramohan and Raju (2020) (21.57%) and Mahapatra and Tripathy (2019) (27.55%) and higher than the efficiency found by Erick César et al. (2020) (2.61%). According to Kumar et al. (2016), the average drying efficiency of a PISD is 13%–25%. Thus, the results of this study are in an acceptable range for a

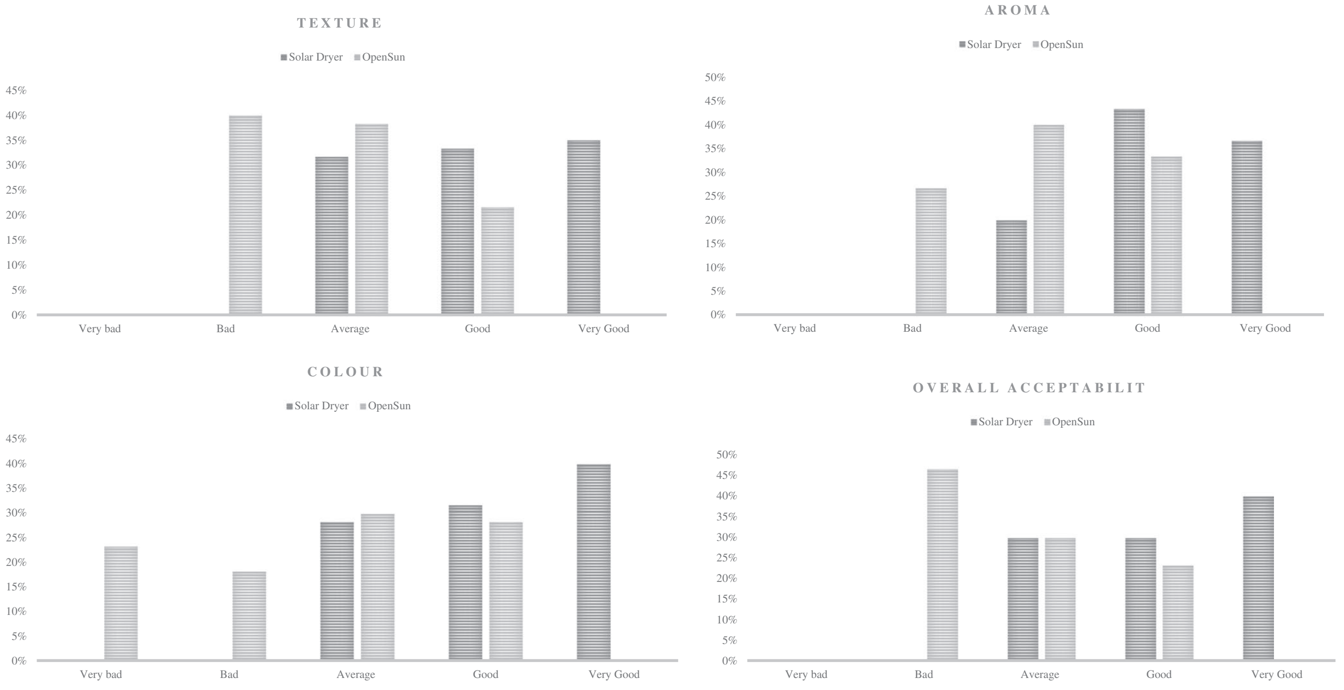

**FIGURE 6** Respondents preference for amaranth leaves sensory attributes

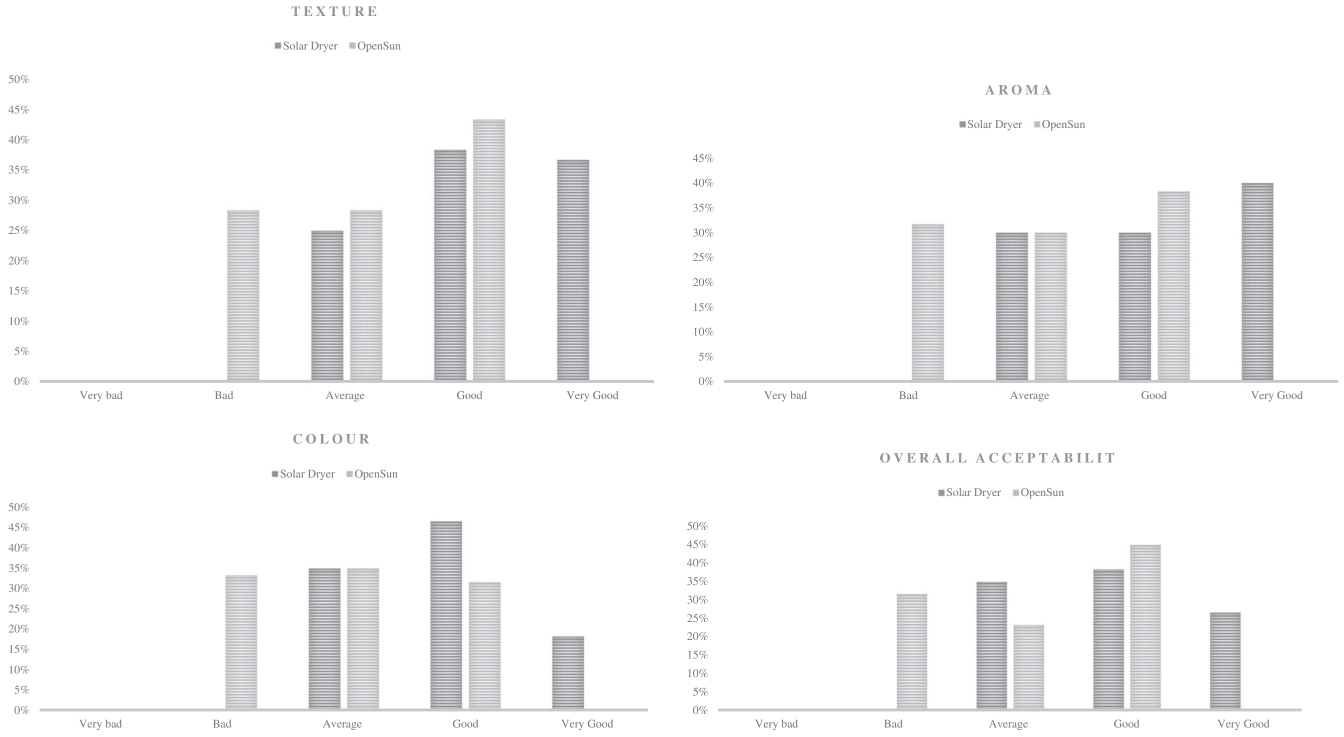

FIGURE 7 Respondents preference for maize sensory attributes

PSD. The differences in the efficiency reported in different studies are, according to Shahi et al. (2011) due to differences in the ambient temperature, relative humidity, hours of sunshine, available solar radiation, frequency and duration of rain, and wind speed.

The sensory attributes are important aspects when a food is presented for consumption. Therefore, it is important for food processors to know the sensory characteristics of their products (Geel et al., 2005). Therefore, we conducted a consumer acceptance analysis to find out which drying method resulted in a product with comparatively better sensory properties (taste, aroma, color and overall acceptability). The results showed that both amaranth and maize from PISD were rated better than those from OSD. The advantages of PSD over OSD in terms of final products quality have been demonstrated in several studies (Hii et al., 2019; Irtwange & Adebayo, 2009; Mohammed, Edna, et al., 2020; Udomkun et al., 2020). Nevertheless, further studies are needed to explore factors such as demographic profile, health status, personality, knowledge, exposure, perceived quality and mood as they may have an impact on consumers' perception and evaluation of a particular product (Owureku-Asare et al., 2017; Rozin & Tuorila, 1993). According to Steenkamp et al. (1994), despite its sensitivity, the human sensory system cannot distinguish minor differences between products. However, in the case of the present study, our results are supported by the fact that the use of solar dryers as a substitute for OSD increases drying air temperatures, thermal energy and drying rate (Kumar et al., 2016; Orphanides et al., 2016), which consequently can improve the organoleptic quality of the dried products (Mohammed, Edna, et al., 2020).

## 5 | CONCLUSION

The performance of a passive indirect solar dryer as compared to OSD was evaluated, using amaranth and maize. In addition, the sensory quality attributes were evaluated by a group of randomly selected individuals. The results showed that in the passive indirect solar dryer, the average drying air temperature was higher and the relative humidity lower, in comparison to the OSD. The sensory quality attributes evaluation showed that passive indirect solar dryer outperformed OSD in terms of texture, aroma, color and overall consumer acceptability. Thus, based on the outcome of this study, it is concluded that the use of passive indirect solar dryer is a sustainable way of drying agricultural products and its use is recommended rather than OSD.

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## CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

## AUTHOR CONTRIBUTIONS

**Custodio Efraim Matavel:** Conceptualization; Formal analysis; Investigation; Methodology; Writing-original draft; Writing-review

& editing. **Harry Hoffmann:** Conceptualization; Funding acquisition; Project administration; Supervision; Writing-review & editing. **Constance Rybak:** Conceptualization; Funding acquisition; Project administration; Writing-review & editing. **Johannes M. Hafner:** Writing-original draft; Writing-review & editing. **João Salavessa:** Writing-review & editing. **Shibire Bekele Eshetu:** Writing-review & editing. **Stefan Sieber:** Conceptualization; Supervision; Writing-review & editing.

## DATA AVAILABILITY STATEMENT

The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

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