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# Performance analysis of an improved solar dryer integrated with multiple metallic solar concentrators for drying fruits

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ABSTRACT

Reducing postharvest losses (PHL) of fresh perishable agro-produce is a key strategic pathway to increasing incomes, food and nutrition security in East Africa. In response, an improved Hybrid Indirect Passive (HIP) solar dryer with a modified solar collector plate and drying cabinet, has been developed and presented as a better food drying alternative against the traditional open sun drying (OSD) method. A conventional active-mode Solar Photovoltaic and Electric (SPE) dryer with an auxiliary thermal-backup system was also fabricated. The fruit drying performance of the HIP and SPE dryers was evaluated using pineapples and mangoes, and compared against the traditional open sun drying (OSD) method. The food drying duration for the SPE, HIP and OSD methods were 10 h, 18 and 30 h; respectively. Drying efficiency of the improved HIP dryer was comparable to the SPE dryer and was 18% higher than the OSD method. Therefore, modifying the solar collector plate with multiple metallic solar concentrators coupled with an improved greenhouse cabinet significantly improves the drying performance of the HIP dryer. The HIP dryer is, therefore recommended for mass adoption against the OSD method.

## 1. Introduction

In East Africa, extreme poverty and food insecurity are often a result of persistently low agricultural productivity, climate change-induced extremities and financial drawbacks (World Bank, 2018). Postharvest loss of agricultural produce is a silent (often forgotten) factor, yet it is one of the leading drivers of food, nutritional and income insecurity in the region. The enormous postharvest losses (PHL) is mainly contributed by poor postharvest processing technologies, where farmers and agro-processors have no feasible options but to exclusively depend on the traditional method of drying agro-produce under the open sun. The farmers have limited access to costly modern food processing technologies such as electric dryers, refrigeration and cold-chain facilities (Kumar et al., 2016; VijayaVenkataRaman et al., 2012; ACORD, 2014).

In Uganda, for instance, farmers solely depend on open sun drying (OSD) method to dry their agro-produce. But the traditional OSD method is highly compromised by variations in ambient weather conditions, mainly in form of abrupt changes in humidity and erratic precipitation, and the agro-produce is often exposed to extreme temperatures during the drying process (APHLIS, 2011; ACORD, 2014; World Bank, 2018). The food loss often occurs due to scavenging, dusts contamination and superfluous moisture gains (World Bank, 2018). And as a result, farmers experience high PHL and estimated at 5–15% in cereal crops, 20–25% in root tuber crops, and over 40% in fruits and vegetables (KARI, 2017). The OSD method also takes more drying time and yard space and is also costly in terms of labour, especially when drying bulk agro-produce. This further reduces the farmers' real income because a substantial amount of their disposable income and time is devoted to drying the agro-produce (ACORD, 2014; World Bank, 2018). Besides, the OSD method is limited to drying cereals and root tuber crops but cannot effectively dry the highly succulent and perishable fruits and vegetables (ACORD, 2014). Consequently, local farmers usually incur over 40% of the PHL in fruits and vegetables (ACORD, 2014; KARI, 2017). This is so because the farmers often experience bumper harvests and their fresh produce flood the market. Consequently, the market prices of most perishable agro-produce usually drop below the 'break-even' point and farmers fail to sell them at a profit. Coincidently, the farmers also fail to efficiently dry their perishable agro-produce (mainly fruits) to extend their shelf life and add-

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value for future consumption and better market prices during scarcity (ACORD, 2014).

The aforementioned limitations in the traditional OSD method has led to the development of numerous food dryer technologies which use renewable solar energy (VijayaVenkataRaman et al., 2012; Nabnean et al., 2016), geoheat flux (Andritsos et al., 2003; Kumar et al., 2016), and biomass energies (Tibebu et al., 2016; Rizal and Muhammad, 2018) as well as their hybrid system combinations (Kumar et al., 2016; Bala and Serm, 2009; Bolaji and Olalusi, 2008). Literature suggests that among these technologies, the solar dryer is so far the most efficient and feasible food dryer technology in solving the challenges associated with drying rate, cost-effectiveness, contamination and efficiency (Samimi-Akhijahani and Arabhosseini, 2018). This is because the solar energy which is employed as a source of heat flux to dry fresh agro-produce is more eco-friendly, cleaner and is freely available in abundance in most locations. As a result, the solar dryer technology has been preferred to dry the highly-succulent fresh produce including; tomatoes (Dorouzi et al., 2018; Kumar et al., 2016), cherry tomatoes (Nabnean et al., 2016), date fruits (Mennouche et al., 2014), potato (Chouicha et al., 2013), banana (Arun et al., 2019; Lingayat et al., 2017), chili pepper (Rabha et al., 2017), red pepper (Mennouche et al., 2014), tarkhineh recipe (Daghigh et al., 2020), and mint and apple slices (Şevik et al., 2019).

The solar dryers are classified into three types namely; direct solar dryers, indirect solar dryers and hybrid solar dryers (Hii et al., 2012; Rizal and Muhammad, 2018). A typical direct solar dryer is made of an enclosed produce drying chamber made of an insulated box covered by a transparent plastic or glass material with perforated air inlet and outlets, where the fresh produce is put, heated directly by the sun's rays and moisture is removed by natural convection (Hii et al., 2012; Jain and Tewari, 2015; VijayaVenkataRaman et al., 2012). The indirect solar dryer is made of a separate solar thermal collecting unit called a solar collector, attached to an opaque food drying cabinet, which gives it a distinct mechanism of solar thermal transfer and moisture removal from the succulent food produce. The solar collector warms the air entering into the drying cabinet; which flows over the succulent food products and provides the heat for drying the produce. The fresh produce is dried by convective heat transfer between the produce and the heated air in its vicinity (Hii et al., 2012; Kumar et al., 2016; Tibebu, 2015; Yassen and Al-Kayiem, 2016a). The hybrid solar dryer uses the features of both the direct and indirect solar dryer systems simultaneously, in which the combined action of the incident direct solar heat flux coupled with the pre-heated drying air in the solar collector, produces cumulative heat flux which also improves the drying process (Hii et al., 2012; Kumar et al., 2016; Tibebu, 2015; Wang et al., 2018). Although the solar dryer technology presents a better and renewable method of food drying than the OSD method, the drying performance of the conventional direct, indirect and hybrid solar dryers still suffer from several drawbacks including inconsistencies in the drying rates, prolonged drying time and reduced drying efficiency (Samimi-Akhijahani and Arabhosseini, 2018). The discrepancies in drying rate and longer drying process are influenced by the abrupt changes in ambient weather conditions such as temperature, solar radiation intensity and sunshine hours, cloud cover, and wind speed (Kumar et al., 2016; Navale et al., 2015; Rad et al., 2013). The low efficiency of the dryer systems is mostly contributed by use of poor design, non-optimized and improper materials in the solar thermal collectors; which compromise the thermal efficiency of the overall dryer systems (Nabnean et al., 2016; Lingayat et al., 2017). Therefore, recent efforts to increase the drying rate and efficiency of the solar-driven dryers have been directed towards developing and testing of various solutions such as concentrating extra solar radiation energy (Fleming et al., 2017), incorporating a phase-change materials (Çakmak and Yıldız, 2011), optimizing the geometric and structural features of the solar collectors (Aboghrara et al., 2017), integrating a heat pumping system (Rad et al., 2013), integrating solar photovoltaic systems (Dorouzi et al., 2018), incorporating a sun-tracking system (Samimi-Akhijahani and Arabhosseini, 2018), using a geothermal flat plate collector (Ananno et al., 2020), and solar dryer made of low-cost iron mesh (Güler et al., 2020). Other modifications involve adding a supplementary recovery dryer (Yassen and Al-Kayiem, 2016a), enhancing a hybrid solar-biomass a dryer with co-generation (Co-Gen) technology (Yassen and Al-Kayiem, 2016b), solar-infrared drying (Şevik et al., 2019), using solar photovoltaic and evacuated tube collectors (Daghigh et al., 2020), and solar-assisted fluidized-bed drying (Mehran et al., 2019).

However, all the aforesaid challenges associated with the drying performance of the solar dryers could also be solved by modifying the solar collector plate with multiple metallic solar thermal concentrators and enclosing the cabinet with specialized plastic greenhouse cover materials. The multiple concentrators and plastic greenhouse cover materials could potentially increase the concentration of solar heat flux and consequently enhance thermal efficiency, respectively. Therefore, a new improved indirect solar dryer dubbed 'Hybrid Indirect Passive (HIP)' dryer; whose conventional solar collector plate was modified to have multiple metallic solar collectors and the drying cabinet walled with specialized plastic greenhouse materials was prototyped and proposed as an alternative food drying method.

But regarding the mode of operation, solar-driven dryers are further classified into two groups namely; natural convection and forced convection dryers which employ passive and active modes, respectively (Hii et al., 2012; Kumar et al., 2016; Lingayat et al., 2017; Navale et al., 2015; VijayaVenkataRaman et al., 2012). The active solar dryers utilize solar energy only as a source of heat flux and the heated food drying air is circulated by forced convection using motorized fans or blowers. In the passive solar dryers, the agro-produce is dried by heated air which circulates by natural convection or buoyancy force due to wind pressure (Belessiotis and Delyannis, 2011), and this feature makes them appropriate for use in many rural areas without electricity. However, the passive solar dryers have no thermal back-up which limits their wide adoption and commercial use under limited solar energy and during nightshifts (Bolaji and Olalusi, 2008; VijayaVenkataRaman et al., 2012). Henceforth, a conventional solar photovoltaic dryer equipped with an electric thermal backup system dubbed solar 'Photovoltaic and Electric (SPE)' dryer was also prototyped to provide the required alternative thermal backup system.

Based on the above context, the modified HIP solar dryer prototype employs a passive drying mode and could potentially serve rural subsistence farming communities in remote locations without electricity. Conversely, the conventional SPE prototype uses solar photovoltaic energy with an electric thermal backup system to facilitate continuous commercial drying of produce even under very limited or without direct solar energy (thus during nightshifts). In this study, the fruit drying performance of the HIP and SPE dryer prototypes was experimentally evaluated using selected varieties of mangoes and pineapples, and compared against the open sun drying (OSD) method. Evaluating the relative drying performance of the modified HIP dryer and the conventional SPE dryer prototypes could pave way for developing more reliable, efficient and feasible food drying systems to replace the traditional OSD method in commercial drying of perishable agro-produce and eventually reduce postharvest losses in Uganda and beyond.

## 2. Materials and methods

### 2.1. Description of the modified Hybrid Indirect Passive (HIP) solar dryer

The modified Hybrid Indirect Passive (HIP) dryer with auxiliary multiple metallic concentrators in the solar concentrator plate and a specialized greenhouse walling material in the dryer cabinet (Fig. 1), was designed at the National Livestock Resources Research Institute (NaLIRRI) in Nakyesasa (latitude: 0°31′26″N; longitude: 32°37′10″E), Uganda. The HIP dryer comprised of a modified rectangular solar collector plate (dimensions: 0.95 m × 2.2 m) and a drying cabinet


**Fig. 1.** Photos of an improved Hybrid Indirect Passive (HIP) dryer: where A is a modified solar collector plate consisting of multiple metallic solar collectors; B and C are the physical prototypes of the HIP without and without a non-perforated greenhouse plastic cover enclosing the dryer cabinet, respectively.

(volume: 1 $m^3$) covered with a specialized greenhouse plastic (Fig. 1B and C). The components and configuration of the solar collector plate in the conventional solar dryer (Belessiotis and Delyannis, 2011; Hii et al., 2012; Kumar et al., 2016; Nabnean et al., 2016; Navale et al., 2015; Tibebu, 2015; Wang et al., 2018), were replaced with multiple cylindrical metallic concentrators made of 15 pieces of steel tubes in the modified solar collector in the HIP prototype (Fig. 1A).

The metallic concentrators serve to absorb extra solar radiation energy along the multiple focal lengths, through which auxiliary solar heat flux is concentrated. Consequently, additional solar heat flux was concentrated and retained internally within the modified solar collector plate. This facilitated faster pre-heating of the incoming produce drying air within the modified solar collector plate (Fig. 1A).

The modified solar collector plate was covered with a transparent plastic material (type: PVC Polyethene; GT4 Plastics, USA) on its top to maximize absorption of incident solar radiation energy, which was transmitted internally along the multiple focal lengths produced by the new cylindrical metallic concentrators. Similarly, the bottommost layer of the modified solar collector plate was aligned with a silver plastic material to reflect the internally-transmitted solar heat flux towards the multiple focal lengths; which further warmed the metallic tubes. As the drying air enters the modified solar concentrator plate via the inlet at its bottom (Fig. 1A), it is pre-heated within the multiple metallic concentrators and hence, becomes denser. The warmed produce drying air drifts upwards to the drying cabinet by natural convection due to the density differences between the cooler incoming ambient air and the warmed produce drying air, as also explained by Hii et al. (2012), Kumar et al. (2016), Nabnean et al. (2016), and Rad et al. (2013).

The insulating materials enclosing the drying cabinet in the conventional passive indirect solar dryers were replaced with the specialized non-perforated greenhouse plastic materials; PVC Plastic Film Polyethylene (specifications; UV-treated and 6 mm thick) in the modified HIP dryer (Fig. 1C). The greenhouse materials enclosing the drying cabinet served to accelerate the internal warming of the agro-produce drying air through the greenhouse effect (IPCC, 2015). As the pre-heated produce drying air enters the drying cabinet, it is exposed to further warming by the greenhouse effect producing additional direct solar heat flux causing further warming of the drying air. The warmed produce drying air generates cumulative internal heat flux which further accelerates drying of the produce by natural convection (Hii et al., 2012; Jain and Tewari, 2015; Lingayat et al., 2017; Mennouche et al., 2014). The excessive heat flux, vapour pressure and moisture in the dryer cabinet are offset by the convective effect through the chimney, and this prohibits over-drying of produce.

### 2.2. Description of the conventional Solar Photovoltaic and Electric (SPE) dryer

The conventional Solar Photovoltaic and Electric (SPE) dryer consisting of an auxiliary electric backup system was fabricated at NaLIRRI Institute, following protocols described by Samimi-Akhijahani and Arabhosseini (2018). The SPE dryer was made of a drying chamber, 4 batteries, air evacuating tubes for recycling warmed moisture, two-60 W solar panels, a 12 V suction fan, an automatic control system equipped with a thermocouple, drying cabinet (area of 1 $m^2$ and 10 mm thickness), stainless steel drying trays (of area 0.95 $m^2$), a charge controller, and an auxiliary electric thermal backup system among other components (Fig. 2).

The direct current from the solar panel photovoltaic system was backed-up in batteries attached to the SPE dryer, and this facilitated the continuous drying of the agro-produce during the day. The auxiliary alternating thermal backup system was used under prolonged cloudy and rainy conditions with very limited direct sunshine to overcome fluctuations and interruptions in drying air temperatures. The electric current backup system could also support the drying process during nightshifts without direct sunlight. The desired air circulation within the drying cabinet was regulated by adjusting the rotational speed of the suction fan while air velocity was preset and controlled by an anemometer (model: YK-2005AM, accuracy: ± 2). The suction fan speed was controlled by presetting the air velocity at 15 $ms^{-1}$ and was maintained at 50% of its rotational capacity. These settings played a critical role in regulating the drying conditions of the SPE unit.

### 2.3. Experimental setup and procedure

Experiments to evaluate the drying performance of the modified HIP and the conventional SPE dryer prototypes against that of the traditional OSD method were conducted under local weather conditions at NaLIRRI, Uganda. To ensure precision and consistency of the experimental results, three independent experimental drying cycles were done between April and June 2018. The three replicate sets of drying experiments were conducted from April 2nd to 4th, May 8th to 11th, and 17th to 19th June 2018 for the 1st, 2nd and 3rd replicate trials, respectively.


**Fig. 2.** The SPE dryer; (1) Evacuating tube, (2) fan, (3) Solar panels, (4) automated-control systems, (5) batteries, (6) Thermocouple, (7) drying cabinet, (8) drying trays, (9) 10 mm size slices of mango cultivar (Bire), and (10) stainless steel mesh trays (Image credit: M. Ssemwanga).

#### 2.3.1. Preparation of fruit samples and research design

Two widely cultivated high-yielding pineapple (*Ananas comosus*) cultivars; Smooth Cayenne and Queens; and mango (*Mangifera indica)*: Duncan and Bire cultivators were selected. To minimize variability among the samples, the two fruit cultivars were harvested at physiological maturity from one randomly selected certified organic farm (location: 0°27′0″N, 32°46′0″E) in Mukono district, Uganda. Only ripe fruits without any physical damage were selected from the harvested lot based on their uniformity in colour, size, and firmness. The selected fruit samples were cleaned with tap water (chlorinated at ~25 $mgCl_2Kg^{-1}$ $H_2O$) and were afterwards drained under ambient temperatures. About 12 kg of each cultivar were peeled to remove the outer layer and seed. Each fruit cultivar was peeled into 3 mm, 6 and 10 mm thickness; and each thickness categories were isolated into three replicate treatment batches of 1 kg. To minimize variability among the sliced fruit cultivars, uniform slice thickness was maintained. The fruit slice thickness categories were 3 mm, 6 and 10 mm; and all of which consisted of a uniform cross-section slabs of 3 cm diameter. These thickness sizes were made following standard procedures outlined by Chavan and Amarowicz (2012). The drying experiments were run for each cultivar type as the treatment, and its thickness categories as the blocking factors in a randomized complete block design (RCBD) (Mead, 2017). A standard uniform loading capacity of 75% for every 1 $m^2$ area of the food cabinet drying trays (ELkhadraoui et al., 2015; Tibebu, 2015), was maintained across the HIP and SPE dryers as well as under the traditional OSD method.

#### 2.3.2. Fruit sample drying procedures

A 1 kg of replicate cultivar samples for the 3 mm, 6 and 10 mm thickness category sets were simultaneously dried under the HIP dryer, SPE dryer and OSD method. Each of the 3 mm, 6 and 10 mm samples were put on individual drying trays and uniformly spread in single layers. The trays were loaded into the drying cabinets of the HIP and SPE dryers and closed. For the OSD method, the 3 mm, 6 and 10 mm samples were spread on a tarpaulin and placed on raised (8 cm) cemented yard to mimic the traditional practice of drying agro-produce under the open sun as being practised within the local farming communities. The yard was located in open ground to avoid interference of shadows from nearby build structures and trees during the drying process.

The cultivar drying experiments were simultaneously started from 8:00 AM to 6:00 PM (mean day length) under identical ambient weather conditions including day length, temperature, humidity, cloudy conditions and wind speed. Drying was continued until the samples attained an optimum safe storage moisture content of 10% or lower (Wills and Golding, 2016). If drying of the sample was to continue for the next day, the partially dried cultivar samples were removed and sealed in air-tight plastic bags to retard further any dehydration and moisture absorption. The samples were kept in a laboratory overnight.

### 2.4. Measurement of drying performance parameters

The measured drying parameters were; solar heat flux, drying air temperatures inside the drying systems, ambient air temperatures outside the drying systems, and mass of the drying fruit samples. The ambient air temperature outside and drying air temperature inside the cabinet of the HIP and SPE dryers, and the OSD method were measured by calibrated T-type thermocouples. The temperature data were recorded at 30 min-intervals by Lutron digital temperature data logger thermometers (model: DL-9601A, accuracy: ± 0.1 °C, range: −200–350 °C), and data was retrieved using RS232 cables connected to a computer. The solar heat flux was measured using integrating solarimeter (model: KIMO, accuracy: ± 1 W $m^{-2}$, range: 1–1300 W $m^{-2}$). The sensors were put on the produce drying trays in the drying cabinet of the HIP and SPE dryers, and on the open trays for the OSD method.

The initial, intermediate and final mass of the slice samples were measured before, during (at every 30 min) and after drying, respectively using a top-loading electronic weighing scale (model: AC-30, accuracy: ± 0.01 g, range: 0–30 kg). For each measuring cycle, three slices from each fruit cultivar sample were randomly picked from the lower, middle and upper trays using forceps. The samples were quickly picked from smaller sliding doors at the backside behind of drying cabinets of the SPE and HIP dryers. The doors were specifically designed and attached at the rear side to minimize interruption of the internal drying conditions with external weather during the collection of the fruit slice samples for weighing. The collected samples were measured and the average mass of the 3 mm, 6 and 10 mm slices were recorded.

### 2.5. Evaluating the drying performance of the dryer systems

The drying performance of the improved HIP dryer, conventional SPE dryer and the traditional OSD method was evaluated using drying air temperature and solar heat flux, moisture content, drying rate, and solar heat flux-use efficiency. These are the leading food drying performance indicator parameters of any dryer system (Nabnean et al., 2016; Rabha et al., 2017; Vijayan et al., 2016; Wankhade et al., 2014).

#### 2.5.1. Determining the moisture content

The moisture content of the mango and pineapple cultivar samples was determined using a wet basis method (Cherotich and Simate, 2016; Chouicha et al., 2013; Wankhade et al., 2014). It was expressed as the weight of water content in the food sample per unit initial weight of fresh food sample. Therefore, the % moisture content of the cultivar samples was determined as the ratio of the difference in the mass of water evaporated to the initial mass of the cultivar samples before drying using Equation (1) (Wankhade et al., 2014; Wang et al., 2018; Chouicha et al., 2013).

$$\text{Moisture Content,MC}\,(\%) = \frac{(M_i - M_t)}{M_i} \times 100. \tag{1}$$

Where: $M_i$ and $M_t$ were the initial mass and mass of dried cultivar sample at any time, t; respectively.

*2.5.2. Determining food drying rate*

Food drying rate was defined as the rate of moisture removal from the drying food product and was estimated using the dry-weight basis method following protocols outlined by Dorouzi et al. (2018), Hegde et al. (2015), and Wankhade et al. (2014). The drying time referred to the duration (time interval) taken in dehydrating the succulent fruit (pineapple and mango) cultivar samples to desired moisture content (Rabha et al., 2017; Vijayan et al., 2016; Wankhade et al., 2014). Hence, the drying rate was expressed as the ratio of the difference in mass of the cultivar sample being dried to the drying time (Equation (2)).

$$\text{Drying Rate}\,(g\ \text{Min}^{-1}) = \frac{\Delta\text{Mass}\,(g)}{\Delta\text{time}\,(\text{Min})} = \frac{(M_1 - M_2)}{(t_1 - t_2)}. \tag{2}$$

where: $M_1$ and $M_2$ were the opening and ending weights of the cultivar samples, respectively. $t_1$ and $t_2$ were the definite drying times in minutes (Min) to dehydrate the samples from $M_1$ to $M_2$.

*2.5.3. Determining food drying efficiency*

Food drying efficiency is defined as the relative quantity of energy required to dehydrate fresh food product to the energy supplied (Wankhade et al., 2014; Navale et al., 2015; Wang et al., 2018). The drying efficiency of the HIP and SPE dryers, as well as the OSD method, was determined using the energy flux method (Cherotich and Simate, 2016; Jain and Tewari, 2015; Wankhade et al., 2014); where its expressed as a percentage ratio of the energy consumed in dehydrating the samples to the total energy supplied into the food drying systems (Equation (3)).

$$\text{Food Drying Efficiency,FDE} = \frac{\sum M\times L_V}{\sum I_t \times A_c \times t} \times 100. \tag{3}$$

M is the total moisture mass (kg) desiccated from the samples, Lv is latent heat of vaporization of water at average dryer recorded temperatures (Lv = 2320 kJ/kg), $I_t$ is total insolation during drying times ($Wm^{-2}$), and $A_c$ is the surface area of insolation input collector of the food dryer systems ($m^2$), and t is total drying time (s).

*2.6. Statistical analysis*

Data obtained were processed for mean values and were analyzed for the existing sources of variation amongst drying parameters using Analysis of Variance (ANOVA) in R-Statistical software (Team, 2017). A one-way ANOVA was used to separate the means for significant variables between the drying methods. The means were separated by Turkey Honest test at 5% significant difference level.

## 3. Results

*3.1. Statistical analysis of the significance of drying variables*

Table 1 shows results for the Analysis of Variance presenting the statistical significance of the experimental variables (drying rate) obtained for drying both mango and pineapple cultivars.

The drying rate of the mango and pineapple cultivars varied significantly ($p \le 0.05$) between the three solar drying methods (thus OSD method, HIP and SPE dryers). However, irrespective of the drying method, there was no significant ($p > 0.05$) variation in the drying rate of the different mango and pineapple cultivars including their slice thickness categories.

**Table 1**
Analysis of Variance (ANOVA) for experimental variables (drying rate).

| Response: Drying rate(g/min) | | Mango cultivars | | Pineapple cultivars | |
|---|---|---|---|---|---|
| *SOV* | *Df* | *Mean Sq.* | *P* | *Mean Sq.* | *P* |
| Method (*drying system*) | 2 | 1.906 | 0.003** | 2.63978 | 0.000** |
| Block (*slice thickness*) | 2 | 0.02460 | 0.913ns | 0.03104 | 0.892ns |
| Variety (*cultivars*) | 1 | 0.00007 | 0.987ns | 0.00004 | 0.990ns |
| Block: Variety | 2 | 0.01473 | 0.947ns | 0.01648 | 0.943ns |
| Residuals | 748 | 0.27051 | | 203.917 | |

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1ns non-significant. *SOV* = Source of Variation, *Df* = degree of freedom, *Mean Sq.* = mean sum of squares, *p = statistical significance at 5%,* Method = method of drying (HIP and SPE dryers, and OSD method), Block = thickness levels of fruit cultivars (3 mm, 6 and 10 mm), Variety = cultivars (mangoes: *Duncan* and *Bire,* pineapples: *Smooth Cayenne* and *Queens*).

*3.2. Solar heat flux and drying air temperatures*

Fig. 3 compares variations in the mean daily ambient and incident solar radiation, solar heat flux and drying air temperatures for the HIP and SPE dryers, and OSD method observed during the three replicate drying cycles. Since the samples under the OSD were dried in the open, the ambient air temperatures were equivalent to the drying air temperatures for the OSD method. The mean drying air temperatures achieved by the HIP and SPE dryers were 27.7 and 40.3 °C, respectively. The drying air temperatures for the SPE dryer were considerably higher than that of the HIP dryer and OSD method with reduced fluctuations during the day (Fig. 3).

The drying air temperatures for the HIP dryer were lower than the ambient temperatures (of the OSD method) mainly during the cloudy hours. This could be because, during the cloudy hours, the HIP dryer exhibited more accelerated decline in the drying air temperatures coupled with higher retention of humidity in its drying cabinet which was enclosed with a greenhouse plastic material. The solar heat flux and drying air temperatures increased with increasing quantities of both the ambient air temperatures and solar radiations, and vice versa.

In this context, ambient solar radiation was defined as the quantity of solar heat flux received per unit surface area whereas solar heat flux for OSD method referred to the quantity of solar heat flux received on the 2.5 $m^2$ surface area under the OSD method. The mean solar thermal energy recorded for the HIP and SPE dryers, and OSD methods were 4795, 5994 and 3595 Watts per square meter ($W/m^2$), respectively.

The intensity of solar heat flux for the three drying systems was low during the morning hours from 8:30 to 11:30 AM, steadily increased to a peak in the afternoon hours at 3:30 PM, and decreased gradually in the evening hours from 4:00 to 6:00 PM. In other words, both the solar thermal energy and drying air temperatures for the three solar drying methods increased with a cumulative intensity of the ambient temperatures and solar radiation during the drying process, and vice versa.

*3.3. Drying rate of the pineapple and mango cultivars*

Table 2 shows variations in the mean drying rates for the pineapple and mango cultivars. The drying rate of both pineapple and mango cultivars varied significantly ($p < 0.05$) between the three drying systems. The drying rate of both the pineapple and mango cultivars was higher in the conventional SPE dryer than in the improved HIP dryer and was lowest under the traditional OSD method (Table 2).

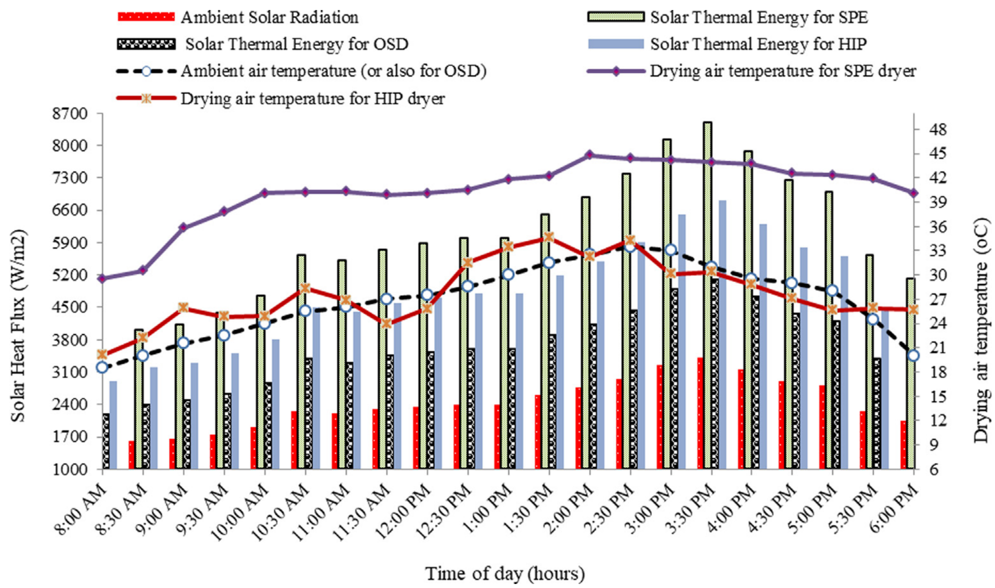


**Fig. 3.** Variation of mean incident solar radiation and drying air temperatures under different drying methods (OSD method, HIP and SPE dryers) from May 3rd to 5th, 2018.

The mean drying rates of the pineapple and mango cultivars were not significantly different between the cultivars and their thickness levels.

### 3.4. Moisture content evaporated from the pineapple and mango cultivars

Table 3 presents the mean quantities of moisture evaporated from the dried pineapple and mango cultivars. The quantity of moisture evaporated from the dried pineapple and mango cultivars varied significantly ($p < 0.05$) between the three drying systems. The evaporated moisture was highest and lowest under the SPE dryer and OSD method, respectively (Table 3).

The mean quantities of moisture content dehydrated from the pineapple and mango cultivars were not significantly different between the cultivars and their thickness levels. The result suggests that the quantity of moisture dehydrated from both the pineapple and mango cultivars were higher in the conventional SPE dryer than in the improved HIP dryers, and was lowest under the traditional OSD method.

### 3.5. Variation between moisture content and drying time of pineapple and mango cultivars

Fig. 4 shows the mean variation in the moisture content of the pineapple and mango cultivars (of 6 mm thickness) with drying time. There was a continued high fluctuation in the moisture content during the entire drying period of both pineapple and mango cultivars for the HIP dryer and OSD method.

The SPE dryer dried the pineapple and mango cultivars in 10 h as opposed to the 18 and 30 h taken by the HIP dryer and OSD method, respectively. This observation suggests that both the conventional SPE dryer and the improved HIP dryer prototype dehydrated the pineapple and mango fruits faster than the traditional OSD method.

There was an accelerated decline in the moisture content of both pineapple and mango cultivars during the initial stages of the drying process. The rate of moisture loss declined in the intermediate stages of drying and remained constant in the final drying stages under the three drying systems (Fig. 4).

### 3.6. Food drying efficiency for the three drying systems

Fig. 5 presents the food drying efficiency of the SPE and HIP dryers

**Table 2**
Mean drying rate (g/min) of pineapple and mango cultivars, from April to June 2018 at NaLIRRI - Nakyesasa, Uganda.

| Response: Drying rate (g/min) | | Thickness (mm) | SPE method (n = 20) | HIP method (n = 41) | OSD method (n = 62) |
|---|---|---|---|---|---|
| Pineapples | Smooth Cayenne | 3 mm | 0.140 ± 0.0060[a] | 0.080 ± 0.0012[b] | 0.063 ± 0.0011[c] |
| | | 6 mm | 0.135 ± 0.0071[a] | 0.079 ± 0.0014[b] | 0.060 ± 0.0009[c] |
| | | 10 mm | 0.132 ± 0.0078[a] | 0.077 ± 0.0017[b] | 0.059 ± 0.0010[c] |
| | Queens | 3 mm | 0.136 ± 0.0070[a] | 0.079 ± 0.0013[b] | 0.064 ± 0.0013[c] |
| | | 6 mm | 0.132 ± 0.0078[a] | 0.077 ± 0.0018[b] | 0.060 ± 0.0010[c] |
| | | 10 mm | 0.130 ± 0.0083[a] | 0.075 ± 0.0023[b] | 0.059 ± 0.0010[c] |
| Mangoes | Duncan | 3 mm | 0.216 ± 0.0083[a] | 0.088 ± 0.0015[b] | 0.077 ± 0.0024[c] |
| | | 6 mm | 0.209 ± 0.0092[a] | 0.086 ± 0.0013[b] | 0.073 ± 0.0020[c] |
| | | 10 mm | 0.201 ± 0.0101[a] | 0.083 ± 0.0012[b] | 0.071 ± 0.0018[c] |
| | Bire | 3 mm | 0.210 ± 0.0088[a] | 0.088 ± 0.0015[b] | 0.076 ± 0.0023[c] |
| | | 6 mm | 0.207 ± 0.0097[a] | 0.087 ± 0.0014[b] | 0.073 ± 0.0019[c] |
| | | 10 mm | 0.197 ± 0.0109[a] | 0.083 ± 0.0013[b] | 0.070 ± 0.0018[c] |

Values are arithmetic means with standard deviation ( ± SD) computed for values taken at every 30-minute interval during drying. Comparisons were made between the pineapple and mango cultivars, and n = number of replicate readings taken. Means in the same row bearing different superscript alphabetic letters are significantly different at 5% confidence level.

**Table 3**
Mean quantities of moisture content evaporated from the pineapple and mango cultivars.

| Response: Moisture Content (%) | | Thickness (mm) | SPE dryer method (n = 20) | HIP dryer method (n = 41) | OSD Method (n = 62) |
|---|---|---|---|---|---|
| Pineapples | Smooth Cayenne | 3 mm | 47.83 ± 7.009[a] | 44.59 ± 4.688[b] | 40.03 ± 3.502[c] |
| | | 6 mm | 48.58 ± 7.009[a] | 44.97 ± 4.684[b] | 41.13 ± 3.502[c] |
| | | 10 mm | 49.21 ± 6.991[a] | 45.36 ± 4.687[b] | 41.65 ± 3.502[c] |
| | Queens | 3 mm | 48.39 ± 7.028[a] | 44.89 ± 4.688[b] | 39.71 ± 3.500[c] |
| | | 6 mm | 49.03 ± 7.009[a] | 45.57 ± 4.684[b] | 41.38 ± 3.502[c] |
| | | 10 mm | 49.52 ± 6.002[a] | 46.17 ± 4.684[b] | 41.77 ± 5.502[c] |
| Mangoes | Duncan | 3 mm | 45.97 ± 7.421[a] | 42.63 ± 4.782[b] | 33.18 ± 3.473[c] |
| | | 6 mm | 46.02 ± 7.448[a] | 43.29 ± 4.775[b] | 34.48 ± 3.473[c] |
| | | 10 mm | 47.22 ± 7.484[a] | 43.94 ± 4.804[b] | 35.45 ± 3.473[c] |
| | Bire | 3 mm | 44.81 ± 7.465[a] | 42.61 ± 4.779[b] | 33.39 ± 3.473[c] |
| | | 6 mm | 45.36 ± 7.457[a] | 43.09 ± 4.775[b] | 34.63 ± 3.473[c] |
| | | 10 mm | 46.89 ± 7.489[a] | 44.14 ± 4.803[b] | 35.78 ± 3.473[c] |

Values are computed arithmetic means with standard deviation (+SD) for values taken at every 30-minute interval during cultivar drying. n = number of readings taken during each of the 3 replicate drying cycles. Comparisons were made between the pineapple and mango cultivars. Means in the same row bearing different superscript alphabetic letters are significantly different ($p < 0.05$).

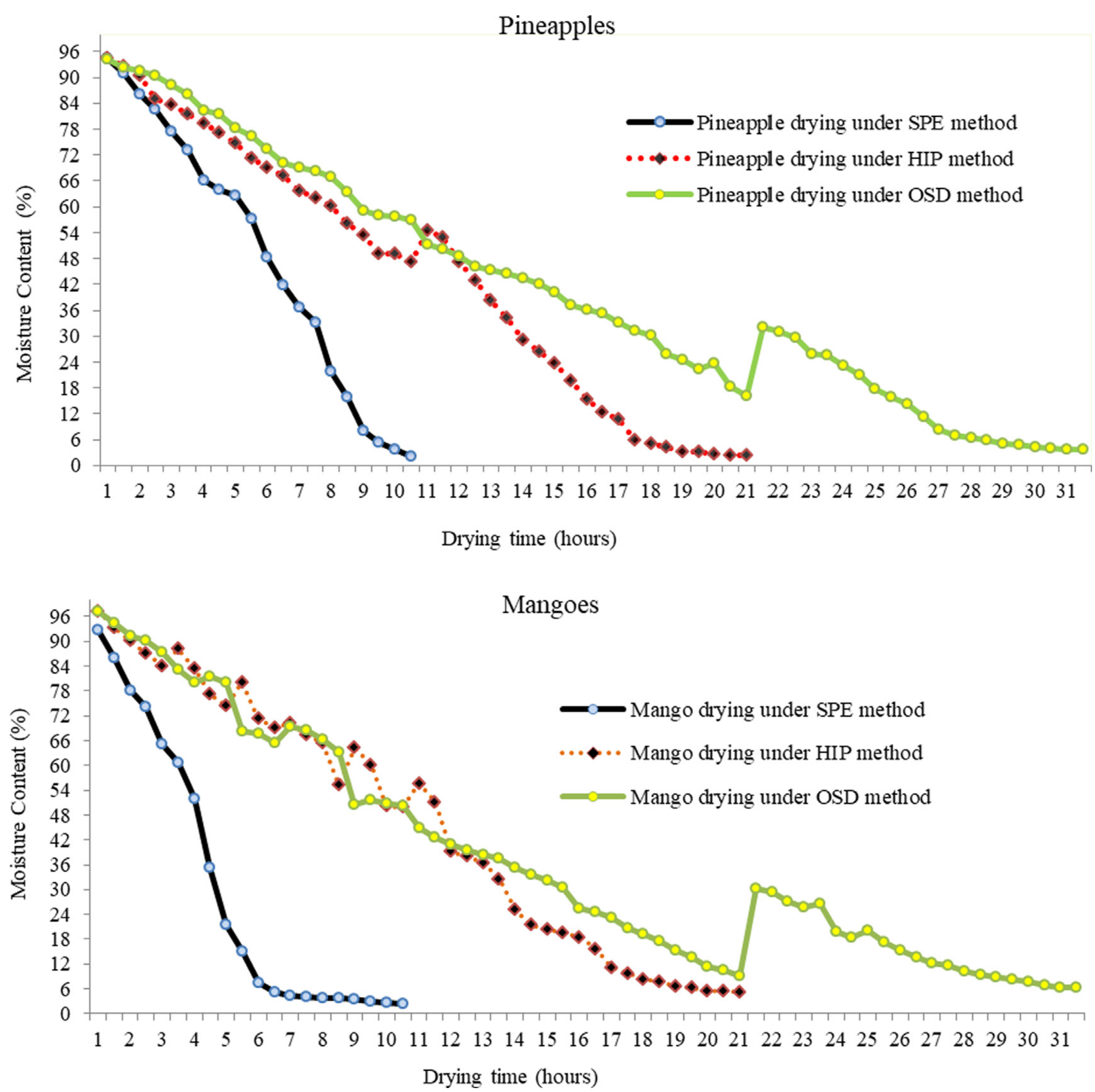


**Fig. 4.** Graph of variation between moisture content and drying time for pineapple and mango.

for the pineapple and mango cultivars. The drying efficiency was higher in the conventional SPE dryer than in the improved HIP dryer and was lowest under the traditional OSD method (Fig. 5).

The results suggest, that modifying the solar concentrator plate in the indirect passive solar dryer with auxiliary multiple metallic concentrator materials coupled with specialized greenhouse walling material to cover the drying cabinet substantially increased the food drying efficiency.

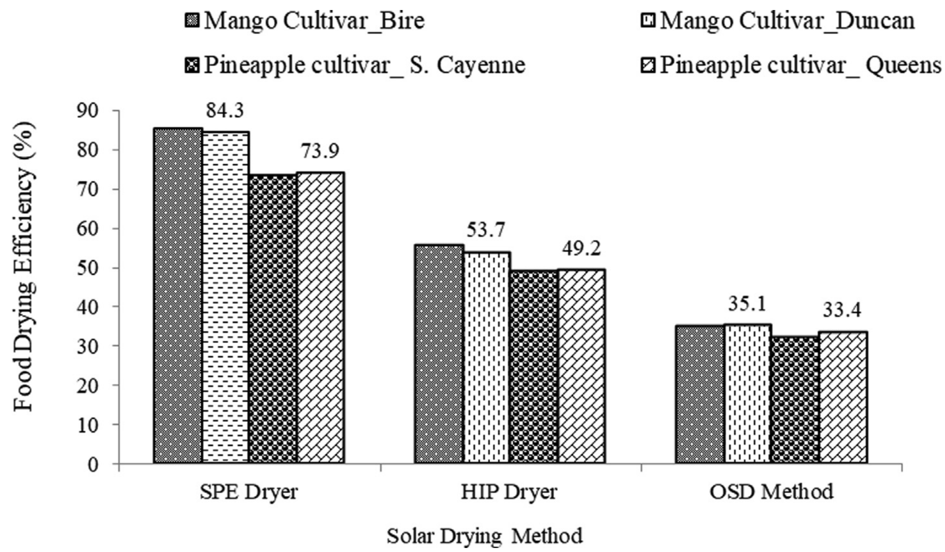


**Fig. 5.** Food drying efficiency for the OSD method, SPE and HIP dryers.

## 4. Discussion

The drying air temperature and solar heat flux for the three drying systems showed a directly proportional relationship with ambient temperature and solar radiation energy, which increased in the afternoon to a peak and declined in the evening (Fig. 3). This observation was consistent with the results of Hegde et al. (2015) and Ayua et al. (2017), who reported higher drying temperatures and internal thermal energies in solar dryers during the afternoon hours between 11:00 AM and 3:00 PM than in the late evening hours. Besides this trend, the quantity of moisture desiccated from the pineapple and mango cultivars under the HIP and SPE dryers and OSD method was comparable that dehydrated under similar active and passive solar dryers and open sun drying method as reported by Tibebu (2015) in pineapples and Bala and Serm (2009) in mangoes.

In the context that, some of the new fruit cultivars are bred to specifically have additional juice content (inclusive of extra moisture) - as a consumer preferred trait than other traditional cultivars (Duarte et al., 2005; Gonzalez-Aguilar et al., 2008); the different mango and pineapple cultivars would be expected to have different variations in moisture content, which would translate into different drying rates under identical experimental drying conditions. But the result suggests that there is no substantial variation in moisture content between the different cultivars of pineapples and mangoes (Table 3).

However, the accelerated decrease in the moisture content of the cultivars during the initial stages of drying corresponded to the higher drying rate due to relaxed desiccation of superfluous moisture from the highly succulent fruit samples (Cherotich and Simate, 2016; Dorouzi et al., 2018). While the decline in the moisture content from a peak in the afternoon to a constant rate during the evening hours was due to sustained stabilization of the drying air temperatures, which stabilized humidity between for the dried samples and drying air temperatures to equilibrium at during the late stages of the sample drying process (Cherotich and Simate, 2016; Dorouzi et al., 2018).

Although the drying air temperatures for the conventional SPE dryer were within the range of 37–60 °C given by other forced convection solar dryers under active mode constructed by Rabha et al. (2017), and Wang et al. (2018); it took a shorter drying duration than other active mode conventional dryer prototypes constructed by Belessiotis and Delyannis (2011). These prototypes took about 15 and 30 h of constant drying to sufficiently dry the pineapple and mango samples, respectively (Fig. 4). This means that the conventional SPE prototype dries agro-produce faster relative to other conventional solar-driven dryers using the active mode of operation.

Regarding the HIP dryer (Fig. 3), it raised the drying air temperatures higher than the conventional hybrid passive-mode solar dryers constructed by Alonge and Adeboye (2012), which only increased the internal drying air temperatures by 6.4 °C and 9 °C; respectively above the ambient temperature. However, the drying air temperatures of the HIP dryer were also lower than other passive indirect solar dryers reported in the following literature; 40–45 °C for passive indirect solar dryer by Jain and Tewari (2015), 40–50 °C for indirect passive dryer by (Vijayan et al., 2016), and 44–55 °C for indirect solar dryer under passive mode by Lingayat et al. (2017).

The observed drying rate of both pineapple and mango cultivars under the OSD method (Table 2), was lower than that witnessed in Ghana by Tibebu (2015), who reported the drying rates of pineapple and mango as 0.258 and 0.395 g/minute, respectively under the open sun. Equally, the pineapple and mango drying rates achieved by the modified HIP dryer were also noticeably lower than 0.420 and 0.307 g/minute drying rate of pineapple and mangoes; respectively which were achieved by the conventional passive indirect solar dryer of Tibebu (2015) in Ghana. In the context that the drying air temperature and solar heat flux of any solar-driven drying system is dependent on the duration and intensity of sunshine hours received in a given area (Krawczyk et al., 2012), the observed differences both in the drying air temperature and drying rate could be contributed by the high variations in the intensity of ambient solar radiation and temperatures due to spatial differences in spatial latitudinal location between Uganda and Ghana. Thus, Ghana experiences higher solar radiation intensity and temperatures than Uganda given its location in the semi-arid climatic zones as opposed to the equatorial weather conditions in Uganda (IPCC, 2015). This could have boosted the drying rate of the solar dryers constructed by Tibebu (2015). Belessiotis and Delyannis (2011), also observed significant variations in the drying rates of fruits dried in solar dryers and under the open sun in different localities with dissimilar ambient temperatures, solar radiation and other weather conditions. It was further reported that the drying air temperatures and drying rate of solar-driven dryers are significantly reduced during the cloudy and rainy hours with limited solar radiation intensity and vice versa (Bhardwaj et al., 2017).

Fluctuations in moisture content of mangoes and pineapples (in Fig. 4) was a result of the non-uniform drying process of the slice samples caused by abrupt changes in the internal drying conditions mainly drying air temperatures for the HIP and SPE dryers, and OSD methods. An abrupt change in drying air temperatures interrupts the

**Table 4**
Comparison of drying efficiency achieved by the conventional active and passive-mode solar dryers against the SPE and HIP dryers.

| Type of solar dryer | Operation | Fruits dried | Efficiency (%) | References |
|---|---|---|---|---|
| SPE dryers | Hybrid | Mangoes & pineapples | 84.3 & 73.9 | Fig. 5 |
| HIP dryers | Hybrid | Mangoes & pineapples | 53.7 & 49.2 | Fig. 1 |
| Indirect forced convection | Active | Mangoes | 33.8 | Wang et al. (2018) |
| Indirect hybrid convection | Active | Ginger | 8.5 | Rabha et al. (2017) |
| Indirect passive dryer | Passive | Mint leaves | 28.2 | Jain and Tewari (2015) |
| Sensible storage indirect | passive | Bitter gourd | 19 | Vijayan et al. (2016) |
| Hybrid indirect | passive | Banana | 22.38 | Lingayat et al. (2017) |
| Hybrid indirect | passive | Ghost chilli pepper | 4.05 | Lingayat et al. (2017) |

food drying rate, and also causes fluctuations in the moisture content of the drying food products (Krawczyk et al., 2012; Tibebu, 2015; Vijayan et al., 2016).

The relative food drying efficiency of the conventional SPE and improved HIP dryers (Fig. 5), were higher than the efficiency of the active and passive natural convective solar dryers reported in the literature. Table 4 compares the fruit drying efficiency achieved by the SPE and HIP dryers against the mean drying efficiency of other conventional solar-driven dryers.

The results in Table 4, suggest that modifying the solar collector plate with multiple metallic concentrators coupled with a specialized greenhouse material enclosing the drying cabinet increases the drying efficiency of the improved HIP dryers relative to other conventional passive-mode solar dryers.

However, the aforementioned variations in the drying performance of the improved HIP and the SPE dryers relative to the other conventional passive and active mode solar-driven dryers could be explained by the differences in the structural modifications, designs and materials used. This conclusion was collaborated by results from several drying experimental studies; Dorouzi et al. (2018), Belessiotis and Delyannis (2011), Tibebu (2015), Vijayan et al. (2016) and Wang et al. (2018), which reported higher drying performance (in terms of drying air temperatures, drying rate and efficiency) in solar-driven dryers with modified designs and structures as well as upgraded quality of fabrication materials. This was because improving the physical structure and design, and use of quality materials when constructing the dryers directly influences the quantity of solar radiation energy collected, stored and used in the actual drying operations (Bolaji and Olalusi, 2008; Hegde et al., 2015; Hii et al., 2012; Mennouche et al., 2014; Tibebu et al., 2016).

## 5. Conclusion

- An improved Hybrid Indirect Passive (HIP) dryer was prototyped and proposed as an alternative against the way of drying food under the open sun.
- The HIP dryer consists of a solar collector modified with multiple metallic solar collectors and drying cabinet walled with specialized plastic greenhouse materials to concentrate additional solar heat flux.
- A conventional active mode Solar Photovoltaic and Electric (SPE) dryer with an auxiliary solar thermal backup system was also fabricated. Food drying performance of the modified passive mode HIP dryer and the conventional active mode SPE dryer was experimentally evaluated for drying pineapples and mangoes and was compared against the traditional open sun drying (OSD) method.
- Based on the results, the drying performance in terms of drying rate and efficiency was higher in the SPE dryer than the improved HIP dryer and was lowest under the traditional OSD method for both pineapples and mangoes.
- The SPE prototype dried the pineapple and mango cultivars in 10 h as compared to 18 and 30 h taken by the improved HIP dryer and the traditional OSD method, respectively. This means that modifying the solar collector plate with multiple metallic solar concentrators coupled with modified greenhouse walling material on the dryer cabinet in the passive indirect solar-driven dryer enhanced the food drying performance.
- The higher drying rate and efficiency coupled with reduced produce drying time for the HIP and SPE dryer could translate into an increased turnover of the dried food products if deployed. Therefore, both the improved HIP dryer and SPE dryers could offer faster and more efficient food drying options than the traditional OSD method.
- Therefore, the dryers could benefit rural-based subsistence farming communities in terms of postharvest loss reduction. Future works could be directed towards making further improvements in the HIP dryer design to further increase the drying air temperatures and modify the cabinet covering to a more durable and climate-resilient greenhouse material for prolonged durability.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solener.2020.04.065.

## References

Aboghrara, A.M., Baharudin, B., Alghoul, M., Adam, N.M., Hairuddin, A., Hasan, H.A., 2017. Performance analysis of solar air heater with jet impingement on corrugated absorber plate. Case Stud. Therm. Eng. 10, 111–120.
ACORD, 2014. Problems facing small scale farmers in Isingiro District, Uganda: Focus on Bananas. In: ACORD (Ed.), From Food Security to Food Sovereignty. ACORD, Kampala, pp. 1–30.
Alonge, A., Adeboye, O., 2012. Drying rates of some fruits and vegetables with passive solar dryers. Int. J. Agric. Biolog. Eng. 5, 83–90.
Andritsos, N., Dalampakis, P., Kolios, N., 2003. Use of geoheat flux for tomato drying. GHC Bull. 24.
Ananno, A.A., Masud, M.H., Dabnichki, P., Ahmed, A., 2020. Design and numerical analysis of a hybrid geothermal PCM flat plate solar collector dryer for developing countries. Sol. Energy 196, 270–286.
APHLIS, 2011. African Post Harvest Losses Information Systems (APHLIS)-Uganda: Post-Harvest Losses explanation in Uganda. Kampala. *Basis of the reseach problem - postharvest food losses.
Arun, K.R., Srinivas, M., Saleel, C.A., Jayaraj, S., 2019. Active drying of unripened bananas (Musa Nendra) in a multi-tray mixed-mode solar cabinet dryer with backup energy storage. Sol. Energy 188, 1002–1012.
Ayua, E., Mugalavai, V., Simon, J., Weller, S., Obura, P., Nyabinda, N., 2017. Comparison of a mixed modes solar dryer to a direct mode solar dryer for African indigenous vegetable and chili processing. J. Food Process. Preserv. 41, e13216.

Bala, B.K., Serm, J., 2009. Solar drying of fruits, vegetables, spices, medicinal plants and fish: Developments and Potentials. In: International Solar Food Processing Conference 2009. Bangladesh Agricultural University, pp. 1–24.
Belessiotis, V., Delyannis, E., 2011. Solar drying. Sol. Energy 85, 1665–1691.
Bhardwaj, A.K., Ranchan, C., Raj, K., Muneesh, S., Adit, R., 2017. Experimental investigation of an indirect solar dryer integrated with phase change material for drying valeriana jatamansi (medicinal herb). In: Faculty of Engineering and Technology, S.U. (Ed.). Case Studies in Thermal Engineering, Solan, India, pp. 302–314.
Bolaji, B.O., Olalusi, A.P., 2008. Performance evaluation of a mixed-mode solar dryer.
Çakmak, G., Yıldız, C., 2011. The drying kinetics of seeded grape in solar dryer with PCM-based solar integrated collector. Food Bioprod. Process. 89, 103–108.
Chavan, U., Amarowicz, R., 2012. Osmotic dehydration process for preservation of fruits and vegetables. J. Food Res. 1, 202.
Cherotich, S., Simate, I.N., 2016. Experimental investigation and mathematical modelling of a natural convection solar tunnel dryer. Int. J. Sci. Eng. Res. 7, 597–603.
Chouicha, S., Boubekri, A., Mennouche, D., Berrbeuh, M.H., 2013. Solar drying of sliced potatoes. An experimental investigation. Energy Procedia 36, 1276–1285.
Daghigh, R., Shahidian, R., Oramipoor, H., 2020. A multistate investigation of a solar dryer coupled with photovoltaic thermal collector and evacuated tube collector. Sol. Energy 199, 694–703.
Dorouzi, M., Mortezapour, H., Akhavan, H.-R., Moghaddam, A.G., 2018. Tomato slices drying in a liquid desiccant-assisted solar dryer coupled with a photovoltaic-thermal regeneration system. Sol. Energy 162, 364–371.
Duarte, I.F., Goodfellow, B.J., Gil, A.M., Delgadillo, I., 2005. Characterization of mango juice by high-resolution NMR, hyphenated NMR, and diffusion-ordered spectroscopy. Spectrosc. Lett. 38 (3), 319–342.
Elkhadraoui, A., Kooli, S., Hamdi, I., Farhat, A., 2015. Experimental investigation and economic evaluation of a new mixed-mode solar greenhouse dryer for drying of red pepper and grape. Renew. Energy 77, 1–8.
Fleming, A., Folsom, C., Ban, H., Ma, Z., 2017. A general method to analyze the thermal performance of multi-cavity concentrating solar power receivers. Sol. Energy 150, 608–618.
Gonzalez-Aguilar, G.A., Celis, J., Sotelo-Mundo, R.R., De La Rosa, L.A., Rodrigo-Garcia, J., Alvarez-Parrilla, E., 2008. Physiological and biochemical changes of different fresh-cut mango cultivars stored at 5° C. Int. J. Food Sci. Technol. 43 (1), 91–101.
Güler, H.Ö., Sözen, A., Tuncer, A.D., Afshari, F., Khanlari, A., Şirin, C., Gungor, A., 2020. Experimental and CFD survey of indirect solar dryer modified with low-cost iron mesh. Sol. Energy 197, 371–384.
Hegde, V.N., Hosur, V.S., Rathod, S.K., Harsoor, P.A., Narayana, K.B., 2015. Design, fabrication and performance evaluation of solar dryer for banana. Energy Sustain. Soc. 5, 23.
Hii, C.L., Jangam, S.V., Ong, S.P., Mujumdar, A.S., 2012. Solar drying: Fundamentals, applications and innovations. TPR Group Publication, Singapore. * Guides the fabrication process of the new solar dryer designs.
IPCC, 2015. Climate change 2014: Mitigation of climate change. Cambridge University Press, UK.
Jain, D., Tewari, P., 2015. Performance of indirect through pass natural convective solar crop dryer with phase change heat flux storage. Renew. Energy 80, 244–250.
KARI, 2017. Crop Post-Harvest Handling and Storage Technologies:The Beehive. Kawanda Agricultural Research Institute (KARI), Kampala, pp. 1–4.
Krawczyk, P., Ali Al-Jumaah, Abdullah Mohamed, Asiri Mohamed Fadil Alshehri Ahmed Mohamed Deash Fahd Minajy Al-Hamzi, A., El-Haggar Mahmoud A Bakry, M.M., Al., E., 2012. Sun and solar drying, techniques and Equipment II. Solar Drying. Renewable and Sustainable Energy Reviews. https://doi.org/ISBN: 978-981-07-3336-0.
Kumar, M., Sansaniwal, S.K., Khatak, P., 2016. Progress in solar dryers for drying various commodities. Renew. Sustain. Energy Rev. 55, 346–360.
Lingayat, A., Chandramohan, V., Raju, V., 2017. Design, development and performance of indirect type solar dryer for banana drying. Energy Procedia 109, 409–416.
Mead, R., 2017. Statistical Methods in Agriculture and Experimental Biology. Chapman and Hall/CRC.
Mehran, S., Nikian, M., Ghazi, M., Zareiforoush, H., Bagheri, I., 2019. Experimental investigation and energy analysis of a solar-assisted fluidized-bed dryer including solar water heater and solar-powered infrared lamp for paddy grains drying. Sol. Energy 190, 167–184.
Mennouche, D., Bouchekima, B., Boubekri, A., Boughali, S., Bouguettaia, H., Bechki, D., 2014. Valorization of rehydrated Deglet-Nour dates by an experimental investigation of solar drying processing method. Energy Convers. Manage. 84, 481–487.
Nabnean, S., Janjai, S., Thepa, S., Sudaprasert, K., Songprakorp, R., Bala, B., 2016. Experimental performance of a new design of solar dryer for drying osmotically dehydrated cherry tomatoes. Renew. Energy 94, 147–156.
Navale, S., Harpale, V., Mohite, K., 2015. Comparative study of open sun and cabinet solar drying for fenugreek leaves. Int. J. Renew. Energy Technol. Res. 4, 1–9.
Rabha, D., Muthukumar, P., Somayaji, C., 2017. Experimental investigation of thin layer drying kinetics of ghost chilli pepper (Capsicum Chinense Jacq.) dried in a forced convection solar tunnel dryer. Renew. Energy 105, 583–589.
Rad, F.M., Fung, A.S., Leong, W.H., 2013. Feasibility of combined solar thermal and ground source heat pump systems in cold climate, Canada. Energy Build. 61, 224–232.
Rizal, T., Muhammad, Z., 2018. Fabrication and testing of hybrid solar-biomass dryer for drying fish. Case Stud. Therm. Eng. 12, 489–496.
Samimi-Akhijahani, H., Arabhosseini, A., 2018. Accelerating drying process of tomato slices in a PV-assisted solar dryer using a sun tracking system. Renew. Energy 123, 428–438.
Şevik, S., Aktaş, M., Dolgun, E.C., Arslan, E., Tuncer, A.D., 2019. Performance analysis of solar and solar-infrared dryer of mint and apple slices using energy-exergy methodology. Sol. Energy 180, 537–549.
Team, R.C., 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria; 2016.
Tibebu, T.B., 2015. Design, construction and evaluation of performance of solar dryer for drying fruit.
Tibebu, T.B., Obeng, G.Y., Mensah, E., Smith, A., 2016. Solar dryer with biomass backup heater for drying fruits: development and performance analysis. J. Sci. Technol. (Ghana) 36, 10–25.
Vijayan, S., Arjunan, T., Kumar, A., 2016. Mathematical modeling and performance analysis of thin layer drying of bitter gourd in sensible storage based indirect solar dryer. Innovative Food Sci. Emerg. Technol. 36, 59–67.
VijayaVenkataRaman, S., Iniyan, S., Goic, R., 2012. A review of solar drying technologies. Renew. Sustain. Energy Rev. 16, 2652–2670.
Wang, W., Li, M., Hassanien, R.H.E., Wang, Y., Yang, L., 2018. Thermal performance of indirect forced convection solar dryer and kinetics analysis of mango. Appl. Therm. Eng. 134, 310–321.
Wankhade, P., Sapkal, D.R., Sapkal, V., 2014. Design and performance evaluation of solar dryer. IOSR-J. Mech. Civ. Eng e-ISSN 2278-1684.
Wills, R., Golding, J., 2016. Postharvest: An Introduction to the Physiology and Handling of Fruit and Vegetables. UNSW Press.
World Bank, 2018. Fact Sheet: The World Bank and Agriculture in Africa. Agriculture in Africa. World Bank. 20433 USA, Washington, DC.
Yassen, T.A., Al-Kayiem, H.H., 2016a. Experimental investigation and evaluation of hybrid solar/thermal dryer combined with supplementary recovery dryer. Sol. Energy 134, 284–293.
Yassen, T.A., Al-Kayiem, H.H., 2016b. Solar-biomass hybrid dryer enhanced by the Co-Gen technique. Drying Technol. 34, 287–295.