# EFFECT OF UV-BLOCKING FILM ON THE THERMAL PERFORMANCE OF GREENHOUSE SOLAR DRYER AND DRYING KINETICS OF TOMATO SLICES

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## Abstract

**Post-harvest losses particularly in horticultural crops continue to contribute to the already widening gap between food demand and supply. Drying is one of the novel techniques that has been employed to mitigate these losses. Polyethylene films cladded solar greenhouse drying has gained popularity particularly among smallholder farmers in tropical countries. However, there exists no information on their comparative effects on the thermal performance of greenhouse solar dryers and quality of the dried products. The objective of this study, therefore, was to determine the effect of UV-blocking (UVB and UVA) and UV-transmitting polyethylene films on the thermal performance of greenhouse solar dryer and drying kinetics of Kilele F1 tomato slices. Two greenhouse solar driers, one cladded with UV-blocking film and the other with UV-transmitting film, were developed and used to dry Kilele F1 tomato slices. Solar radiation, UV-transmission intensity, temperature, relative humidity, wind velocity, moisture content, and colour were measured periodically in each dryer and the results analysed statistically using STATA SE Version 16.0. Lower average room and ground greenhouse temperature, that is 40.32±6.25 and 45.12±5.86 ºC, respectively were attained in UV-blocking greenhouse solar dryer compared to the respective temperatures, 42.48±6.48 and 46.10±6.33 ºC attained in UV-transmitting greenhouse solar dryer. The 5 mm thick tomato slices were dried from an initial moisture content of 2785.53 % (db) in both dryers to a final moisture content of 34.63 and 34.18 % (db) in UV-blocking and UV-transmitting dryer, respectively, in 12 hours. In addition, an average drying rate of 57.88 (g/g)/hr and 65.02 (g/g)/hr were obtained in UV-blocking and UV-transmitting dryers, respectively. Lower effective moisture diffusivity of 2.03 $\times 10^{-10}$ $m^2/s$ was attained in UV-transmitting dryer compared to 2.11 $\times 10^{-10}$ $m^2/s$ attained in UV-blocking dryer. While UV-blocking dryer registered better performance in colour retention, UV-transmitting dryer registered higher shrinkage ratio and rehydration ratio. Further, non-linear regression analysis established that Page model provided the best description of the drying kinetics of tomato slices in both dryers with $R^2$ of 0.9962 and 0.9975, $\chi^2$ of 0.0004 and 0.0002, RMSE of 0.0190 and 0.0161, for UV-blocking and UV-transmitting dryer, respectively. Therefore, the results indicate that both films can be used in greenhouse solar dryers to dry tomato slices economically without leading to significant physical and nutritive quality deterioration.**

**Keywords**: Greenhouse solar dryer, UV-blocking, UV-transmitting, tomatoes, postharvest losses

## Introduction

Tomato (*Solanum lycopersicum*) is an instrumental vegetable in human dietary. Its global production and consumption are second to that of potato (Tan et al., 2010). Production of tomato is estimated to account for 4.8 million hectares of harvested land worldwide (FAOSTAT, 2014). According to FAOSTAT (2017), more than 178 million tons of tomato were produced in 2017 globally, with China accounting for the largest percentage of the production followed by USA, India, Egypt and

Turkey. Tomato's popularity is attributable to two factors, namely, its nutritional and healthy benefits as well as a growing diversification in its consumption. An Epidemiological study carried out by Harvard School of Public Health (2010) has shown that tomato is a key source of lycopene whose antioxidant activity has been established to provide efficient scavenging effect on cancer. In particular, tomato's lycopene has been found to be effective in fighting various types of cancers including cervical, prostate, stomach, rectum, and esophageal cancers as well as preventing cardiovascular diseases. Also, tomato consumption has other medicinal benefits such as gut maintenance, skin protection, vision improvement, and prevention of gallstones among others (Abano et al., 2011). These benefits are attributed to its rich source of vitamin C, beta-carotene, and minerals such as potassium. Moreover, tomato consumption is extensively diverse as it is intertwined with consumer cultures as well as the ever-growing development of food technology (Beckles, 2012; Doymaz, 2007). Tomato is often consumed fresh in form of salads, salsa and sandwiches as well as processed into secondary tomato products such as paste, juice, dehydrated tomato and sauce.

Tomato as a vegetable has a high perishability which is attributable to its high moisture content with a post-harvest life span of two to three weeks (César et al., 2019; Haile & Safawo, 2018). Consequently, massive qualitative and quantitative post-harvest losses are incurred at various levels of the tomatoes production chain, most of which occur during storage and transportation (Idah et al., 2007). Moreover, studies have reported higher tomato post-harvest losses in Africa than in developed economies. Sibomana et al. (2016) have reported 10.1%, 10.2, and 13.4% tomato losses in Kenya, South Africa and Nigeria, respectively which were significantly higher compared to those of Spain, Italy and USA at 5%, 4% and 5.5%, respectively as reported by FAOSTAT (2015). Consequently Arah et al. (2015) has reported that post-harvest losses render tomato production an unprofitable venture in most part of the world.

Various measures have been developed to curtail these massive post-harvest losses in tomato. Among them is temperature reduction in the form of freezing and use of cold storages (Parnell et al., 2004). The operation principle of these techniques is anchored in temperature reduction, which in turn inhibits enzymatic activity and microbial spoilage of the tomato. However, the energy requirement of these techniques makes them expensive and unapplicable in areas with no electrical connectivity. As a result, researchers have developed various inexpensive techniques such as evaporative coolers (Balogun et al., 2019) and use of edible coatings (De Jesús Dávila-Aviña et al., 2011) among others to preserve tomato. Nevertheless, these methods have a major limitation of resulting in relatively shorter shelf-life of tomato as well as complexity in their usage. Consequently, farmers and processers have turned to drying as the best alternative in managing tomato post-harvest losses.

Drying has extensively been used in the preservation and management of post-harvest loses of vegetables and fruits. It is an important food shelf-life extension technique as it reduces the moisture content and hence inhibits enzymatic and microbial activity. In so doing, drying reduces both enzymatic and microbial spoilage as well as chemical changes in dried fruits and vegetables (Horuz et al., 2017). Moreover, drying results in reduced volume of the dried products, which facilitates easier packaging, storage, and transportation (Kamwere et al., 2015). In this respect, drying enhances food security by curbing the shortage of tomatoes particularly during the off-seasons.

Advances in production of polyethylene films, particularly for use in greenhouse production have led to the development of spectral filtering materials with various benefits to the grower (Max et al., 2012). However, the application of these films has been extended to greenhouse solar drying of agricultural products due to their ability to trap solar heat energy. Kagande et al. (2012) and Arun et al. (2014) found the usage of UV-transmitting and UV-blocking polyethylene films, respectively, to be effective in drying of tomatoes in solar tunnel greenhouse dryers. In both studies, the greenhouse solar dried tomatoes were established to be of superior quality compared to the open sun dried tomatoes. Nevertheless, there is no study in literature that has carried out a comparative investigation on the effect of both films on the drying process and the quality of the dried products. Consequently, this study was carried out to evaluate the effect of UV-blocking and UV-transmitting polyethylene films on the thermal performance of greenhouse solar dryer and drying kinetic of tomato slices.

## MATERIALS AND METHODS

### Experimental Setup

The study was carried out at Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya, located in Juja (37.05$^{o}$E longitude, 1.19$^{o}$S latitude, and 1532 m altitude). Two models of even span greenhouse solar dryers measuring 1.5 m long, 1 m wide and 0.5 m high to the gutter and 0.728 m to the ridge were used. One of the dryers was cladded with a 200 µm UV-blocking (Suncover 205N / C 659, with 0% transmission of UV transmission between 300 – 380 nm) and the other one with 200 µm UV-transmitting polyethylene film (Sunsaver Nectarine Diffused / C 750, with 65 % transmission of UV transmission between 300 – 380 nm) to be used as a control. For air exchange, two inlet openings of 0.12 m diameter provided below the trays and one outlet opening of 0.24 m diameter was provided above the trays at the ridge of the East side of the dryers. The two dryers were installed on a 0.5 m raised black oxide painted concrete floor to enhance heat absorption within the dryers and operated on active mode at 0.6 $m^3$/s air velocity.

### 2.2 Experimental Procedure

Experiments were carried out on 4$^{th}$ to 9$^{th}$ November, 2021. Fresh tomatoes were harvested from a greenhouse, cleaned thoroughly using running water to remove foreign materials such as dirt, and wiped dry using a piece of cloth. The tomatoes were then sorted on based on weight and ripeness before being sliced into 5 mm slices using a Generic tomato slicer. 1 kg of tomato slices was then spread in each of the two greenhouse solar dryers and dried under passive conditions. For purpose of data collection, 150 g of the tomato slices were monitored in each dryer throughout the drying duration.

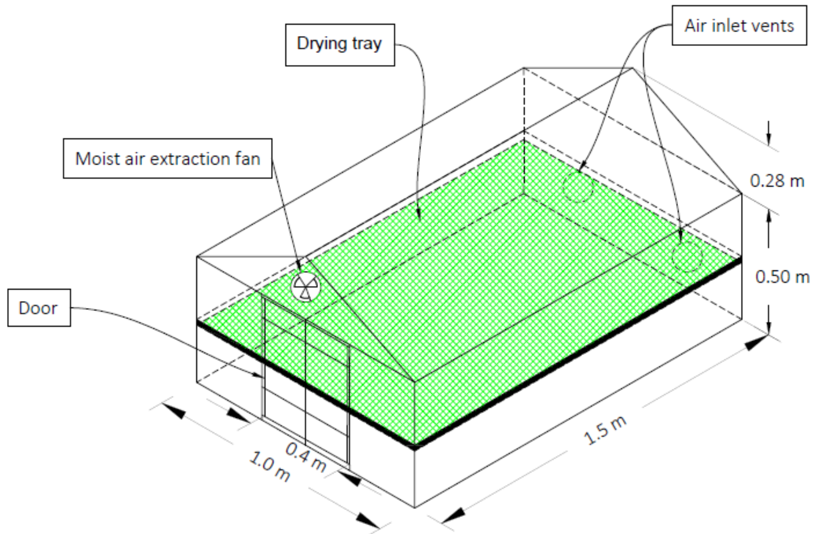


Figure 1: Schematic diagram of a greenhouse solar dryer

**2.3 Data Collection and Analysis**

Crucial weather conditions, that is, solar radiation, temperature, relative humidity, and wind speed influencing the drying process as well as the weight of the tomatoes were monitored throughout the drying period. Solar radiation was measured using a L1-200R pyranometer. Ambient temperature and floor and room temperatures in both greenhouse solar dryers were measured using Type K thermocouples. Data on ambient and dryers' room relative humidity was recorded using an E&E 071 sensor. The ambient wind speed data was measured by means of R.M. Young Wind Sentry anemometer (Model 03101, from Campbell Scientific). All data was automatically recorded at 30-minute interval using a 32-channel relay multiplexer supported CR1000 from Campbell Scientific. Ambient and greenhouse solar dryer UV transmission intensity was measured using a digital UVAB light meter (General, UV513AB). The weight of the drying tomatoes was recorded hourly using a digital weighing scale (CAS SW-II-30, India). Statistical analysis of the data was carried out using STATA SE Version 16.0 (Stata Corp LP, TX, USA) from which corresponding relations were established.

The moisture content of tomato sample was determined using the oven drying method. The sample were weighed and dried in an oven drier at 103 ± 2 °C for 24 hours. The moisture content (dry basis) $M_{db}$ was then calculated as in (1), where $M_i$ and $M_d$ represent the initial and dry weight, respectively.

$$M_{db} = \frac{M_i - M_d}{M_i} \times 100\% \qquad (1)$$

The drying rate of the tomatoes was calculated as in (2)

$$R_c = \left(\frac{dM}{dt}\right) = \frac{M_i - M_d}{t} \qquad (2)$$

where, $R_c$ is the drying rate (g/h), $dM$ is change in mass (g), $dt$ is change in time (h), $t$ is the total drying time (h), $M_i$ is the initial weight of the sample (g), and $M_d$ is the final weight of the dried sample (g).

Effective moisture diffusivity ($D_{eff}$) was determined using the Fick's second law in which the thin tomato slices were considered to be a slab as in (3).

$$\text{Moisture ration } (MR) = \frac{M_t - M_e}{M_i - M_e} = \frac{8}{\pi^2} e^{-\frac{D_{eff}\pi^2 t}{4L^2}} \qquad (3)$$

where $M_i$, $M_t$, $M_e$ are initial moisture content, moisture content at a given time t, and equilibrium moisture content (EMC) at a given drying condition (% d.b), respectively and $L$ is the half the thickness of the tomato slices. By linearization, (3) is expressed as in (4).

$$\ln MR = ln\left(\frac{M_t - M_e}{M_i - M_e}\right) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{D_{eff}\,\pi^2}{4L^2}\right)t \quad (4)$$

Therefore, plotting the experimental data in form of ln($MR$) versus drying time gives a straight line whose slope ($S$) is used to calculate effective moisture diffusivity as in (5).

$$D_{eff} = \frac{4L^2 S}{\pi^2} \quad (5)$$

The drying kinetics of the tomato slices was modelled by fitting the moisture ratio data to five thin layer drying models in Table 1 which have been commonly used in literature to describe thin layer drying of tomatoes. The drying data was fit into the models using regression analysis carried out using Microsoft Excel Solver function.

Table 1: Thin layer drying empirical models

| S/No. | Model Name | Model* |
|---|---|---|
| 1 | Page | $MR = \exp(-kt^n)$ |
| 2 | Modified Page | $MR = \exp(-kt)^n$ |
| 3 | Henderson and Pabis | $MR = a\exp(-kt)$ |
| 4 | Two Term | $MR = a\exp(-k_1 t) + b\exp(-k_2 t)$ |
| 5 | Logarithmic | $MR = a\exp(-kt) + c$ |

*$a$, $b$, $c$, $k$, $k_1$, $k_2$, $n$ are parameters of the models.

The quality of the fit was evaluated using coefficient of determination ($R^2$), reduced chi-square ($\chi^2$), and root mean square error (RMSE) as in (6), (7) and (8). The neared the value of $R^2$ to 1 ($R^2 \cong 1$) and the lower the values of $\chi^2$ and RMSE, the better the quality of fit (Kucuk et al., 2014). These parameters are described in (6), (7) and (8).

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR}_{pre,i} - MR_{exp,i}\right)^2}\right] \quad (6)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \quad (7)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2} \quad (8)$$

where which $MR_{exp,i}$ is the i$^{th}$ experimental moisture ratio, $MR_{pre,i}$ is the i$^{th}$ predicted moisture ratio, N is the number of observations and z is number of constants (Taheri-Garavand et al., 2011).

Moreover, the drying models were also be compared on the basis of their prediction performances ($\eta_p$) as in (9), where $N_c$ is the number of correctly predicted data and $N_t$ is the number of correctly trial data (Ronoh et al., 2010). The performance was based on a ±5% residual error interval. The absolute residual error ($\varepsilon$) is defined as in (10).

$$\eta_p\ (\%) = 100 \times \frac{N_c}{N_t} \quad (9)$$

$$\varepsilon\ (\%) = \left|\frac{(MR_{pre,i} - MR_{exp,i})}{MR_{exp,i}} \times 100\right| \quad (10)$$

**Shrinkage Ratio**

Shrinkage essentially describes the dimensional changes of product and it is related to thickness, surface or volume of the dried product. Volumetric changes of the tomato slices were estimated and shrinkage ration determined as in (11) in which $S_b$ is relative volumetric shrinkage, V is volume of the dry product and $V_o$ is the initial volume of the tomato slices. The analysis assumed that volumetric changes in the tomato samples were equal to the evaporated moisture as well as the samples had pores and a solid structure that had specific volume and density. Moreover, it was assumed that the pores were filled with water (Samimi-Akhijahani, & Arabhosseini, 2018). Consequently, toluene displacement method was used evaluate shrinkage in which three tomato slices of both varieties of tomatoes selected and their volume determined before and after drying by placing them in a 250 ml beaker with 200 ml of toluene.

$$S_b = \frac{V}{V_o} \tag{11}$$

### Colour

The colour of the samples was measured after every two hours of the drying period using a colourimeter (Chroma Meter – CR-400, Konica Minolta, US). The colour parameters that were measured are lightness (L*), redness (a*), and yellowness (b*). Prior to the measurements, the meter was calibrated using a white standard tile provided by the manufacturer. For each sample, the measurements were replicated three times. Chroma (C), which indicates colour intensity, and hue angle ($H^o$) were calculated from the values of L*, a*, and b* as in (12) and (13).

$$\mathrm{C} = \sqrt{a^{*2} + b^{*2}} \tag{12}$$

$$\mathrm{H}^0 = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{13}$$

Hue angle is an important parameter in food drying as it indicates the pureness of different colour. Its values vary from $0^o$ (pure red colour), $90^o$ (pure yellow colour), $180^o$ (pure green colour) to $270^o$ (pure blue colour) (Seerangurayar et al., 2019). The total colour difference (ΔE) is also a commonly used parameter as it indicates by what degree the colour of a dried product has deviated from the colour of its fresh form. ΔE was determined using Equation 3.12 in which $L_o$*, $a_o$* and $b_o$* are the L*, a* and b* values of the fresh product and L*, a* and b* are corresponding values of the dried product, respectively (Guiné & Barroca, 2012).

$$\Delta E = \sqrt{(L_0{}^* - L^*)^2 + (a_0{}^* - a^*)^2 + (b_0{}^* - b^*)^2} \tag{14}$$

### Rehydration Ratio

Rehydration ratio of the dried tomato was determined by soaking a sample of the tomatoes in distilled water. 2 g of each variety of dehydrated tomato were added to 50 ml distilled water at 25 °C in a 500 ml beaker and stored properly for 24 hours. The distilled water was then drained for 5 minutes and the excess water absorbed by blotting onto tissue paper. The samples were then weighed using a digital weighing scale (CAS SW-II-30, India) and rehydration ratio determined using Equation 3.15 in which RR is rehydration ratio, $W_r$ and $W_d$ are weights of rehydrated and dry samples, respectively.

$$RR = \frac{W_r}{W_d} \tag{15}$$

## RESULTS AND DISCUSSION

### UV-Intensity Analysis

Figure 1 shows the variation of UV transmission intensity of both greenhouse solar dryers and the ambient with time of the day. Both dryers recorded a significant low ($p<0.05$) UV-transmission intensity compared to the ambient conditions. Ambient UV-transmission intensity ranged between 4.16 – 8.29 mW/cm² with a mean of 7.95±0.33 mW/cm². An average UV-transmission intensity of 0.03±0.005 and 3.70±0.14 mW/cm² were registered in the UV-blocking and UV-transmitting solar dryer respectively. Notably, the UV-blocking film had zero UV transmission in the range 300-380 nm, however, the UVAB light meter had a measuring range of 280 – 400 nm. Consequently, the low UV transmission intensity of 0.03 mW/ cm² registered in the UV-blocking polyethylene film is as a result of the overlap of ±0.20 nm in the measuring range of the UVAB light meter over that of the film's UV-blocking range. Further, the UV transmission intensity was significantly different ($p<0.05$) between the dryers. The results are in agreement with manufactures specification of both polyethylene films.

**Ambient Parameters Analysis**

Ambient parameters play a crucial role in describing the performance of greenhouse solar dryers (Chauhan, 2016). Figure 2 depicts the variation of ambient temperature ($T_a$), relative humidity ($Rh_a$), windspeed and solar radiation with time of day for two successive days of experiment. Temperature and relative humidity were found to be influenced by solar radiation. It was observed that increment in solar radiation resulted in increment of temperatures and reduction of relative humidity. Solar radiation ranged from 196.6 – 1046.0 W/m$^2$ and 140.7 – 979 W/m$^2$ in the first and second day of experiment, respectively. The high variation of solar radiation observed in second day of experiment was occasioned by the presence of clouds in the atmosphere. Similarly, ambient temperature varied from 19.79 – 36.34 ºC for first day and 25.05 – 36.32 ºC for second day. For the first day, the maximum temperature was 36.34 ºC at 1500 hrs which was lower than second day's maximum temperature of 36.32 ºC registered at 1530 hrs. On the other hand, ambient relative humidity ranged from 19.95 – 41.47 % and 23.26 – 37.47 % in first and second days of experiment, respectively. Generally, windspeed during the two experiment days was low ranging from 0.379 – 1.716 m/s for first day and 0.821 – 1.671 m/s for second day. Moreover, presence of clouds resulted in more variation of ambient parameters, particularly during the second day.

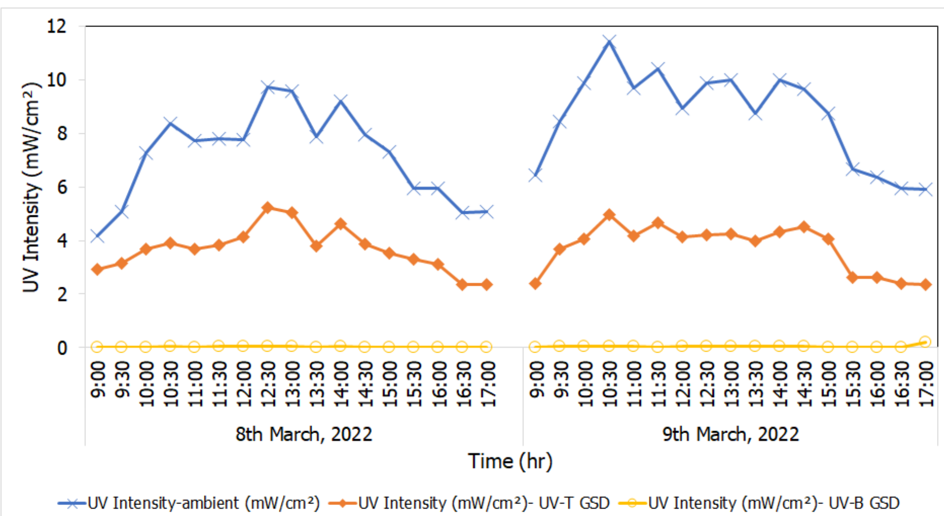


Figure 1: Profile of UV transmission intensity on two typical days

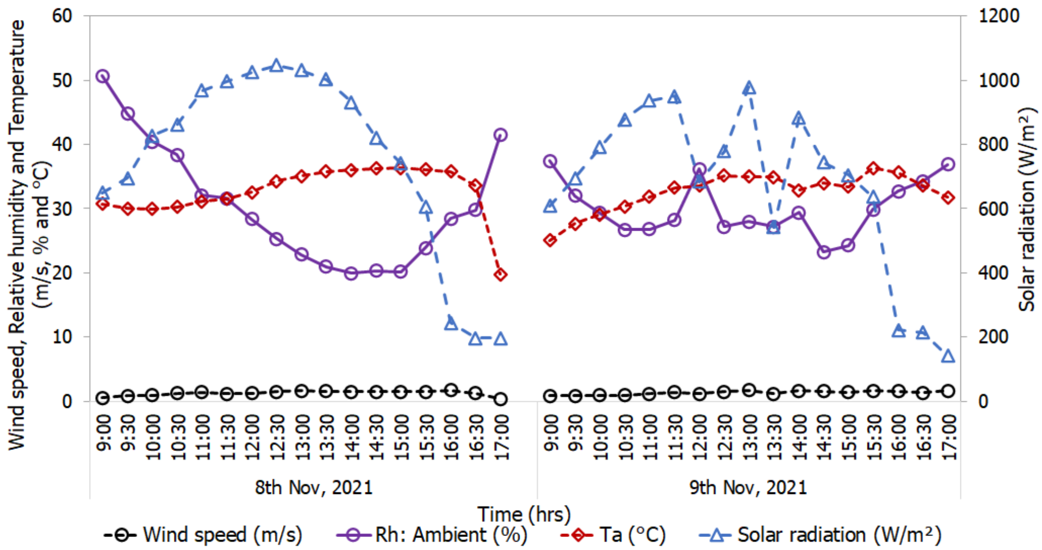


Figure 2: Variation of ambient parameters

**Solar Radiation and Ambient Temperature Effect on Greenhouse Solar Dryers' Ground and Room Temperature**

From Figure 3, it was established that increment in solar radiation and ambient temperatures ($T_{a)}$ resulted in increment in ground temperature ($T_{gd}$) and room temperature ($T_{rm}$) of the UV-blocking and UV-transmitting cladded greenhouse solar dryers. The $T_{gd}$ and $T_{rm}$ in both dryers were found to be significantly ($p<0.05$) higher than the $T_a$. More specifically, the mean $T_{gd}$ and $T_{rm}$ of the UV-blocking cladded dryer were 31.76% and 40.03% higher than $T_a$ for first day and 18.21% and 37.39% higher for the second day. Similarly, the average $T_{gd}$ and $T_{rm}$ in UV-transmitting cladded dryer were 36.76% and 44.79%, and 26.56% and 38.25% higher than average $T_a$ for first and second day, respectively. Moreover, UV-blocking cladded solar greenhouse dryer recorded lower temperatures compared to UV-blocking cladded dryer. The average $T_{gd}$ and $T_{rm}$ in UV-blocking cladded dryer were 40.32±6.25 and 45.12±5.86 ºC, respectively compared to the corresponding 42.48±6.48 and 46.10±6.33 ºC registered in UV-transmitting cladded dryer. Nevertheless, there was no significant difference ($p>0.05$) between the $T_{gd}$ and $T_{rm}$ of the two dryers.

**Evaluation of Greenhouse Solar Dryers' Relative Humidity with respect to Solar Radiation and Ambient Relative Humidity**

As depicted in Figure 4, it was observed that UV-blocking dryer recorded higher relative humidity compared to UV-blocking dryer. In addition, the $Rh_a$ was found to be significantly ($p<0.05$) higher than the greenhouse dryer's relative humidity. An average of 30.25±7.27% of $Rh_a$ was recorded during the experiment compared to 23.31±7.26% and 20.39±6.38% mean relative humidity registered in the UV-blocking and UV-transmitting dryers, respectively. The difference between the dryers' relative humidity was due to the ability of the UV-transmitting dryer to develop higher temperatures as compared to UV-blocking dryer. However, despite the difference there was no significant difference ($p>0.05$) between the relative humidity of both dryers. Overall, increment in solar radiation intensity was established to result in reduction of ambient and greenhouse solar dryers' relative humidity. Similar inversely proportional relationship between solar radiation and relative humidity in solar drying has been reported by Ahmad and Prakash (2020).

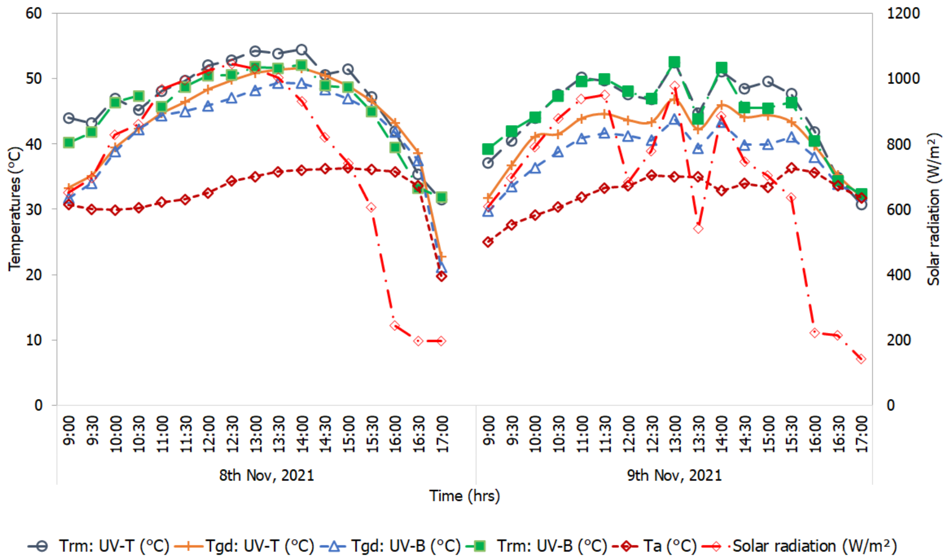


Figure 3: Variation of solar radiation, ambient temperature, and ground and room temperatures of the greenhouse solar dryers.

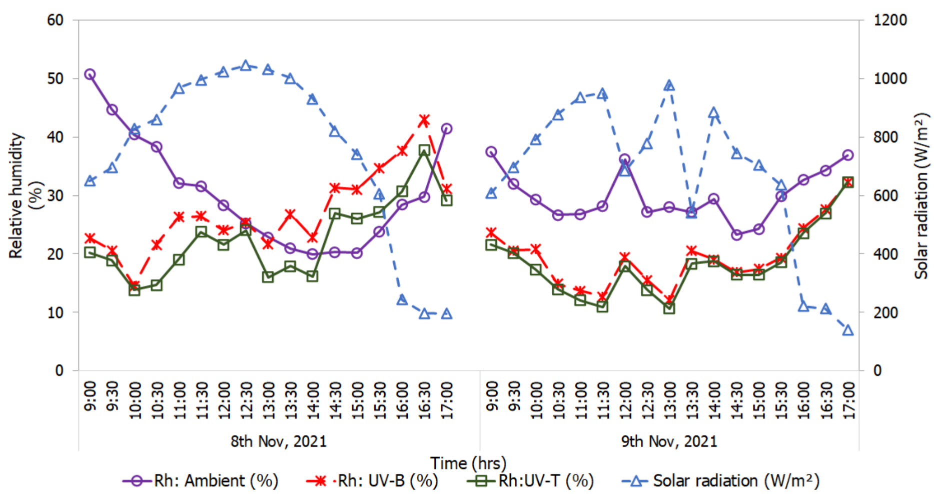


Figure 4: Variation of solar radiation, ambient relative humidity and dryer relative humidity.

**Drying Characteristics**

The moisture degradation curves of the tomato slices dried in the UV-blocking and UV-transmitting greenhouse solar dryers are shown in Figure 5. Tomato slices were dried from an initial moisture content of 2785.53% (db) to a final moisture content of 34.63 and 34.18% (db) in UV-blocking and UV-transmitting dryer, respectively in approximately 12 and 11 hours, respectively.

As shown in Figure 5, only the falling rate period of the drying of the tomato slices was observed. The observation is attributable to the relatively long monitoring time interval of 30 minutes of moisture content which made it difficult to observe the constant rate period. Similar observations have been reported by Patila et al. (2015) and Picado et al. (2021) during drying of tomatoes.

**Drying Rate**

The drying rate curves of the tomato slices dried in UV-blocking and UV-transmitting greenhouse solar dryer are shown in Figure 6. UV-blocking dryer registered lower drying rates with a mean of 57.88 (g/g)/hr compared to that of 65.02 (g/g)/hr obtained in UV-transmitting dryer. However, despite this difference, analysis of variance yielded no significant difference ($p>0.05$) between the drying rates of the UV-blocking dried and UV-transmitting dried tomato slices.

Generally, the drying rates increased rapidly within the first one hour of drying due to the availability of free moisture at the surface of the tomatoes and temperature increment in the greenhouse solar dryers. However, as drying progressed, the drying rates decreased with time as a result of reduction of surface moisture on the tomatoes. This behavior is attributable to extraction of moisture from deeper interior parts of the tomato slices which needs higher heat energy to evaporate bounded moisture, hence the decreased drying rate. Similar observations have been reported by Ebadi (2021) in drying of tomato slices (4, 6 and 8 mm) over different temperatures (55, 65 and 75 °C) in a hybrid compound parabolic concentrator solar dryer.

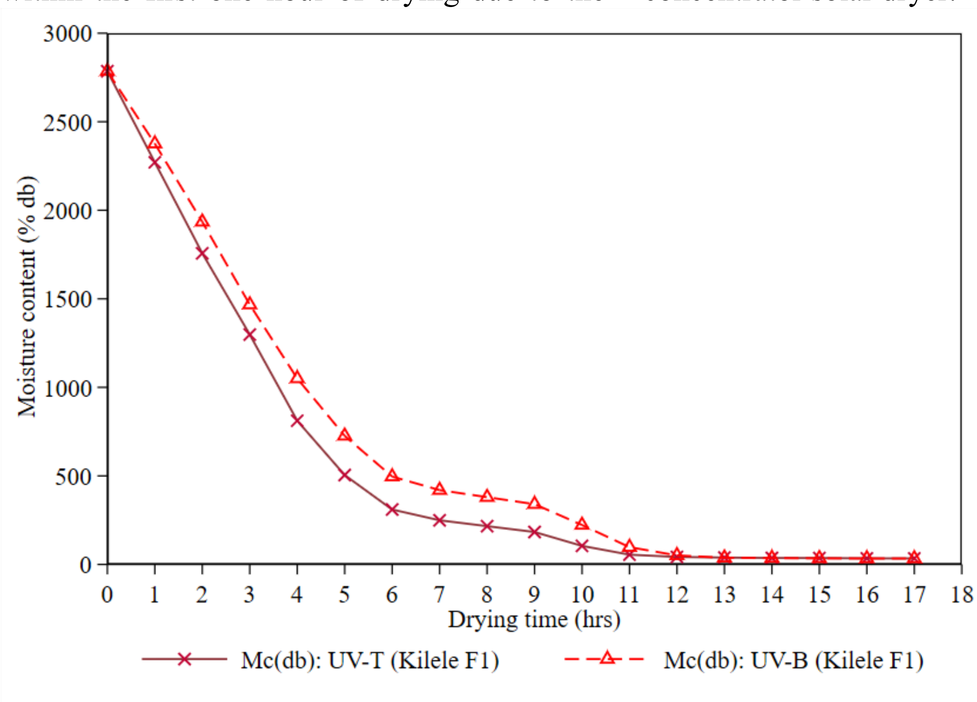


Figure 5: Drying curves of Kilele F1 tomato slices under UV-transmitting and UV-blocking greenhouse solar dryer.

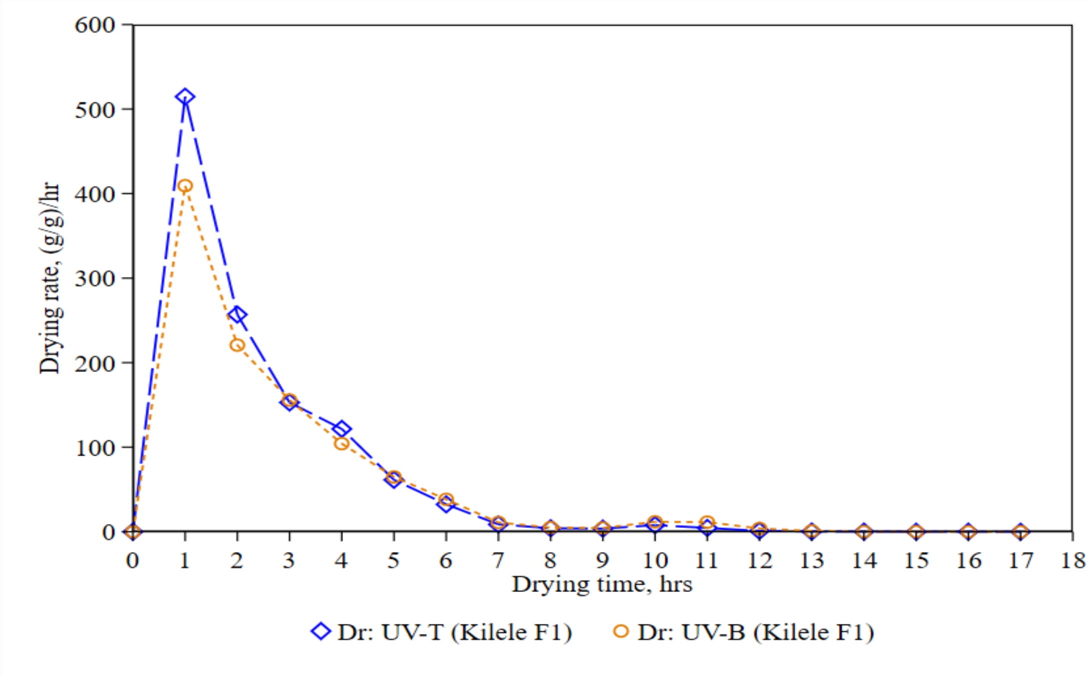


Figure 6: Drying rates of Kilele FI in UV-transmitting and UV-blocking greenhouse solar dryers.

**Effective Diffusivity**

The mean effective moisture diffusivity ($D_{eff}$) of the tomato slices dried in UV-blocking and UV-transmitting dryer were 2.11 $\times10^{-10}$ and 2.03 $\times10^{-10}$ m²/s, respectively. The higher $D_{eff}$ in UV-transmitting dried tomato slices is attributable to the relatively higher temperatures attained by the dryer. Dianda et al (2015) have reported that increment in drying temperature results in increment in $D_{eff}$ values. It is worth noting that the $D_{eff}$ values of the tomato slices were within the $10^{-11}$ – $10^{-9}$ m²/s general range for food materials as reported by Honoré et al. (2014). The obtained results are in agreement with those reported by Dufera et al. (2021) during drying of tomato slices in a twin layer solar tunnel dryer.

**Rehydration Ratio**

Rehydration ratio is a crucial quality indicator in dried products, particularly in products whose consumption is preceded by re-constitution of the product (Doymaz, 2014). A lower rehydration ratio of 3.58±0.12 was established for tomato slices dried under UV-blocking drying condition compared to 4.52±0.13 for UV-transmitting drying condition. This difference can be attributed to lower moisture content of tomato samples dried under UV-transmitting conditions which increased their ability to rehydrate. There was, however, no significant difference ($p>0.05$) between the rehydration obtained in the two dryers. The results of this study are consistent to those reported by Mwende et al. (2018) in drying of tomato quarters.

**Colour**

Colour is a crucial quality indicator as well as a key influencer in consumer purchasing preference of dried food products (Ringeisen et al., 2014). Consequently, any undesirable degradation of colour in dried product during the drying process affects its quality and marketability. The results indicate that the *L*-value decreased during drying the tomato samples in both dryers. The decrease, however, was lower in UV-blocking dryer compared to the UV- transmitting dryer. This difference can be attributed to the difference in drying temperatures within the two dryers. Das et al. (2013) reported that increment in temperature resulted in reduced *L*-value, which meant that the dried tomatoes slices were darker under higher temperature as a result of higher browning reactions. Similarly, the *a*-value decreased with increase in drying temperature in the tomato samples. The reduction, which was higher in UV-transmitting dryer, can be attributed to higher degradation of lycopene content, which has been reported by Mwende et al. (2018) to impart the characteristic red colour in tomatoes. The total colour change (ΔE) of the dried tomatoes was established to be 10.87 and 6.77 for Kilele F1 in UV-transmitting and UV-blocking dryer. Overall, lower ΔE was established in UV-blocking dryer compared to UV-transmitting dryer, although the difference was statistically significant ($p>0.05$). Consequently, the UV-blocking drying condition were established to provide superior dried tomatoes in respect to colour preservation.

Table 2: Hunter colour parameters of the Undried and UV-transmitting and UV-blocking greenhouse solar dryer dried tomatoes

| Hunter colour parameter | UV-transmitting | | UV-blocking | |
|---|---|---|---|---|
| | Undried | Dried | Undried | Dried |
| L* | 78.44±1.27 | 72.01±1.24 | 73.65±0.26 | 71.29±0.14 |
| a* | 69.35±3.13 | 64.33±1.65 | 69.47±1.73 | 66.60±0.10 |
| b* | 10.58±1.53 | 3.39±0.07 | 9.36±0.15 | 3.70±0.27 |
| C | 68.53±1.77 | 64.24±1.57 | 70.09±0.52 | 68.16±1.86 |
| h° | 8.67±0.68 | 3.01±0.87 | 7.67±0.40 | 3.17±0.40 |
| ΔE | | **10.87** | | **6.77** |

L*, a*, b*, C, h° and ΔE are colour parameters denoting lightness, redness, yellowness, chroma, hue angle and total colour change, respectively.

**3.10 Shrinkage Ratio**

Shrinkage is an essential quality parameter in dried products as it influences both the rehydration capability of the product as well as its consumer acceptance. The results established lower shrinkage ratio, that is, 4.96±0.16 for Kilele F1 slices dried under UV-blocking drying condition compared to 5.84±0.25 under UV-transmitting conditions The higher shrinkage ratio in the UV-transmitting conditions can be attributed to the higher drying temperature in the UV-transmitting greenhouse solar dryer that resulted in lower final moisture content in both variety of tomatoes compared to UV-blocking dried tomatoes. Similar observation have been reported by Giri & Prasad (2007) and Hafezi e al. (2014) during drying of mushroom and potato slices, respectively. Both studies established shrinkage ratio as a function of drying temperature as well as the total amount of moisture extracted from a dried food product.

**Mathematical modelling**

The thin layer drying kinetics of tomato slices in greenhouse solar dryers were evaluated by carrying out regression analysis on five existing drying models, namely, Logarithmic, Henderson and Pabis, Two-Term, Page and Modified Page models. A comparison of all the models showed that Page model attained the highest $R^2$ values of 0.9962, the lowest $\chi^2$ and RMSE values of 0.0004 and 0.0190, respectively, $\varepsilon$ of 20.87±20.6% and $\eta_p$ of 38.89% for Kilele F1 in UV-blocking dryer. Similarly, Page model attained the highest $R^2$ values of 0.9975 and the lowest $\chi^2$ values of 0.0002 as well as RMSE values of 0.0161 for Kilele F1 tomato slices, respectively under UV-transmitting dryer. Moreover, the model attained absolute residual ($\varepsilon$) value of

37.92±34.64 % and 27.78% performance prediction ($\eta_p$). Consequently, Page model was established to be the best model to characterize the drying behaviour of Kilele F1 tomato slices in both UV-blocking and UV-transmitting dryer. The results are in agreement with those reported by Dufera et al. (2021) in which Page model was established to best describe drying kinetics of tomato slices in a twin-layer tunnel dryer.

Table 3: Thin-layer drying models' parameters and comparison criteria of moisture ratio for drying of tomatoes in UV-transmitting and UV-blocking greenhouse solar dryer

| Model | Dryer | model constants and coefficients | $R^2$ | $\chi^2$ | RMSE | Ɛ (%) | $\eta_p$(%) |
|---|---|---|---|---|---|---|---|
| Logarithmic | UV-Transmitting | $k$=0.3099, $a$=1.0559 | 0.9893 | 0.0011 | 0.0313 | 26.96±22.9 | 22.22 |
| | UV-Blocking | $k$=0.2588, $a$=1.0595 | 0.9907 | 0.0011 | 0.0303 | 41.36±55.4 | 22.22 |
| Henderson and Pabis | UV-Transmitting | $k$=0.3099, $a$=1.0559 | 0.9893 | 0.0011 | 0.0313 | 26.96±22.9 | 22.22 |
| | UV-Blocking | $k$=0.2588, $a$=1.0595 | 0.9907 | 0.0010 | 0.0303 | 41.36±55.4 | 22.22 |
| Two-Term | UV-Transmitting | $k_1$=0.3100, $k_2$=0.3099, $a$=0.5146, $b$= 0.5413 | 0.9893 | 0.0012 | 0.0313 | 26.96±22.9 | 22.22 |
| | UV-Blocking | $k_1$=0.2588, $k_2$=0.2588, $a$=0.5937, $b$= 0.4658 | 0.9907 | 0.0011 | 0.0303 | 41.36±55.4 | 22.22 |
| Page | UV-Transmitting | $k$=0.1966, $n$=1.2923 | 0.9975 | 0.0002 | 0.0161 | 37.92±34.64 | 27.78 |
| | UV-Blocking | $k$=0.1692, $n$=1.2349 | 0.9962 | 0.0004 | 0.0190 | 20.87±20.6 | 38.89 |
| Modified Page | UV-Transmitting | $k$=1.0486, $n$=0.2815 | 0.9896 | 0.0013 | 0.0351 | 31.70±28.0 | 5.56 |
| | UV-Blocking | $k$=1.0393, $n$=1.2349 | 0.9915 | 0.0013 | 0.0352 | 52.08±66.7 | 16.67 |

**Conclusion**

The findings show that both UV-blocking and UV-transmitting polyethylene films can satisfactorily be used in thin layer drying of tomato slices and other fruits and vegetables. However, in cases where fast drying rates, shrinkage ratio, rehydration ratio and effective diffusivity are required, UV-transmitting film performed best. On the other hand, UV-blocking film gave better results in respect to quality attribute such as colour retention of the dried product. Further, Page model provided the best description of the thin layer drying kinetics of the tomato slices in both dryers. Further research, however, may be carried out to evaluate how other cladding material can perform against the polyethylene films in greenhouse solar drying of agricultural products.

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## References

Abano, E. E., Ma, H., & Qu, W. (2011). Influence of air temperature on the drying kinetics and quality of tomato slices. *Journal of Food Processing & Technology*, *2*(5), 2-9.

Ahmad, A., & Prakash, O. (2020). Performance Evaluation of a Solar Greenhouse Dryer at Different Bed Conditions Under Passive Mode. *Journal of Solar Energy Engineering*, *142*(1), 1-10.

Arah, I. K., Amaglo, H., Kumah, E. K., & Ofori, H. (2015). Preharvest and postharvest factors affecting the quality and shelf life of harvested tomatoes: a mini review. *International Journal of Agronomy*, *2015*, 1-6.

Arun, S., Ayyappan, S., & Sreenarayanan, V. V. (2014). Experimental studies on drying characteristics of tomato in a solar tunnel greenhouse dryer. *IJRTE*, *3*(4), 32-37.

Balogun, A. A., Ariahu, C. C., & Ikya, J. K. (2019). Quality evaluation of fresh tomato stored in evaporative coolers. *Asian Food Science Journal*, *11* (3), 1-8.

Beckles, D. M. (2012). Factors affecting the postharvest soluble solids and sugar content of tomato (*Solanum lycopersicum L.)* fruit. *Postharvest Biology and Technology*, *63*(1), 129-140.

César, L. V. E., Lilia, C. M. A., Octavio, G. V., Isaac, P. F., & Rogelio, B. O. (2019). Thermal performance of a passive, mixed-type solar dryer for tomato slices (*Solanum lycopersicum*). *Renewable Energy*, *147*, 845-855.

Chauhan, P. S., & Kumar, A. (2016). Performance analysis of greenhouse dryer by using insulated north-wall under natural convection mode. *Energy Reports*, *2*, 107-116.

Das P. M., Nath, A., Deka, B. C., & Mahanta, C. L. (2013). Thin layer drying of tomato slices. *Journal of Food Science and Technology*, *50*(4), 642-653.

De Jesús Dávila-Aviña, J. E., Villa-Rodríguez, J., Cruz-Valenzuela, R., Rodríguez-Armenta, M., Espino-Díaz, M., Ayala-Zavala, J. F., & González-Aguilar, G. (2011). Effect of edible coatings, storage time and maturity stage on overall quality of tomato fruits. *American Journal of Agricultural and Biological Sciences*, *6*(1), 162-171.

Dianda, B., Ousmane, M., Kam, S., K, T., & Bathi&ebo, D. J. (2015). Experimental study of the kinetics and shrinkage of tomato slices in convective drying. *African Journal of Food Science*, *9*(5), 262-271.

Doymaz, I. (2007). Air-drying characteristics of tomatoes. *Journal of Food Engineering*, *78*(4), 1291-1297.

Doymaz, İ. (2014). Mathematical modeling of drying of tomato slices using infrared radiation. *Journal of Food Processing and Preservation*, *38*(1), 389-396.

Dufera, L. T., Hofacker, W., Esper, A., & Hensel, O. (2021). Experimental evaluation of drying kinetics of tomato (*Lycopersicum Esculentum L.*) slices in twin layer solar tunnel dryer. *Energy for Sustainable Development*, *61*, 241-250.

Ebadi, H., Zare, D., Ahmadi, M., & Chen, G. (2021). Performance of a hybrid compound parabolic concentrator solar dryer for tomato slices drying. *Solar Energy*, *215*, 44-63.

FAOSTAT (2014). Global Tomato Production in 2012. Rome, FAO.

FAOSTAT (2015). Food and Agricultural Organization of the United Nation. [Internet]. Available at: http://faostat.fao.org/. Accessed: (16th March 2015).

FAOSTAT. (2017). Food and Agricultural Organization of the United Nation. [Internet] Available at: https://www.fao.org/faostat/en/#data/QCL: Accessed:(16th March, 2022).

Giri, S. K., & Prasad, S. (2007). Modeling shrinkage and density changes during microwave-vacuum drying of button mushroom. *International Journal of Food Properties*, *9*(3), 409-419.

Guiné, R. P., & Barroca, M. J. (2012). Effect of drying treatments on texture and colour of vegetables (pumpkin and green pepper). *Food and Bioproducts Processing*, *90*(1), 58-63.

Hafezi, N., Sheikhdavoodi, M. J., & Sajadiye, S. M. (2014). The Effect of drying kinetic on shrinkage of potato slices. *International Journal of Advanced Biological and Biomedical Research*, *2*(11), 2779-2782.

Haile, A., & Safawo, T. (2018). Shelf life and quality of tomato (Lycopersicon esculentum Mill.) fruits as affected by different Packaging Materials. *African Journal of Food Science*, *12*(2), 21-27.

Harvard School of Public Health (2010) Harvard University Press

Honoré, O. K., François, Z., Raguilignaba, S., Aboubacar, T., & Hélène, D. (2014). Characterization of okra convective drying, influence of maturity. *Food and Nutrition Sciences*, *2014*(5), 590-597.

Horuz, E., Jaafar, H. J., & Maskan, M. (2017). Ultrasonication as pretreatment for drying of tomato slices in a hot air–microwave hybrid oven. *Drying Technology*, *35*(7), 849-859.

Idah, P. A., Ajisegiri, E. S., & Yisa, M. G. (2007). Fruits and vegetables handling and transportation in Nigeria. *Australian Journal of Technology 10* (3): 176-183.

Kagande, L., Musoni, S., & Madzore, J. (2012). Design and performance evaluation of solar tunnel dryer for tomato fruit drying in Zimbabwe. *IOSR Journal of Engineering*, *2*(12), 1-7.

Kamwere, M. M., Kanali, C. L., Mutwiwa, U. N., & Kituu, G. M. (2015). Thin Layer Drying Characteristics of Stinging Nettle (Urticadioica L.) in a Solar Tunnel Dryer. *International Journal of Engineering and Advanced Technology*, *4*(12), 428-434.

Kucuk, H., Midilli, A., Kilic, A. & Dincer, I. (2014). A review on thin-layer drying-curve equations. *Drying Technology*, *32*(7), 757-773.

Max, J. F., Schurr, U., Tantau, H. J., Mutwiwa, U. N., Hofmann, T., & Ulbrich, A. (2012). Greenhouse Cover Technology. *Horticultural Reviews*, *40*(1), 259-396.

Mwende, R., Owino, W., & Imathiu, S. (2018). Effects of pretreatment during drying on the antioxidant properties and color of selected tomato varieties. *Food Science and Nutrition*, *6*(2), 503-511.

Parnell, T., Suslow, T., & Harris, L. (2004). Tomatoes: safe methods to store, preserve, and enjoy. *UCANR* Publications.

Patila, B. S., Champawatb, P. S., Murumkara, R. P., Jainc, S. K., & Pisalkara, P. S. (2015). Convective Drying of Tomato Slices using Re-circulatory Tray Dryer. *Journal of Ready to Eat Food| April-June*, *2*(2), 44-50.

Picado, A., Alfaro, S., & Gamero, R. (2021). Drying kinetics and thermodynamic analysis of tomato in a tunnel dryer. *Nexo Revista Científica*, *34*(03), 31-45.

Ringeisen, B., Barrett, D. M., & Stroeve, P. (2014). Concentrated solar drying of tomatoes. *Energy for Sustainable Development*, *19*, 47-55.

Ronoh, E. K., Kanali, C. L., Mailutha, J. T., & Shitanda, D. (2010). Thin layer drying kinetics of amaranth (*Amaranthus cruentus*) grains in a natural convection solar tent dryer. *African Journal of Food, Agriculture, Nutrition and Development*, *10*(3), 2218-2233.

Samimi-Akhijahani, H., & Arabhosseini, A. (2018). Accelerating drying process of tomato slices in a PV-assisted solar dryer using a sun tracking system. *Renewable Energy*, *123*, 428-438.

Seerangurayar, T., Al-Ismaili, A. M., Jeewantha, L. J., & Al-Habsi, N. A. (2019). Effect of solar drying methods on colour kinetics and texture of dates. *Food and Bioproducts Processing*, *116*, 227-239.

Sibomana, M. S., Workneh, T. S., & Audain, K. (2016). A review of postharvest handling and losses in the fresh tomato supply chain: a focus on Sub-Saharan Africa. *Food Security*, *8*(2), 389-404.

Taheri-Garavand, A., Rafiee, S., & Keyhani, A. (2011). Mathematical modeling of thin layer drying kinetics of tomato influence of air dryer conditions. *International Transaction Journal of Engineering, Management, and Applied Sciences and Technologies*, *2*(2), 147-160.

Tan, H. L., Thomas-Ahner, J. M., Grainger, E. M., Wan, L., Francis, D. M., Schwartz, S. J., & Clinton, S. K. (2010). Tomato-based food products for prostate cancer prevention: what have we learned? *Cancer and Metastasis Reviews*, *29*(3), 553-568.