Mathematical Modeling of Drying Processes of Selected Fruits and Vegetables

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This study investigates the behavior of fruit and vegetable samples during drying. The experimental data are fitted to several different thin-layer drying models. Regression analysis is used to determine model parameters, while statistical indicators serve to evaluate the goodness of fit. The power function model gives the best fit for all examined samples. Based on this model, different drying and heat storage technologies can be combined to ensure that the required residual moisture content of an agricultural product is reached. It is demonstrated on the case of a specific Togolese processing plant that under favorable conditions, fossil fuel consumption can be decreased by 33 %.

Keywords: Drying, Energy saving, Food processing, Mathematical modeling

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1 Introduction

The agricultural and food sector accounts for around 30 % of the global energy demand and causes over 35 % of global greenhouse gas emissions per year [1]. A survey on the energy consumption in the food manufacturing sector is available in [2]. Another study [3] states that in the European Union, the carbon footprint of food products is one of the largest. The Food and Agriculture Organization of the United Nations (FAO) estimates that diet-related social costs of greenhouse gas emissions are projected to exceed 1.7 trillion USD per year by 2030 [4]. Against a background of global efforts for reduction of greenhouse gas emissions, it has become significant to improve the energy efficiency and increase the use of renewable energy in the food industry [5].

Most energy-intensive operations in food processing require a phase change. A typical example is drying, which is one of the oldest methods of preserving fruits and vegetables, going back as far as 20 000 BCE [6]. Presently, drying is of great importance within the food processing sector worldwide [7]. It plays a significant role in enhancing global food security and in sustainable global development [8]. It also contributes to reducing post-harvest losses that are significant in developing countries [9, 10].

The general objectives of the drying process are preserving the foods from spoilage, keeping their taste, texture, flavor, and color, and producing ingredients and additives [11, 12]. Preservation by drying also brings about a substantial reduction in weight and volume due to shrinkage, and, therefore, storage and transportation costs are minimized [13].

Drying is associated with coupled heat and mass transfer, i.e., the transport of water bound in raw food material from the inside to the surface and its removal to the environment [14]. Due to the required latent heat of evaporation, drying consumes a large amount of energy that depends primarily on the initial water content in the food material. To ensure the dried food product has a high quality, lipid oxidation, nonenzymatic browning, enzymatic reactions, spoilage, degradation of vitamins, and protein denaturation should be inhibited [15]. A measure for assessing the stability and marketability of dried foods is the water activity [16] that should be lowered to about 20 % [17].

The earliest drying technique is drying under the sun which is still practiced and varies between countries, cultures, and sectors. Even though open sun drying is cost-effective, a consistent product quality can rarely be guaranteed [18].

Convective drying is a more suitable method which ensures a consistently higher level of product quality. Such drying systems consist of an energy supply system heating

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the ambient air and a drying chamber in which the food to be dried is placed. Generally, the air heating is carried out by means of fossil fuels or renewable energy sources. In direct-fired dryers, fuel is burned, and the combustion gases are used directly as the hot inlet gas for the convective dryer [19, 20].

In [21], the application of a convective solar drying process of pineapple slices was investigated and compared with the original direct-fired drying [22]. Considering the obtained residual moisture content in the dried pineapple fruit, the performance of the solar dryer alone was deemed insufficient. To meet the required product quality, a post-solar drying procedure consisting of combustion of fossil fuels [23] or of applying heat storage technologies [24] had to be added.

The present study considers the hot air drying of selected fruits and vegetables cultivated in Togo [25] and determines their thin-layer drying characteristics. Information derived from the obtained mathematical models can then be used as a basis for the operation of an energy-efficient two-stage drying process. Although there are other ways to improve energy efficiency, e.g., alternative drying methods or modified arrangements of the drying process, this study focuses exclusively on solar (pre-)drying. That is because for the plant operators in the respective sub-Saharan country, solar (pre-)drying is one of the easiest-to-implement ways to decrease the energy consumption of the production process.

2 Materials and Methods

The prepared food samples were dried under standardized conditions in a laboratory drying oven. Moisture content was determined by weighing the samples before and after the drying process. The drying curves obtained from the experimental data were then fitted to different thin-layer drying models.

2.1 Sample Preparation

Fresh pineapples, mangoes, onions, and tomatoes were peeled and cored (if necessary), manually cut up into 5- to 15-g pieces, and divided into glass dishes. Pineapple samples were also prepared in the shape of slices using a pineapple slicer. These were 6–8 mm thick and 90–100 mm in diameter.

2.2 Experimental Setup and Measurement Devices

The initial moisture content of fresh samples was determined according to DIN EN 322 [26] and DIN EN 15414-3 [27]. The samples were weighed using a Mettler Toledo AT250 digital scale (Mettler-Toledo GmbH, Gießen; readability: ±0.01 mg) before being placed in a Heraeus UT 6060 forced-air circulation laboratory drying oven (Kendro Laboratory Products GmbH, Hanau; total volume: 52 L, temperature range: 20–300 ± 0.5 °C over time, maximum air flow rate at 20 °C: 2 m^3h^{-1}) set to 105 ± 2 °C to be fully dried. The ambient air entering the drying oven was characterized by a temperature of 25 °C, relative humidity of 30 wt %, and pressure of 1.012 bar. The drying air velocity was fixed to 0.62 $m\,s^{-1}$ at the fresh air connection. This was measured using a Voltcraft PL-135HAN hot wire digital anemometer (Conrad Electronic SE, Hirschau; velocity range: 0.1–25 ± 0.01 $m\,s^{-1}$). Subsequently, the dried samples were cooled in a desiccator filled with drying agent (silica gel, blue) and weighed again. The initial moisture content was expressed on total material basis as:

$$X_0 = \frac{m_0 - m_{\mathrm{end}}}{m_0} = \frac{m_{\mathrm{W0}}}{m_{\mathrm{DM}} + m_{\mathrm{W0}}} \qquad (1)$$

Eq. (1) only applies if just water, i.e., no other volatile substances, evaporates during the drying process. The experimentally determined initial moisture contents of fresh fruits and vegetables were compared with reference data from [28] (see Tab. 1). Some deviations between the measured and reference data could be explained by differences in the geographical origins of fruits and vegetables, harvesting times, states of maturity, and storage conditions.

The pineapple slices were dried analogously to the chopped samples except that the drying temperature was lower (70 ± 2 °C) to enable a comparison with the actual industrial drying process of pineapple slices in Togo [21].

2.3 Time-Dependent Drying Process

To ensure steady conditions at the beginning of the drying process, the drying oven was run for at least 30 min before the samples were placed on the drying shelves. The drying process was continued until a sample was dried completely, i.e., until it reached a constant weight m_{end}. In other words, the relevant data were obtained for the entire drying process irrespective of the target residual moisture content of the

Table 1. Initial and final moisture content and drying periods of the chopped fruit and vegetable samples.

Drying good	Initial moisture content X_0 [$g\,g^{-1}$]	Reference data X_0 [$g\,g^{-1}$] [28]	Final moisture content X_{end} [$g\,g^{-1}$]	Drying period τ_{end} [min]
Pineapple	0.8936 ± 0.0008	0.8448	0.0072 ± 0.0036	210
Mango	0.8535 ± 0.0105	0.8371	0.0192 ± 0.0050	300
Tomato	0.9445 ± 0.0029	0.9394	0.0056 ± 0.0043	210
Onion	0.8755 ± 0.0041	0.9153	0.0108 ± 0.0067	210

dried pineapple fruit commercially produced in Togo. Weight of the samples was monitored by manually removing and weighing them at regular intervals according to the test requirements. Dried samples were cooled in a desiccator.

During drying, the external changes in the samples were documented. It was observed that free water from the sample surface could be easily removed by vapor pressure difference between the product and ambient conditions. The subsequent moisture removal from the inner regions of raw material was driven by a moisture concentration gradient. Diffusion of water from the inner matrix to the surface was continuous but slow, resulting in a low drying rate at the final stage of the drying process. As shown in Fig. 1, the pineapple samples featured notable discoloration. This was also accompanied by extensive degradation of the pore structure due to significant shrinkage.

Compared to pineapple with a higher content of free water, mango has a finer pore structure and water is primarily bound to the fruit matrix by solution in the cells and fiber walls and by retention in capillaries (Fig. 2). Therefore, complete drying took longer (see Tab. 1).

Tomato has the highest water content of all the analyzed fruits and vegetables. A large amount of water is available as free water, which is evident from the residues on the right in Fig. 3.

Fig. 4 shows the samples of onion, which contains less free water and whose pore structure is not as finely structured as that of mango.

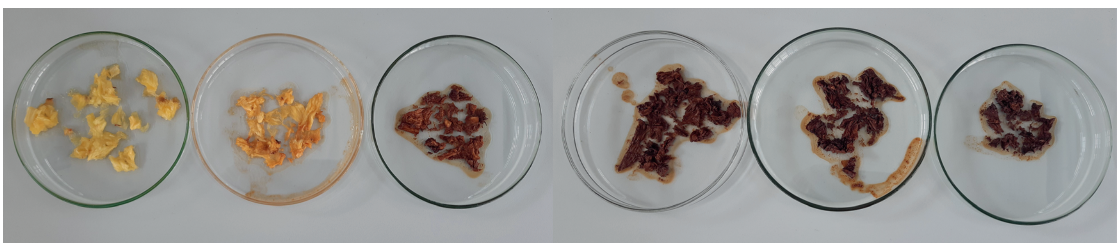

Figure 1. Pineapple samples after drying times of 0, 30, 90, 120, 150, and 210 min (left to right).

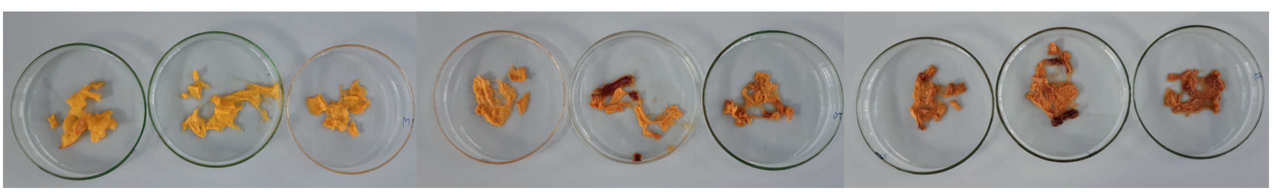

Figure 2. Mango samples after drying times of 0, 30, 60, 90, 120, 150, 180, 210, and 300 min (left to right).

Figure 3. Tomato samples after drying times of 0, 30, 60, 90, 120, and 210 min (left to right).

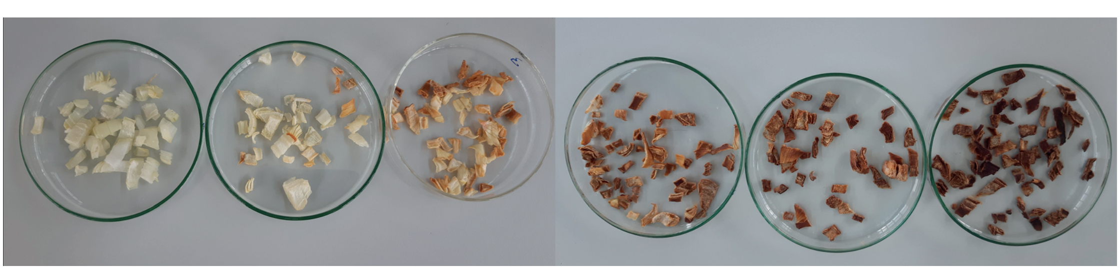

Figure 4. Onion samples after drying times of 0, 30, 60, 90, 120, and 210 min (left to right).

In contrast to the chopped samples, the experiments involving pineapple slices took markedly longer. That was why the slices were dried only to the final moisture content of 13.6 wt %, i.e., the value corresponding to the dried pineapple fruit commercially produced in Togo [22]. The respective total drying time was 1440 min. The samples did not significantly change either in shape or color which is important for high quality of the final product. Only a volume shrinkage in radial and longitudinal direction could be observed (see Fig. 5).

Figure 5. Pineapple slices after drying times of 0, 120, 180, 240, 300, 360, 420, 480, 540, 660, and 1440 min (top left to bottom right).

2.4 Mathematical Modeling of Drying Curves

The drying kinetics of the evaluated fruits and vegetables were determined by measuring the total material basis moisture content:

$$X(\tau) = \frac{m_W(\tau)}{m(\tau)} = \frac{m_W(\tau)}{m_{DM} + m_W(\tau)} = \frac{m_{W0} - [m_0 - m(\tau)]}{m_{DM} + m_{W0} - [m_0 - m(\tau)]} = \frac{X_0 m_0 - \Delta m(\tau)}{m_{DM} + X_0 m_0 - \Delta m(\tau)} \quad (2)$$

The total drying time depended on the actual fruit or vegetable and was chosen to ensure a constant sample mass. Moisture content was determined every 30 min. The drying tests were repeated twice for each fruit and vegetable, and average moisture contents were reported.

Drying kinetics were determined on the basis of thin-layer drying models. This approach assumes that the temperature and humidity distributions are kept constant throughout the thin layer of the material [29] and is widely used in the case of fruits and vegetables [30]. A typical drying curve for convective drying of agricultural products at constant external conditions is presented in Fig. 6. The drying process can be divided into three characteristic periods [31]. Within the initial (zeroth) drying period from τ_0 to τ_1, the material is preheated while evaporation of free moisture from the solid surface occurs. Compared to the total drying period, the initial drying period is usually very short and can be neglected in practice. In the first drying period from τ_1 to τ_2, the moisture content decreases nearly linearly with time at a constant drying rate of $dX(\tau)/d\tau$. The water bound in the food matrix is gradually transported from the inside to the surface. This process takes place until the critical point C, depending on the material properties and external conditions, is reached. The second and further (if observed) drying periods from τ_2 to τ_3 and from τ_3 to τ_{end} are characterized by a decreasing drying rate which leads to a nonlinear drying curve. These later drying periods are diffusion-driven. The moisture movement depends on internal and external transport resistances. The drying process stops when steady-state equilibrium at the relative humidity and temperature of the drying air is reached.

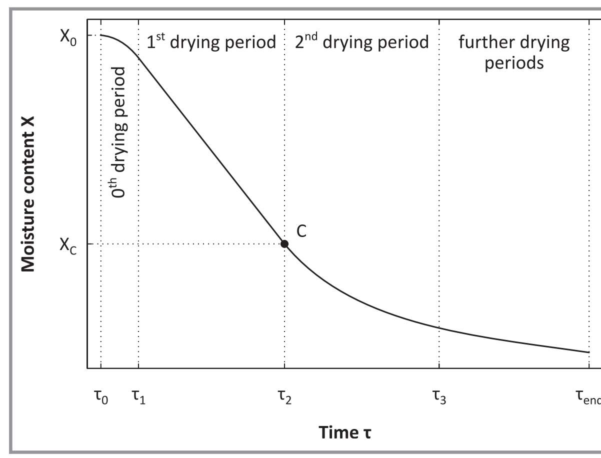

Figure 6. A typical drying curve for convective drying of agricultural products at constant external conditions (adapted from [31]).

Many semi-theoretical mathematical models for the description of thin-layer drying processes are available [32]. These models are usually derived from the Fick's second law of diffusion or from its simplified variation, i.e., the Newton's exponential law of cooling. Quality of a mathematical model can be assessed using various statistical indicators such as the residual sum of squares (*RSS*), residual mean square (*RMS*), residual standard deviation (*RSD*), or the coefficient of determination (R^2). These can be calculated as follows:

$$RSS = \sum_{i=1}^{N} (X_i - X(\tau_i))^2 \quad (3)$$

$$RMS = \frac{RSS}{\nu} \quad (4)$$

$$RSD = \sqrt{RMS} \quad (5)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (X_i - X(\tau_i))^2}{\sum_{i=1}^{N} (X_i - \bar{X})^2} \tag{6}$$

The lower the values of *RSS, RMS*, and *RSD* of a particular mathematical model, the more suitable the model is for predicting the drying behavior of the investigated product. R^2 ranges from 0 to 1 with higher values indicating a higher prediction quality. It is important to highlight that not only R^2 values close to 1 identify a usable mathematical model – the remaining three statistical indicators must be considered as well.

This study focused primarily on predicting the drying times needed to reach the residual moisture content of 13.6 wt % typical for the dried fruits and vegetables produced in Togo [22]. The experimentally obtained data points that were far beyond the respective residual moisture content could negatively influence the quality of the regression models and, therefore, were ignored. The remaining data points were split into two subsets. The first subset covered the initial (zeroth) drying period and was always approximated using a linear function. The second subset covered the relevant part of the first/second drying period and was approximated using the three nonlinear models listed in Tab. 2. The Newton model and the Henderson & Pabis model are widely used for most agricultural products. In the case of the evaluated samples, however, the standard power function yielded the best results. The least-squares problems were solved and the statistical indicators obtained using Maplesoft Maple [33].

3 Results and Discussion

3.1 Mathematical Modeling of Drying Curves

The drying curves obtained for the chopped samples dried at a temperature of 105 °C are shown in Fig. 7. It can be seen that the pineapple, mango, and onion samples reached the target residual moisture content more quickly than the tomato sample. Based on the plots, it was concluded that drying of all the samples occurred predominantly in the first drying period at a constant drying rate. In the case of pineapple, mango, and onion samples, this first drying period began about 55 min from the start of the drying process. In the case of tomato samples, the initial delay was about 85 min.

The transition from the first drying period to the subsequent diffusion-driven drying periods, i.e., the critical point C as shown in Fig. 6, was estimated to occur at the relatively low residual moisture content of approx. 0.2 to 0.3 wt %

Table 2. Drying models $X = f(\tau)$ used in the study.

Name	Model	Number of parameters	Reference
Linear (initial drying period)	$X(\tau) = a\tau + b$	2	
Newton	$X(\tau) = \exp(-a\tau)$	1	[34]
Henderson & Pabis	$X(\tau) = a\exp(-b\tau)$	2	[35]
Power function	$X(\tau) = a\tau^{-b}$	2	

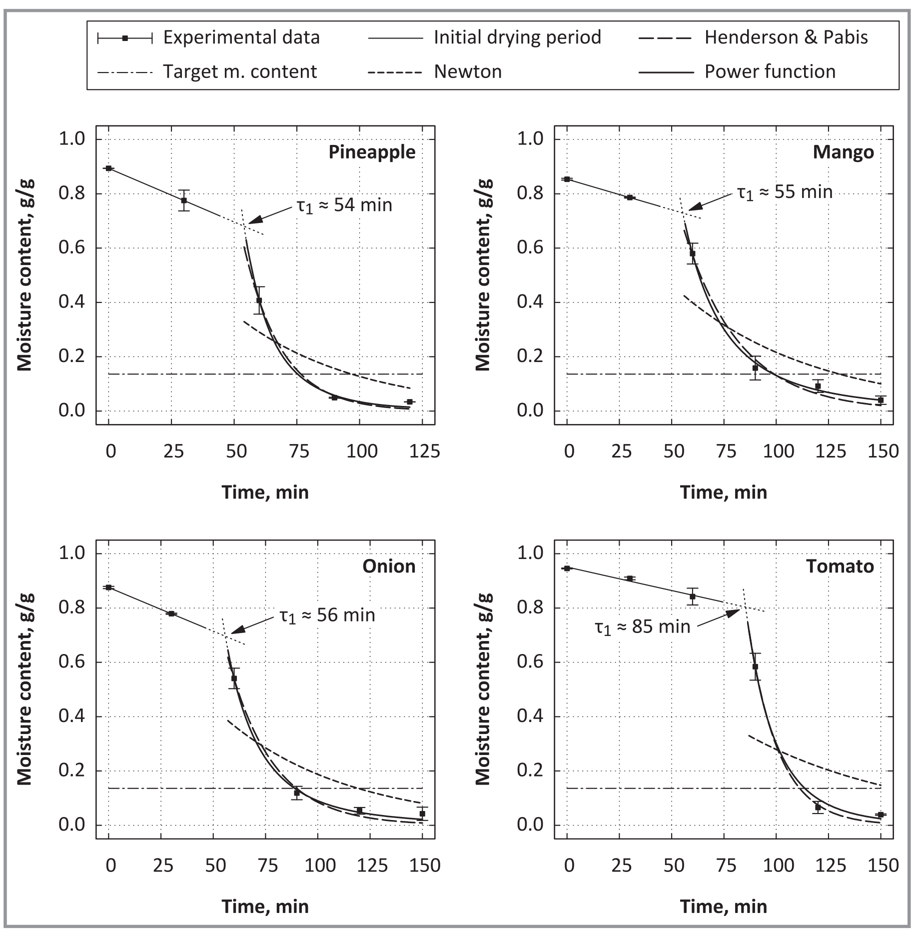

Figure 7. Experimental data and regression models for the chopped samples dried at a temperature of 105 °C; the indicated target moisture content (dash-dotted line, 13.6 wt %) corresponds to the dried pineapple fruit commercially produced in Togo.

depending on the actual sample. Estimating the location of the critical point with more precision would require more frequent sampling during the experiments. Because that could negatively influence the quality of the obtained data, sampling frequency was not increased from the default value of 2 h^{-1} (see Sect. 2.4).

The results of the regression analyses are presented in Tab. 3. Accuracy of the linear regression for the initial (zeroth) drying period was acceptable for all four samples. As for the first/second drying period, the power function always provided the best fit in terms of all considered statistical indicators (R^2, *RSS, RMS, RSD*).

The drying curve for pineapple slices at 70 °C is shown in Fig. 8. In contrast to the chopped samples, the slices were not dried completely. The residual moisture content of about 13.6 wt %, corresponding to that of dried pineapple slices produced in Togo [22], was reached after 1440 min.

The initial (zeroth) drying period lasted approx. 430 min. A significant portion of the drying took place also in the second drying period. The transition from the first period to the subsequent diffusion-driven periods was estimated to occur at the residual moisture content of approx. 0.3 wt % to 0.4 wt %. Just as in the case of the chopped samples, increasing the sampling frequency during the experiments (which would lead to a more accurate estimate of the location of the critical point) was avoided so as not to decrease the quality of the obtained data.

The results of the respective regression analyses are listed in Tab. 4. Again, the power function model had the largest R^2 value and the smallest *RSS, RMS*, and *RSD* values among the models used to fit the data beyond the initial drying period.

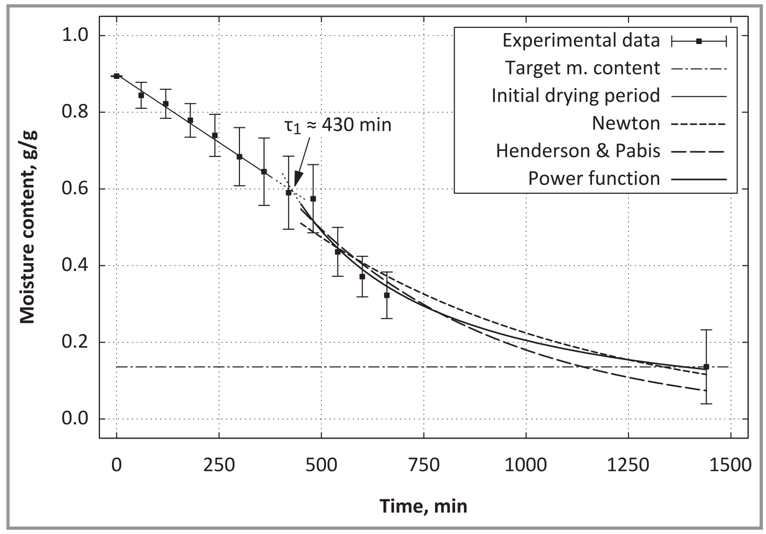

Figure 8. Experimental data and regression models for 6–8 mm-thick pineapple slices dried at a temperature of 70 °C; the indicated target moisture content (dash-dotted line, 13.6 wt %) corresponds to the dried pineapple fruit commercially produced in Togo.

Table 3. Parameters of the drying models and goodness of fit for the chopped samples.

Sample	Model	Parameters	*RSS*	*RMS*	*RSD*	R^2
Pineapple	linear (initial drying period)	$a = -0.00395$, $b = 0.89360$	0.0000	–	–	1.0000
	Newton	$a = 0.02059$	0.0277	0.0277	0.1666	0.6894
	Henderson & Pabis	$a = 21.2174$, $b = 0.06590$	0.0007	0.0007	0.0271	0.9918
	power function	$a = 1.56331 \cdot 10^8$, $b = 4.82785$	0.0005	0.0005	0.0213	0.9949
Mango	linear (initial drying period)	$a = -0.00225$, $b = 0.85350$	0.0000	–	–	1.0000
	Newton	$a = 0.01531$	0.0496	0.0248	0.1575	0.7273
	Henderson & Pabis	$a = 5.24292$, $b = 0.03687$	0.0038	0.0013	0.0357	0.9814
	power function	$a = 8.42047 \cdot 10^4$, $b = 2.90431$	0.0011	0.0004	0.0193	0.9946
Onion	linear (initial drying period)	$a = -0.00322$, $b = 0.87551$	0.0000	–	–	1.0000
	Newton	$a = 0.01673$	0.0490	0.0245	0.1566	0.7091
	Henderson & Pabis	$a = 8.54641$, $b = 0.04608$	0.0018	0.0009	0.0301	0.9892
	power function	$a = 9.07154 \cdot 10^5$, $b = 3.50127$	0.0006	0.0003	0.0173	0.9964
Tomato	linear (initial drying period)	$a = -0.00173$, $b = 0.95065$	0.0002	0.0002	0.0123	0.9722
	Newton	$a = 0.01275$	0.1106	0.0553	0.2352	0.4942
	Henderson & Pabis	$a = 277.684$, $b = 0.06851$	0.0018	0.0009	0.0297	0.9920
	power function	$a = 7.47617 \cdot 10^{11}$, $b = 6.19718$	0.0017	0.0009	0.0292	0.9922

Table 4. Parameters of the drying models and goodness of fit for pineapple slices.

Model	Parameters	*RSS*	*RMS*	*RSD*	R^2
Linear (initial drying period)	a = –0.00071, b = 0.89872	0.0005	0.0001	0.0095	0.9919
Newton	a = 0.00150	0.0118	0.0039	0.0627	0.8853
Henderson & Pabis	a = 1.35965, b = 0.00202	0.0101	0.0034	0.0581	0.9019
Power function	a = 1240.80, b = 1.26077	0.0049	0.0016	0.0404	0.9806

3.2 Estimation of the Drying Time

The drying time at a constant temperature that is required to reach a given residual moisture content can be determined using the derived mathematical models. Such prediction is especially important if different drying technologies must be combined to ensure acceptable residual moisture content of an agricultural product. This is the case if solar drying technologies are applied and the available sunshine duration is not sufficient to meet the specified product requirements [22]. As a result, it is then necessary to complement the solar drying process by suitable post-solar drying technologies.

The average sunshine duration per day in Lomé, Togo, varies from 4 to 8 h [36]. Considering 6–8 mm-thick pineapple slices and several different residual moisture contents, the power function model from Tab. 4 was used to predict the required total drying times. The predicted time needed to reach the final residual moisture content of 13.6 wt % was about 60 min shorter than the measured time, which corresponded to a tolerable relative error of approx. –4 %. Please note that the drying times had to be obtained numerically because no symbolic solution of the respective equation was available. Eq. (7) was then employed to find the remaining post-solar drying times to be covered by other technologies (see Tab. 5).

$$\tau_{\text{rem}} = \tau_{\text{tot}} - \tau_{\text{solar}} \quad (7)$$

Table 5. Required drying times obtained using the power function model from Tab. 4 for 6–8 mm-thick pineapple slices and different target residual moisture contents.

Residual moisture content $X(\tau)$ [g g^{-1}]	Required total drying time τ_{tot} [min]	Remaining drying time τ_{rem} for the average daily sunshine duration [min]	
		τ_{solar} = 4 h	τ_{solar} = 8 h
0.500	493	253	13
0.300	739	499	259
0.200	1019	779	539
0.136	1381	1141	901

3.3 Post-solar Drying to the Required Residual Moisture Content

According to the power function model, a total solar-only drying time of 1381 min (see Tab. 5) would be needed for the final product to reach the required residual moisture content of 13.6 wt %. Given the average sunshine duration of 4–8 h in Lomé, an additional drying time of 901–1141 min in, e.g., a conventional gas dryer would be necessary. These values can serve as a basis for the design of a suitable post-solar drying technology.

As described in [21], butane-fired ovens are used in Togo for the drying of pineapple slices. The plant discussed in the mentioned paper processes approx. 900 kg d^{-1} of raw pineapples (incl. the crowns, stems, etc.), which leads to a butane consumption of 49.5 kg d^{-1} (see [21] for details). If the available daily sunshine duration was assumed to be near the upper end of the average range of 4–8 h, pineapple slices could easily be pre-dried using a solar dryer to the residual moisture content of, e.g., 55 wt % (according to the model, this would take 457 min). The resulting fossil fuel savings would be 16.4 kg d^{-1}, i.e., 33 % of the original daily consumption. Considering the butane specific energy of 49.1 MJ kg^{-1}, the primary energy savings would reach 0.80 GJ d^{-1}. The entire drying process could even be fossil fuel-free if solar drying were combined with heat storage technologies.

4 Conclusion

Thin-layer drying characteristics of chopped fruits and vegetables and pineapple slices were investigated at constant drying temperatures of 105 and 70 °C, respectively, that are commonly used in the corresponding commercial drying processes. Drying of all chopped samples occurred predominantly in the first drying period at a constant drying rate, whereas in the case of pineapple slices this happened in the first and second drying periods.

Data for the initial (zeroth) drying periods were always fitted using a linear function, with the lowest R^2 among the resulting regression functions being 0.9722. Data for the subsequent drying periods down to just below the residual moisture content of 13.6 wt % (the target value as per the dried pineapple fruit commercially produced in Togo) were fitted using three semi-empirical mathematical models. Of these, the power function model ($X(\tau) = a\tau^{-b}$) provided the best fit for all studied samples, with the lowest R^2 being 0.9806. Therefore, this mathematical model can help to design post-solar drying technologies that are necessary to ensure that the requirements on dried food products are met. The discussed model was then applied to the drying of pineapple slices in a specific plant in Togo with the processing capacity of 900 kg d^{-1} of raw pineapples [21]. It was estimated that under favorable conditions, the pineapple slices could be pre-dried using a solar dryer to the residual moisture content of, e.g., 55 wt %. This would lead to the fossil fuel savings of 33 %, i.e., 16.4 kg d^{-1} of butane or 0.80 GJ d^{-1} in the case of the discussed Togolese processing plant.

Future research will focus on the improvement of solar drying technologies and their coupling with heat storage technologies. In this way, developing countries can be supported in building-up a sustainable and energy-efficient processing of local agricultural products as well as in increasing their utilization of renewable energy sources.

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Symbols used

a	[–]	parameter
b	[–]	parameter
m	[kg]	mass
Δm	[kg]	mass difference
n	[–]	parameter
N	[–]	number of measurements
R^2	[–]	coefficient of determination
RMS	[–]	residual mean square
RSD	[–]	residual standard deviation
RSS	[–]	residual sum of squares
X	[kg kg^{-1}, %]	moisture content on total material basis
$\bar{X}$	[kg kg^{-1}, %]	mean value of moisture content on total material basis

Greek letters

ν	[–]	degrees of freedom in the least-squares problem
τ	[min]	time
τ_{solar}	[h]	average daily sunshine duration

Sub- and superscripts

0	before drying
C	critical
DM	dry matter
end	after complete drying
i	test number
rem	remaining
W	water

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