Modeling of drying thin layer of tomato slices using solar and convective driers

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Abstract: This paper presents a mathematical modeling of thin layer drying of tomato (Solanum lycopersicum L.). To this end, two different methods are used to dehydrate tomato slices namely the solar drying (in an indirect solar drier), and the forced convective drying (in a convective drier). In the solar drier, the experiments are carried out at a constant air velocity of 1 m s^{-1} and average temperatures of 37.2°C, 39.9°C and 42.5°C. In the convective drier, the experiments are performed with five different temperatures (30°C, 40°C, 50°C, 60°C and 70°C) at a constant air velocity of 1 m s^{-1}. In order to estimate and select the appropriate drying curve equation, fifteen different thin layer mathematical drying models available in the literature are applied to the experimental data. The models are compared using the correlation coefficient (r) and the standard error (s) and are predicted by a non-linear regression analysis using the Curve Expert software. The Midilli-Kucuk model shows a better fit to the experimental drying data according to (r) and (s) for the two drying methods. The effect of the drying temperature on the parameters of this model is also determined. The experimental drying curves show only a falling drying rate period. On average, tomatoes are dried until the moisture content to 0.15 kg water kg^{-1} dry matter from 14.36 kg water kg^{-1} dry matter in the solar drying, and to the moisture content of 0.10 kg water kg^{-1} dry matter from 12.66 kg water kg^{-1} dry matter in the convective drying.
Keywords: solar drying, convective drying, tomato slices, thin layer, mathematical modeling, curve expert software

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1 Introduction

The tomato, among other fruits and vegetables, is highly seasonal and available in plenty amounts in particular times of the year. In the peak season, the selling prices are usually at the minimum and this may lead to lower profits or even losses for the grower (El-Beltagy et al., 2007). However, drying is the most common form of food preservation and extends the food self-life. The major objective in drying agricultural products is the reduction of the moisture content to a level, which allows safe storage over an extended period (Doymaz, 2007).

The tomato was, for a long time, the concern of many scientific researchers because of its benefactions and its wide use. In particular, a large number of studies dedicated to drying can be found. Khama, et al. (2016b) reported in their work that the drying characteristics of tomatoes were investigated at 55°C, 60°C, 65°C and 70°C with air flow rate of 1.5 m s^{-1} by Doymaz (2007).

The study of the drying of tomato can also be found in the work of Gaware et al. (2010) where five different methods were used to dehydrate tomato slices, viz., hot air, solar cabinet, heat pump, microwave vacuum, and

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freeze drying.

Bennamoun et al. (2015) studied the forced convective drying of a single cherry tomato (with and without skin). Based on the diffusion model, two approaches were proposed. It was observed that the drying time, for the unpeeled single cherry tomato, was dramatically higher than for the peeled one. In addition, taking into account of the shrinkage phenomenon during drying was necessary in the modeling of the process, in particular for the estimation of the moisture diffusion coefficient. Azhdaria and Emami (2019) confim this last result in their work where they studied a model to simulate the drying of tomato. Indeed, the comparison between the models with and without shrinkage shows an influence of parameters in qualitative agreement with the expected physical behavior: the model with shrinkage needs a shorter time for drying.

Khama, et al. (2016b) and Doymaz and Kipcak (2018) also studied the drying of cherry tomato, but to investigate the influence of the skin on water removal and to study the effect of pre-treatment and air temperature on drying time, respectively.

Azam et al. (2020) studied the drying of tomatoes in a greenhouse dryer with an integrated solar air collector and small PV system. Different pretreatments before drying and comparison with open sun drying were investigated. Results indicated that the dried tomatoes have reached the equilibrium moisture content after 1020 - 1920 min and 1020 - 2460 min for non-osmotically and osmotically treatments, respectively.

Sahdev et al. (2016) reported in their review that Sacilik et al. (2006) presented the thin layer drying characteristic of organic tomato in a solar tunnel greenhouse dryer in the climatic conditions of Ankara, Turkey. The fruit was dried in 4 days in solar greenhouse tunnel dryer as compared to 5 days in open sun drying.

Through the experimental and theoretical study of Djebli et al. (2019), the results obtained during the solar drying of tomatoes of the KAWA type, in a mixed forced convection solar dryer, showed that the fruit in the shape of flat slices took the least amount of time to dry when compared to the wedge shape. In addition, the thinnest slice thicknesses dried faster.

The work realzed by Abdel-Mohsen et al. (2019) consisted of the solar and sun drying of tomato. The main results were: (i) The drying performance was influenced by the fruit shape during both drying methods. (ii) The mass of the dried tomato slices was lower in the solar drying case. (iii) Solar drying was the quick and efficient method for dehydrating tomato slices.

The optimization of processing parameters for hot air drying of tomato slices using the Taguchi technique was investigated by Hussein et al. (2021). The results showed that the drying temperature was the most significant processing parameter controlling the drying time, lycopene, β-carotene, and ASA contents.

According to Gunhan et al. (2005), the most important aspect of drying technology is the mathematical modeling of the drying processes and equipment. To optimize drying accurate simulation models are needed in order to predict the performance of each item to be dried under the conditions each time applied (Belessiotis and Delyannis, 2011). The thin-layer drying models, describing the drying process, can be distinguished in three main categories, namely the theoretical, the semi-theoretical and the fully empirical ones. The empirical models are derived from statistical relations and they directly correlate moisture content with time, having no physical connection with the drying process itself. This type of models is valid in the specific ranges of temperature, air velocity and humidity for which they are developed (Babalis et al., 2006).

Several researchers have investigated the drying kinetics of tomato in order to evaluate different mathematical models for describing the thin-layer drying characteristics and then the drying behavior of the product has been studied. For example, Lopez-Quiroga et al. (2020) studied experimentally and then modeled the drying and rehydration kinetics of freeze-dried tomatoes. The results showed that the Page model was the most accurate in describing of the drying kinetics.

Hussein et al. (2016) studied the thin layer drying behavior of tomato slices dried using three methods namely, hybrid, solar and open sun drying. They found that, among the six mathematical models they used, the

Page model was the better in describing the drying kinetics for the three methods used in tomato drying. However, in the work of Sadin et al. (2017), the Middili model was the best model to predict the moisture during tomato thin layer drying in combined infrared-hot air dryer, at different temperatures and speeds.

The main objective of this study is to determine and test the suitable thin layer drying curve model for understanding the drying behavior of tomato slices during the application of both the solar and convective drying techniques.

2 Materials and methods

2.1 Fruit

Good quality of tomato was purchased from a local fruit market of Ouargla, Algeria (Longitude: 5° 19’ 30” E – Altitude: 138 m) for the solar drying tests, and from a local fruit market of Liège, Belgium for the convective drying ones. Before the experiments, the fruits were washed into water to remove the skin dirt and cut into slices of 0.5 cm thickness. The seeds were removed and the slices obtained were uniformly laid out on each tray of the two driers. The average mass of the samples used for the drying experiment was about 1.267 kg in the solar drier and about 0.061 kg in the convective drier. The average initial moisture contents of tomatoes, for solar and convective drying tests, were 13.89 kg of water kg^{-1} d.m (93.28% wb) and 14.56 kg of water kg^{-1} d.m (93.57% wb) respectively. The drying process of the tomato was continued until the product achieved its final mass, corresponding to the stabilization of the value recorded in the balance. After each drying experiment, the dry mass of tomato, M_d, was determined by putting the entire dried product, during 24 hrs, in a regulated drying oven at 105°C.

2.2 Solar drier

The indirect solar drier used in the solar drying experiments was realized by (Khama, 2016; Khama, et al., 2016a) and it is shown in Figure 1. It mainly consisted of a flat-plate solar collector (A) and a drying chamber (B). The solar collector was 1.14 m in width and 1.90 m in length. It was oriented directly towards the equator, facing the south to maximize the incident solar radiation on it and tilted to an angle about 32°. A glass sheet was used as a transparent cover (a_1) to prevent the top heat losses. A copper sheet painted black (no reflective) was used as an absorber plate (a_2) for absorbing the incident solar radiation. 7 cm thick glass wool insulation (a_3) was used on the sides and bottom of the collector to prevent heat losses from these areas. The air was drawn between the cover and the absorber plate. The drying chamber (B), with total dimensions of 1.14 × 1.14 × 1.66 m^3, was constructed with insulated galvanized iron walls and well insulated with 7 cm thick glass wool. It ended by a chimney (b_1) evacuating the humid air naturally or thanks to a blower (b_2) of 75 W powers, in the forced ventilation case. The heated air was allowed to enter in the drying chamber from the bottom of the tray (b_3) and flow upward through the product and then through the chimney. The solar experiments were conducted, during summer, at Laboratory of Process Engineering at the University of Ouargla, Algeria (Latitude: 31° 56’ 57” N - Longitude: 5° 19’ 30” E – Altitude: 138 m). Drying started at 7:00 a.m. and continued until 19:00 p.m. The changes in mass of tomato were monitored at 15 min intervals for the first three hours and 30 min for subsequent drying times to equilibrium. If the drying did not finish, the tomatoes were placed in a plastic box in order to induce the loss of water within the drying samples. These were again placed in the drier in the next morning and the drying process continued. In this study, the average temperature was 37.2 - 42.5°C, with a constant air velocity of 1 m s^{-1}. The climate temperature and relative humidity were measured by a thermo-hygrometer with accuracy ± 2% of reading ± 0.1°C and ± 1% of reading ± 1.5%. The solar radiation was measured by a Kipp and Zonen pyrometer with 0.1 W m^{-2} accuracy. The inlet and outlet temperatures of air in the solar collector were measured by calibrated chromel-alumel K-type thermocouples with accuracy of ± 0.01°C. The temperature and relative humidity of air in the drying chamber were measured by a thermo-hygrometer with accuracies ± 2% of reading ± 0.1°C and ± 1% of reading ± 1.5% HR. The moisture losses of tomato mass were recorded using a digital balance (KERN balance) having accuracy ± 0.1 g and maximum capacity 10100 g.

2.3 Convective drier

The convective experiments were conducted at Dept of Chemical Engineering at the University of Liège, Belgium (Longitude: 5° 34' 02" E – Altitude: 66 m). These experiments were carried out in a discontinuous pilot-scale drier (Figure 2) reproducing most of the operating conditions prevailing in a full-scale continuous belt drier (Léonard et al., 2008; Huron et al., 2009; Li et al., 2014). A fan (a) sucks ambient air that is heated up to the required temperature by a set of electrical resistances (b). If needed, air is humidified just after heating by adding vapor produced by a vapor generator. Hot air flows through the bed of tomato (c), which lies on a perforated grid (d) linked to scales (e). Three operating parameters may be controlled: the temperature, the superficial velocity and the humidity of the air.

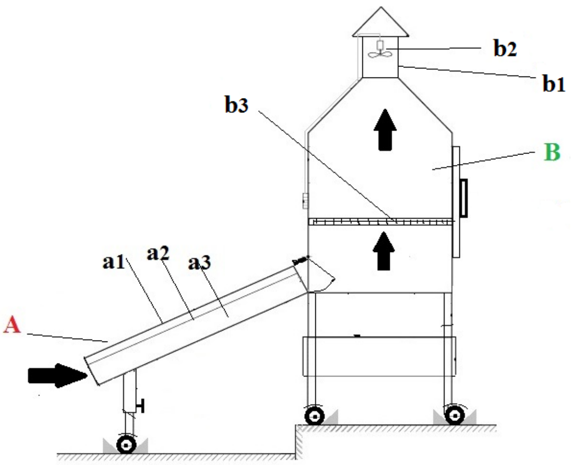

Figure 1 Solar drier

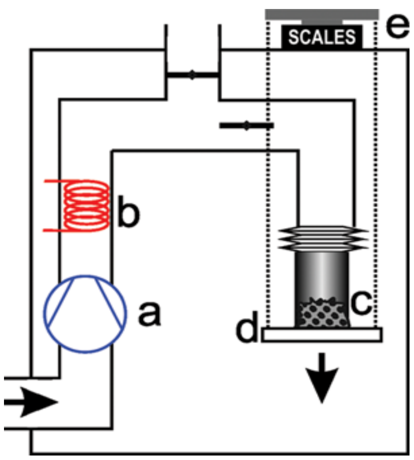

Figure 2 Convective drier (Li et al., 2014)

In this study, the temperature was controlled between 30°C-70°C, with a constant air velocity of 1 m s^{-1}. No additional air humidification was carried out. At the adopted drying temperature, the daily variations of the ambient air humidity can be considered as negligible. The sample was continuously weighed during the drying test and its mass was recorded every 5 s.

2.4 Mathematical modeling of the drying curves

The water content on a dry basis, X(t) in kg $_{water}$ kg^{-1} $_{dry\ matter}$, can be defined using Equation 1 (Zhu and Jiang, 2014).

$$X(t) = \frac{M_h(t) - M_d}{M_d} \tag{1}$$

Where: $M_h(t)$ is the instantaneous wet mass in kg and M_d is the dry mass in kg.

As reported by (Dadali et al., 2007; Evin, 2012), the drying rate, DR in kg $_{water}$. kg $_{dry\ matter}^{-1}$ s^{-1}, during the drying process can be determined using Equation 2.

$$DR = \frac{X(t) - X(t+\Delta t)}{\Delta t} \tag{2}$$

Where : $X(t)$ and $X(t+\Delta t)$ in kg $_{water}$ kg^{-1} $_{dry\ matter}$, are the moisture content at the moments t and $(t+\Delta t)$, respectively; Δt is the step of time in s.

The product moisture ratio, XR, at one moment t, can be calculated using Equation 3 (Dadali et al., 2007; Doymaz, 2007).

$$XR = \frac{X(t)}{X_0} \tag{3}$$

Where : $X(t)$ and X_0 in kg $_{of\ water}$ kg^{-1} $_{dry\ matter}$ are, respectively, the instantaneous water content and the initial water content.

For the mathematical modeling, the thin layer fifteen drying models in Table 1 (Khama, 2016) are tested to select the best model for describing the drying curve equation of tomato slices during two drying processes: the indirect solar drying and the convective drying. The drying data are fitted to the models using the Curve Expert software. The correlation coefficient (r) and the standard error (s) are used as the criteria for the accuracy of the fit. Indeed, the drying model with the highest (r) and the smallest (s) is chosen as the best model describing the thin layer drying of tomato slices. In this study, the relationship of the parameters of the best suitable model with the drying air temperature is also determined and the effect of the temperature on the equation parameters is investigated.

Table 1 Mathematical models applied to the drying curves

N°	Model equation	Model name	References
1	$MR = exp(-kt)$	Newton	(Akpinar ,et al., 2003a)
2	$MR = exp(-kt^n)$	Page	(Babalis et al., 2006)
3	$MR = exp(-(kt)^n)$	Modified Page	(Koua et al., 2009)
4	$MR = a\ exp(-kt)$	Henderson and Pabis	(Akpinar, et al., 2003b)
5	$MR = a\ exp(-kt) + c$	Logarithmic	(Togrul et al., 2003)
6	$MR = a\ exp(-k_0t) + b\ exp(-k_1t)$	Two term	(Akpinar, et al., 2003b)
7	$MR = a\ exp(-kt) + (1-a)\ exp(-kat)$	Two-term exponential	(Evin, 2012)
8	$MR = 1 + at + bt^2$	Wang and Singh	(Koua et al., 2009)
9	$MR = a\ exp(-kt) + (1-a)\ exp\ (-kbt)$	Diffusion approach	(Sacilik et al., 2006)
10	$MR = a\ exp(-kt) + b\ exp(-gt) + c\ exp(-ht)$	Modified Henderson and Pabis	(Togrul et al., 2003)
11	$MR = a\ exp(-kt) + (1-a)\ exp(-gt)$	Verma et al.	(Evin, 2012)
12	$MR = a\ exp(-kt^n) + bt$	Midilli-Kucuk	(Sacilik et al., 2006)
13	$MR = exp(-(t/\beta)^\alpha)$	Weibull	(Koua et al., 2009)
14	$MR= exp(-k(t/L^2)^n)$	Modified Page equation-II	(Evin, 2012)
15	$MR = a\ exp(-c(t/L^2))$	Simplified Fick's diffusion equation (SFFD)	(Togrul et al., 2003)

3 Results and discussion

3.1 Solar drying curves

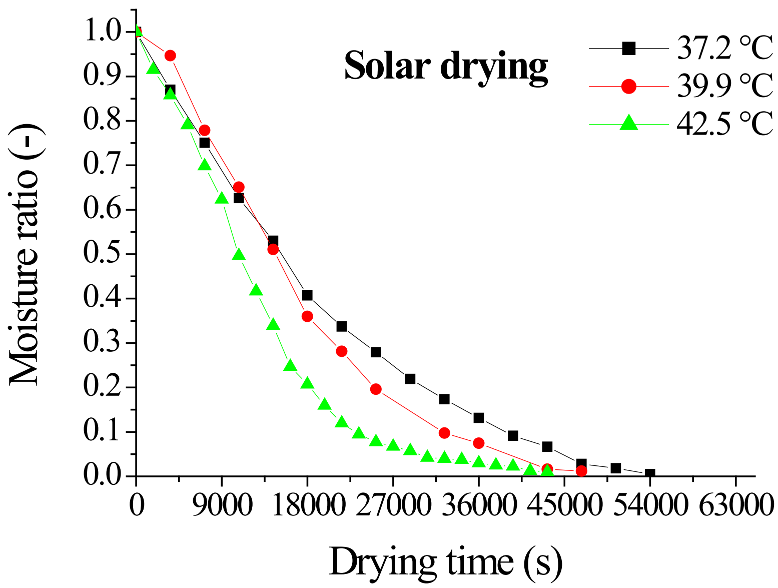

Figure 3 Influence of the temperature on tomato slices moisture ratio during solar drying

Figure 3 shows the drying curves $X/X_0 = f(t)$, obtained for the three investigated average temperatures of 37.2 °C, 39.9 °C and 42.5°C. They express the evolution of the dimensionless moisture of the tomato slices according to time. The effect of the temperature on the kinetics is very clear, as found by several researchers as in (Dadali et al., 2007; Doymaz, 2007), indeed the drying time is shorter with increasing this operating condition. The drying time of the tomato, at 37.2°C, is 54 000 s (15 hrs) whereas it is 46 800 s (13 hrs) at 39.9°C and 43 200 s (12 hrs) at 42.5°C.

The solar drying rate versus moisture content curves of tomato slices at the obtained average temperatures is shown in Figure 4. The effect of the temperature can also be clearly observed, especially between 39.9°C and 42.5°C, with higher drying rates throughout the drying process. The drying rate is higher at drying air temperature of 42.5°C for the first 16 200 s (4.5 hrs) with values significantly exceeded the values of the other rates. At this moment, the drying rate is about 7.34×10^{-4} kg $_{water}$ kg $_{dry\ matter}^{-1}$ s^{-1}, 6.33×10^{-4} kg $_{water}$. kg $_{dry\ matter}^{-1}$ s^{-1} and 3.70×10^{-4} kg $_{water}$. kg $_{dry\ matter}^{-1}$ s^{-1} at 42.5°C, 39.9°C and

37.2°C, respectively. The drying process takes place in the falling rate period. The drying rate decreases continuously with the moisture content and with the drying time.

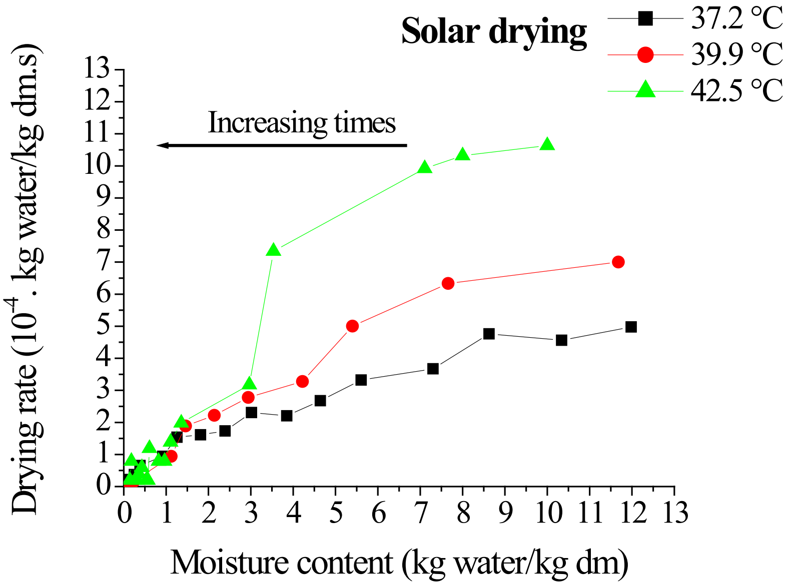

Figure 4 Influence of tomato slices moisture content on drying rate during solar drying

3.2 Convective drying curves

Figure 5 shows the drying curves $X/X_0 = f(t)$, obtained for the five investigated temperatures of 30°C, 40°C, 50°C, 60°C and 70°C. They express the evolution of the dimensionless moisture of the tomato slices according to time. The effect of the temperature on the kinetics is very clear, as found by several researchers; indeed the drying time is shorter by increasing this parameter. However, the total drying times required to reach the final moisture content are about 36 000 s (10 hrs), 14 400 s (4 hrs), 10 800 s (3 hrs), 9 000 s (2.5 hrs) and 5 400 s (1.5 hrs) at 30°C, 40°C, 50°C, 60°C and 70°C, respectively. So the influence of the temperature on the drying duration is very important. For example, the drying time (at 30°C) ≈ 2.5 × drying time (at 40°C) ≈ 3.34 × drying time (at 50°C) ≈ 4 × drying time (at 60°C) ≈ 6.67 × drying time (at 70°C).

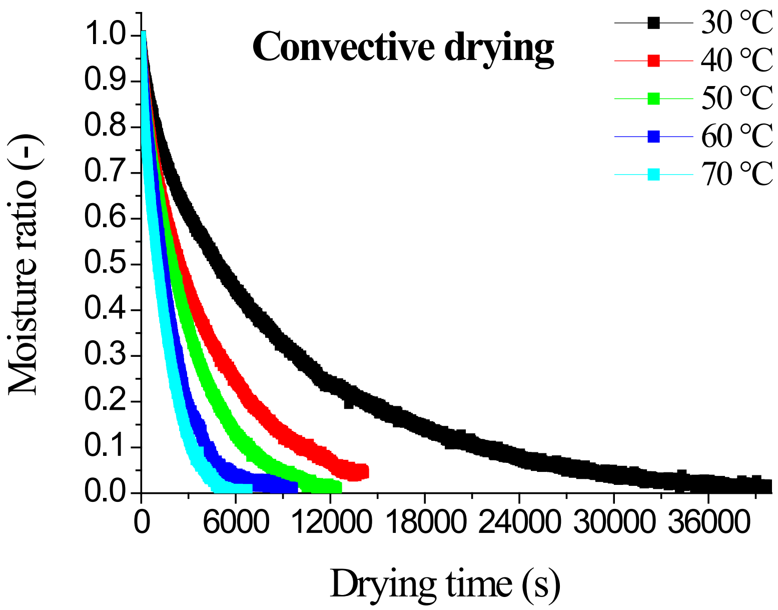

Figure 5 Influence of tomato slices temperature on moisture ratio during convective drying

The convective drying rate versus the moisture content curves of tomato slices at a range of 30°C-70°C is shown in Figure 6. The effect of the temperature can also be clearly observed with higher drying rates throughout the drying process. The drying rate is almost higher at the drying air temperature of 60 and 70°C during all the drying process. Indeed, the curves obtained at 60°C and 70°C are not very distant one of the other one. The curves obtained at 30°C and 40°C are also very close and show the lowest rate. As in the solar drying case, the entire drying process of tomato slices takes place in a falling rate period only.

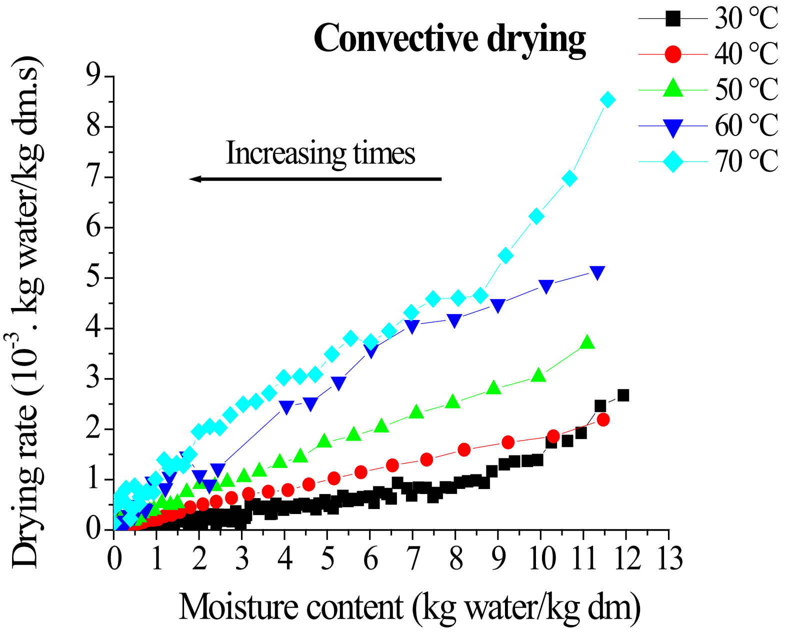

Figure 6 Influence of tomato slices moisture content on drying rate during convective drying.

3.3 Modeling results

The results of the statistical analyses for the drying data models expressing the changes in the moisture ratios are presented in Table 2 for the solar drying and in Table 3 for the convective drying. It is assumed that the model, which has the highest (r) and the lowest (s) is the best-suited one. Consequently, the Midilli-Kucuk model is selected to represent the thin layer drying behavior of tomato slices for both the solar and convective drying.

Table 2 Results of statistical analyses on the modeling of the solar drying of tomato

Model	Temperature	Model constants	R	s
1	37.2°C	k = 0.17472	0.994545	0.032541
	39.9°C	k = 0.20130	0.981889	0.067584
	42.5°C	k = 0.27775	0.980752	0.063916
2	37.2°C	k = 0.11962 n = 1.20140	0.999499	0.010225
	39.9°C	k = 0.08066 n = 1.54267	0.999550	0.011074
	42.5°C	k= 0.13130 n = 1.52304	0.998765	0.016598
3	37.2°C	k = 0.17076 n = 1.20140	0.999499	0.010225
	39.9°C	k = 0.19556 n = 1.54267	0.999550	0.011074
	42.5°C	k= 0.26368 n = 1.52304	0.998765	0.016598
4	37.2°C	a = 1.04834 k = 0.18314	0.996119	0.028421
	39.9°C	a = 1.11343 k = 0.22262	0.988102	0.056790
	42.5°C	a = 1.11520 k = 0.30627	0.986779	0.054146
5	37.2°C	a = 1.13271 k = 0.14286 c = - 0.11331	0.999293	0.012600
	39.9°C	a = 1.17215 k = 0.18288 c = - 0.08494	0.992657	0.046352
	42.5°C	a = 1.16309 k = 0.25434 c = - 0.07639	0.990774	0.046252
6	37.2°C	a = 0.51641 k_0 = 0.18313 b = 0.53192 k_1 = 0.18313	0.996119	0.030698
	39.9°C	a = 0.50225 k_0 = 0.22258 b = 0.61108 k_1 = 0.22258	0.988102	0.061340
	42.5°C	a = 0.55207 k_0 = 0.30627 b = 0.56312 k_1 = 0.30626	0.986779	0.056553
7	37.2°C	a = 1.74176 k = 0.23783	0.999459	0.010620
	39.9°C	a = 2.07024 k = 0.32715	0.999351	0.013297
	42.5°C	a= 2.02525 k = 0.43220	0.997992	0.021159

8	37.2°C	a = - 0.13192 b = 0.00458	0.999073	0.013901
	39.9°C	a = - 0.14585 b = 0.00525	0.995085	0.036563
	42.5°C	a= - 0.19908 b = 0.00987	0.994020	0.036481
9	37.2°C	a = 1.00000 k = 0.17472 b = 1.00000	0.994545	0.034955
	39.9°C	a = 1.00000 k = 0.20130 b = 1.00000	0.981889	0.072596
	42.5°C	a = 1.00000 k = 0.27775 b = 1.00000	0.980752	0.066637
10	37.2°C	a = - 2.62777 k = 0.32966 b = 1.81202 g = 0.26998 c = 1.81204 h = 0.26792	0.999540	0.011587
	39.9°C	a = - 23.34267 k = 0.44596 b = 12.17085 g = 0.42687 c = 12.17100 h = 0.42667	0.999575	0.012739
	42.5°C	a = 81.41934 k = 0.43996 b = 81.42307 g = 0.43936 c = -161.79190 h = 0.44116	0.992968	0.043325
11	37.2°C	a = 13.60420 k = 0.28731 g = 0.30119	0.999545	0.010113
	39.9°C	a = 21.89540 k = 0.42555 g = 0.44689	0.999575	0.011177
	42.5°C	a = 28.36414 k = 0.56263 g = 0.58304	0.998448	0.019009
12	37.2°C	a = 0.99912 k = 0.12570 n = 1.14592 b = - 0.00205	0.999743	0.007905
	39.9°C	a = 1.00861 k = 0.08325 n = 1.53458 b = 0.00032	0.999614	0.011078
	42.5°C	a = 0.97427 k = 0.10987 n = 1.65198 b = 0.00167	0.999270	0.013331
13	37.2°C	β = 5.85606 α = 1.20140	0.999499	0.010225
	39.9°C	β = 5.11357 α = 1.54267	0.999550	0.011074
	42.5°C	β = 3.79250 α = 1.52304	0.998765	0.016598
14	37.2°C	k = 0.20594 L = 1.25369 n = 1.20139	0.999499	0.010611
	39.9°C	k = 2.62856 L = 3.09313 n = 1.54267	0.999550	0.011492
	42.5°C	k = 0.99080 L = 1.94153 n = 1.52304	0.998765	0.016955
15	37.2°C	a = 1.04834 c = 21.79576 L = 10.90927	0.996119	0.029494
	39.9°C	a = 1.11343 c = 29.42405 L = 11.49667	0.988102	0.058934
	42.5°C	a = 1.11520 c = 49.82687 L = 12.75502	0.986779	0.055310

Table 3 Results of statistical analyses on the modeling of the convective drying of tomato

Model	Temperature	Model constants	R	s
1	30°C	k = 0.44313	0.986680	0.035708
	40°C	k = 0.89583	0.990050	0.032107
	50°C	k = 1.24413	0.998101	0.014934
	60°C	k = 1.90811	0.999045	0.010849
	70°C	k = 2.44690	0.997365	0.017783
2	30°C	k = 0.55242 n = 0.79396	0.998904	0.010276
	40°C	k = 0.94933 n = 0.82295	0.999111	0.009619
	50°C	k = 1.24630 n = 0.93650	0.998912	0.011308
	60°C	k = 1.94755 n = 1.04814	0.999369	0.008824
	70°C	k = 2.37591 n = 0.96251	0.997684	0.016686
3	30°C	k = 0.01028 n = 0.79396	0.998904	0.010276
	40°C	k = 0.93877 n = 0.82295	0.999111	0.009619
	50°C	k = 1.26505 n = 0.93650	0.998912	0.011308
	60°C	k = 1.88882 n = 1.04814	0.999369	0.008824
	70°C	k = 2.45735 n = 0.96251	0.997684	0.016686
4	30°C	a = 0.86583 k = 0.37944	0.997720	0.014817
	40°C	a = 0.89305 k = 0.79289	0.998036	0.014294
	50°C	a = 0.94746 k = 1.17795	0.999513	0.007565
	60°C	a = 1.01088 k = 1.92849	0.999093	0.010577
	70°C	a = 0.96407 k = 2.35006	0.998426	0.013758
5	30°C	a = 0.86249 k = 0.40641 c = 0.01678	0.998142	0.013376
	40°C	a = 0.88536 k = 0.85443 c = 0.02108	0.998400	0.012908
	50°C	a = 0.95012 k = 1.13733 c = - 0.00980	0.999643	0.006477
	60°C	a = 1.01143 k = 1.90630 c = - 0.00322	0.999117	0.010441
	70°C	a = 1.00928 k = 2.00521 c = - 0.06623	0.999308	0.009133

6	30°C	a = 0.17690 k_0 = 3.37705 b = 0.80169 k_1 = 0.35343	0.999710	0.005286
	40°C	a = 0.15724 k_0 = 7.01379 b = 0.83474 k_1 = 0.74402	0.999782	0.004765
	50°C	a = 0.40083 k_0 = 1.17796 b = 0.54663 k_1 = 1.17795	0.999513	0.007568
	60°C	a = 8.78071 k_0 = 1.55872 b = -7.77930 k_1 = 1.51997	0.999248	0.009637
	70°C	a = 0.95312 k_0 = 2.17266 b = - 0.00632 k_1 = -1.93852	0.999349	0.008862
7	30°C	a = 0.18701 k = 1.95629	0.997940	0.014082
	40°C	a = 0.16708 k = 4.49860	0.999174	0.009274
	50°C	a = 0.60974 k = 1.53059	0.998329	0.014013
	60°C	a = 1.00107 k = 1.00101	0.745868	0.165469
	70°C	a = 0.86490 k = 2.49607	0.997366	0.017793
8	30°C	a = - 0.28050 b = 0.01962	0.916961	0.087586
	40°C	a = - 0.64257 b = 0.10839	0.955199	0.067540
	50°C	a = - 0.80536 b = 0.16020	0.962437	0.065839
	60°C	a = - 1.13731 b = 0.30745	0.955843	0.073004
	70°C	a = - 1.96371 b = 1.08306	0.990701	0.033376
9	30°C	a = 1.00000 k = 0.44313 b = 1.00000	0.986680	0.035713
	40°C	a = 1.00000 k = 0.89583 b = 1.00000	0.990050	0.032118
	50°C	a = 1.00000 k = 1.24413 b = 1.00000	0.998101	0.014940
	60°C	a = 1.00000 k = 1.90811 b = 1.00000	0.999045	0.010854
	70°C	a = 1.00000 k = 2.44690 b = 1.00000	0.997365	0.017808
10	30°C	a = - 0.36832 k = 0.37944 b = - 0.36832 g = 0.37944 c = 1.60248 h = 0.37944		
	40°C	a = - 0.16683 k = 0.79288 b = - 0.16683 g = 0.79288 c = 1.22671 h = 0.79289	0.997720	0.014821
	50°C	a = 0.32197 k = 1.17796 b = 0.32197 g = 1.17796 c = 0.30351 h = 1.17794	0.998036	0.014304
	60°C	a = -0.77763 k = 1.45132 b = - 0.77762 g = 1.45718 c = 2.55677 h = 1.61345	0.999513	0.007571
	70°C	a = 0.48414 k = 2.35860 b = 0.48660 g = 2.37191 c = -0.01374 h = 15.47945	0.999246	0.009653
			0.998440	0.013736

Model	Temperature	Model constants	R	s
11	30°C	a = 0.80745 k = 0.35537 g = 4.07607	0.999685	0.005514
	40°C	a = 0.83673 k = 0.74536 g = 7.55611	0.999777	0.004816
	50°C	a = 0.06070 k = 34.82979 g = 1.16814	0.999637	0.006531
	60°C	a = 8.49200 k = 1.55279 g = 1.51232	0.999247	0.009638
	70°C	a = 0.04076 k = 85.54204 g = 2.33740	0.998502	0.013433
12	30°C	a = 0.97365 k = 0.52754 n = 0.77694 b = - 0.00263	0.999704	0.005340
	40°C	a = 0.99403 k = 0.90511 n = 0.77334 b = - 0.00971	0.999776	0.004832
	50°C	a = 0.95314 k = 1.15994 n = 0.96891 b = - 0.00421	0.999672	0.006216
	60°C	a = 0.96057 k = 1.96300 n = 1.13069 b = 0.00382	0.999661	0.006476
	70°C	a = 0.98062 k = 1.83881 n = 0.86453 b = - 0.09656	0.999604	0.006913
13	30°C	β = 2.11160 α = 0.79396	0.998904	0.010276
	40°C	β = 1.06522 α = 0.82295	0.999111	0.009619
	50°C	β = 0.79048 α = 0.93650	0.998912	0.011308
	60°C	β = 0.52943 α = 1.04814	0.999369	0.008824
	70°C	β = 0.40694 α = 0.96251	0.997684	0.016686
14	30°C	k = 0.63081 L = 1.08715 n = 0.79396	0.998904	0.010276
	40°C	k = 0.57213 L = 0.73516 n = 0.82295	0.999111	0.009621
	50°C	k = 0.93899 L = 0.85970 n = 0.93650	0.998912	0.011311
	60°C	k = 6.12545 L = 1.72741 n = 1.04814	0.999369	0.008826
	70°C	k = 1.00776 L = 0.64049 n = 0.96251	0.997684	0.016697
15	30°C	a = 0.86583 c = 130.16227 L = 18.52130	0.997720	0.014818
	40°C	a = 0.89305 c = 5.68543 L = 2.67777	0.998036	0.014296
	50°C	a = 0.94746 c = 0.65789 L = 0.74733	0.999513	0.007566
	60°C	a = 1.01088 c = 3.96404 L = 1.43371	0.999093	0.010580
	70°C	a = 0.96407 c = 4.04537 L = 1.31202	0.998426	0.013767

The moisture content data at the different drying air temperatures are converted to a moisture ratio, then fitted against the drying time. To account for the effect of the drying variables on the Midilli-Kucuk model constants, the value of *a*, *k*, *n* and *b* are regressed against those of the drying air temperature using multiple regression analysis. Based on the multiple regression analysis, the accepted model constants are shown in Table 4.

Table 4 Constants relationships of the Midilli-Kucuk model

Drying method	*a*	*k*	*n*	*b*
Solar drying	1.0000	$76365.7100 - 3841.9341\ T + 48.2013\ T^2$	$- 2.4023 + 0.1611\ T$	$- 0.0300 + 0.0012\ T$
Convective drying	1.0000	$- 1.3100 + 0.0691\ T - 0.0003\ T^2$	$-1.6601 + 0.0940\ T$	$-0.1440 + 0.0071\ T$

The validation of the Midilli-Kucuk model is evaluated by comparing the computed moisture ratio (predicted values) in any particular drying conditions with the observed moisture ratios (experimental values). The consistency of the model at the different drying air temperatures is illustrated in Figure 7 for the solar drying and in Figure 8 for the convective drying.

Figure 7 and Figure 8 show the variation of the predicted moisture ratio values versus the experimental moisture ratio values in the solar and convective drying respectively. The model predictions and the drying data banded around a straight line, which show the suitability of the selected model in describing the drying behavior of tomato slices for the two drying methods.

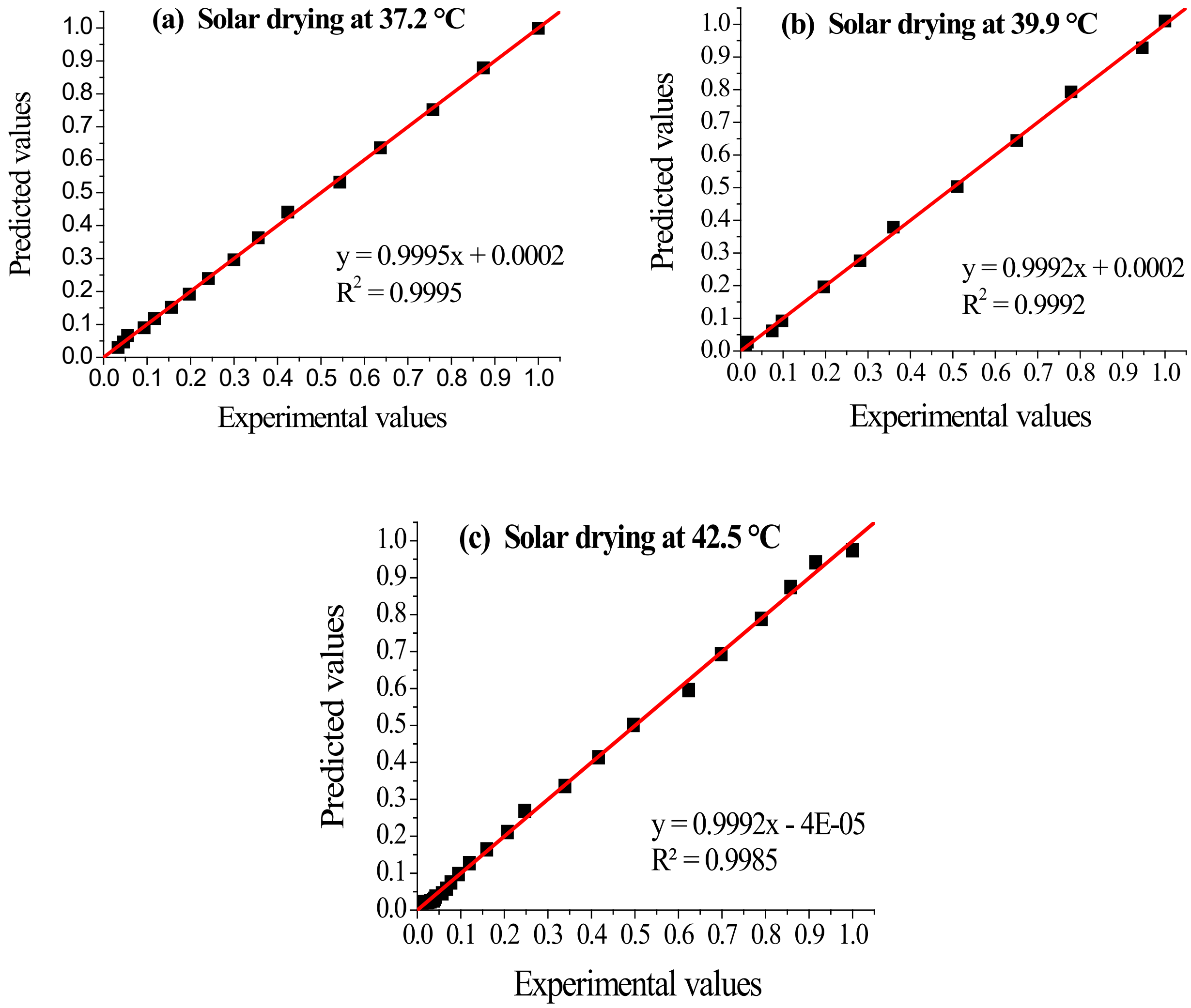

Figure 7 Experimental and predicted moisture ratios for different air temperatures: Case of the solar drying of the tomato slices

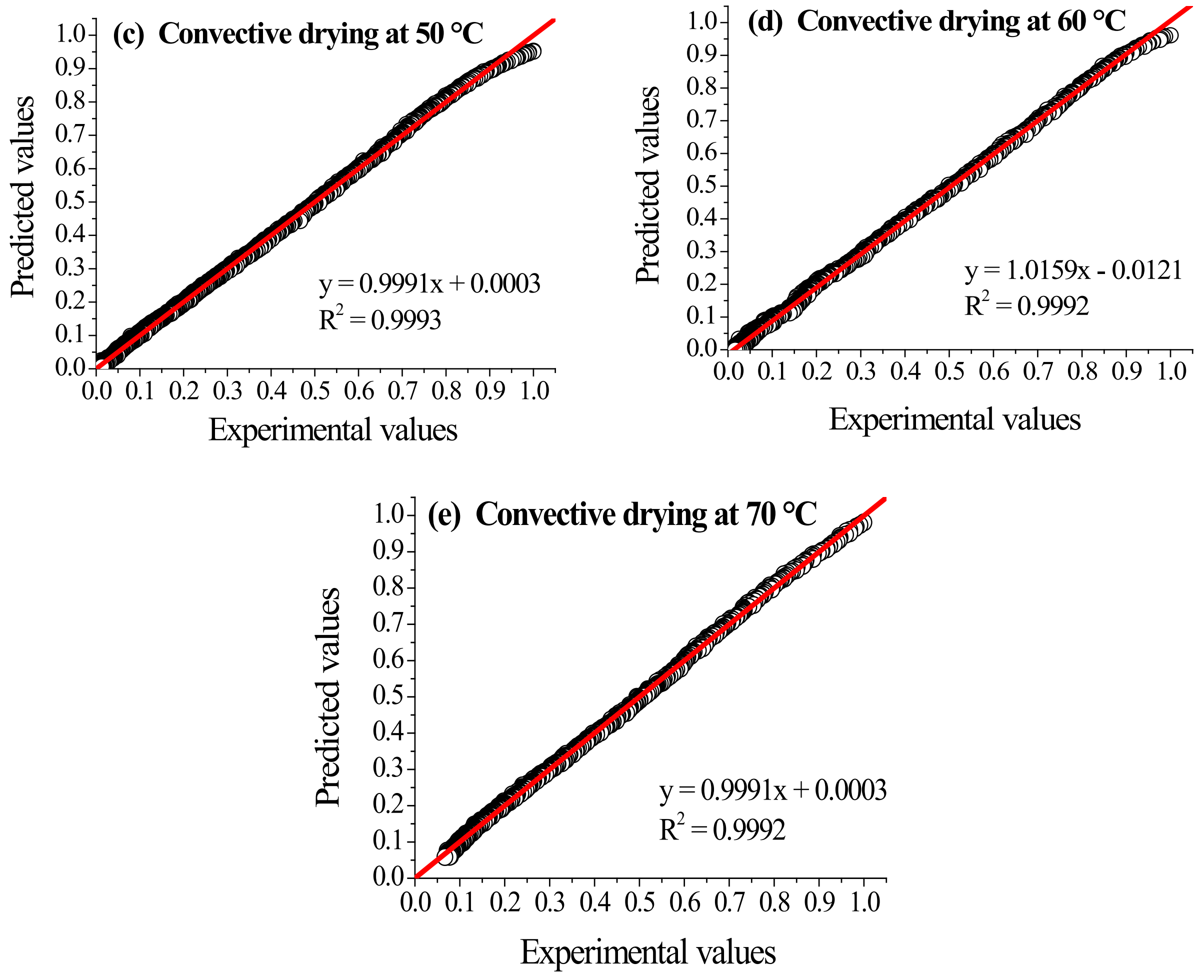

Figure 8 Experimental and predicted moisture ratios for different air temperatures: Case of the convective drying of the tomato slices

4 Conclusion

According to the results, it can be concluded that the Midilli–Kucuk model describes well the drying behavior of tomato in the drying process at a temperature range of 37.2°C-42.5°C with 1 m s^{-1} air velocity in the solar drying, and at a temperature range of 30°C-70°C with 1 m s^{-1} air velocity in the convective drying.

References

Abdel-Mohsen, H., A. A. Abd El-Rahmam, and H. E. Hassan. 2019. Drying of tomato fruits using solar energy. *CIGR Journal*, 21(2): 204-215.

Akpinar, E. K., A. Midilli, and Y. Bicer. 2003a. Single layer drying behavior of potato slices in a convective cyclone dryer and mathematical modeling. *Energy Conversion and Management*, 44(10): 1689-705.

Akpinar, E. K., Y. Bicer, and C. Yildiz. 2003b. Thin layer drying of red pepper. *Journal of Food Engineering*, 59(1): 99-104.

Azam, M. M., M. A. Eltawil, and M. A. A. Baher. 2020. Thermal analysis of PV system and solar collect or integrated with greenhouse dryer for drying tomatoes. *Energy*, 212: 118764.

Azhdaria, E., and A, Emami. 2019. Analytical and numerical study of drying of tomato in non-shrinkage and shrinkage model. *Mathematics and Computers in Simulation*, 166(C): 253-265.

Babalis, S. J., E. Papanicolaou, N. Kyriakis, and V. G. Belessiotis. 2006. Evaluation of thin-layer drying models for describing drying kinetics of figs (Ficus carica). *Journal of Food Engineering*, 75(2): 205-214.

Belessiotis, V., and E. Delyannis. 2011. Solar drying. *Solar Energy*, 85(8): 1665-1691.

Bennamoun, L., R. Khama, and A. Léonard. 2015. Convective drying of single cherry tomato : modeling and experimental study. *Food and Bioproducts Processing*, 94: 114-123.

Dadali, G., D. K. Apar, and B. Özbek. 2007. Microwave drying kinetics of okra. *Drying Technology*, 25(5): 917-924.

Djebli, A., S. Hanini, O. Badaoui, and M. Boumahdi. 2019. A new approach to the thermodynamics study of drying tomatoes in mixed solar dryer. *Solar Energy*, 193: 164-174.

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

Doymaz, I., and A. S. Kipcak. 2018. Effect of pre-treatment and air temperature on drying time of cherry tomato. *Journal of*

Thermal Engineering, 4(1): 1648-1655.

El-Beltagy, A., G. R. Gamea, and A. H. A. Essa. 2007. Solar drying characteristics of strawberry. *Journal of Food Engineering*, 78(2): 456-464.

Evin, D. 2012. Thin layer drying kinetics of Gundelia tournefortii L. *Food and Bioproducts Processing*, 90(C2): 323-332.

Gaware, T. J., N. Sutar, and B. N. Thorat. 2010. Drying of tomato using different methods: Comparison of dehydration and rehydration kinetics. *Drying Technology*, 28(5): 651-658.

Gunhan, T., V. Demir, E. Hancioglu, and A. Hepbasli. 2005. Mathematical modelling of drying of bay leaves. *Energy Conversion and Management*, 46(11-12): 1667-1679.

Hussein, J. B., K. B. Filli, and M. O. Oke. 2016. Thin layer modelling of hybrid, solar and open sun drying of tomato slices. *Research Journal of Food Science and*

Hussein, J. B., M. O. Oke, O. O. Abiona, and Q. Adebayo. 2021. Optimization of processing parameters for drying of tomatoes (Solanum lycopersicum L.var) slices using Taguchi technique. *Journal of Food Processing and Preservation*, 45(4): e15149.

Huron, Y., T. Salmon, M. Crine, G. Blandin, and A. Léonard. 2009. Effect of liming on the convective drying of urban residual sludges. *Asia-Pacific Journal of Chemical Engineering*, 5(6): 909-914.

Khama, R. 2016. Conception, réalisation et simulation d'un séchoir solaire opérant en mode convectif utilisé pour le séchage de produits agroalimentaires. Ph.D. diss., Département de Génie des procédés. Université Abderrahmane Mira Béjaia (UAMB), Algérie.

Khama, R., F. Aissani, and R. Alkama. 2016a. Design and performance testing of an industrial-scale indirect solar dryer. *Journal of Engineering Science and Technology*, 11(9): 1263-1281.

Khama, R., F. Aissani, R. Alkama, L. Bennamoun, L. Fraikin, T. Salmon, E. Plougonven, and A. Léonard. 2016b. Convective drying of cherry tomato : Study of skin effect. *Journal of Engineering Science and Technology*, 11(3): 443-457.

Koua, K. B., W. F. Fassinou, P. Gbaha, and S. Toure. 2009. Mathematical modelling of the thin layer solar drying of banana, mango and cassava. *Energy*, 34(10): 1594-1602.

Léonard, A., E. Meneses, E. Le Trong, T. Salmon, P. Marchot, D. Toye, and M. Crine. 2008. Influence of back mixing on the convective drying of residual sludges in a fixed bed. *Water Research*, 42(10-11): 2671-2677.

Li, J., L. Bennamoun, L. Fraikin, T. Salmon, D. Toye, R. Schreinemachers, and A. Léonard. 2014. Analysis of the shrinkage effect on mass transfer during convective drying of sawdust/sludge mixtures. *Drying Technology*, 32(14): 1706-1717.

Lopez-Quiroga, E., V. Prosapio, P. J. Fryer, I. T. Norton, and S. Bakalis. 2020. Model discrimination for drying and rehydration kinetics of freeze-dried tomatoes. *Journal of Food Process Engineering*, 43: e13192.

Sacilik, K., R. Keskin, and A. K. Elicin. 2006. Mathematical model of solar tunnel drying of thin layer organic tomato. *Journal of Food Engineering*, 73(3): 231-238.

Sadin, R., G. Chegini, and M. Khodadadi. 2017. Drying characteristics and modeling of tomato thin layer drying in combined infrared-hot air dryer. *CIGR Journal*, 19(1): 150-157.

Sahdev, R. K., M. Kumar, and A. K. Dhingra. 2016. A review on applications of greenhouse drying and its performance. *CIGR Journal*, 18(2): 395-412.

Togrul, I. T., and D. Pehlivan. 2003. Modelling of drying kinetics of single apricot. *Journal of Food Engineering*, 58(1): 23-32.

Zhu, A., and F. Jiang. 2014. Modeling of mass transfer performance of hot-air drying of sweet potato (Ipomoea batatas L.) slices. *Chemical Industry and Chemical Engineering Quarterly*, 20(2): 171-181.