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Mathematical modeling of solar drying Of thin layer tomato

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Last but not least, I'd like to thank my parents, family and friends for giving me full support throughout the whole period of conducting this work and being very understanding so that I can concentrate and give my best.

Thank you

Abstract:

Drying experiments for tomato slices in the hybrid solar dryer with heat exchanger (HSD) were conducted by comparing traditional solar dryer (TSD). Seven mathematical models of drying characteristics were employed to select the most suitable model for describing the drying curves of tomato slices.

Under the same drying time condition, the drying capacity of the TSD is better than the hybrid solar dryer but the HSD is better for saving the quality of the dried product which is the tomato in our study. Meanwhile, it was found that the Demir et al model is the best suitable model to describe the tomato slices drying behaviour.

Keywords: Mathematical modeling, Diffusion, Convective drying, Tomato, Solar dryer

ملخص:

تم اجراء تجارب تجفيف لشرائح الطماطم من خلال استعمال مجفف شمسي معدل مع مبادل حراري ومصدر للمياه الساخنة تقارب حرارتها حرارة المياه الجوفية المتواجدة بمنطقة ورقلة - الجزائر وذلك من اجل ضمان استمرارية عملية التجفيف ليلا حيث تم مقارنة هذا المجفف مع مجفف شمسي عادي يعمل فقط في ظل وجود اشعة الشمس.

تم استخدام سبعة نماذج رياضيتية لاختيار أفضل نموذج لوصف عملية التجفيف لكلا المجفيفين حيث وجد ان نموذج Demir et al هو الأمثل لوصف عملية تجفيف شرائح الطماطم .

الكلمات المفتاحية: نمذجة رياضياتية , الانتشار , طماطم , مجفف شمسي , مبادل حراري

Résumé :

Des expériences ont été menées pour le séchage de tranches de tomates grâce à l'utilisation d'un séchoir solaire modifié avec un échangeur de chaleur et une source d'eau chaude dont la température est proche de la température de la nappe phréatique dans la région de Ouargla - Algérie, afin d'assurer la continuité du processus de séchage la nuit.

Sept modèles mathématiques ont été utilisés pour choisir le meilleur modèle pour décrire le processus de séchage pour les deux séchoirs, où il a été constaté que le modèle de Demir et al est optimal pour décrire le processus de séchage des tranches de tomates.

Mots clés : Modélisation mathématique, Séchoir solaire, Tomate, Diffusion, Séchage convectif, échangeur.

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Nomenclature

m_t	Mass of the product at the time t (g)
m_d	Mass of dry matter (g)
M_t	The moisture content at the time t (kg water/kg dry matter, d.b)
M_0	Initial moisture content (kg water/kg dry matter, d.b)
M_e	Equilibrium moisture content (kg water/kg dry matter, d.b)
MR	Experimental moisture ratio
$MR_{exp,i}$	The observed moisture ratio
$MR_{pre,i}$	The predicted moisture ratio
DR	Drying rate
f	Dimensionless drying rate
r	Correlation coefficient
$RMSE$	Root mean sqaure error
χ^2	Chi-square
N	Number of observations
P	Number of constants
L	Half thickness (m)
TSD	Traditional solar dryer
HSD	Hybrid slar dryer
D_{eff}	Effective moisture diffusivity ($m^2\ s^{-1}$)
D_0	The pre-exponential factor of the Arrhenius equation ($m^2\ s^{-1}$)
E_a	The energy of activation ($kJ\ mol^{-1}$)
T	Drying temperature (°C)
T_{abs}	Absolut temperature (K)
R	Universal gas constant (8.3143 $J\ mol^{-1}\ K^{-1}$)
t	Time (h), (s)

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General introduction

Tomato (Lycopersicon esculentum) widely consumed either fresh or in processed form as: pastes, sauces, ketchup (catsup) … etc.

Solar drying of tomato allows to preserve its nutritional qualities and must be properly designed in order to meet particular drying requirements and give satisfactory performance concerning energy consumption. Mathematical modeling of tomato solar drying reveals the suitable models that can describe the drying behavior of tomato. This study was undertaken to fit the experimental data to 07 mathematical models available in literature, to assess the variation in tomato's moisture using continuous and discontinuous solar drying process on hand, and to determine effective moisture diffusivity on the other hand.

Chapter I

Literature review of solar drying technologies

I.1 Introduction:

The present part aims to investigate in the literature review the classification of solar drying systems used recently for agro-products and another materials preservation on one hand. Four types of solar dryers are discussed. Otherwise, innovative drying process namely swell drying is investigated.

I.2 Advanced in solar drying systems:

Solar drying is a technological process works on the principle of greenhouse effect (1). This system which needs a simple technology allow to be adapted to the rural regions for drying applications (2), also in the most developing countries where supplies of non-renewable sources of energy are either unavailable, unreliable or, for many farmers, too expensive this technology can be used (3). The produce is dried using solar thermal energy in a cleaner and healthier fashion. In broad terms, solar drying system can be classified into two major groups, namely: (1) Passive dryer (conventionally termed natural circulation). Active dryer (most types of which are often called forced convection solar dryers). Otherwise, according to the solar dryer types, there are four types of solar dryers (4). The main categories of solar dryers are presented in Figure (1.1) and detailed with their advantages and limitations in Table (1-1).

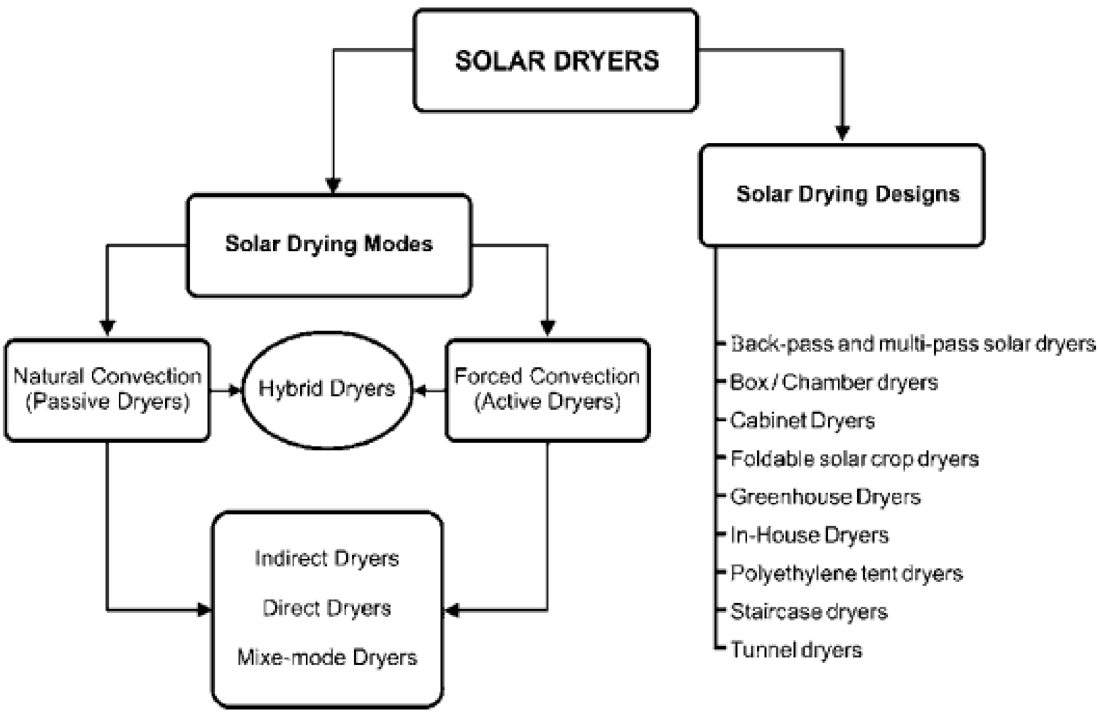

Figure I.1: *Classification of solar drying systems* (Banout, 2017)

***Table I.1**: presents the main advantages and limitations of various solar dryer types*

Type	*Advantages*	*Limitations*
Direct type	- Least expensive - Simple	- UV can damage the product - Small capacity - Required long drying time - Low efficiency - The d product to be dried itself acts as an absorber
Indirect type	- Less damage from high temperature - Products protected from UV - High efficiency	- More complex and inexpensive than direct type
Mixed-mode	- High efficiency - Less damage from high temperature	UV radiation may cause damage to the product - More complex and inexpensive than direct sun
Hybrid system	- The ability to work without the sun reduces - Loss of product is minimized - Allows better control of drying - High efficiency - Required short drying time - Good quality	- Expensive - May cause fuel dependence

I.2.1 Direct Solar Dryer :

Solar energy is specifically used for dehydration crops in the direct-type solar dryer. In the direct mode solar dryer. The researches and structure of direct solar dying is quick and operational and cost of maintenance are often lower and limited amount amounts of the food product can be dried (5) . A direct-type solar dryer is commonly used in areas that receive direct sunlight for longer periods during the day (6). In these dryers, the material to be dried is placed in an enclosure, with transparent covers or side panels. Heat is generated by absorption of solar radiation on the product itself as well as the internal surfaces of the drying chamber. This heat evaporates the moisture from the drying product and promotes the natural circulation of drying air (7). A direct solar dryer also is known as a solar cabinet dryer. Previous works on this type are presented below.

Piles of wood Perea-Moreno et al., (2016), rehydrated Deglet-Nour Dates Mennouche et al., (2014), the performance analysis of a greenhouse dryer with insulated north wall in no-load

condition Chauhan and Kumar (2016), solid waste from steel wire industry Ferreira et al., (2014), tomatoes Ringeisen et al., (2014), chilli pepper Tunde-Akintunde (2011).

I.2.2 Indirect Solar Dryers :

In indirect solar dryers, the drying process depends mainly on the drying conditions (air mass flow rate, and airflow temperature and relative humidity) in the drying chamber and on the drying kinetics of the product at those conditions. The drying conditions at the inlet of the drying chamber depend on the air heating process in the solar collector (8), and thus the drying process is highly dependent on the ambient conditions and the solar irradiance. While the solar drying process has characterizes by variable drying conditions, the drying kinetics is generally studied at constant drying conditions (8). The indirect solar drying system is more efficient as compared to the direct solar drying system, since the air is heated by the operation of a solar air heater and the heated air flow in the room where the crop is stored. Several works on this system are cited below:

granny smith apples Lucía Blanco-Cano et al., (2016), Thymus and mint El-Sebaii and Shalaby (2013), cocoa beans Koua et al., (2019), pistachio Mokhtarian et al.,(2017), tomatoes Bagheri et al., and Manaa et al., (2013), banana Lingayat et al., (2017), red chilli Castillo-Téllez et al., (2017) and Fudholi et al., (2014).

I.2.3 Mixed-mode solar dryers :

The combination of direct and indirect solar dryer is called mixed mode solar dryer; The product is dehydrated by this process. either by indirect solar radiation or when ambient air is first heated. It is passes through the room where the crop is kept at that time (9).

Some works in this type of solar dryer from the literature are cited bellow:

Sultana grape and red pepper ELkhadraoui et al., (2015), grapes Pardhi and Bhagoria, (2013), red peppers Azaizia et al., (2017).

I.2.4 Hybrid solar dryers:

Hybrid solar drying systems are dryers where the solar energy is just one of more sources of energy used for heating the drying air. They employ solar energy with additional electric or fossil fuel-based heating systems and ventilators to ensure air circulation. Commonly the hybrid solar dryers operate under forced convection mode. If they are warm enough, the drying air heated by solar energy could be used directly for the drying process; otherwise, the dehydrator operated by fossil fuel is used to achieve required values of drying temperatures (e.g., during nights or during the time with low insolation like rainy seasons) (10). Furthermore, Fudholi et al., (2010) described in their work different hybrid dryer designs such as shown in Figure (1.2):

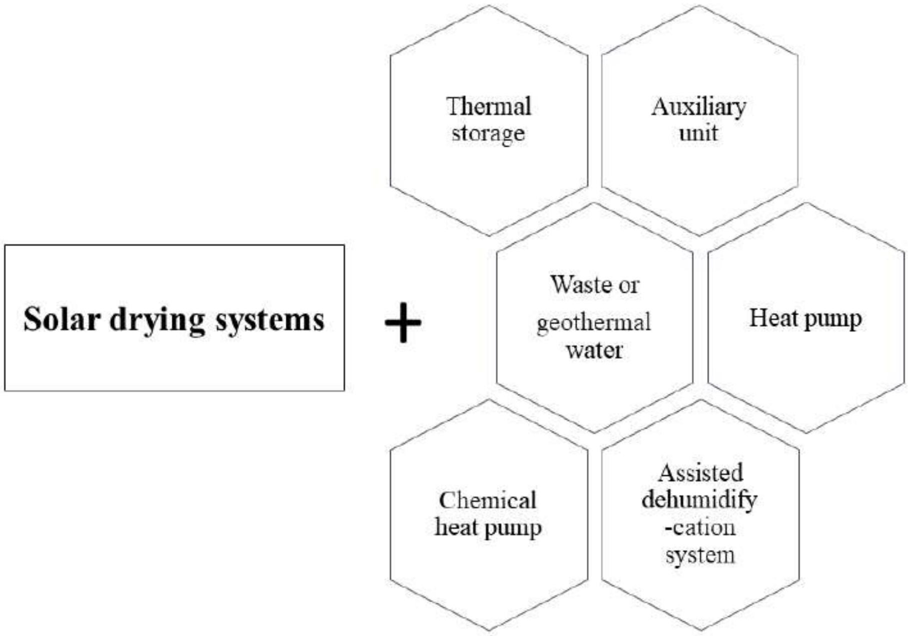

Figure Error! No text of specified style in document..1: *Solar drying systems with various heating systems*

Potato Singh and Kumar (2013), cashew kernel Dhanushkodi et al., (2017), natural rubber sheet Sonthikun et al., (2016), red chili Yassen & Al-Kayiem (2016), tomato Akhijani et al., (2016), pineapples Sekyere et al., (2016) , potatoes Ziaforoughi and Esfahani (2016) , cassava Yahya et al., (2016), Moroccan rosemary leaves Mghazli et al., (2017), raw olive pomace and deoiled olive pomace Koukouch et al., (2017), sludge Ali et al., (2016), raw olive pomace Koukouch et al., (2015), thyme Lahnine et al., (2016), peppermint Morad et al., (2017), the effect of N-PVT solar collector on the energy and exergy analysis Tiwari and Tiwari (2017), analyzes of the energy and exergy of fluidized bed dryer integrated with biomass furnace Yahya et al., (2017), and biomass (coconut coir) Atnaw et al., (2017).

a) Dryers with thermal energy storage:

In order to avoid the intermittent effects in solar dryers, some of the researchers integrated it with thermal energy storage to store excess heat energy in the sunshine time and utilize it in the off-sunshine time. The surplus solar energy can be stored in solids or well-insulated fluids in the form of sensible heat or latent heat or thermos-chemical. Among these methods, latent heat storage provides higher storage with small temperature difference between storing and releasing energy (11). Figure (1.3) shows some of the major techniques involved in thermal energy storage.

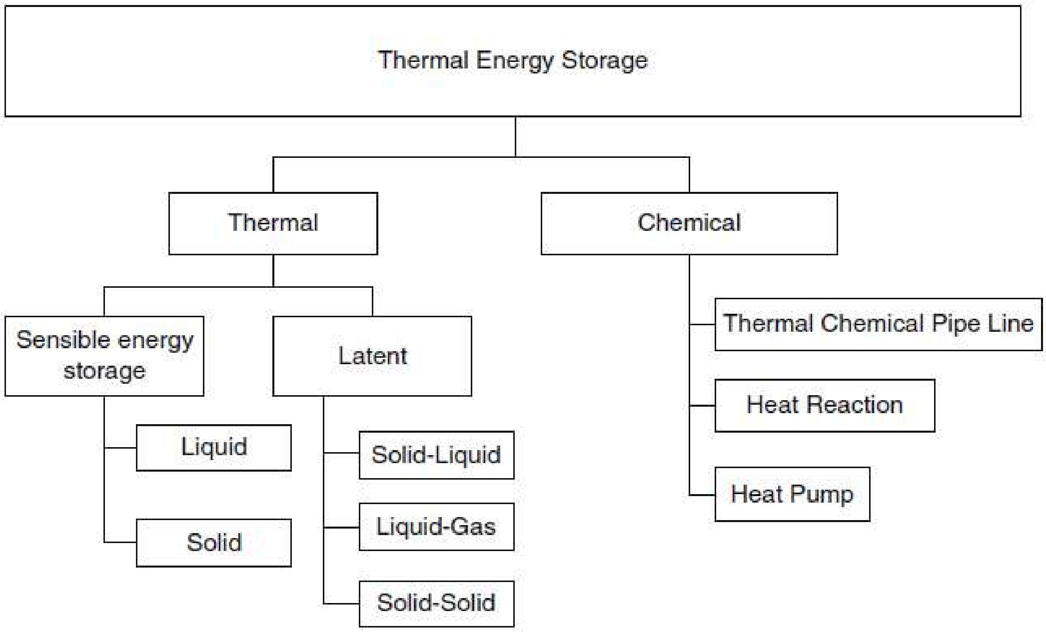

***Figure Error! No text of specified style in document..2**: Various types of thermal energy storage* (Bal et al., 2010)

Thermal storage with barren floor (BCC), floor covered with black PVC sheet (PVC) and black coated (BPCF) in no-load conditions Prakash et al., (2016), gost chilli pepper Rabha et al., (2017), red chilli Rabha & Muthukumar (2017), vitis vinifera and momordica charantia Natarajan et al., (2017), fresh leafy herbs Jain and Tewari (2015), cocoa beans Dina et al., (2015), mushrooms Reyes et al., (2014) , osmotically dehydrated cherry tomatoes Nabnean et al., (2016), apricot Baniasadi et al., (2017), investigation of the shell and tube latent heat storage using paraffin wax as heat change material Agarwal and Sarviya (2016), apple Atalay et al., (2017), bitter gourd Vijayan et al.,(2016), and valeriana jatamansi Bhardwaj et al., (2017).

I.3 Conclusion:

Drying can be done either by traditional sun drying or industrially through the use of solar dryers or hot air drying. Selecting the solar dryers and the drying methods is generally limited to the amount of production and the proprieties of the surrounding conditions (location).

Chapter II

Experimental procedure and mathematical modeling

II.1 Introduction:

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. In the Mediterranean countries the traditional technique of fruit and vegetable drying is by using the sun, but it requires long drying times that may have adverse consequences to the product quality and the final product may be contaminated from dust and insects or suffer from enzyme and microbial activity (12). In order to improve the quality, a hybrid solar dryer (HSD) has been used alongside a traditional solar dryer (TSD).

II.2 Solar dryer description:

In this study, two dryers were employed; one was a traditional solar dryer (discontinuous drying process), the other was a hybrid solar dryer (continuous drying process).

II.2.1 Hybrid Solar Dryer:

The hybrid solar Dryer ***Figure II.1*** is used in order to ensure the continuity of the drying process during the night, or cloudy days. It has a heat exchanger ***Figure II.2*** fed by a source of hot water ***Figure II.3***. This system presents a simulation device of heat exchanger supplied with the Albien water. The temperature of the hot water is fixed at 70°C. This temperature is justified by a measurement of temperature in several sites of the Albien water source in Ouargla city (13).

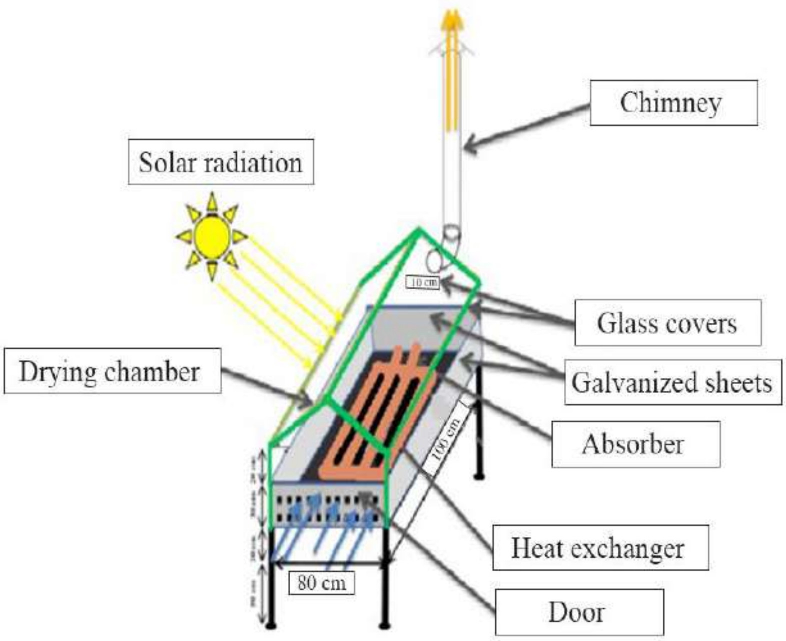

Figure II.1: *Schematic diagram of the hybrid solar dryer HSD.*

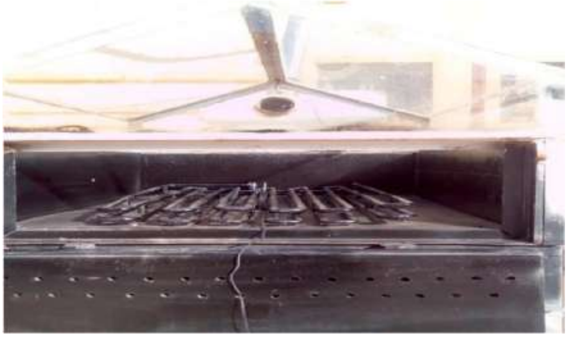

Figure II.2: *Emplacement of the heat exchanger inside the drying room.*

Figure II.3*: Picture of the hot water source device*

Figure II.4: *Picture of the direct solar dryer.*

II.2.2 Traditional Solar Dryer :

This dryer uses solar energy for drying during daytime while the product is stored in an isolated place during the night till the next day.

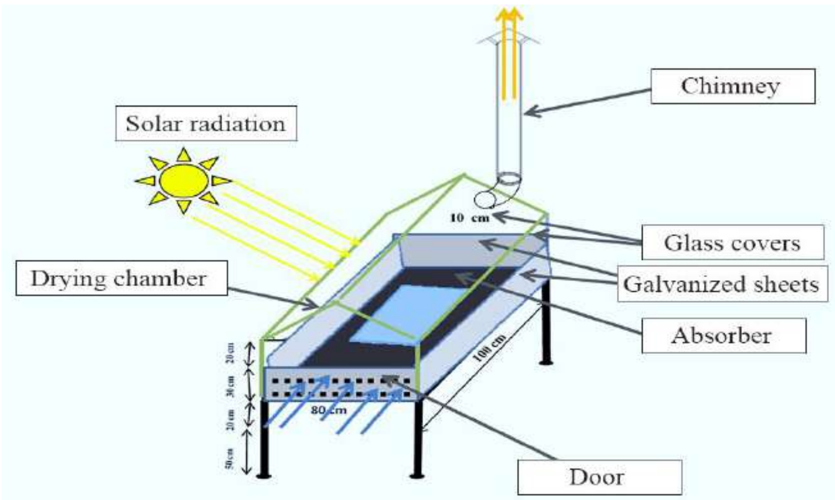

Figure II.5: *Schematic diagram of the traditional solar dryer TSD.*

II.3 Sample preparation:

Ten kilograms of fresh tomato were dried in these experiments. The slices of 1 cm thickness were selected one by one using a visual criterion such as height, lack of physical injury, and uniform ripening degree. The tomato slices were skinned and cut into half of 0.5 cm thickness.

Figure II.6: *Tomato slices in the drying chamber the drying chamber of the HSD (continuous)*

Figure II.7: *Tomato slices in of the TSD (discontinuous)*

II.4 Drying kinetics:

a) Determination of moistures and drying rate:

The initial moisture content of tomato slices was measured by utilizing a moisture analyser (type MA 45) with 3g of tomato slices at 105 °C. The moisture content (M), moisture ratio (MR), and drying rate (DR) values were determined using Eqs. 1, 2, and 3 as follows:

$$M_t = \frac{m_t - m_d}{m_d} \quad (1)$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (2)$$

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (3)$$

II.5 Mathematical modeling :

Mathematical modelling represents the real system or process in terms of mathematical equations and works to be the most efficient technique to realize the profundity of drying in the postharvest operation of agro-products. In other word, it's a principled activity based on principles of overarching or meta-principle phrased as questions regarding the objective and rationale of mathematical modelling. Also, the correlation coefficient (*r*), chi-square and root mean square error (*RMSE*) are the most important criteria for selecting the best curve equation. Researchers reported that the best suitable model should have higher values of *r* and lower values of chi-square χ^2 and *RMSE* (14).

In the current study, the experimental outputs were fitted to seven empirical and semi-empirical models to predict the variation in the moisture content of tomato slice during continuous (with heat exchanger) and discontinuous process (without heat exchanger). Among the tested models, the most appropriate one was selected according to the statistical parameters given in Eqs. 7, 8, and 9. OriginPro 2021 software (OriginLab Corporation) is used for the regression analyses. The obtained drying curves of experimental *MR* which were fitted with seven models are given in ***Table II.1***.

Table II.1: *Moisture ratio equations applied to the experimental drying curves*

Model name	Model	Reference
Lewis/Newton	$MR = exp(-kt)$	(15)
Logarithmic	$MR = a\ exp(-kt) + c$	(16)
Two-term	$MR = a\ exp(-kt) + b\ exp(-k_1 t)$	(17)
Wangh and Singh	$MR = 1 + at + bt^2$	(18)
Verma et al.	$MR = aexp(-kt) + (1-a)exp(-gt)$	(19)
Demir	$MR = aexp(-(kt)^n) + b$	(20)
Midili and Kucuk	$MR = aexp(-kt^n) + bt$	(21)

We used drying mathematicals models to select the most suitable model for describing the drying curves of tomato during the drying process, as given in the ***Table II.1***. According to Akpinar and Bicer (22) hypothesis, the most appropriate drying model can be selected by applying the following statistical parameters :

Correlation coefficient (*r*) – The highest !

$$r = \frac{\sum_{i=1}^{n}(MR_i - MR_{pre,i}).\sum_{i=1}^{n}(MR_i - MR_{\exp,i})}{\sqrt{\left[\sum_{i=1}^{n}(MR_i - MR_{pre,i})^2\right].\left[\sum_{i=1}^{n}(MR_i - MR_{\exp,i})^2\right]}}$$ (23) (7)

Root Mean Square Error (RMSE) – The lowest !

$$RMSE = \sqrt{\left[\frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{\exp,i})^2}{N}\right]}$$ (24) (8)

Reduced chi-square (χ^2) - The lowest!

$$x^2 = \frac{\sum_{i=1}^{n}(MR_{\exp,i} - MR_{pre,i})^2}{N - P}$$ (25) (9)

II.6 Effective moisture diffusivity :

The effective moisture diffusivity is defined by the term (D_{eff}) in ($m^2\ s^{-1}$) and used to describe all means of transporting water inside a sample. It's the main physical property in the drying of food and other products that allow modelling of the moisture movement from the core to the surface. It characterizes a function of drying temperature and moisture content evolution in material [41]. Usually, the effective moisture diffusivity calculated by using the second simplified Fick's law as givenin Eq. 10:

$$\frac{\partial MR}{\partial t} = \nabla\left[D_{eff}\nabla\left(\frac{M_t - M_e}{M_0 - M_e}\right)\right] = D_{eff}\nabla^2\left(\frac{M_t - M_e}{M_0 - M_e}\right)$$ (26)

Based on Crank [42] correlation, answering Fick's second law by assuming:

(i): The drying process is exclusively diffusional.

(ii): The diffusion coefficient and product temperature are constants.

(iii): Shrinkage during the drying process is neglected.

(iv): Infinite slab geometry.

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\pi^2\frac{D_{eff}.t}{4L^2}\right)$$ (27) (11)

For a considerably longer drying time, all terms of the above series are marginal relative to the first term. Thus, **Error! Reference source not found.** becomes:

$$MR = \frac{8}{\pi^2} \exp\left(\pi^2 \frac{D_{eff}.t}{4L^2} \right) \qquad (28)\ (12)$$

Effective moisture diffusivity was found by plotting experimental drying results for ln(*MR*) vs drying time (s). After the slope of the straight line is determined, D_{eff} has been calculated using Eq. 13:

$$Slope = -\frac{\pi^2 D_{eff}.t}{4L^2} \qquad (29)\ \ (13)$$

II.7 Conclusion :

The integration of the heat exchanger inside solar dryer ensures the continuity of drying process at the night and even during cloudy days. Mathematical modelling is the most efficient technique to realize the profundity of drying in the postharvest operation of agro-products

Chapter III

Findings

III.1 Introduction :

In order to describe the drying behavior of tomato slice two solar dryers have been used. The experiment was carried out in LENREZA laboratory, University of Ouargla, Algeria. Moreover, numerical simulation was carried out and the results were compared with the experimental results.

III.2 Data Source :

The data used in this study has been taken from the experimental results of Guessoum & Houti Master's thesis.

III.3 Surrounding conditions:

The change of the drying chamber temperature in the solar dryer with and without heat exchanger is shown in Figure III.1 The range of ambient temperature inside the drying chamber with heat exchanger HSD was 41.8~64.7 ◦C. Meanwhile, the range of temperature inside the drying chamber without heat exchanger TSD was 33.3~55.7 ◦C.

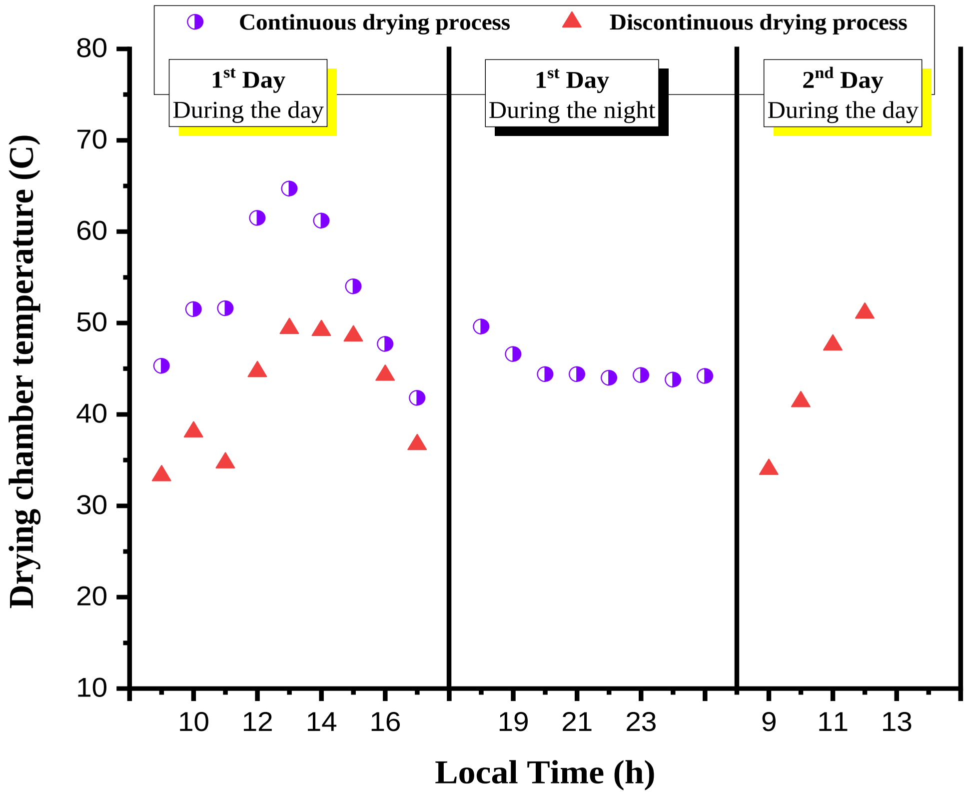

Figure III.1: *Experimental measurements of the drying chamber temperature in the solar dryer with and without heat exchanger*

III.4 Kinetics :

The change of tomato slices' moisture content is shown in **Figure III.2** The tomato slices moisture content of solaer dryer without the heat exchanger TSD was 1.110307g g−1 lower than that of the solar dryer with the heat exchanger HSD at the end of first day and tomato slices moisture content of continuous and discontinuous process was 0.110307 g g−1 and 0.134444 g g−1 respectively at the end of drying. These results indicate that the drying capacity of the solar dryer without heat exchanger TSD is higher than that with heat exchanger HSD under the same conditions. Furthermore, according to **Figure III.2**, drying temperature has an important influence on the different solar drying curves of tomato slices.

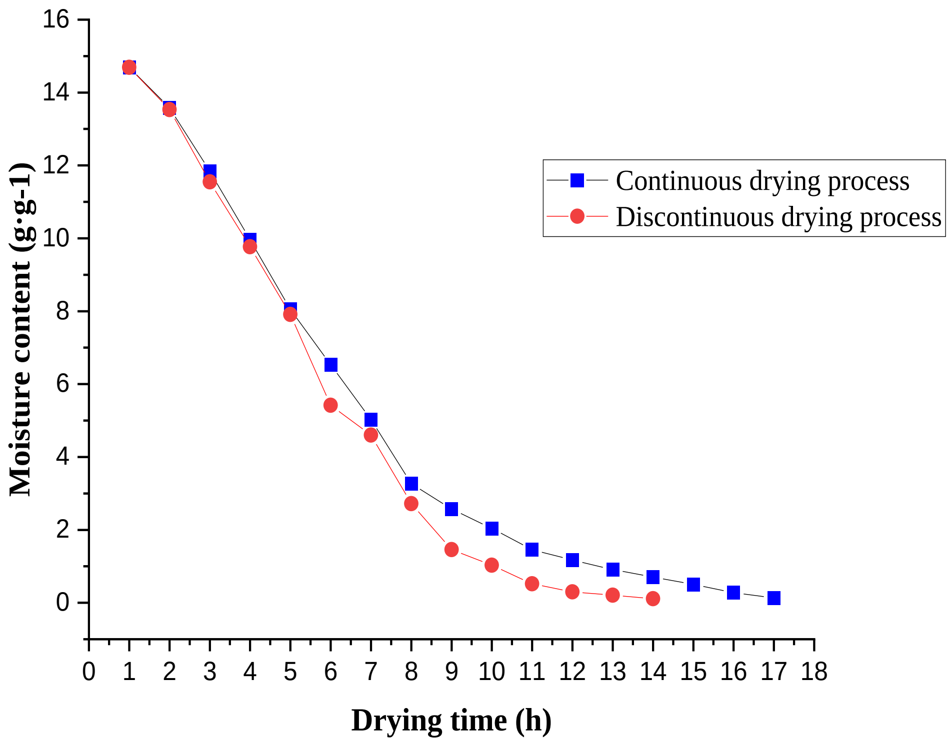

Figure III.2: *The change of tomato moisture content*

Figure III.2 represented the change of moisture ratio for tomato slices. The moisture ratio ranged from 1 to final moisture ratio of about 0.009 with the heat exchanger dryer HSD. Meanwhile, the moisture ratio ranged from 1 to the final moisture ratio of about 0.007 under the discontinuous operation mode TSD. These results again indicate that the solar dryer with the heat exchanger HSD its drying capacity was lower than that of without heat exchanger TSD under the same conditions. In addition, the decrease in the rate of the moisture ratio was faster at the beginning of the drying experiment and later decreased, as shown in Figure III.3. This is because the tomato slices' surface water evaporated during the initial drying process, and the water content of tomato slices diffuses from inside to the surface of drying mate

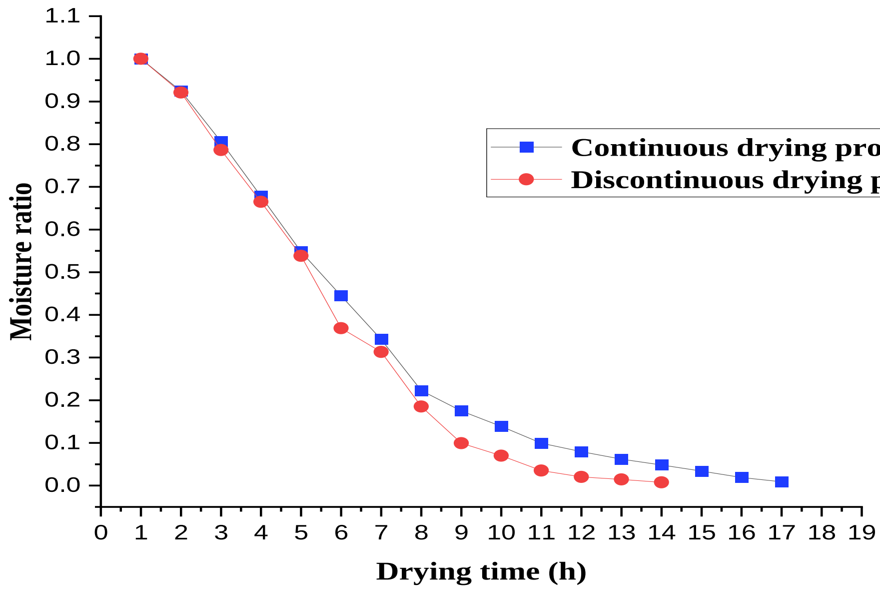

Figure III.3: *The change of moisture ratio for tomato drying.*

Figure III.4 shows that the traditional solar dryer (TSD) offered highest drying rate during the first day.

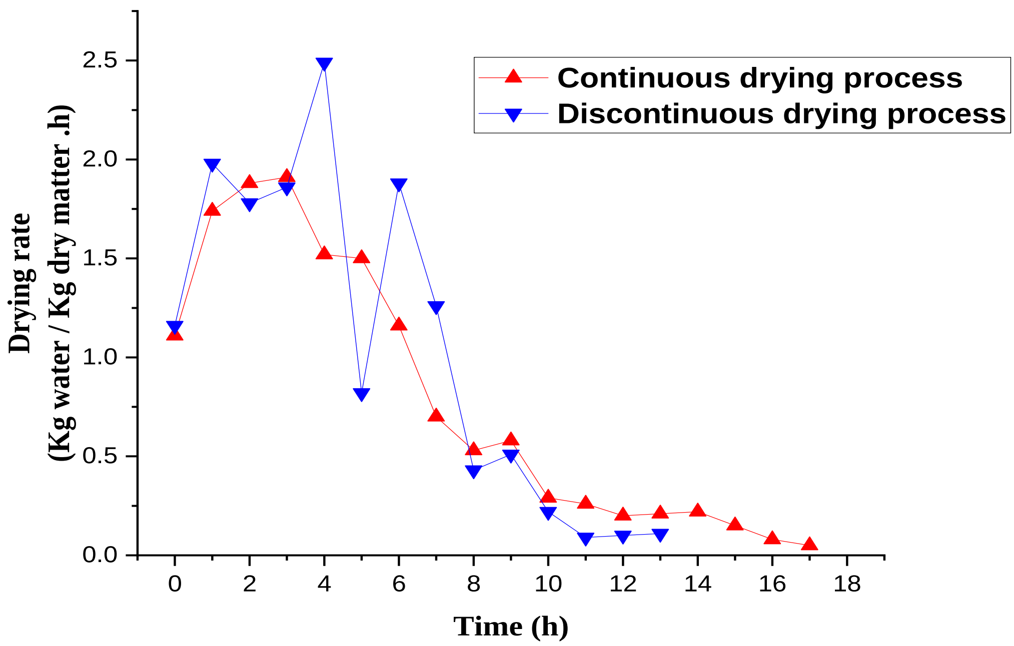

Figure III.4 : Drying rate (DR) against drying time for the experimental conditions

III.5 Mathematical modeling:

The OriginLab software has been used for the statistical average calculations of the parameters as shown in ***Table III.1*** for both continuous and disconinuous process. Even though the correlation coefficient "*r*" remains high for the seven empirical models it can be concluded that

Demir et al model can be selected as the best model for fitting the tomato slices drying because it showed the highest vlue of correlation coefficient and the lowest value of *RMSE* with *r* value of 0.99907 and *RMSE* value of 0.01149 for the continuous process and r value of 0.01646 and *RMSE* value of 0.01646 for discontinuous process. Therefore, the Demir et al model is the most suitable to describe the drying behaviour of tomato slice.

Table III.1: *Average values of modelling parameters (*R, RMSE, *and* χ^2*)*

	Continuous process			Discontinuous process		
Models	*r*	*RMSE*	χ^2	*r*	*RMSE*	χ^2
Lewis/Newton	0.90873	0.10237	0.01048	0.87275	0.12824	0.01645
Logarithmic	0.9878	0.04002	0.0016	0.98395	0.04952	0.00245
Two-term	0.97711	0.05688	0.00324	0.95784	0.08417	0.00708
Wang and Singh	0.96319	0.06715	0.00451	0.95303	0.08109	0.00658
Verma *et al.*	0.99842	0.01442	2.07891E-4	0.99099	0.03709	0.00138
Demir et al	0.99907	0.01149	1.31922E-4	0.99839	0.01646	2.708E-4
Midilli-Kucuk	0.89713	0.12058	0.01454	0.95822	0.08378	0.00702

Figure III.5 and ***Figure III.6*** show a good enough alignment of experimental values of moisture ratios and the calculated values delivered by Demir et al model.

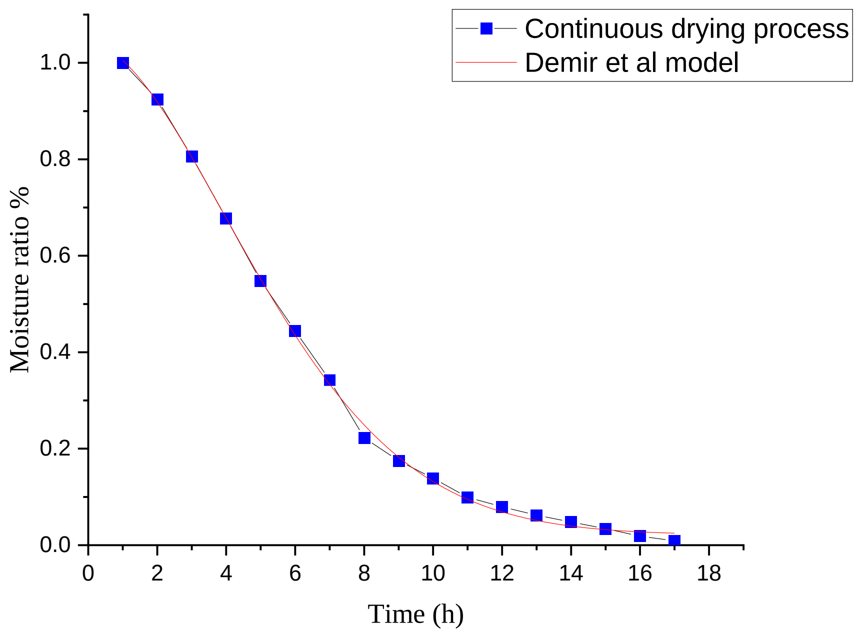

Figure III.5: *Predicted and experimental moisture ration with Demir et al model for continuous drying process*

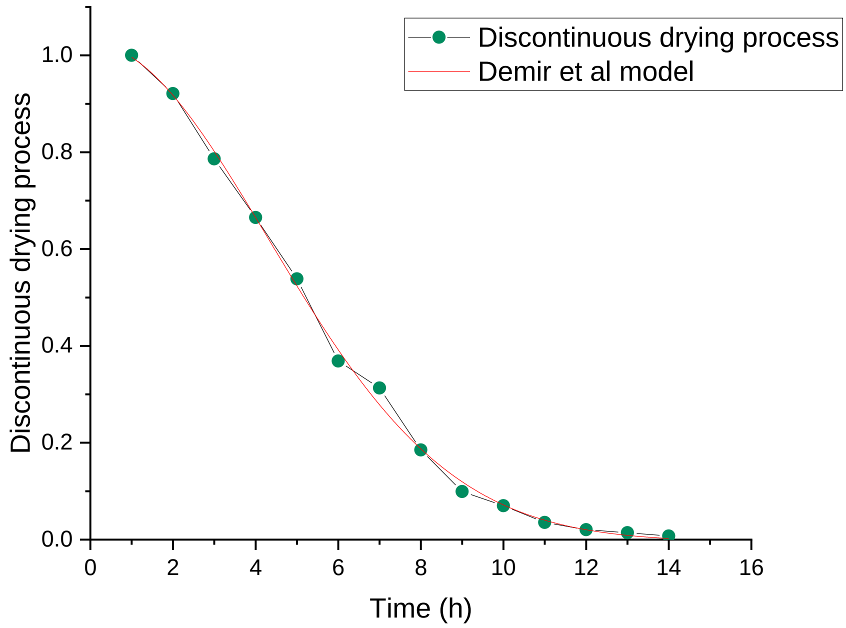

Figure III.6: *Predicted and experimental moisture ration with Demir et al model for discontinuous drying process*

Figure III.7 to ***Figure III.18*** show the calculated values delivered by the rest 6 models for both processes

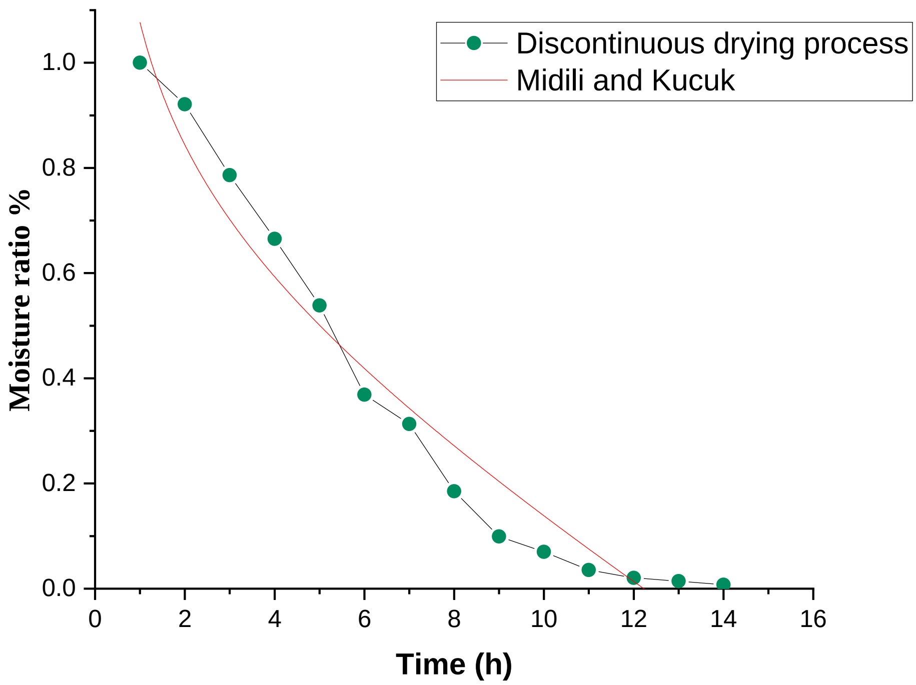

Figure III.7: *Pr and Exp MR with Midli and Kucuk model for discontinuous drying process*

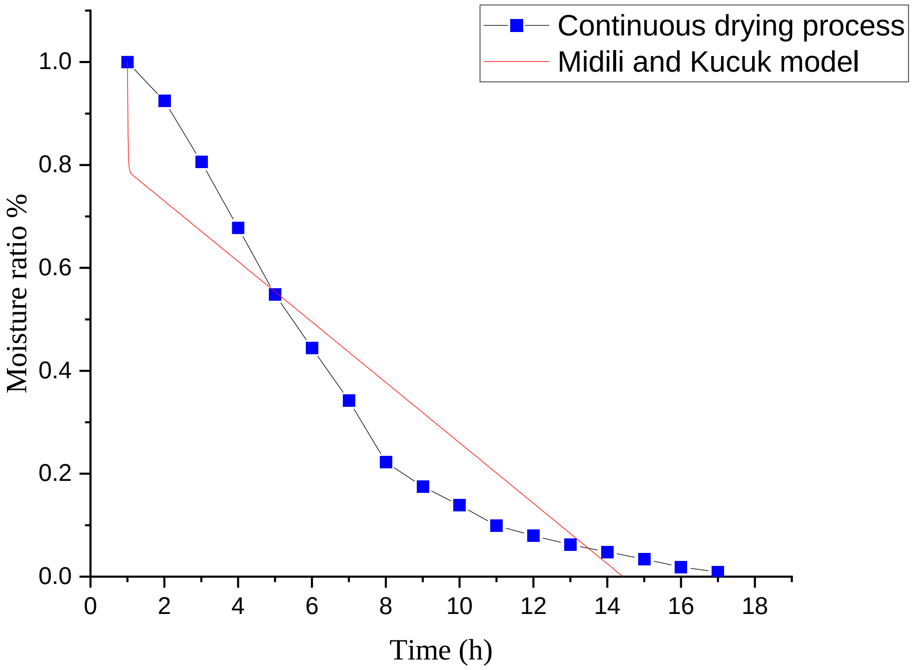

Figure III.8: *Pr and Exp MR with Midli and Kucuk model for continuous drying process*

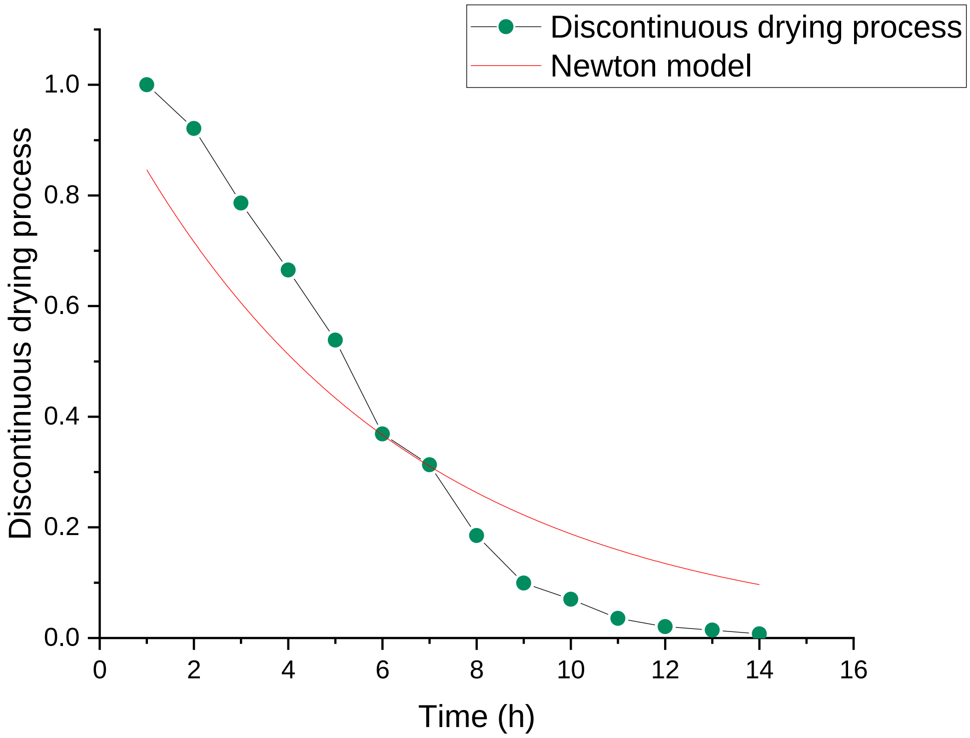

Figure III.9: *Pr and Exp MR with Newton/Lewis model for discontinuous drying process*

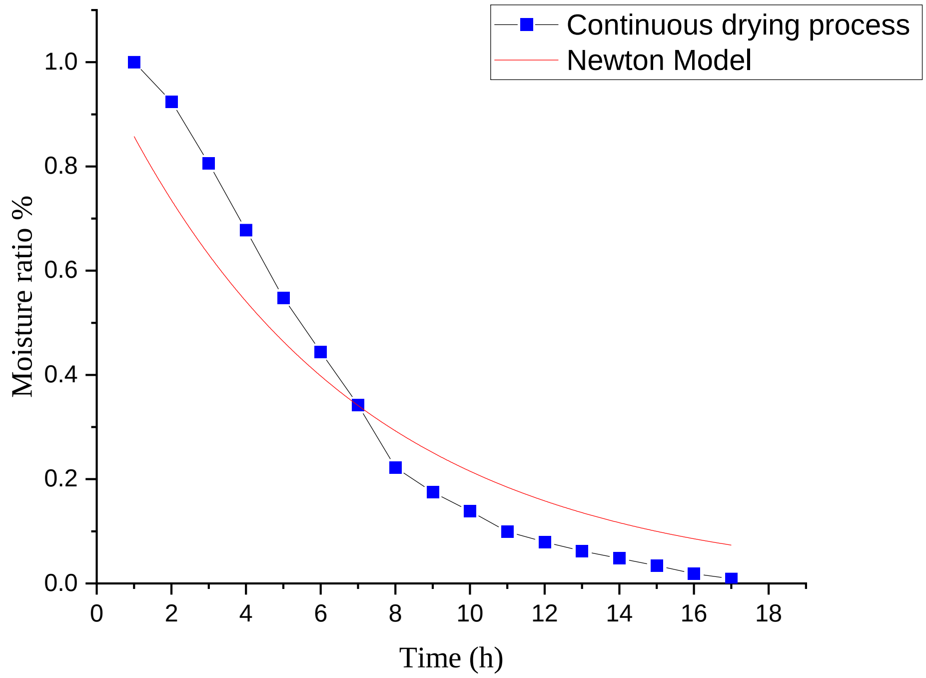

Figure III.10: *Pr and Exp MR with Newton/Lewis model for continuous drying process*

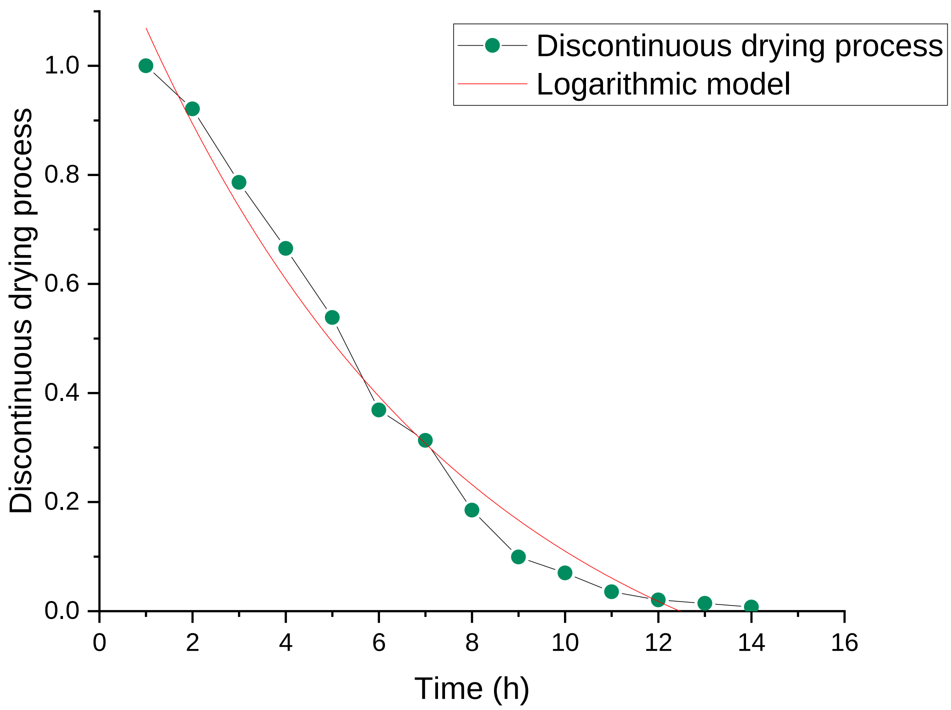

Figure III.11: *Pr and Exp MR with Logarithmic model for discontinuous drying process*

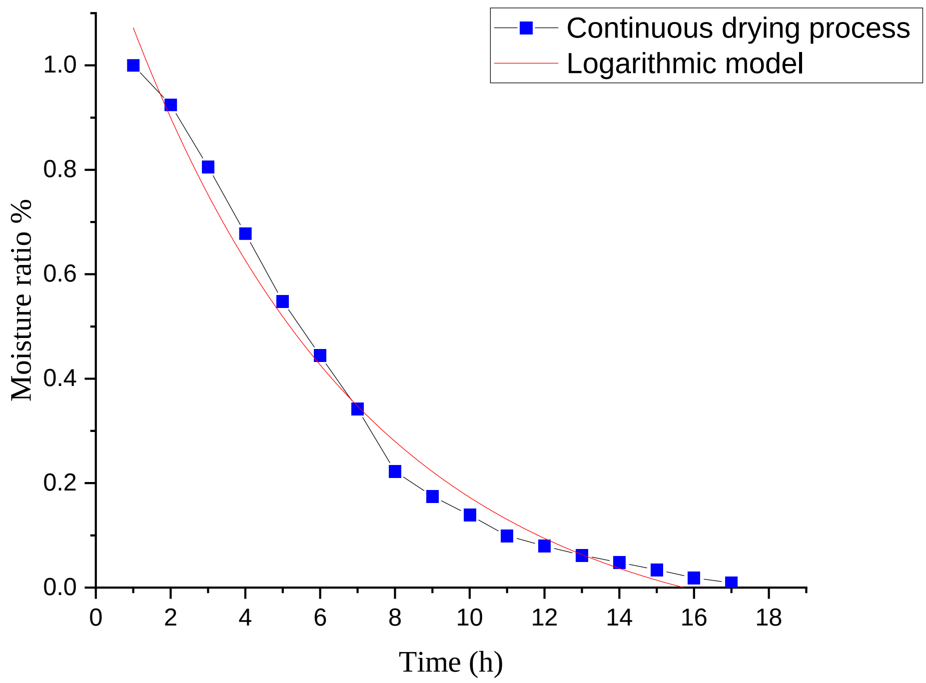

Figure III.12: *Pr and Exp MR with Logarithmic model for continuous drying process*

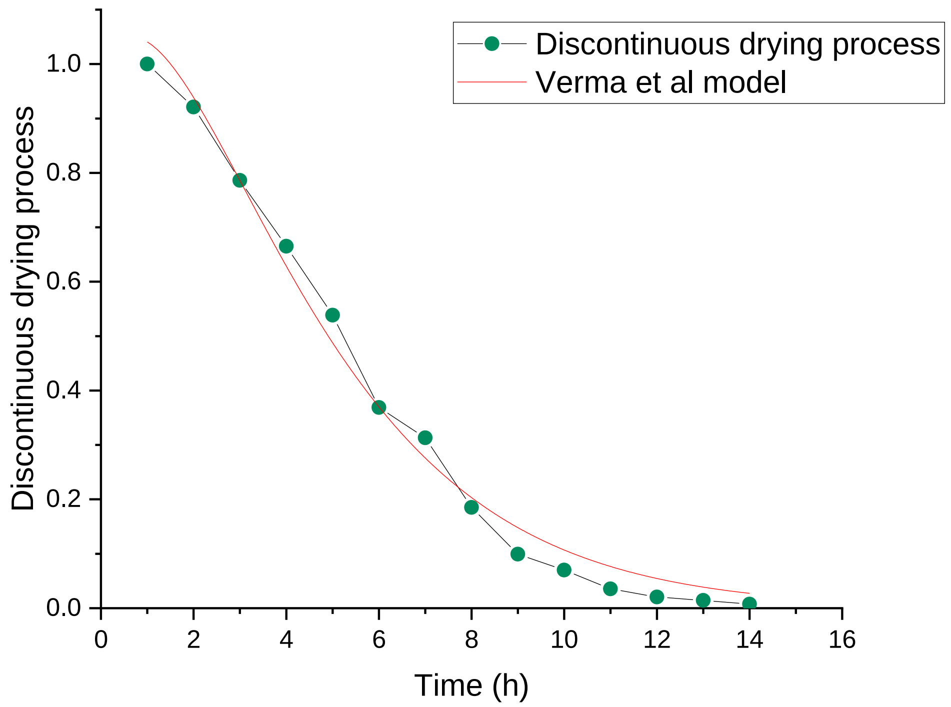

Figure III.13: *Pr and Exp MR with Verma et al model for discontinuous drying process*

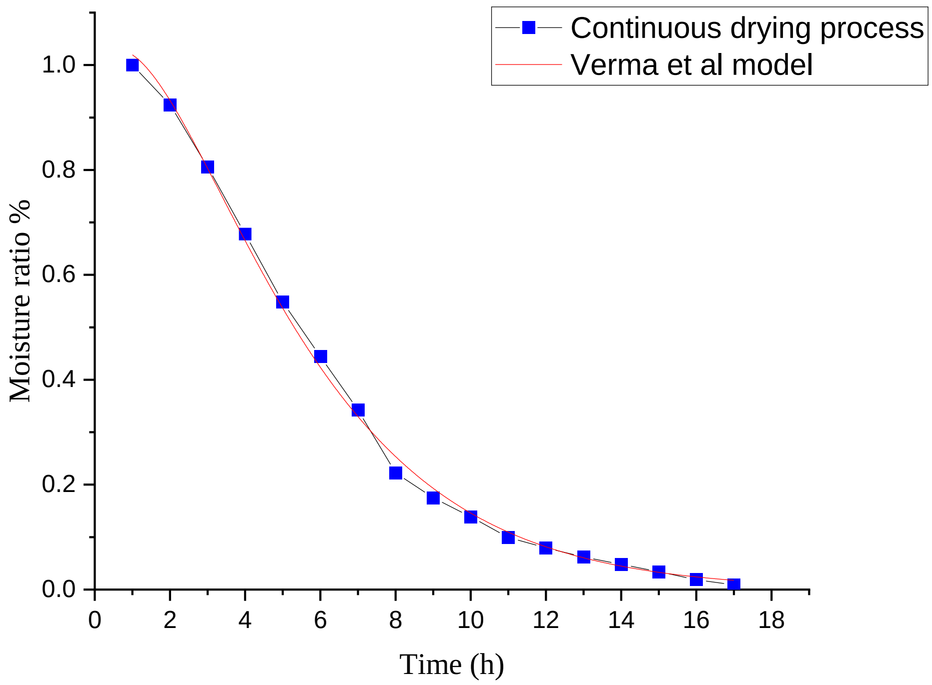

Figure III.14: *Pr and Exp MR with Verma et al model for continuous drying process*

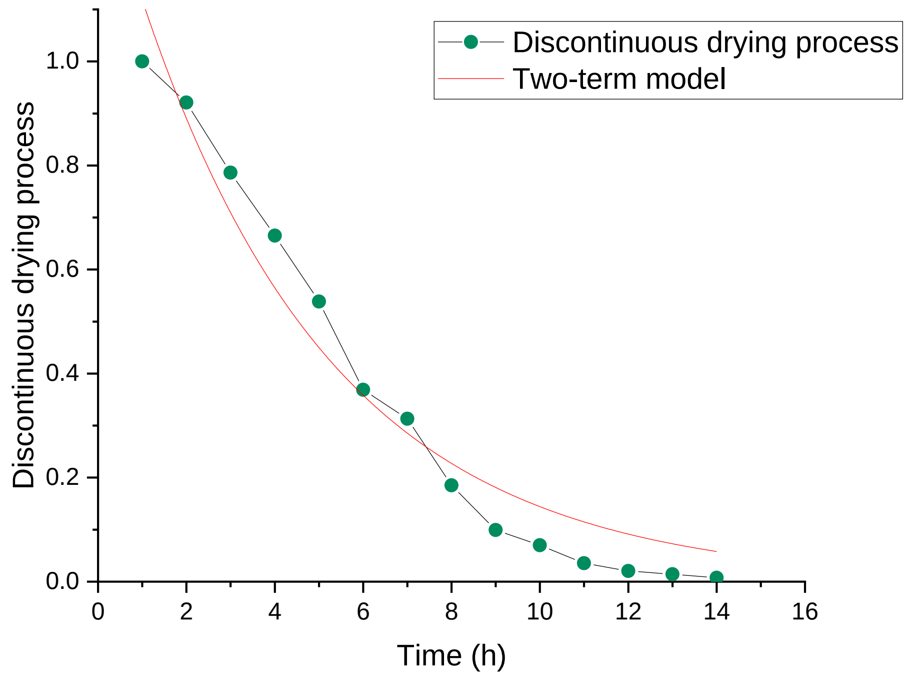

Figure III.15: *Pr and Exp MR with Two-term model for discontinuous drying process*

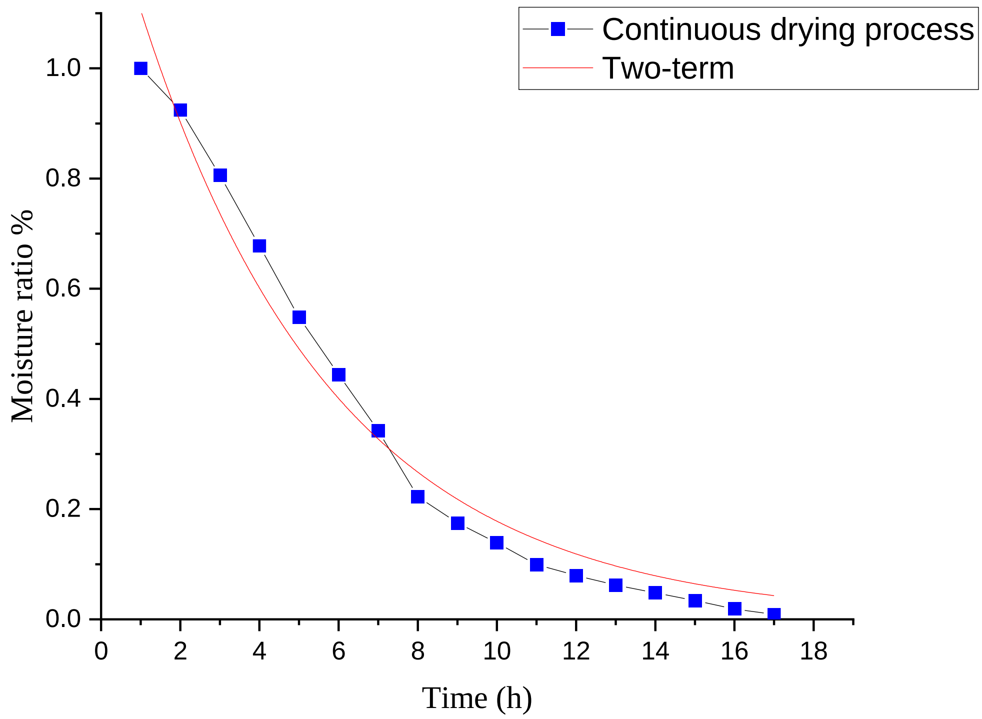

Figure III.16: *Pr and Exp MR with Two-term model for continuous drying process*

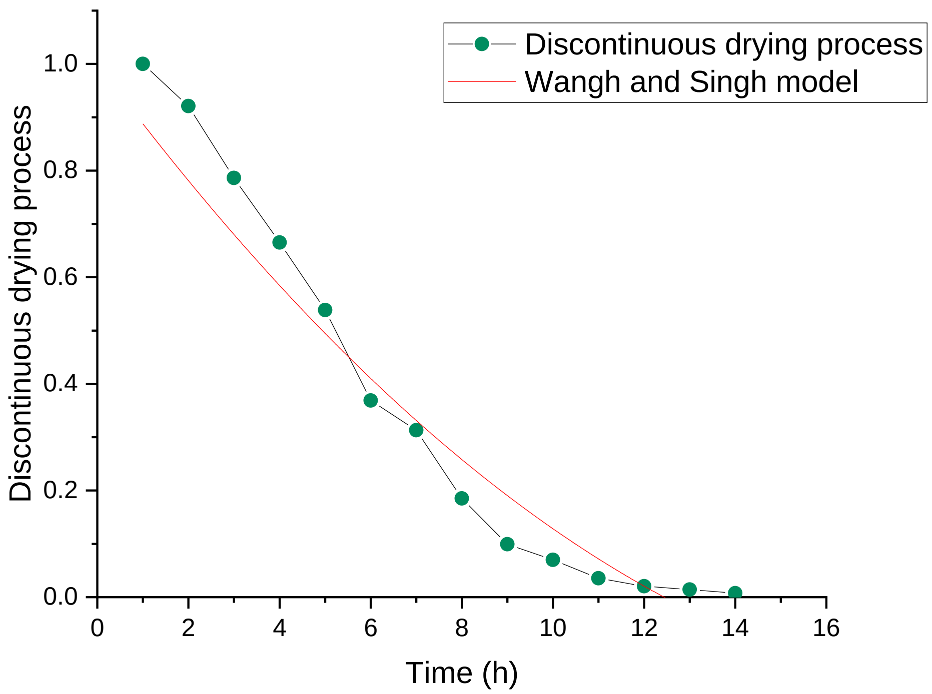

Figure III.17: *Pr and Exp MR with Wangh and Singh model for discontinuous drying process*

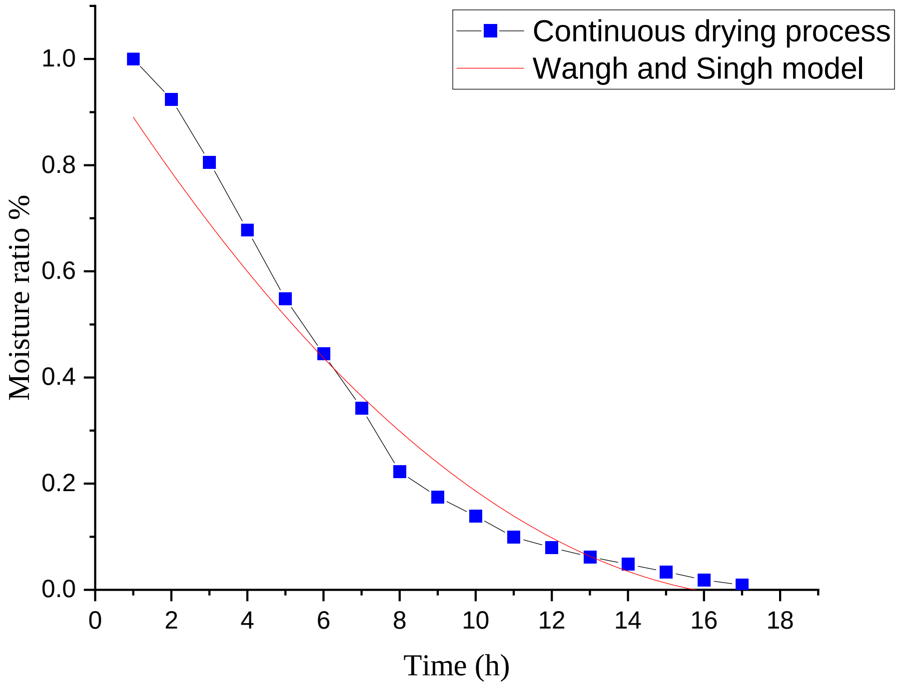

Figure III.18: *Pr and Exp MR with Wangh and Singh model for continuous drying process*

III.6 Effective moisture diffusivity :

The diffusivity values are given in ***Table III.2***. It shows that the values of D_{eff} ranged between 10^{-8} and 10^{-12} m^2 s^{-1} which is good for dried food products (30).

Table III.2: *Displays the calculated effective moisture diffusivity for both drying process during the drying time with the help of MS Excel 2019*

	Effective moisture diffusivity (m^2 s^{-1})	
Drying time (h)	**Continuous Process (With heat exchanger)**	**Discontinuous process (Without heat exchanger)**
0	0	0
1	3.80874E-10	4.39511E-10
2	2.40148E-10	2.32457E-10
3	1.97134E-10	1.95545E-10
4	1.45323E-10	2.62522E-10
5	1.44993E-10	9.11331E-11

6	1.99366E-10	2.43252E-10
7	9.55889E-11	2.46903E-10
8	8.01931E-11	1.21138E-10
9	1.03245E-10	2.10952E-10
10	6.15091E-11	1.52791E-10
11	6.34632E-11	9.00694E-11
12	5.7449E-11	1.49682E-10
13	7.49267E-11	/
14	1.15043E-10	/
15	1.42084E-10	/
Deffusivity Totale (m^2 s^{-1})	D_{efft} = 7.76192 10^{-10} (m^2 s^{-1})	D_{efft} = 1.08358 10^{-9} (m^2 s^{-1})

Figure III.19 show that the effective moisture diffusivity of the traditional solar dryer (TSD) is greater than the hybrid solar dryer (HSD)

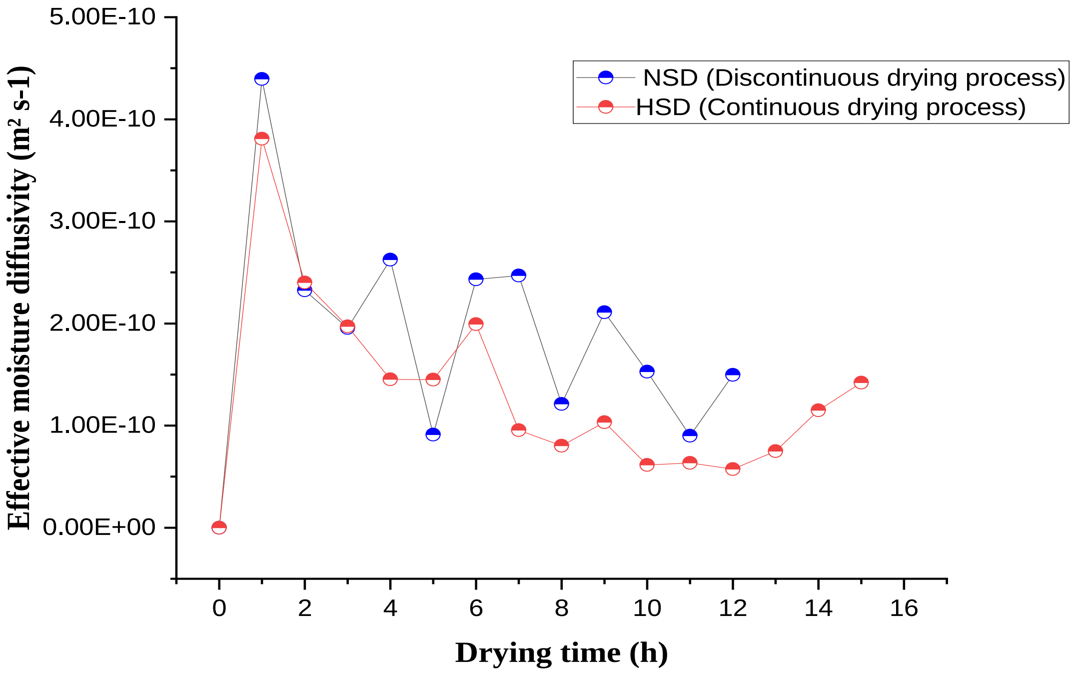

Figure III.19: *Effective moisture diffusivity Changement during the drying time*

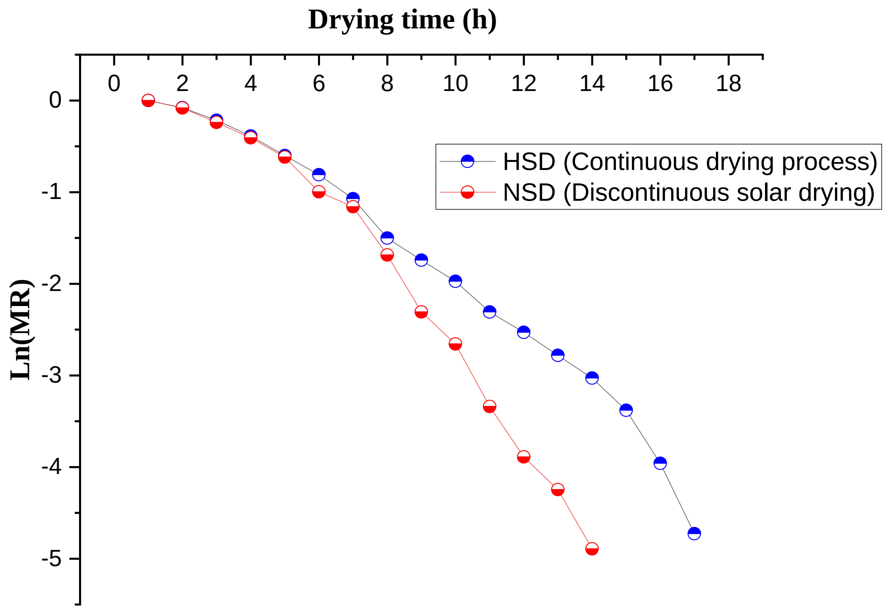

Figure III.20: *Ln (MR) vs drying time*

III.7 Conclusion:

Drying curves were established and fitted using 7 models, drying rate and drying efficiency curves were determined, effective moisture diffusivity was estimated and quality of dry tomato slices was evaluated. Results showed that drying curves for both continuous and discontinuous process were suitably fitted by Demir et al model (with r = 0.99907 for HSD and r = 0.99839 for TSD. Traditional solar dryer offered highest effective moisture diffusivities and a highest drying rate during the first day.

General conclusion

In this study, mathematical modelling of solar drying of thin layer tomato were performed using two solar dryers one with a heat exchanger HSD and a traditional solar dryer without a heat exchanger TSD

The drying characteristics and operational performance of the hybrid solar dryer for drying tomato slices have been analyzed. From the above studies, the following conclusions have been reached :

The obtained Effective moisture diffusivity results range is good for dried food products based on recent studies.

Under the same drying time condition, the drying capacity of the TSD is better than the hybrid solar dryer but the HSD is better for saving the quality of the dried product which is the tomto in our study. Meanwhile, it was found that the Demir et al model is the best suitable model to describe the tomato slices drying behaviour.

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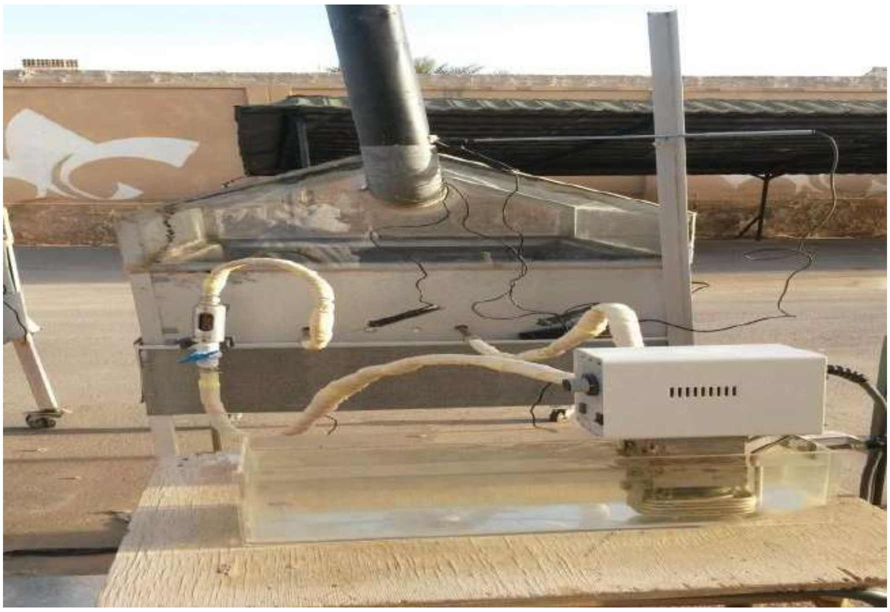
Annex

Hybrid solar dryer HSD and normal solar dryer TSD



HSD with hot water source

Dried tomato slices from TSD

Dried tomato slices from HSD