Mathematical modeling and environmental analysis of a novel intermittent solar drying system

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Abstract. The current study investigated the environment indicators of a novel intermittent solar drying system (ISD) for drying agri-food products, and the drying behavior of onion slices during study. Mathematical modeling and environmental analysis of the ISD were compared with the stationary solar drying process (SDP). Thirteen well-known mathematical models were fitted to the drying data of the ISD and SDP. The obtained results revealed the lowest drying time using SDP at 13 h compared to ISD at 18 h. Where tempering in drying time decreased the diffusional process, consequently increasing the drying time. Among the examined mathematical models, Wang and Singh's well expressed the drying behavior of onion slices during the ISD and SDP, with the highest correlation coefficient R^2 = 0.99933 and 0.99691, respectively. The environmental indicators; the energy payback time (*EPBT*) was estimated = 1.81 using the ISD compared to 3.62 when using the SDP and the *yearly CO_2emission* values = 0.205 and 0.123 tons using SDP and ISD, respectively. Both drying systems were found with high NetCO2mitigation = 49.3 and 19.6 tons per year using the SDP and ISD, respectively. The earned credit carbon (*ECC*) ranges from 980-3920 and 247-987 USD using the ISD and SDP, respectively. The ISD was found more suitable for drying agri-food products in terms of environmental indicators and *ECC*.

Keywords: Intermittent drying, mathematical modeling, environmental analysis

1 Introduction

For decades, drying technology has been the oldest processing method for preserving food, pharmaceutical products, marine products, and other materials. Seeking better drying performances, several drying techniques have been applied such as open sun drying (OSD), solar drying (SD), and electrically assisted dryers such as hot air convective dryers (HACD), freeze dryers (FD), heat pump dryers (HPD)…etc.

Recently, the intermittent drying process was highlighted as a promising solution for improving the drying outcomes without increasing both of the capital cost and the initial investment of the drying system.

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Several intermittent drying operations using experimental investigations, modeling, or numerical simulation were studied in the literature. Geraldo Acacio Mabass et al. [1] introduced a fixed-bed experimental dryer working at 373 K and an air-drying speed of 0.02 m/s. Intermittency in drying time was tested for drying the corn grains with tempering of 0, 4, 8, 12, and 16 h, on the one hand, and its effect on storage mean of 270 days was investigated, on the other hand. Mabasso et al. [2] subjected the maize grain to 100 ^{o}C, with 0.34 ± 0.01 (dry basis - d.b) initial moisture content and 15.4 m3 (min.t) air-flow. Maize grain was dried using a bed dryer continuously and intermittently in 4, 8, 12, and 16 tempering hours. S.J. Kowalski and A. Pawłowski [3] examined the intermittency in drying temperature and humidity of air drying for cylindrical-shaped kaolin in a laboratory-scale drying chamber. These experimental investigations have been carried out using the conventional drying systems working with fossil fuels, also with simple process. However, the current experimental investigation aims to improve the environmental indicators of agri-food drying using a novel drying technology named intermittency in drying by tempering in drying time. Moreover, installing the current intermittent solar dying systems aims to help achieve the Sustainable Development Goals (SDGs), which the United Nations has set forward to create a prosperous and peaceful world for all people by 2030 [4]. Throughout conserving renewable and sustainable energy consumption, it’s expected that the intermittent solar drying systems contribute significantly to the SDGs program's 17 pillars, which include improving food resilience and reducing food waste. Thus, this installation aligns with SDGs goals such as no poverty (SDGs 1), zero hunger (SDGs 2), affordable and clean energy (SDGs 7), sustainable cities and communities (SDGs 11), and climate action (SDGs 13).

2 Methods and Materials

2.1 Drying setup

The dryer was used to dry fresh onion slices under 70 ^{o}C with two drying methods: ISD and SDP. Drying fresh onions at 11.4±0.08 kg/kg (or 94.2 ±1.8 % w.b) were proceeded to the desired moisture content of 0.2 kg/kg. For SDP, the drying system received the operating power from the incident solar radiation into the solar collector (1.2×2m) and an adjusted electric heater of 9 kWh combined with a blower to deliver the hot air inside the drying chamber. The intermittency in the drying process was achieved by tempering in drying time by 60 min. The electric heater was adjusted to turn on/off every one drying hour. Then, the drying chamber receives the processing energy only from the solar collector when the electric heater is in a turn-off case, so the ISED was achieved (see Fig. 1). A data analogy (HIOKI-U8551 Model) was used to register the variation in operating drying temperatures each 5 min. The external drying conditions were registered using a metrological station set up in the school.

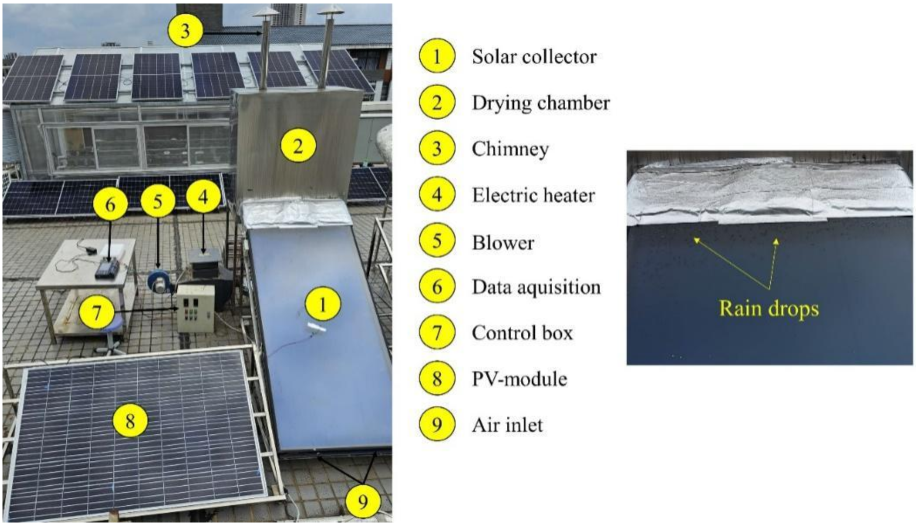

Fig. 1: Experimental setup for drying onion slices under cloudy and rainy conditions

2.2 Kinetics

The drying process of agri-food products and other materials is mainly characterized by the ability to extract/remove water over the process. This phenomenon can be defined as the evolution of drying kinetics over processing time. Drying kinetics is based mainly on three parameters which are moisture content variation at any time (M_t) in $kg_{water}/kg_{dry.matter}$ (kg/kg) and variation in moisture ratio named (MR) with the unidimensional unit. These parameters can be only calculated by knowing the initial moisture content (M_i) and equilibrium moisture content of the product (M_{eq}). The following equations express the mathematical formula of M_t, and MR over processing time.

$$M_t = \frac{m_t - m_d}{m_d} \; kg/kg \tag{1}$$

$$MR = \frac{M_t - M_{eq}}{M_i - M_{eq}} \tag{2}$$

Where m_t and m_d in (kg) are respectively, the mass over time and dry mass of the product, t_1 and t_2 are successive measurements time of the product's mass evolution.

Once the M_{eq} is considered << to M_i, thus Eq. 3 is simplified to:

$$MR = \frac{M_t}{M_i} \tag{3}$$

2.3 Mathematical Modeling

The characteristic drying curves of stationary and intermittent drying processes of onion slices were fitted to mathematical models using empirical and semi-empirical equations. Table 1 presents thirteen well-known empirical and semi-empirical equations for fitting the resulting drying curves of *MR* against drying time. Determined modeling characteristics correlation coefficient (R^2), root-mean-square (*RMSE*), and reduced chi-square χ^2 were calculated using Eqs. 4-6 as follows:

$$R^2 = \frac{{}_{i=1}^{n}(MR_i - MR_{pre,i}).\ {}_{i=1}^{n}(MR_i - MR_{exp,i})}{\sqrt{\left[{}_{i=1}^{n}(MR_i - MR_{pre,i})^2\right]\left[{}_{i=1}^{n}(MR_i - MR_{exp,i})^2\right]}} \tag{4}$$

$$RMSE = \frac{{}_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})}{N} \tag{5}$$

$$\chi^2 = \frac{{}_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})^2}{N - P} \tag{6}$$

Table 1: Fitted mathematical models to the drying curves of SDP and IDS; empirical and semi-empirical equations

No	Model	Equation
i.	Newton [5]	$MR = exp(kt)$
ii.	Page [6]	$MR = exp(-kt^n)$
iii.	Modified Page [7]	$MR = exp(-(kt)^n)$
ix.	Logarithmic [8]	$MR = aexp(-kt) + c$
v.	Midilli-Kucuk [9]	$MR = aexp(-kt^n) + bt$
vi.	Henderson and Pabis [10]	$MR = aexp(-kt)$
vii.	Modified Henderson and Pabis [11]	$MR = aexp\,(-kt) + bexp\,(-gt) + cexp\,(-ht)$
iix.	Diffusion of approximation [12]	$MR = aexp(-kt) + (1-a)exp(-kbt)$
ix.	Verma et al. [13]	$MR = aexp(-kt) + (1-a)exp(-gt)$
x.	Two-terms [14]	$MR = aexp(-kt) + bexp(-k_1t)$
xi.	Two-terms exponentials [15]	$MR = aexp(-kt) + (1-a)exp(-kat)$
xii.	Wang and Singh [16]	$MR = 1 + at + bt^2$
xiii	Noomhorm and Verma [17]	$MR = aexp(-kt) + bexp(-nt) + c$

2.4 Environmental analysis

Dioxide carbon emissions (*CO_2*) and the energy payback time (*EPBT*) are crucial factors in the industrial sector to reach the seventeen Sustainable Development Goals. Recently, several drying systems were designed and constructed to reduce the $CO_{2emission}$ and *EPBT*. However, these parameters mainly depend on the delivered-fossil energy amount to the drying system on one hand, and the material kind and quantity to construct the system. Hence, the embodied energy (E_{mb}) in kWh is decisive in predicting the *EPBT*. Embodied energy is the overall energy used in the production of all things, systems, and services. Table 1 presents the coefficient Emb and Emb values of the different materials that are used in the construction of the current drying systems.

Table 2: The calculation of total embodied energy for SDP and ISP.

No:	Component materials	Quantity (kg)	Coefficient of E_{mb} (kWh/kg)	E_{mb} (kWh)
i	Iron	45	25	1125
ii	Copper	1.5	19.61	29.415
iii	Glass cover	8	7.28	58.24
iv	Fiberglass sheet	10	4.044	40.44
v	Plastic	1	19.44	19.44
vi	Paint	0.8	25.11	20.088
vii	Aluminum tray	6	55.28	331.68
ix	Fittings (nuts, screws, bolts, and rivets)	1.8	8.89	16.164
			Total:	**1640.467 kWh**

Energy payback time (*EPBT*).

The *EPBT* is the effective useful life years to recover the embodied energy amount used in manufacturing the drying system and expressed as:

$$EPBT = \frac{E_{mb}}{E_{out}} \tag{7}$$

Where the E_{out} is the annual outlet energy and is defined as the total working sunshine days in a year (320 days) multiplied by the output energy of the solar drying system per day (E_{od}). The E_{od} amount in kWh can be calculated using Eq. 8.

$$E_{od} = \frac{m_{ev} \times h_w}{3.6 \times 10^6} \tag{8}$$

CO2 emissions

By knowing that one kWh of electricity production from coal is equivalent to 0.98 kg of $CO_{2emission}$, the emission of carbon dioxide emissions per year can be defined as follows:

$$CO_{2emission} = \frac{0.98 \times E_{mb}}{N_{dl}} \tag{9}$$

Where the N_{dl} represents the estimated lifetime of the drying systems by the constructor, which is given as 15 and 25 years for SDP and IDP, respectively. Where the increase in processing electric energy reduced the lifetime of the drying system.

The yearly $CO_{2emission}$ can be calculated depending on the real transmission and internal losses L_t and L_i, respectively. Hence, Eq. expresses the *Yearly* $CO_{2emission}$:

$$Yearly\ CO_{2emission} = \frac{E_{mb}}{N_{dl}} \times \frac{1}{1 - L_t} \times \frac{1}{1 - L_i} \times 0.98 \tag{10}$$

In a real application, L_t and L_i are taken 35% and 20%, respectively, then Eq. 10 can be simplified to:

$$Yearly\ CO_{2emission} = \frac{E_{mb}}{N_{dl}} \times 1.88\ kg/year \tag{11}$$

Carbon dioxide (CO_2) mitigation and earned carbon credit

The $CO_{2mitigation}$ of the current solar-electric dryer in CDP and IDS is determined as follows:

$$CO_{2mitigation} = (E_{out} \times N_{dl} \times E_{mb}) \times 1.88 \tag{12}$$

The earned credit carbon (*ECC*) is calculated by multiplying the *Net* $CO_{2mitigation}$ during the lifetime of the drying system by the unit price per tonne (cost of carbon credit). *Net* $CO_{2mitigation}$ can be evaluated using Eq. 13.

$$\begin{aligned} Net\ CO_{2mitigation} &= Total\ CO_{2mitigation} - Total\ CO_{2emission} \\ &= (E_{out} \times N_{dl} \times 1.88 - E_{mb}) \end{aligned} \tag{13}$$

Consequently, *ECC* can be calculated as:

$$ECC = Net\ CO_{2mitigation} \times d \tag{14}$$

Where d expresses the unit price of carbon credit, which varies from 5 to 20 USD/ton of $CO_{2mitigation}$.

2.5 Uncertainty analysis

Errors and uncertainties during the experimental investigation of SDP and ISD of onion slices were expressed using the following relation [18].

$$U_F = \left[\left(\frac{\partial R}{\partial y_1}u_1\right)^2 + \left(\frac{\partial R}{\partial y_2}u_2\right)^2 + \left(\frac{\partial R}{\partial y_3}u_3\right)^2 + \ldots + \left(\frac{\partial R}{\partial y_n}u_n\right)^2\right]^{1/2} \tag{15}$$

3 Results and discussion

3.1 Mathematical modeling

Fitting the SDP and ISD data to the examined mathematical model (see Fig. 2) revealed a high alignment of variation in MR with the Wang and Singh mathematical model. Table 3 displays the mathematical modeling constant of fitted models to the drying data. Wang and Singh's model was determined the suitable model to express the drying behavior of onion slices using both SDP and ISD. Where the highest R^2 values were recorded as 0.99933 and 0.99691 for the SDP and ISD respectively. Moreover, low χ^2 are equal to $8.064\times10^{-5}$and 0.00523 and $RMSE$ = 0.00898 and 0.01754, respectively for SDP and ISD (see Table. 4).

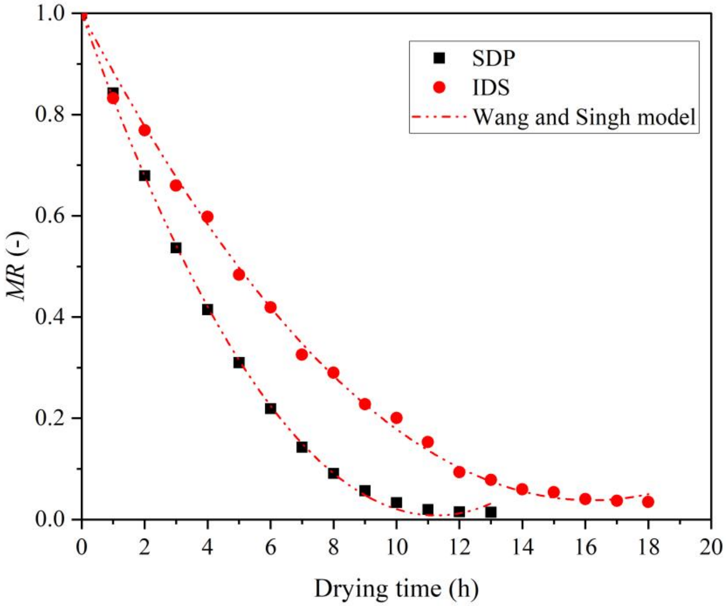

Fig. 2: Fitting the Wang and Singh mathematical model to ISD and SDP data

Table 3: Mathematical modeling parameters of the SDP and IDS of onion slices

No	Model name	SDP	IDP
	Newton	k = -0.24477	k = -0.15991
i.	Page	k = 0.14832 n = 1.31375	k = 0.10884 n = 1.19166
ii.	Modified Page	k = 0.23392 n = 1.31443	k = 0.15547 n = 1.19292
iii.	Logarithmic	a = 1.13757 k = 0.20226 c = -0.10498	a = 1.11066 k = 0.12904 c = -0.10677
ix.	Midilli-Kucuk	$a = 8.13001\times10^{-5}$ k = -9.32623 n = -0.04817 b = -0.02827	a = 1 k = -0.08783 n = 279.38589 b = -0.25943
v.	Henderson and Pabi	a = 1.06123 k = 0.25838	a = 1.03467 k = 0.16526
vi.	Modified Henderson and Pabi	a = 0.35425 k = 0.25835 b = 0.35421 g = 0.25835 c = 0.35273 h = 0.25834	a = 0.34489 k = 0.16526 b = 0.34489 g = 0.16526 c = 0.34489 h = 0.16526
vii.	Diffusion of approximation	a = 1 k = 0.24472 b = 1	a = 1.29486 k = 0.0932 b = 1

iix.	Verma et al.	$a = 74.88968$ $k = 0.44291$ $g = 0.44748$	$a = 61.61145$ $k = 0.26192$ $g = 0.26448$
ix.	Two-terms	$a = 0.53059$ $k = 0.25834$ $b = 0.53059$ $k_1 = 0.25836$	$a = 0.51737$ $k = 0.16528$ $b = 0.51737$ $k_1 = 0.16528$
x.	Two-terms exponentials	$a = 1.85566$ $k = 0.34997$	$a = 1.71521$ $k = 0.21324$
xi.	Wang and Singh	$a = -0.17612$ $b = 0.00782$	$a = -0.11887$ $b = 0.00367$
xii.	Simplified-Ficks diffusion	$a = 1.06137$ $b = 1.53601$ $l = 2.43778$	$a = 1.03479$ $b = 10.02134$ $l = 7.78623$
xiii.	Noomhorm and Verma	$a = 0.56879$ $k = 0.20224$ $b = 0.56879$ $n = 0.20226$ $c = -0.105$	$a = 0.55533$ $k = 0.12905$ $b = 0.55533$ $n = 0.12905$ $c = -0.10675$

Table 4: Modeling characteristics of Wang and Singh mathematical model (R^2, χ^2, and *RMSE*)

Model name	SDP			ISD		
	χ^2	*RMSE*	R^2	χ^2	*RMSE*	R^2
Newton	1.514×10^{-4}	0.0123	0.99874	0.00128	0.03584	0.98633
Page	1.513×10^{-4}	0.0123	0.99874	4.869×10^{-4}	0.02207	0.99511
Modified Page	1.513×10^{-4}	0.0123	0.99874	4.868×10^{-4}	0.02206	0.99511
Logarithmic	6.334×10^{-4}	0.02517	0.99517	4.974×10^{-4}	0.0223	0.99529
Midilli-Kucuk	0.10269	0.32046	0.28769	0.11369	0.52126	0.21467
Henderson and Pabi	0.00175	0.04185	0.98542	0.00121	0.03477	0.98785
Modified Henderson and Pabi	0.00263	0.05126	0.98542	0.00158	0.03976	0.98785
Diffusion of approximation	0.00247	0.0497	0.98115	4.710×10^{-4}	0.0217	0.99554
Verma et al.	2.079×10^{-4}	0.01442	0.99841	$\mathbf{4.443\times10^{-4}}$	0.02108	0.9958
Two-terms	0.0021	0.04585	0.98542	0.00137	0.03701	0.98785
Two-terms exponentials	2.654×10^{-4}	0.01629	0.99779	4.629×10^{-4}	0.02152	0.99535
Wang and Singh	$\mathbf{8.064\times10^{-5}}$	**0.00898**	**0.99933**	0.00523	**0.01754**	**0.99691**
Simplified-Ficks diffusion	0.00191	0.04371	0.98542	0.00128	0.03584	0.98785
Noomhorm and Verma	7.741×10^{-4}	0.02782	0.99517	5.685×10^{-4}	0.02384	0.99529

3.2 Environmental indicators

The ratio of every contributing material to construct the main solar drying system is graphically presented using Fig. 3. Observing the highest rate is for iron at 61% of the total quantity with about 45 kg. Where it appears the main material of the electric heater with a low quantity used for the dryer body. On the other side, the drying system seems to be with high isolation as the fiberglass sheets present 14% of the total quantity with an 8 kg contribution. The glass cover was used only to construct the cover of the solar collector which presents 11% of the total quantity, followed by aluminum material used to fabricate the trays with an 8% contribution. A rate of 2% of copper material and fittings (nuts, screws, bolts, and rivets) was found, with the lowest rate at 1% registered for both paint and plastic. The constructed dryer system seems to be eco-friendly with a low total quantity estimated at 74.1 kg with a capacity that can reach 30 kg.

Table 5 presents the environmental indicators of both SDP and IDP systems. The results revealed the high effect of drying time on the *EPBT*. Where the increase in drying time systematically increased the *EPBT* from 1.81 using the IDP compared to 3.62 when using the SDP. However, the intermittency in the useable time of the electric heater reduced the *Yearly* $CO_{2emission}$. Where a shortening of 40% in *Yearly* $CO_{2emission}$ is observed with determined values at 0.205 and 0.123 tons using SDP and IDP, respectively. Both drying systems were found with high $NetCO_{2mitigation}$ at 49.3 and 19.6 tons per year using the SDP and IDP, respectively. Where the increase in drying time reduced the $NetCO_{2mitigation}$ from the atmosphere. In contrast, reducing the useable electric energy improved the EEC and reached the range of 980-3920 and 247-987 USD using the IDP and SDP, respectively. The obtained results were found more sustainable compared to 1518 kg of $CO_{2emissions}$ to the atmosphere as shown by Ayyappan et al. [19] using a solar greenhouse dryer equipped with a biomass heater. Also, the ISD is predicted to be a promising drying technique for drying agri-food products due to the feasible $NetCO_{2mitigation}$ from the atmosphere, which causes less damage to the environment.

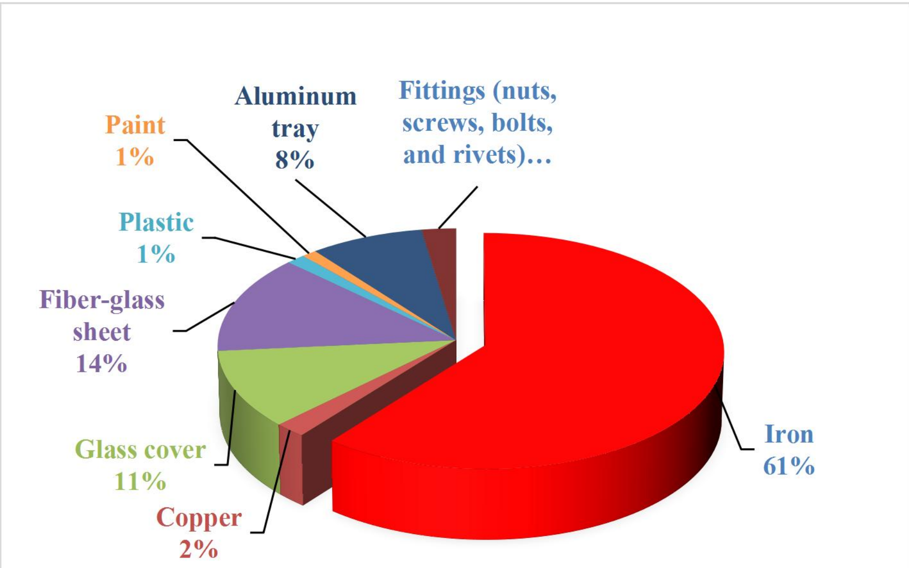

Fig. 3: Embodied energy of the solar drying system

Table 5: Energy-environmental parameters of the SDP and IDP

Drying process	*EPBT*	*Yearly* $CO_{2emission}$ (ton)	$CO_{2mitigation}$ (ton)	$NetCO_{2mitigation}$ (ton)	*ECC* (USD)
SDP	1.81	0.205	4.18E+04	49.3	247-987
IDS	3.62	0.123	3.49E+04	19.6	980-3920

Conclusion

Based on the goal of transition toward sustainability, intermittency in the solar drying sector is proposed in the current investigation. An ISD was constructed and compared with SDP for drying onion slices. Moreover, mathematical modeling of the drying data has been analyzed. The main outcomes of the study can be listed as follows:

- The ISD increased the drying time on one side, and decreased the electric energy consumption on the other side, compared to SDP. Where the SDP took 13 drying hours to reach the safe moisture level and 18 drying hours using the ISD.
- Among thirteen mathematical models, fitting the drying curves of *MR* for the ISD and SDP revealed that Wang and Singh was found the the most suitable model to express the drying brhavior of onion slices using both drying techniques. Highest R^2 = 0.99933 and 0.99691 respectively for drying data of SDP and ISD. However, Low χ^2= 8.064×10^{-5} and 0.00523, and *RMSE* = 0.00898 and 0.01754 were obtained for SDP and ISD respectively.
- The environmental analysis indicated a promising ISD technique for drying agri-food products with low energy consumption. Low $CO_{2emission}$ to the atmosphere was obtained using the ISD = 123 kg compared to 205 kg using the SDP technique. Also, high EEC using the ISD was observed in the range of 980-3920 USD compared to 247-987 using the SDP. The increase in processing time increased the EPBT from 1.81 years using SDP to 3.62 years using the ISD.

Implementing the intermittency by tempering in drying time was found a promising technique to improve the drying performances and reduce the energy consumption on one hand, and reach sustainable indicators on the other hand.

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