EXERGETIC ANALYSIS OF THE SOYBEAN DRYING PROCESS WITH SOLAR ENERGY IN HOT-HUMID CLIMATES

ANÁLISIS EXERGÉTICO DEL PROCESO DE SECADO DE SOJA CON ENERGÍA SOLAR EN CLIMAS CÁLIDOS-HÚMEDOS

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1.- INTRODUCTION

Mexico is a major importer and consumer of soybeans worldwide [1]. This food is important for its nutritional properties, and the high production led by Campeche at national level [2], which in 2021, contributed 47.5 % (118,000 tons) of national production [3]. In Campeche, the agro-industrial sector needs to dry soybeans, to give them a longer shelf life and added value, with a view to entering the international market; therefore, an efficient drying method is required for a hot-humid climate, which ensures the quality and hygiene of the product [4].

Preservation of agricultural products is considered essential to ensure their availability for further use and also to reduce post-harvest losses. It is estimated that in smallholder agriculture, production is currently reduced by 10-40% due to poor post-harvest handling and inadequate grain drying and cleaning practices [5].

One of the most energy-intensive operations in industrial processes is drying. In most industrialized countries, between 7 % and 15 % of national industrial energy is used for drying [6].

Drying is a basic process to reduce the humidity of any product, so that the final product has very different characteristics from the initial one. Traditionally, farmers used the natural drying technique, which achieves drying through the use of natural wind, solar radiation, temperature and relative humidity of the environment. Obviously, the speed of drying is very slow, so crops remain in the open air usually for 10 to 30 days, depending on the product and the climatic conditions of the location. The most obvious limitations are that the crops suffer from air pollution, dust, insect and rodent attacks. Due to these limitations, the quality of the product may degrade beyond edibility.

In addition to the above, the energy to carry out the drying is supplied from various sources such as fossil fuels, natural gas and solar energy. Due to the higher cost of fossil fuels, uncertainty regarding future availability and their effect on the environment, the development of renewable energies has been taken into account [7].

All these disadvantages can be eliminated by a solar dryer [8]. Solar drying has been a technique used for the preservation of food products, mainly grains, meat, fish, plants and some fruits and vegetables [9]. In addition, it helps to overcome the main problems faced by developing countries, such as rising fuel prices and environmental pollution. In this sense, designing and developing solar dryers is a priority for the food industry, because solar energy is considered one of the most promising, due to the known problems of depletion of fossil fuels, and its correspondence with the emission of greenhouse gases, in addition to the high energy consumption in conventional drying processes [10].

To discover the energy interactions and thermodynamic behaviour of the air in a drying chamber, an exergetic analysis of the process must be performed, which can help to achieve the goal of more efficient use of energy resources by determining the actual locations, types and magnitudes of losses. As a result, exergetic analyzes can reveal where and to what extent it is possible to design more efficient thermal systems by reducing the sources of inefficiencies [11]. This makes exergy one of the most powerful tools to provide optimal drying conditions.

The exergetic sustainability indicators (the improvement potential "IP", sustainability index "SI" and residual energy ratio "WER"), are the parameters used to identify how exergetic efficiency and exergy flux loss values affect the sustainable development of the drying process. These parameters are useful to achieve more efficient, environmental, sustainable and economic energy use in drying systems [12].

One of the priorities of economic and social development is to promote productive activities in support of the development of rural areas, especially food-producing areas, which have incipient means and a lacking energy infrastructure to improve the quality and hygiene of their produce [13]. In Campeche, efficient drying of agricultural products, particularly soybeans, is required for a hot-humid climate with a relative humidity of 50 % and an average temperature of 27°C, in order to preserve the quality and hygiene of their products to be dried [14].

2.- EXPERIMENTAL STUDY

2.1.- INSTRUMENTS

The research instruments used to obtain data on the variables used in the analysis are shown in Table 1:

Equipment	Model	Operation range
Anemometer	CIH20DL	±3%
Precision scale	Boeco-BPS40PLUS	±0.0001 g
Drying trays	Kiltik	Maximum temperature 75°C
Flowmeters	NRG-Systems Wind Sensor Series #200P P2546C-OPR	±0.3 m/s
Pyranometer	LI-COR LI-200R	Azimuth < ±1% in 360° a 45° elevation.
Solar dryer (Cabinet-type)	Design by PhD Margarita Castillo Téllez	
Temperature sensors (Termocouple type K).	MAX6675	0.25°C
Data acquisition system	AGILENT-34970A	0.0004%
Dial thermometers	NRG-Systems-110S	±1.1°C
Portable hygrometers	Termohygrometer-Brannan	±3%

Table 1. Research instruments

Figure 1 shows the dryers used, made with a transparent plastic surface of a 0.5 m2. The sides, bottom and back have perforations to allow the circulation and extraction of hot and humid air. They can operate with natural air circulation or forced convection by means of a fan placed at the back with a maximum speed of 2.9 m/s.

Fig. 1. Cabinet-type solar dryers

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2.2.- METHODOLOGY

The methodology of the process was the following:

- Sample unification (size and color).
- Weighing of 20 g of the simple on a high-precision scale and placement in dryers.
- During drying, a scale was kept next to the dryer to prevent the sample from gaining moisture when transporting it to the laboratory.
- Samples were taken every hour to correlate them with weight and moisture loss. Data were taken on dryer temperature, ambient temperature and humidity.
- The process ended with the stabilization of weight loss.

2.3.- DATA ANALYSIS

The following parameters were used to analyze the performance of the dryers [15]:

Exergy flow input to the drying chamber:

$$Ex_{dci} = \dot{m}_a C_p \left[(T_{dci} - T_a) - T_a ln\left(\frac{T_{dci}}{T_a}\right) \right] \qquad (1)$$

Where:

Ex_{dci}: Exergy flow input to the drying chamber (W)

$\dot{m}_a$: Air mass flow (kg/s)

Cp: Specific heat of air (J/kg °C)

T_{dci}: Inlet temperrature to the drying chamber (°C)

Ta: Ambient temperature (°C)

Exergy flow ouput from the drying chamber:

$$Ex_{dco} = \dot{m}_a C_p \left[(T_{dco} - T_a) - T_a ln\left(\frac{T_{dco}}{T_a}\right) \right] \qquad (2)$$

Where:

Ex_{dco}: Exergy flow ouput from the drying chamber (W)

T_{dco}: Outlet temperatura from the drying chamber (°C)

Exergy flow losses:

$$Ex_{loss} = Ex_{dci} - Ex_{dco} \qquad (3)$$

Donde:

Ex_{loss}: Exergy flow losses (W)

Exergy effiency:

$$\eta_{Ex} = \frac{Ex_{dco}}{Ex_{dci}} = 1 - \frac{Ex_{loss}}{Ex_{dci}} \qquad (4)$$

Where:

η_{Ex}: Exergy efficiency

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Improvement potential:

$$IP = (1 - \eta_{Ex})Ex_{loss} \quad (5)$$

Sustainability index:

$$SI = \frac{1}{1 - \eta_{Ex}} \quad (6)$$

Waste energy ratio:

$$WER = \frac{Ex_{loss}}{Ex_{dci}} \quad (7)$$

2.4.- VARIABLES

The variables involved in the study are shown in Table 2.

Variable	Unit	Type
Exergy efficiency	%	Output
Exergy flow (Input/Output/Loss)	W	Input/Output
Relative humidity	%	Input
Waste energy ratio	Non-dimensional	Output
Sustainability index	Non-dimensional	Output
Improvement potential	W	Output
Solar radiation	W/m^2	Input
Dryer inlet temperatura	°C	Input
Dryer outlet temperatura	°C	Output
Drying time	Minutes	Output
Air velocity inside the dryer	m/s	Input

Table 2. Variables

3.- RESULTS AND DISCUSSION

3.1.- ENVIRONMENTAL CONDITIONS

The tests were carried out on 10, 11 and 17 November 2021 between 9:00 am and 4:00 pm.

Figure 2 shows the variation of the environmental parameters during the tests. It shows that the maximum solar radiation was 736.5 W/m^2, reached at midday on the second day; the average was 459 W/m^2. The average ambient temperature was 29.8°C, varying between 26.6°C and 31.2°C. On the other hand, relative humidity ranged from 41% to 84%, the average being 59%.

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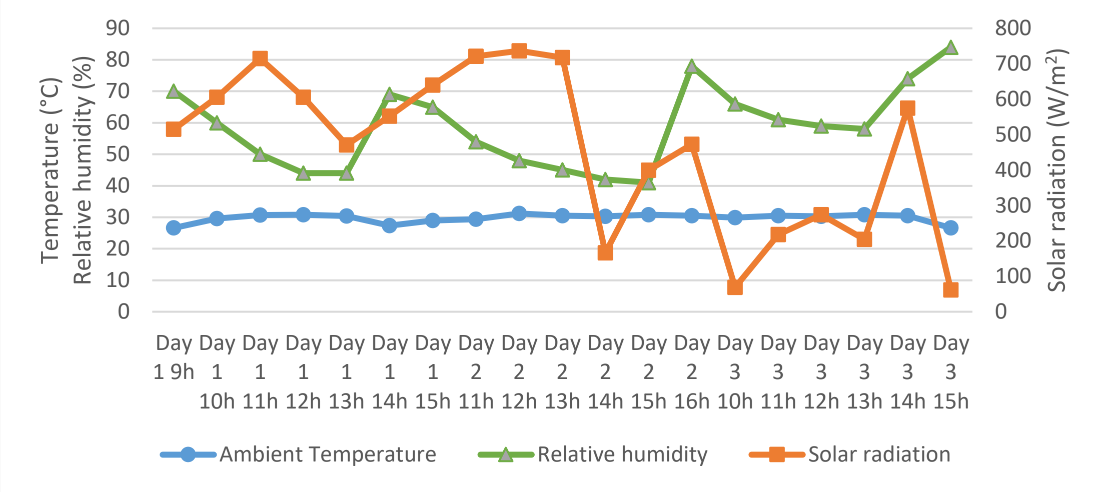

Fig. 2. Environmental conditions during testing days.

3.2.- MOISTURE CONTENT

The final moisture ranged between 7.36% and 7.48%. The final values of the water activity indicate that there is no possibility of microbial growth in the dehydrated product. In natural convection, the lowest values were obtained in terms of moisture content and water activity.

The humidity and water activity values of the samples are presented in Table 3.

Solar drying Technology	*Humidity (%)*		*Water activity*	
	Initial	*Final*	*Initial*	*Final*
Natural convection	*70*	*7.36*	*0.95*	*0.35*
Forced convection	*70*	*7.48*	*0.95*	*0.38*

Table 3. Humidity and water activity

The drying kinetics were obtained in both dryers; three experiments were carried out in each case. Figure 3 shows the drying rate; as can be seen, natural convection minimizes the time to reach equilibrium moisture compared to forced convection, whose air mass flow rate was 0.018 kg/s. The time for moisture to stabilize was 420 min (natural convection) and 580 min (forced convection); the velocity periods were constant, with natural convection being slightly longer, due to the lower humidity and higher temperature inside the drying chamber because of a lower thermal exchange with the air that has a low velocity inside the chamber.

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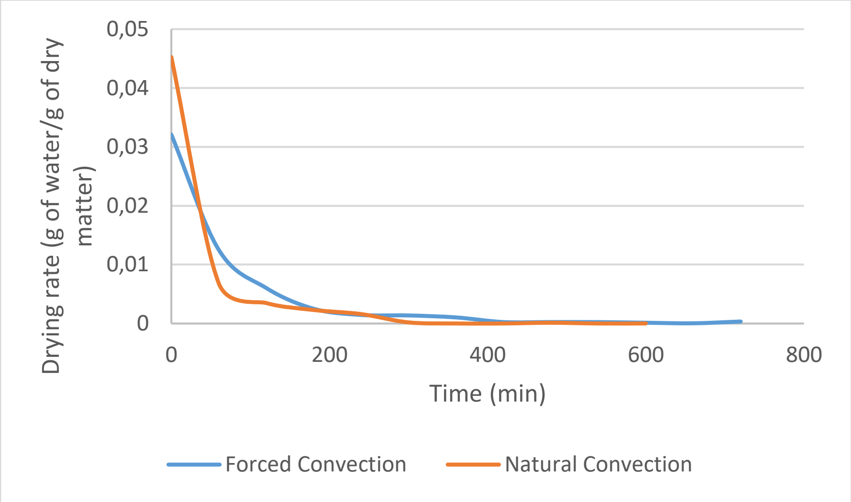

Fig. 3. Drying speed

3.3.- EXERGETIC ANALYSIS

The results of the exergy analysis are shown in Table 4 and Table 5.

Time (min)	Day	Time	Drying chamber temperature (°C)		Exergy flow (W)		
			Inlet	Outlet	Inlet	Outlet	Loss
0	1	9:00	32	30	4.86	2.01	2.84
60		10:00	50	41	49.01	17.63	31.39
120		11:00	55	49.8	64.25	42.66	21.60
180		12:00	54	45.5	59.30	26.93	32.38
240		13:00	54	42.5	61.58	19.22	42.37
300		14:00	55	52	86.12	71.37	14.75
360		15:00	54	50	69.99	52.24	17.75
420	2	11:00	52	49	58.58	46.01	12.58
480		12:00	57	55	70.26	61.37	8.89
540		13:00	47	40	33.24	12.35	20.90
600		14:00	39	32	10.56	0.46	10.10
660		15:00	49	36	39.15	3.97	35.18
720		16:00	51	39	48.39	10.06	38.33

Table 4. Exergy parameters (natural convection)

Time (min)	Day	Time	Drying chamber temperature (°C)		Exergy flow (W)		
			Inlet	Outlet	Inlet	Outlet	Loss

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0	2	11:00	34	33	12.80	9.46	3.34
60		12:00	36	35	13.18	9.88	3.31
120		13:00	41	40	32.93	27.98	4.95
180		14:00	41	39	23.09	15.14	7.95
240		15:00	43	41	36.58	26.69	9.89
300		16:00	37	36	11.69	8.62	3.07
360	3	10:00	38	33	13.19	1.36	11.83
420		11:00	38	37	16.85	13.18	3.66
480		12:00	42	41	31.48	26.69	4.79
540		13:00	34	30	3.78	0.02	3.75
600		14:00	37	32	9.96	0.41	9.55
660		15:00	38	36	14.35	8.01	6.34
720		16:00	30	28	3.62	0.64	2.98

Table 5. Exergy parameters (forced convection)

The exergy flow input was higher in natural convection, reaching its maximum value at 300 min; for forced convection it was reached at 240 min. The exergy flow input was higher in the first case, since higher inlet temperatures were recorded in this process, which proves the high dependence of both parameters.

The maximum exergy flow output was reached at 300 min for natural convection and at 120 min for forced convection, being higher in the first case due to higher outlet temperatures.

The maximum peaks of exergy flow loss were reached at 240 min and 360 min for natural and forced convection, respectively. The exergy flow loss was increasing at the beginning of both processes because most of the moisture content was removed from the product in that period.

The average exergetic efficiency, behaved similarly in both dryers, reaching its maximum value at 480 min. Values between 4.37 % and 87.34 % and 0.71 % and 84.96 % were obtained in the natural and forced convection processes, respectively; these values are similar to those reported in the literature: blackberry (21.3-93.3 %) [16]red seaweed (1-93 %) [17], potato (3.17-100 %) [18] and red chilli (24.3-98.9 %) [19]. The average value of the exergy efficiency was 47.40 % for natural convection and 53.57 % for forced convection, which indicates that better results were found in the forced convection process.

The inflow, outflow and exergy losses in the forced convection process showed a decrease compared to natural convection while the exergy efficiency increased by 13.23 %.

Figure 4 and Figure 5 show the dependence of the parameters in Table 4 and Table 5 (except for the exergy flow losses, since this parameter is a function of the difference between the inlet and outlet exergy flow) on the inlet temperature of the dryers. It is observed that the exergy parameters show a behavior directly proportional to the inlet temperature to the dryers. The maximum and minimum peaks coincide with the increase and decrease of the inlet temperature, respectively.

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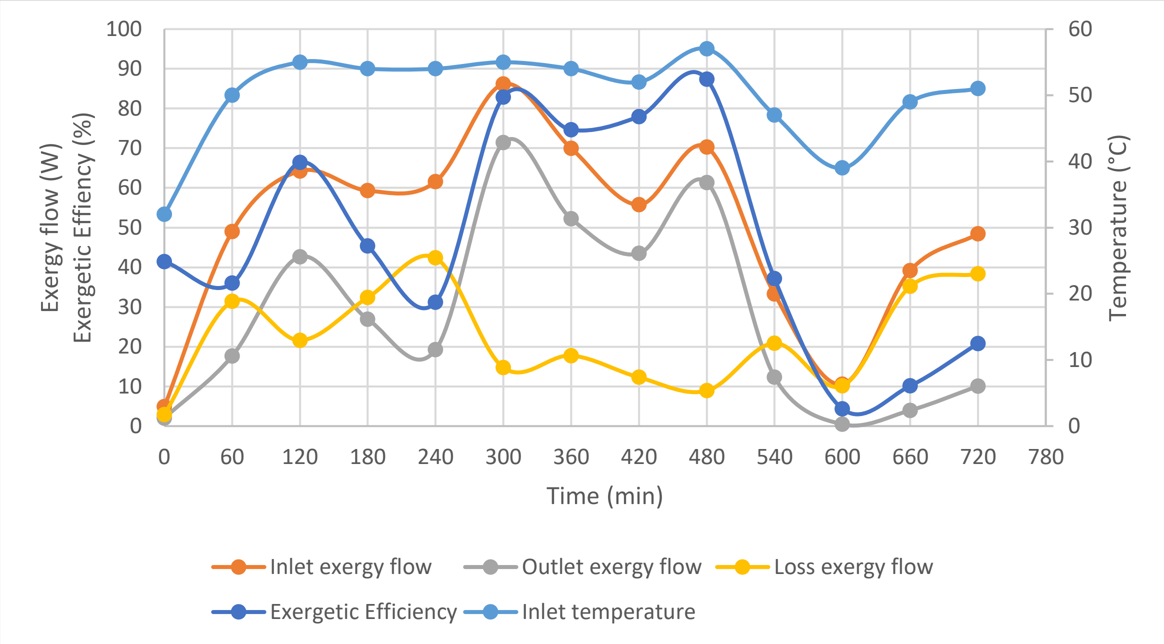

Fig. 4. Behavior of the exergy parameters respect to the inlet temperature (Natural convection)

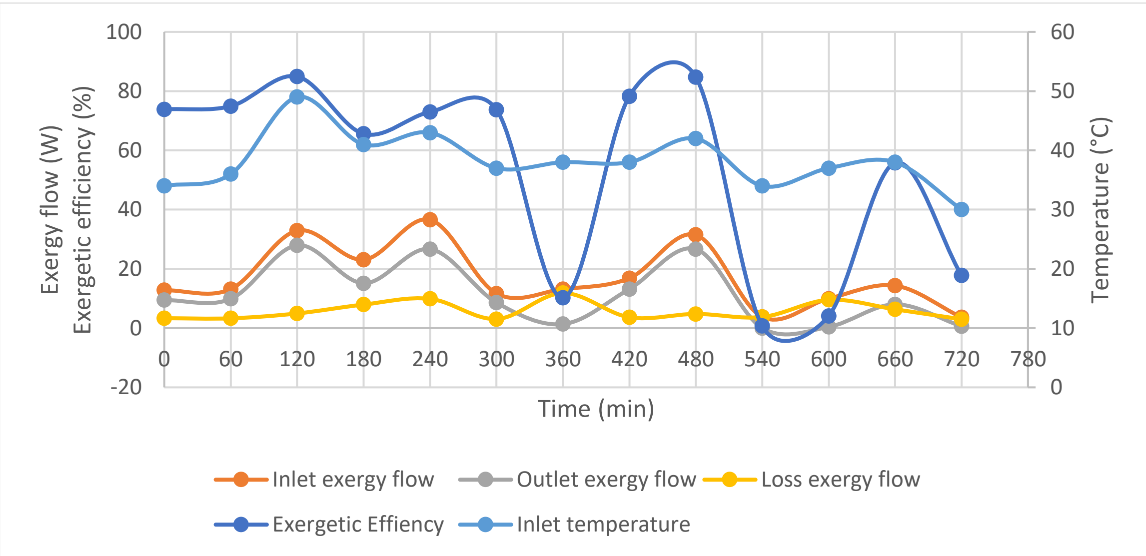

Fig. 5. Behavior of the exergy parameters respect to inlet temperature (Forced convection)

3.4.- SUSTAINABILITY INDICATORS

Figure 6 presents the sustainability indicators for both dryers. The improvement potential (IP) indicates the possibility of improving the process by reducing losses in the dryer. It is noticed that the IP is higher in natural convection, this is because the air mass flow was lower, which caused the outlet temperature and exergy flow losses to decrease as well. As the exergy flow losses increase, the IP increases. The calculated values are in the range of 1.12 W to 31.61 W for natural convection and 0.72 W to 10.61 W for forced convection. The average values were 2.99 W and 13.19 W for forced and natural convection, respectively, and are similar to those reported by [14].

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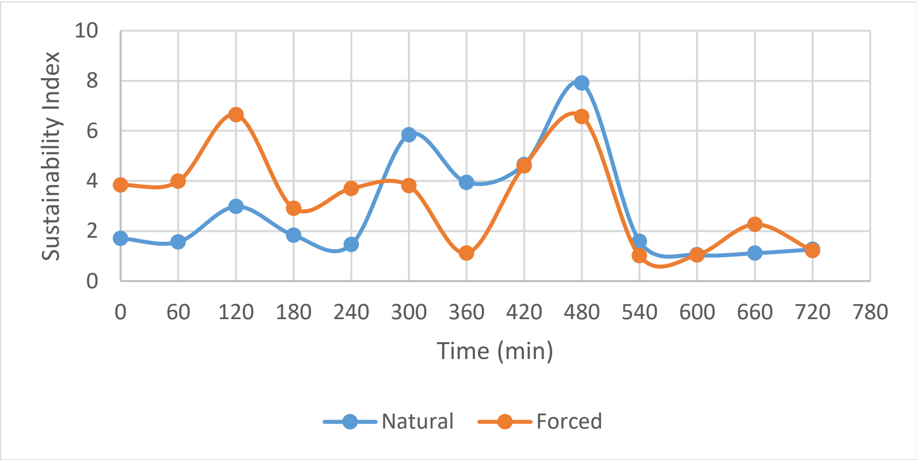
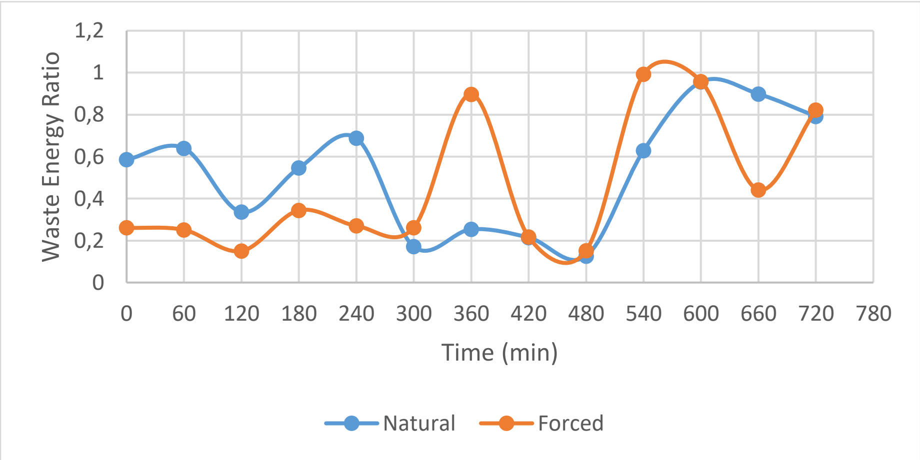
The sustainability index (SI) is a function of exergy efficiency and indicates the percentage of exergy flow input for a given exergy flow loss. The SI is found to be higher in forced convection, which is explained by the fact that with increasing mass flow the ratio of exergy inflow to exergy flow lost increases. The calculated values are in the range of 1-6.64 for forced convection and 1.04-7.9 for natural convection. The average values were 2.83 and 3.28 for natural and forced convection, respectively, and are similar to those reported by [20].

The residual energy ratio (WER) describes the percentage exergy flow loss for a given exergy flow input and therefore acts inversely to the SI. It is observed that the WER is higher in natural convection, since, with increasing mass flow the residual energy ratio decreases, and the exergy flow losses were higher in natural convection. The calculated values are in the range of 0.15-0.99 for forced convection and 0.12-0.95 for natural convection. The average values were 0.46 for forced convection and 0.52 for natural convection and correspond with those presented by [12].





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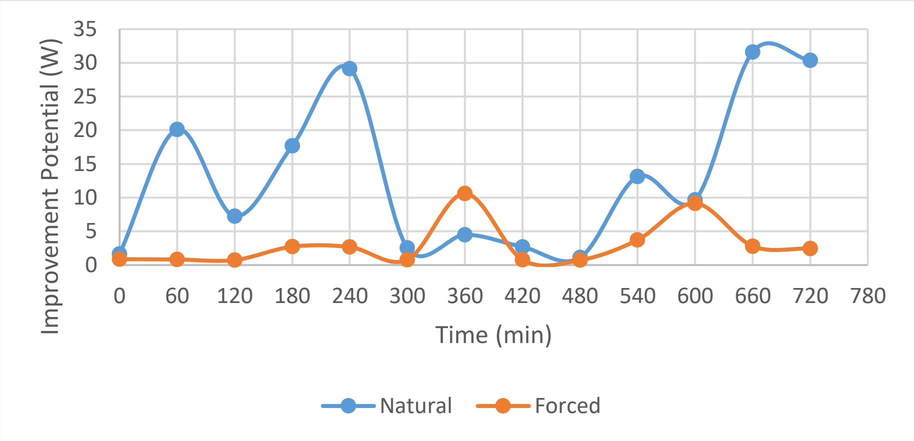

Fig. 6. Sustainability indicators of the soybean drying process

The improvement potential and the residual energy ratio are directly proportional to the exergy flow losses, while the sustainability index is indirect to the exergy flow losses. The improvement potential and the residual energy ratio were lower in forced convection because the exergy flow losses were lower compared to natural convection due to lower dryer temperatures and higher air mass flow. The sustainability index in the forced convection process was higher, as the ratio of input exergy flow to exergy flow loss was higher due to the increased mass flow of air.

4.- CONCLUSIONS

The environmental conditions were analyzed, the exergy analysis was carried out and the sustainability indicators of the soybean drying process were obtained, leading to the following conclusions:

- The average values for solar radiation, ambient temperature and relative humidity were 456 W/m^2, 29.8°C and 59 %, respectively.
- Moisture content was reduced from 70 % to a minimum of 7.36 % in natural convection. Water activity was kept within the values to avoid the possibility of microbial growth.
- The drying kinetics was faster in natural convection, the drying time was 420 min, to reach a dry matter moisture content of 0.4189 g water/g dry matter, and a drying rate of 0.00001 g dry matter/g min. This is due to the higher temperatures due to a lower heat exchange with the air which has a low velocity inside the drying chamber.
- The average values of inflow, outflow, exergy loss were 50.4 W, 28.17 W and 22.23 W for natural convection, and 17.21 W, 11.39 W and 5.82 W for forced convection, respectively. The average exergy efficiency values were 47.40 % and 53.57 % for natural and forced convection, respectively.
- The average values of the exergy sustainability indicators, such as improvement potential, sustainability index and waste energy ratio were 13.19 W, 2.83 and 0.52 for natural convection, and 2.99 W, 3.28 and 0.46 for forced convection, respectively.

The results show that a dehydrated product was obtained in which the null proliferation of pathogenic microorganisms is guaranteed in addition to a final humidity and water activity appropriate for its commercialization, therefore, solar drying is feasible, specifically using natural convection since better results were obtained; this technology would allow agricultural producers to reduce costs while contributing to the care of the environment.

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