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The effects of some exergetic indicators on the performance of thin layer drying process of long green pepper in a solar dryer

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Abstract

In this study, exergy analysis of the thin layer drying process of long green pepper was performed in solar dryer with forced convection. The effects of some exergetic indicators on the performance of a thin layer solar drying system by using the experimental data in the literature for long green pepper (Akpinar and Bicer in Energy Convers Manag 49: 1367–1375, 2008) were investigated. For this purpose, the exergetic indicators such as exergetic efficiency, waste exergy ratio, environmental impact factor, exergetic sustainability index and improvement potential, previously used in the literature, were taken into account (Zisopoulos et al. in Crit Rev Food Sci Nutr 57(1):197–211, 2017, Midilli and Kucuk in Int J Exergy 16(3): 278–292, 2015, Van Gool 1997). The exergetic efficiency and improvement potential of the solar drying system decreased with the increase of drying time. The waste exergy ratio increased with the increase of drying time. The exergetic sustainability index increased with increasing the exergetic efficiency, decreased with decreasing the exergetic efficiency. The environmental impact factor decreased with increasing the exergetic efficiency.

Keywords Solar drying · Forced drying · Long green pepper · Exergetic indicators

Nomenclature

c_p	specific heat of drying air, $(kJkg^{-1}K^{-1})$
EUR	energy utilization ratio
EIF	environmental impact factor
ESI	exergetic sustainability index
$\dot{Ex}$	Exergy, (kW)
h	enthalpy, (kJ/kg)
IP	Improvement potential, (kW)
$\dot{m}$	mass flow rate, (kgs^{-1})
WER	waste exergy ratio

Greek letters

η	efficiency

Subscripts

c	collector
d	destruction
da	drying air
dci	drying cabinet inlet
dco	drying cabinet outlet

eus	exergy used
ex	exergy, exergetic
f	fan
i, in	inlet
L	loss
o	outlet
sol	solar

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1 Introduction

Solar energy is the most widely used renewable energy source in the drying process. It has been used by humankind for many decades. The traditional open sun drying is the largest application of solar energy, and it is a cheap drying technique. However, the longer drying time, contamination, difficulty in controlling the drying process, losses of the natural colours and minerals, losses of products due to insect, bird and adverse weather, large drying area requirement, and high labour cost are the major limitations associated with the open sun drying [1, 2].

Thermodynamics plays an important role to perform the energy efficiency of the industrial processes. The energy used in a system or process is significant and therefore represents

an often reducible element of process cost. It is possible to identify the operating conditions in which potential savings can be made using an exergy analysis [3]. The exergy of a thermodynamic system is defined as the maximum theoretical useful work (shaft work or electrical work) that can be obtained until thermodynamic equilibrium with the environment is reached, in presence of no other interacting system [4]. In order to achieve an efficient use of energy resources, exergy losses should be reduced as much as possible in all physical processes. In this sense, one of the main goals of exergetic analysis is to locate and characterize the causes of exergy destruction or exergy loss, as well as to quantify the corresponding rates [5]. Exergetic indicators, which address different aspects of thermodynamic performance, are useful to obtain a better understanding of irreversibilities and exergy losses. A single exergetic indicator might not be sufficient to describe completely the thermodynamic performance [6]. The exergy-based environmental and sustainability parameters previously were presented in the literature for various applications [6–9]. Zisopoulos et al. [6] reviewed the methodology of exergy analysis and the exergetic indicators that are most appropriate for use in the food industry. The exergy-based environmental and sustainability parameters had been defined based on the operating principle and the impressive parameters affecting the system performance of the single layer drying process in the literature by Midilli and Kucuk [9].

Drying involves a double transfer of heat and mass, thus it is a very inefficient operation. The energy needed for drying depends mainly on the nature of the product to be dried and the drying rate. Hence the usefulness of an energy and exergy analysis for each product in order to quantify the energy needed for drying and to locate the exergy losses in each step of the process [10].

During the past few decades, thermodynamic analysis, particularly exergy analysis, has appeared to be an essential tool for system design, analysis and optimization of thermal systems [11]. For evaluating the performance of food drying systems, energy analysis method has been widely used, while the studies on exergy analysis are relatively limited (A number of studies have been performed on the energy and exergy analyses of the solar drying process of agricultural products [5, 12–23]. Rabha et al. [23] investigated energy and exergy analyses of the solar drying processes of ghost chilli pepper in a solar tunnel dryer. Akpinar [18] performed energy and exergy analyses of drying of red pepper slices in a convective type dryer. However, detailed literature review of the present study has shown that there is no information on exergetic sustainability indicators of solar drying system for green pepper in literature to the best of the authors' knowledge.

This study demonstrates the effects of some exergetic indicators on the performance of a single layer solar drying system by using the experimental data in the literature for long green pepper [24].

Table 1 List of some exergetic indicators found in literature [6, 9, 25]

Exergetic indicators		
Exergetic efficiency	$\eta_{ex} = \sum \dot{E}x_{eus}/\dot{E}x_{in}$	(7)
Waste exergy ratio	$WER = \left(\sum \dot{E}x_d + \dot{E}x_L\right)/\sum \dot{E}x_{in}$	(8)
Environmental impact factor	$EIF = WER\frac{1}{\eta_{ex}}$	(9)
Exergetic sustainability index	$ESI = \frac{1}{EIF}$	(10)
Improvement potential	$IP = (1-\eta_{ex})\left(\dot{E}x_{dci}-\dot{E}x_{dco}\right)$	(11)

2 Analysis

In this study, the effects of energy utilization ratio and some exergetic indicators on the drying performance of long green pepper in a thin layer solar drying system were investigated. The various exergetic indicators found in literature as
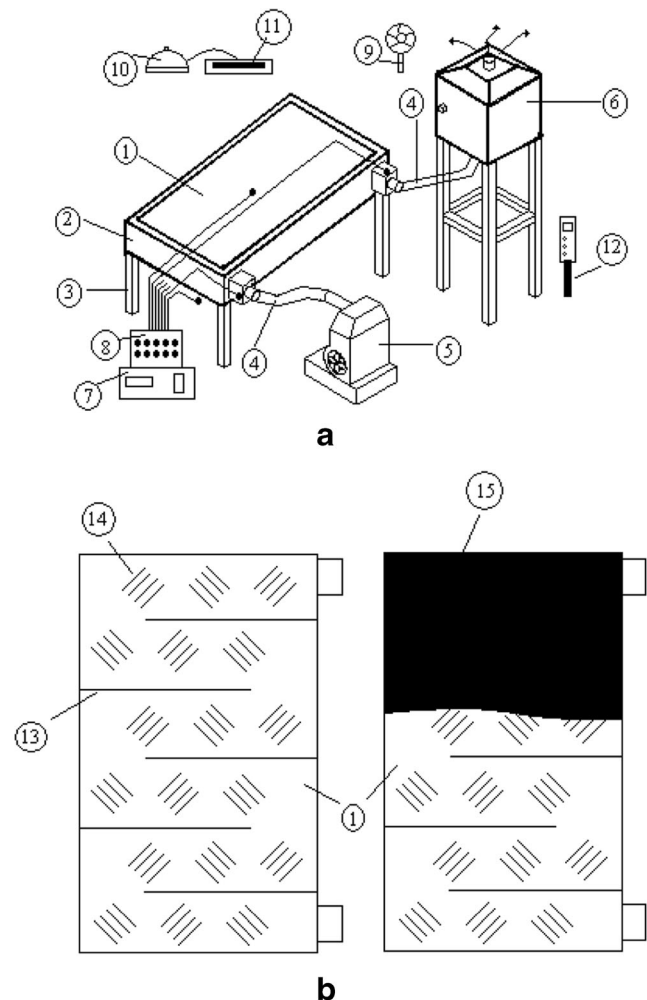

Fig. 1 Experimental set-up. 1-Solar collector; 2-Frame; 3-Foot; 4-Connection pipe; 5-Circulation fan; 6-Drying cabinet; 7-Channel selector; 8-Digitial thermometer 9-Anenometer; 10- Pyrometer; 11- Digital solar integrator; 12- Hygrometer; 13-Fin (Type I); 14- Fin (Type II); 15-Copper sheet

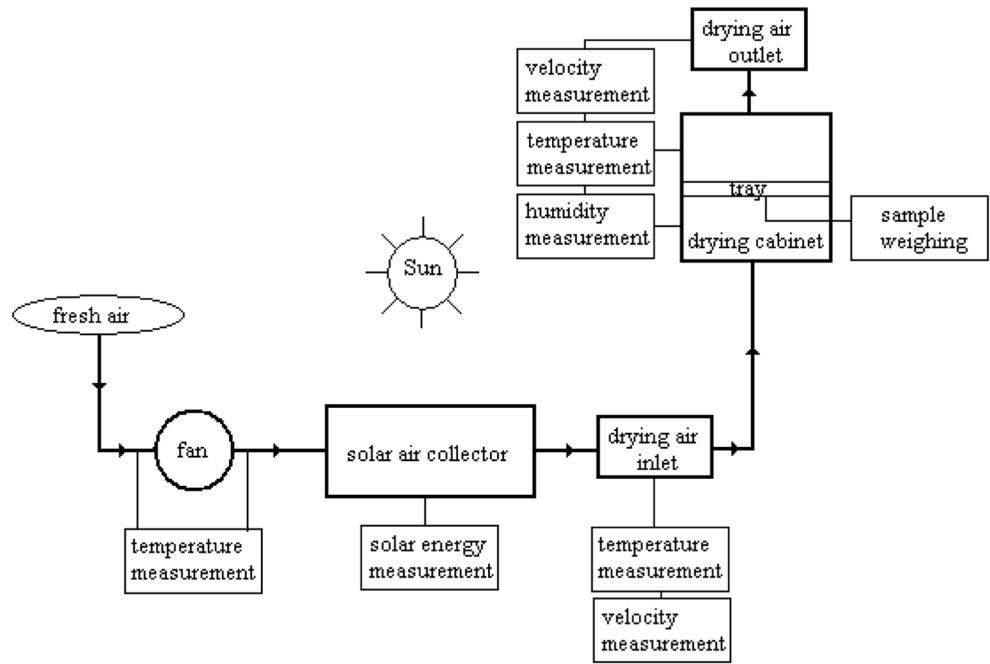**Fig. 2** Flow diagram of thin layer forced solar drying process

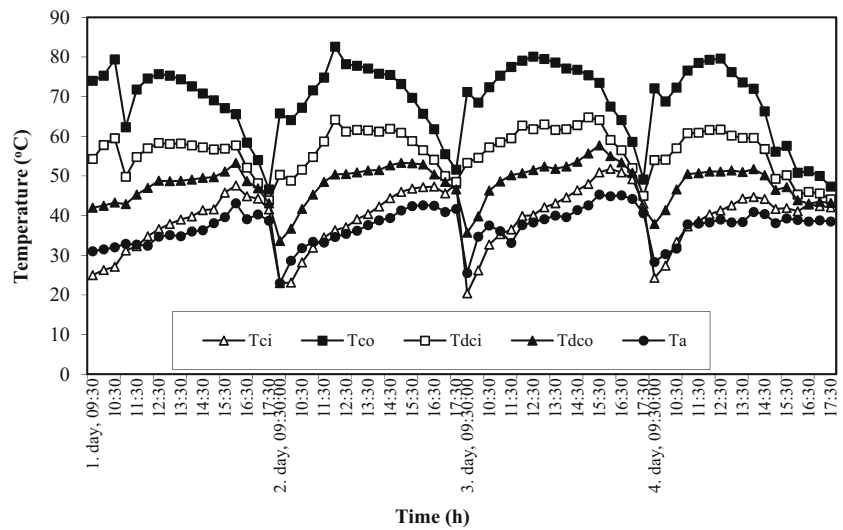**Fig. 3** Variation of temperatures in the solar dryer

Fig. 4 Variation in the direct radiation and wind speed
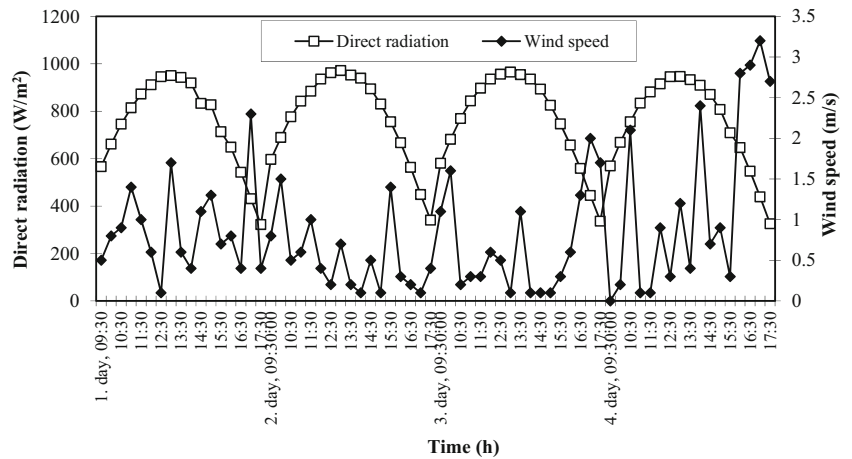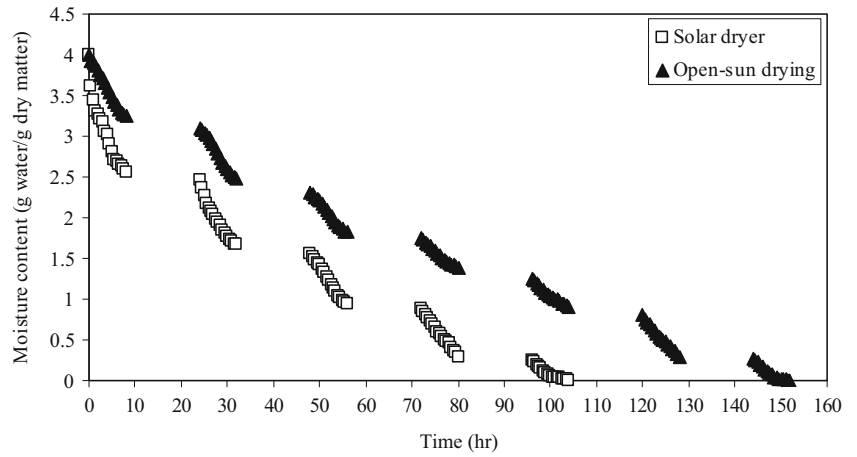
Fig. 5 Variation of moisture content with time of long green peppers

exergetic efficiency, waste exergy ratio, environmental impact factor, exergetic sustainability index and improvement potential were used for the exergetic assessment of solar drying system [9].

2.1 Performing energy analysis

The energy utilization ratio (EUR) is stated as the ratio to the energy utilization of the useful energy obtained from the solar

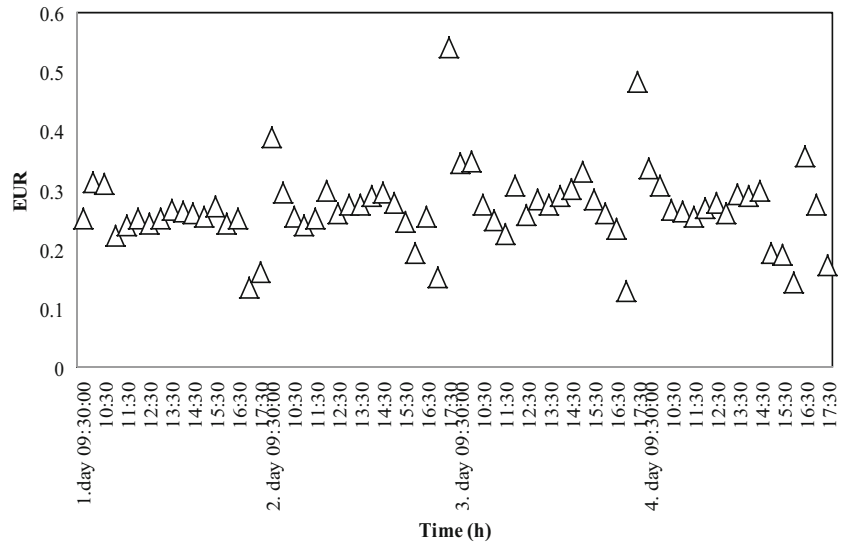**Fig. 6** Variation of EUR with time

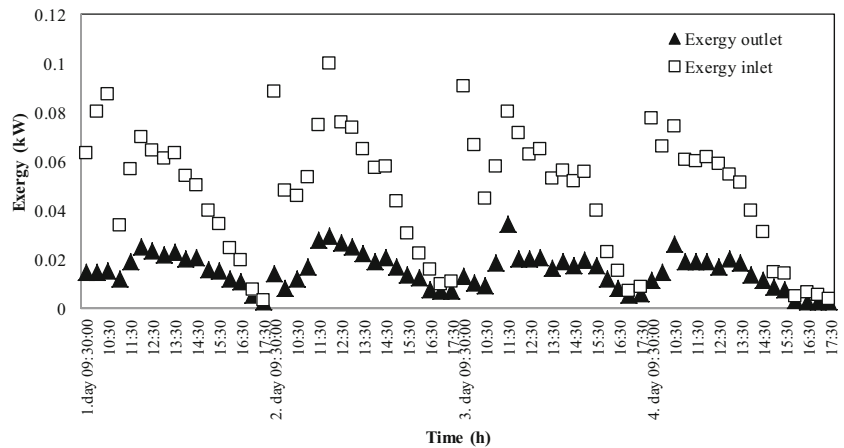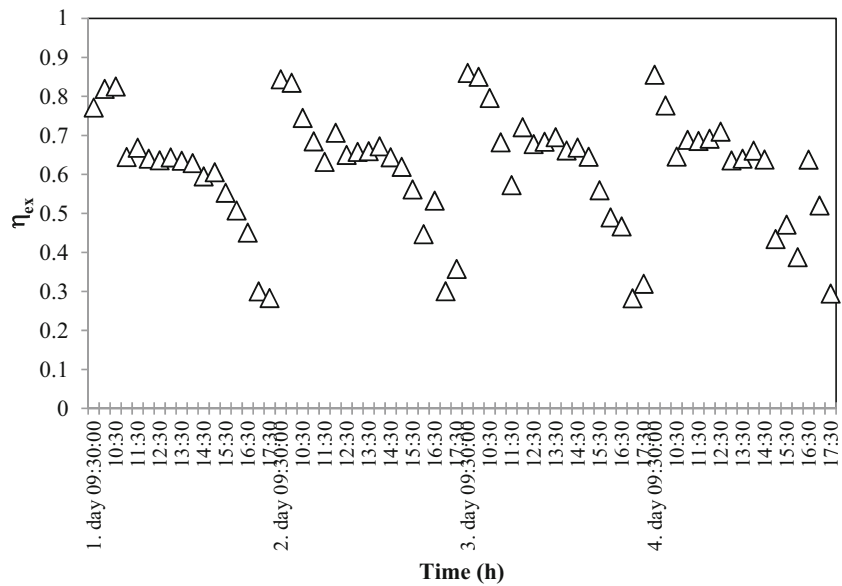**Fig. 7** Variation of exergy inlet and outlet with time

Fig. 8 Variation of exergetic efficiency (η_{ex}) with time

air collectors. The energy utilization ratio of the cabinet is determined as [14],

$$EUR = \frac{\dot{m}_{da}(h_{dci}-h_{dco})}{\dot{m}_{da}c_{p_{da}}(T_{co}-T_{ci})} \qquad (1)$$

2.2 Performing exergy analysis

Exergy balance of a solar drying system is defined as,

$$\sum \dot{E}x_{in} = \sum \dot{E}x_L \ + \ \sum \dot{E}x_d + \sum \dot{E}x_{eus} \qquad (2)$$

where

$$\sum \dot{E}x_d = \sum \dot{E}x_{input,f} \ + \ \sum \dot{E}x_{input,sol} - \sum \dot{E}x_{dci} \qquad (3)$$

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{input,f} \ + \ \sum \dot{E}x_{input,sol} \qquad (4)$$

$$\sum \dot{E}x_L = \sum \dot{E}x_{dco} \qquad (5)$$

where $\sum \dot{E}x_{input,f}$ is inlet exergy from the fan, $\sum \dot{E}x_{input,sol}$; gained exergy from solar air collector [9].
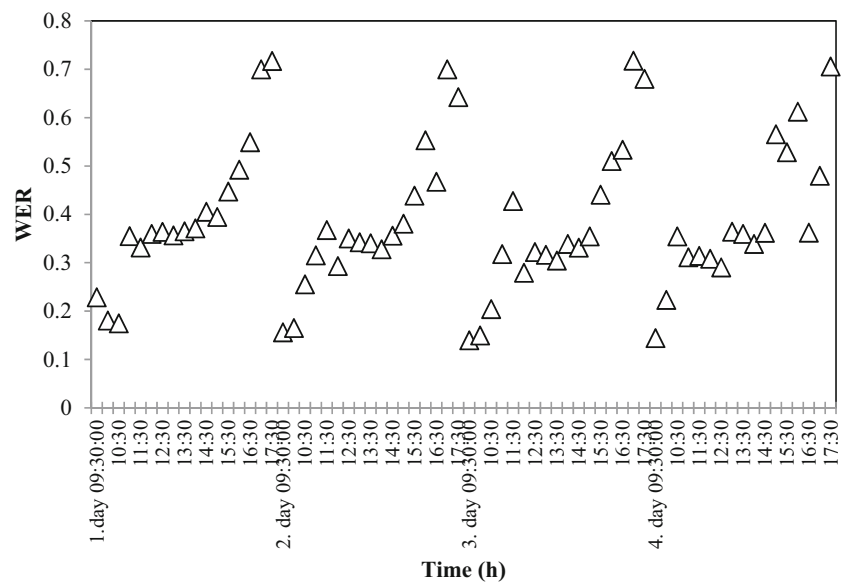
If Eq. (3–5) are replaced into Eq.(2):

$$\sum \dot{E}x_{eus} = \sum \dot{E}x_{dci} \ - \ \sum \dot{E}x_{dco} \qquad (6)$$

where $\sum \dot{E}x_{dci}$ is exergy inlet to the drying cabinet, $\sum \dot{E}x_{dco}$; outlet exergy from drying cabinet.

The various exergetic indicators have been used for the exergetic assessment of solar drying processes, a summarized list with their definitions is shown in Table 1 [6, 9, 25].

Fig. 9 Variation of waste exergy ratio (*WER*) with time

3 Materials and procedure

3.1 Experimental set up

Solar drying system consists of three main parts: (i) solar air collector (ii) drying cabinet and (ii) circulation fan (Fig. 1a). Fins (Type I; Type II) were located in flow area to increase the heat transfer coefficient and output temperature of air (Fig. 1b). The experimental set-up was described in detail in the previous work [24] by the author.

3.2 Experimental procedure

Solar drying experiments were performed in June 2006 in Elazig, Turkey. Each of experiment started at 9:30 a.m. and continued untill 17:30 p.m. Elazig is locate at 38°60'N and 39°28'E and above 950 m of sea level in the eastern part of Anatolia, Turkey.

In the experiments, weather temperature and relative humidity, inlet and outlet temperatures of air in the solar collector, the temperatures at the various points of drying cabinet, humidity, inlet and outlet temperatures of air in the cabinet, wind speeds, the amount of solar radiation, and mass loss of long green peppers were measured and recorded at 30 mins intervals. The flow charts of the thin layer forced and open sun drying processes are presented in Fig. 2.

The measuring instruments used in experiments and the total uncertainties of the measured parameters were presented in [24] by Akpinar and Bicer (2008).

4 Results and discussion

During the solar drying experiments, the temperature of ambient air, the temperature of the drying air at the inlet and the outlet of the drying cabinet varied between 23 and 45.3 °C, 43.9–64.8 °C, and 33.6–57.7 °C, respectively (Fig. 3). The drying temperature in solar dryer and ambient temperature varied continuously with a long drying time. The solar drying temperature was greater than the ambient temperature. The direct instantaneous solar radiation received the highest value, 971 Wm^2 (Fig. 4). Solar radiation energy was maximum at midday and at a minimum in the morning. It was also zero at night during the experiment. Wind speeds varied between 0 ms^{-1} and 3.2 ms^{-1} during the experimental working days (Fig. 4). Moreover, the mean wind speed was determined as 1.2 ms^{-1} by meteorological values [24].

The long green peppers of 4 g $_{water}$/g $_{dry\ matter}$ average initial moisture content, were dried to 0.10 g $_{water}$/g $_{dry\ matter}$ in the solar drying cabinet or were spread out on the ground
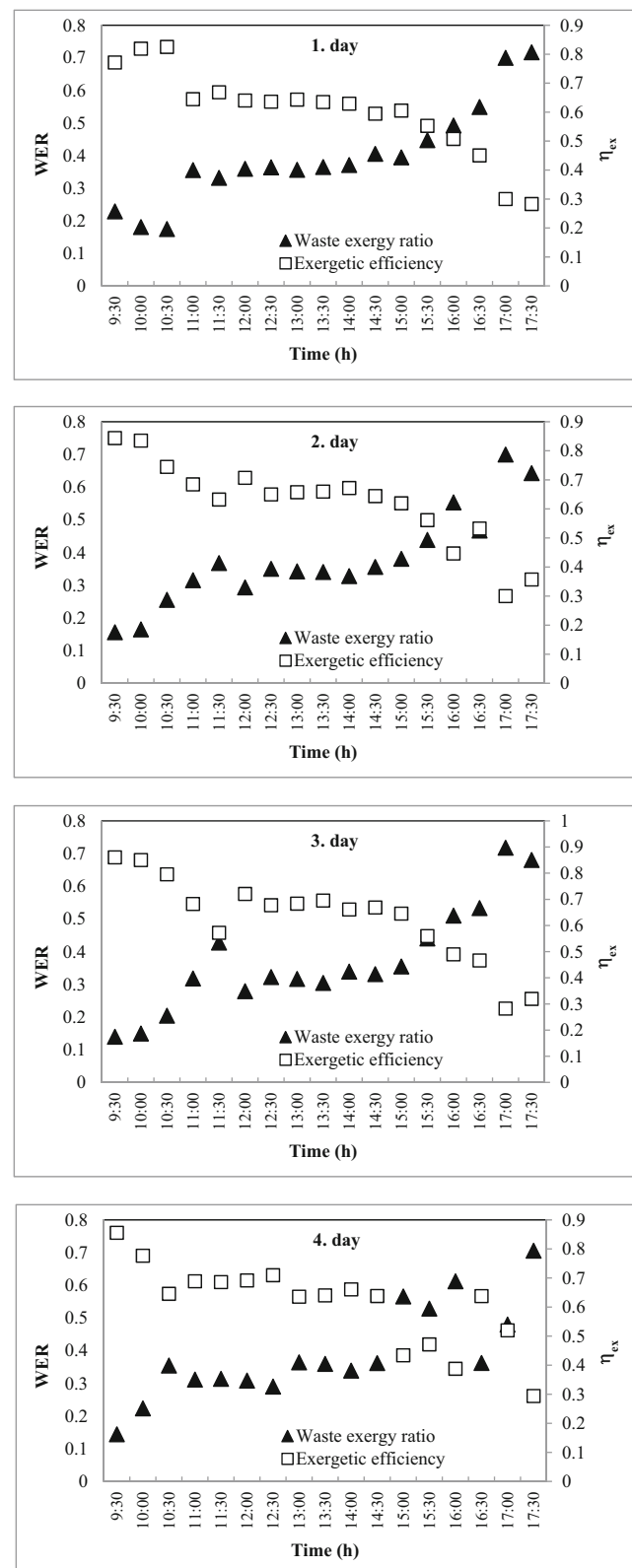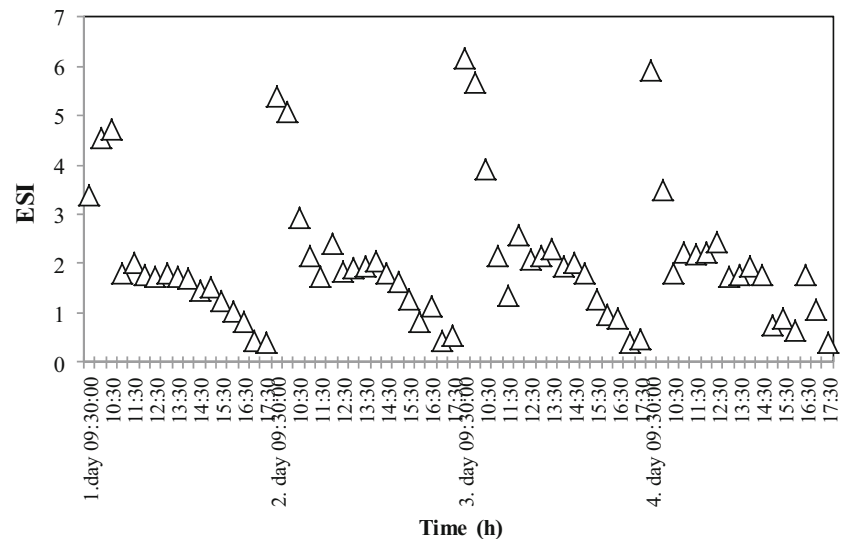

Fig. 10 Variation of exergetic efficiency (η_{ex}) and waste exergy ratio (WER) with time

**Fig. 11** Variation of exergetic sustainability index *(ESI)* with time

for open air sun drying. The changes in the moisture contents per amount of the dry matter of long green peppers with time are shown in Fig. 5. The interruptions of the lines in Fig. 5 represent the night periods of the drying operation. Final drying levels are realised in 104 h in the solar dryer, while it takes about 152 h in the open-air sun drying. The drying rate in the solar dryer, operating under forced convection, could be much higher than the natural open-air sun drying. Depending on the increase in the drying rates, the present system practically shortens the drying time of long green peppers by 2 days.

The *EUR* is an important parameter to analyze the energy utilization in drying processes. At the same time, the *EUR* is based on the structure and the moisture content of the dried products. Figure 6 exhibits the

variation of the *EUR* as a function of time. The *EUR* was calculated using Eq. (1). It was noticed that the *EUR* varied between 12.766 and 54.285% in the solar drying cabinet. The *EUR* of the cabinet reached a maximum in the morning hours (the beginning of experiment), and was at a minimum in the evening hours (the end of experiment). The EUR received values close to each other throughout the day, but generally showed a declining trend.

Figure 7 shows the variation of exergy inlet and exergy outlet with drying time. The exergy inflow and outflow to the drying chamber varied between 0.0022–0.034 kW and 0.00319–0.080 kW, respectively. The exergy inflows decreased with the increase of time. The exergy outflow values were at a minimum in the

Fig. 12 Variation of environmental impact factor *(EIF)* with time
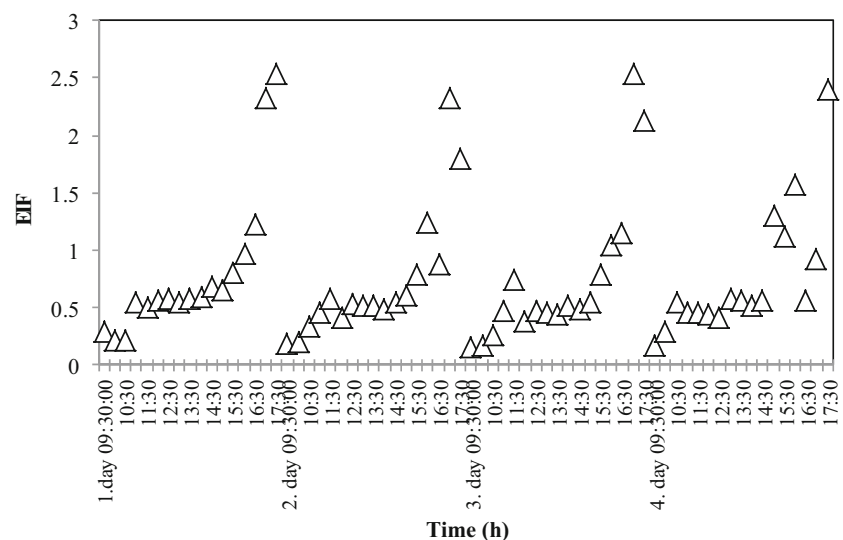
morning and the evening hours. The values showed a decreasing tendency within day.

The exergetic efficiency (η_{ex}) is one of the most frequently used indicators for the sustainability assessment of a solar drying system. It shows how well the exergetic inputs are utilized within the process. The exergetic efficiency is mainly based on the total exergy input and the total exergy used in the drying cabinet for a solar drying system. The waste exergy ratio (WER) is an important parameter to refer to the necessity of waste energy management of the solar drying system [9]. The exergetic performance and exergetic sustainability increase with the decrease of the WER of a solar drying system. The lower the WER value indicates a better efficiency. The exergetic efficiency and waste exergy ratio for the solar drying system was defined in Eqs. (7) and (8), respectively. The changes of exergetic efficiencies and waste exergy ratios with drying time were illustrated on Figs. 8, 9, and 10. The η_{ex} of the cabinet decreased with the increase of time. The η_{ex} varied between 28.22 and 86.02% for the cabinet. The values of the WER changed from 13.97 to 71.77%. The WER values increased with the increase of time. As seen in Fig. 10, the η_{ex} values decreased while the WER values increased. Because, the waste exergy ratio of solar drying system is a result of exergy losses in the solar air collector, drying cabinet and fan.

The environmental impact factor (EIF) was described with Eq. (9) as a function of waste exergy ratio and exergetic efficiency for a solar drying system and the exergetic sustainability index (ESI) was defined with Eq. (10). The environmental impact factor is an important parameter that indicates whether the environment has been damaged due to the waste energy output [9]. The change of the exergetic sustainability index and the environmental impact factor with time for a solar drying system were given in Figs. 11 and 12, respectively. As shown in Figs. 11 and 12, the ESI and the EIF values significantly varied with drying time. When drying time increased, the ESI values decreased, and the EIF values increased. It was determined that the ESI values changed between 0.3932 and 6.1560 for the solar drying system. Also, the EIF values changed from 0.1624 to 2.5429 for the solar drying system. The variation of the ESI and EIF values as a function of η_{ex} values were shown in Fig. 13 for a solar drying system. As shown in Figs. 11, 12, and 13, the ESI values increased with the increase of the η_{ex} and the EIF decreased with the increase of the η_{ex}. The ESI and the EIF values were inversely proportional. The increased η_{ex} resulted in the reduced environmental damage for solar drying system. When the total waste exergy outflows from the solar drying system increased, the ESI decreased, and therefore the EIF increased [9]. Figure 14
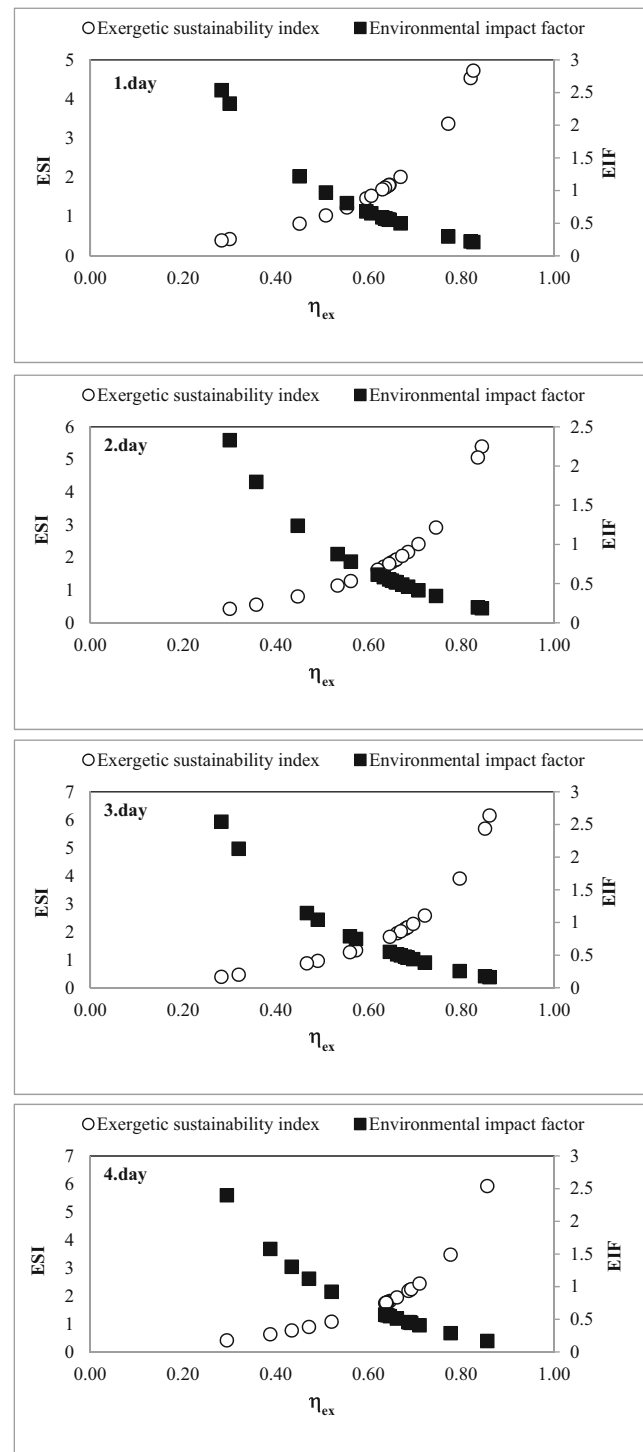

Fig. 13 Variation of exergetic sustainability index *(ESI)* and environmental impact factor *(EIF)* with exergetic efficiency

illustrates the variation of the improvement potential (IP) with time. The improvement potential was given with Eq. (11). The values of IP changed from 0 to 0.067 kW. The IP values decreased with the increase of drying time.

Fig. 14 The variation of improvement potential (*IP*) with time
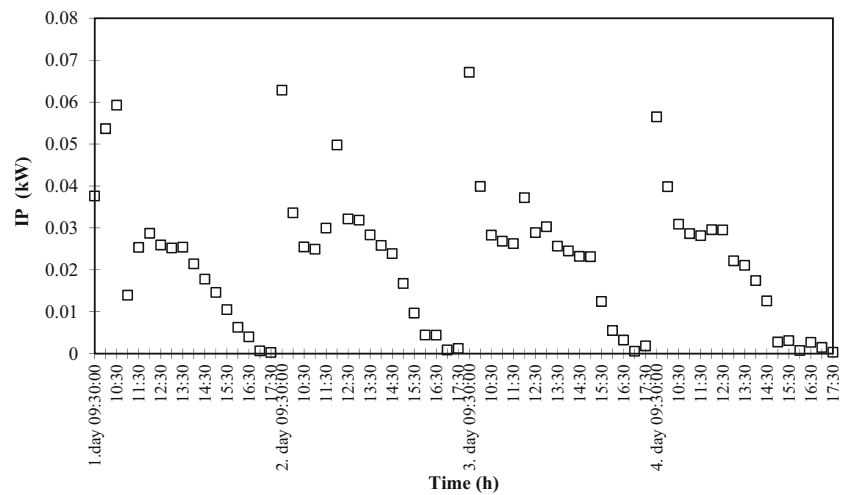
5 Conclusions

The long green peppers were successfully dried in the solar air dryer in 104 h in a drying air temperature range of 43.9 and 64.8 °C. Exergy analyses of the solar drying process were performed. The effects of the energy utilization ratio and some exergetic indicators on the drying performance of long green peppers in a thin layer in the solar drying system were investigated. The results showed that the *EUR* and the exergy efficiency varied between 12.766–54.285%, and 28.22% - 86.02% for the solar drying system, respectively. The values of waste exergy ratio changed from 13.97 to 71.77%. The exergetic sustainability indexes ranged from 0.3932 to 6.1560 for the solar drying system. The environmental impact factors changed from 0.1624 to 2.5429 for the solar drying system. The improvement potential changed between 0 and 0.067 kW.

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