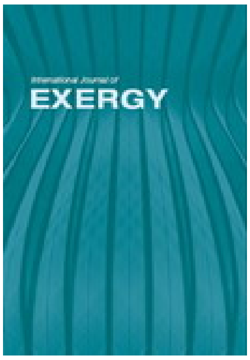
INDERSCIENCE PUBLISHERS
Linking academia, business and industry through research



International Journal of Exergy

ISSN online: 1742-8300 - ISSN print: 1742-8297
https://www.inderscience.com/ijex

Comprehensive exergy analysis of dandelion root during physical pre-treatment by convective solar drying

Haytem Moussaoui, Khaoula Chatir, Azim Doğuş Tuncer, Ataollah Khanlari, Abdelkader Lamharrar, Ali Idlimam

DOI: 10.1504/IJEX.2024.10062028

Article History:

Received:	15 November 2023
Last revised:	23 December 2023
Accepted:	31 December 2023
Published online:	01 February 2024

Comprehensive exergy analysis of dandelion root during physical pre-treatment by convective solar drying

Haytem Moussaoui*

Laboratory of Engineering in Chemistry
and Physics of Matter (LICPM),
Faculty of Sciences and Technics,
Sultan Moulay Slimane University,
BP 523, 23000 Beni Mellal, Morocco
Email: haytem.moussaoui@usms.ma
Email: haytem.moussaoui@gmail.com
*Corresponding author

Khaoula Chatir

Team of Solar Energy and Medicinal Plants EESPAM,
Laboratory of Processes for Energy and Environment ProcEDE, ENS,
Cadi Ayyad University,
Marrakech 40000, Morocco
Email: khaoula.moussaoui.h@gmail.com

Azim Doğuş Tuncer

Department of Energy Systems Engineering,
Burdur Mehmet Akif Ersoy University,
Burdur, Turkey
Email: azimdtuncer@gmail.com

Ataollah Khanlari

Department of Mechanical Engineering,
Faculty of Engineering,
Tarsus University,
Tarsus, Mersin, Turkey
Email: ata_khanlari@yahoo.com

Abdelkader Lamharrar and Ali Idlimam

Team of Solar Energy and Medicinal Plants EESPAM,
Laboratory of Processes for Energy and Environment ProcEDE, ENS,
Cadi Ayyad University,
Marrakech 40000, Morocco
Email: alamharrar@yahoo.fr
Email: aidlimam@gmail.com

Abstract: In this study, a controlled indirect solar dryer was used to dry dandelion roots at three temperatures of 60°C, 70°C, and 80°C, together with two air flow rates of 0.0417 m^3/s and 0.0834 m^3/s. The main aim of this research is to carry out an exergetic analysis on the dryer chamber and the drying process in order to improve the exergetic efficiency of the solar dryer. The outcomes showed that the level of exegetic performance depends on the variation of the operating conditions. The exergy yield of the drying chamber of six drying configurations was obtained between the ranges of 48.1141%–68.2755%.

Keywords: solar energy; solar drying; exergy analysis; dandelion root.

Reference to this paper should be made as follows: Moussaoui, H., Chatir, K., Tuncer, A.D., Khanlari, A., Lamharrar, A. and Idlimam, A. (2024) 'Comprehensive exergy analysis of dandelion root during physical pre-treatment by convective solar drying', *Int. J. Exergy*, Vol. 43, No. 1, pp.81–91.

Biographical notes: Haytem Moussaoui is a Professor at the Department of Physics, Sultan Moulay Sulayman University, Morocco. He completed his Engineering Diploma in Industrial Engineering at the Hassan I University, Morocco, in 2015. He also obtained his PhD in the Department of Energetics Physics at Cadi Ayyad University, Marrakesh, Morocco, in 2020. His main research interests include renewable energy systems, sorption isotherms, thermal energy systems decision-making, design of experiments (DOE), and 4E analysis. He has authored over 44 research publications.

Khaoula Chatir is a PhD student in the Ecole Normale Supérieure, Cadi Ayyad University, Marrakesh, Morocco. His main ranges of scientific interests are renewable energy, solar drying, thermodynamic properties of food, food storage, heat and mass transfer.

Azim Doğuş Tuncer is a research assistant in the Burdur Mehmet Akif Ersoy University, Burdur, Turkey. He completed his MSc and PhD studies in the Department of Energy Systems Engineering, Gazi University, Ankara, Turkey in 2018 and 2022, respectively. His main research interest includes renewable energy systems, HVAC-R systems, heat exchangers, nanoparticles/nanofluids, computational fluid dynamics, and life cycle assessment. He has over 120 research items in total.

Ataollah Khanlari is an Associate Professor at the Department of Mechanical Engineering, Tarsus University, Turkey. He completed his MSc in the Department of Clean-Renewable Energies, Hacettepe University, Ankara, Turkey in 2013. Also, he completed his PhD in the Department of Energy Systems Engineering, Gazi University, Ankara, Turkey in 2018. His main research interest includes renewable energy systems, heat exchangers, nanoparticles/nanofluids, HVAC-R applications, computational fluid dynamics, and life cycle assessment. He has over 60 articles that published in international referred journals.

Abdelkader Lamharrar is a Professor of Physics in the Teacher's Training College, Cadi Ayyad University. His areas of research are focused on renewable energy and medicinal plant research.

Ali Idlimam is a Professor of Physics in the Teacher's Training College, Cadi Ayyad University. His areas of research are focused on solar energy, and food quality. He is the Director of a Laboratory of the Solar Energy Team and Aromatic Plant.

1 Introduction

Drying is a widely utilised food preservation method from ancient times for increasing the utilisation period of the product (Dinçer and Zamfirescu, 2016; Idlimam et al., 2022; Selimefendigil and Şirin, 2022). However, conventional drying procedure is an energy-intensive process that could increase the total cost of dried agricultural material (Acar et al., 2022). Due to the long drying time, open sun drying also has certain detrimental consequences on product quality, such as an increased chance of contamination. Therefore, effective indirect or direct solar energy-assisted dryers can be developed and used for drying various types of products. In addition, forced convection solar drying systems have some advantages such as preventing heat damage to the drying product, accelerating the drying process, and reducing the overall consumed energy.

Solar dryers (SDs) usually consist of a solar air collector (SC) and a drying chamber (DC), and the products are placed on a grid (Kouhila et al., 2020; Şirin et al., 2023; Khanlari and Tuncer, 2023). The radiation heats and dries the air circulating in the SC, which then enters the DC and dehydrates the plants. Exergy analysis of drying systems is quite important in terms of determining the usability of the generated energy. Generally, the exergy examination of solar drying through the second law of thermodynamics has been applied to evaluate and develop various representations of exergy-conversion drying systems. Exergy is the greatest work that is possible when the solar system uses many mechanisms to complete the thermodynamic balance. Optimisation is the exergy's primary goal. The naming of the energy consumption process originates from the fact that the original research has a distinct conceptual description and uses the first and second laws of thermodynamics to analyse the amount of energy (Beigi et al., 2017). Instead, energy consumption in the drying system is the main cause of environmental problems like water and air pollution, solid waste disposal, seawater, land use, acid deposition, global warming, and the depletion of the stratospheric ozone layer. Therefore, many articles in the literature associate energy use with the environment, and investigate the best way to control the environmental impact of energy consumption. As these themes are an important foundation for sustainable development, the 'firepower fever' also laid the foundation for the development and understanding of sustainability policies (Khanali et al., 2013).

Medicinal and aromatic plants also need to be dried effectively and sustainably. Dandelions are also grouped among this type of plant. The dandelion is a plant whose benefits were discovered in antiquity but were confirmed only in the 16th century. The dandelion has many properties including purifiers and diuretics. It is effective for gallstones and kidney stones as well as being useful for loss of appetite or certain skin diseases (Moussaoui et al., 2020; Rauwald and Huang, 1985). Chemical research of dandelion roots shows that this plant is rich in important chemical constituents. As is well knowledge, the application of dandelion root encompasses the domains of phytotherapy, pharmacology, and traditional folk use, while also accounting for the plant's seasonality. This plant's drying and storage has become essential components in these fields (Yogendrarajah et al., 2015). It's also critical to remember that it's appropriate to reconsider how it will be dried and stored.

The main purpose of the current study is to experimentally investigate the exergetic performances of the solar drying process of the dandelion root and the drying chamber as impacted by different drying parameters including drying air temperature and airflow rate. Different from other works available in the scientific literature that analysed solar drying systems, the present study focused on the exergetic effectiveness metrics of the dandelion root drying process considering varying aerothermal parameters containing drying temperature and airflow rate.

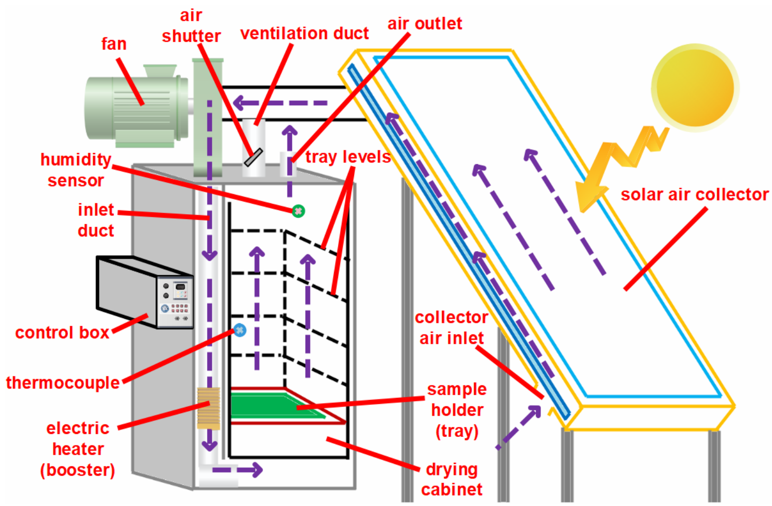
2 Material and methods

2.1 Description of the solar drying system and operation details

The developed forced convection SD is shown in Figure 1 in a diagrammatic view. To carry out the drying process, the developed SD utilises two energy resources: electrical energy and solar energy. In addition to electrical resistors, the device's components include a thermoregulatory, a DC, an aeration duct, a centrifugal fan, and a SC. A chronometer and a digital balance have been utilised to measure the time-dependent change of the removed water (Moussaoui et al., 2019). The details of the components can be listed as:

- A 2.5 m^2 (2.5 m × 1 m) SC with simple glazing operated with forced convection that is facing south and sloped 31° to the horizontal level. The SC's transparent outer cover is composed of regular glass. The 0.5 mm thick, opaque absorber is made of an iron-galvanised sheet with a conventionally coated surface. The thick polyurethane foam used as the back thermal insulator measures 0.05 m and is positioned between two steel sheets. There is a 0.02 m absorber-cover distance and an absorber isolator distance of 0.025 m.
- An aeraulic channel that aspirated was made up of a parallelepiped tunnel segment. The air that exits the DC after going through every shelf can be fully or partially recycled owing to a double T-pipe of recycling, which is made up of two nested T-pipes. The register (valve) butterfly on the double T-pipe allows users to change the airflow rate.
- A DC has ten floors organised into trays that are 1.40 metres high, 0.90 metres deep and 0.50 metres broad.
- A centrifugal fan (8 cm EC; 220 V, 0.1 kW) may achieve a maximum speed of 1.7 m/s in theory. Its regulator makes it possible to adjust the flow rate between 0.028 and 0.083 m^3/s.
- To adjust the intended temperature at the DC's inlet, an electric auxiliary heater is utilised in conjunction with a thermo-regulator that has a precise range of 0°C–100°C with an accuracy of 0.1°C. The thermo-regulator is coupled to a PT100 platinum probe.
- Four kilowatts of electrical resistance serving as a backup source.

Figure 1 Solar dryer with forced convection (see online version for colours)



2.2 *The protocol of the experiments*

The fresh dandelion roots utilised in this study were obtained from the surroundings of the province of Settat, Morocco. The mass of fresh dandelion root as the sample used in each drying experiment is 30±0.2 g per tray; the sample is uniformly dispersed on the drying tray and then put on the first shelf. The heated air-drying enters the drying chamber under the tray, and the fresh dandelion root is placed directly into the drying chamber. The relative humidity is determined by a capacitive sensor. In order to determine the mass loss of the dandelion root during the indirect solar drying process, a digital balance device (Humicolor probe-2, accuracy: ±0.001 g) has been utilised. It should be noted that the initial moisture content of the drying samples was determined by oven drying method at 105°C for 24 hours.

The drying experiments have been performed in May 2022. In every drying experiment, the dandelion root on the tray was taken out of the drying chamber for a duration of 15 to 20 seconds in order to calculate the mass loss. This procedure was carried out every ten minutes at the beginning of the drying experiment and every 60 minutes at the end of the experiment, which is present by the hygroscopic equilibrium of the samples. The moisture content at an instant *t* was calculated by the formula below:

$$X_{eq} = \frac{m_w - m_d}{m_d} \tag{1}$$

In equation (1), m_d and m_w and are the mass after and before drying in an oven for 48 h at 70°C, respectively.

2.3 *Exergetic investigation of the drying chamber*

According to the second law of thermodynamics, thorough analyses of the drying process' energy were presented (Aghbashlo et al., 2012; Beigi et al., 2017). The following equation develops the exergy balance that is related to the solar drying process with forced convection:

$$\sum \dot{E}x_{loss} = \sum \dot{E}x_{out} + \sum \dot{E}x_{destroyed} \tag{2}$$

The equation (3) presents the exergy loss in the DC of the SD:

$$\dot{E}x_{loss} = \dot{E}x_{id} + \dot{E}x_{od} \tag{3}$$

where $\dot{E}x_{id}$ is the exergy of inlet air and $\dot{E}x_{od}$ is the exergy of exit air of the controlled DC, the equations (4) and (5) calculate the exergy inflow and outflow, respectively (Tuncer et al., 2023):

$$\dot{E}x_{id} = \dot{m}_a \dot{c}_a \left[(T_{id} - T_0) - T_0 \ln\left(\frac{T_{id}}{T_0}\right) \right] \tag{4}$$

$$\dot{E}x_{od} = \dot{m}_a \dot{c}_a \left[(T_{od} - T_0) - T_0 \ln\left(\frac{T_{od}}{T_0}\right) \right] \tag{5}$$

where $\dot{m}_a$ denotes the mass flow rate of the flowing air in the DC (kg/s). This metric can be attained as below:

$$\dot{m}_a = \rho_a D_v \tag{6}$$

In equation (6), ρ_a depicts the density of air (kg/m^3) and D_v shows the volumetric flow rate (m^3/s).

The exergy transfer rate from evaporation related to the drying sample can be determined as below:

$$\dot{E}x_{evap} = \left[1 - \frac{T_0}{T_p} \right] \dot{Q}_{evap} \tag{7}$$

where:

$$\dot{Q}_{evap} = \frac{Q_{evap}}{t} \tag{8}$$

In equation (8), t depicts the drying period (time).

The exergetic yield of drying process can be determined by exploiting the equation (9):

$$\eta_{pro} = \frac{\dot{E}x_{evap}}{\dot{E}x_{in}} \tag{9}$$

The exergetic efficiency of DC can be calculated using the following expression (Tuncer et al., 2023):

$$\eta_{DC} = \frac{\dot{E}x_{od}}{\dot{E}x_{id}} \tag{10}$$

In this paper, the reference air temperature and air pressure were considered by the value of 25°C and 101.325 kPa, respectively considering the standard temperature and pressure (STP) for experimental measurements.

3 Results and discussion

In this work, six different aerothermal configurations for the indirect solar drying process of dandelion root have been tested experimentally. Figure 2 displays the exergy loss for drying conditions of dandelion roots (three drying air temperatures 60°C, 70°C, and 80°C: two drying air flow rates 0.0417 m^3/s and 0.0834 m^3/s. According to Figure 2, the exergy loss values of the DC for tests performed at lower flow rate at 60°C, 70°C, and 80°C were obtained as 2.2003, 2.7783 and 3.4124 kW, respectively. These values were obtained in the tests done at higher flow rate as 4.0629 kW, 4.2912 kW and 4.9814 kW, respectively. It should be noted that exergy loss of the DC of the dandelion roots increases with the raise of the air flow rate. Additionally, the value of the exergy loss decreases with a decrease of the air-drying temperature.

Figure 3 shows the rate of exergy transfer from the evaporation of drying dandelion root at varying temperatures of 60°C, 70°C, and 80°C, also with two drying air flow rates 0.0417 m^3/s and 0.0834 m^3/s. From this figure, it could be noted the exergy transfer rate from the evaporation of the drying root takes values that varied between 0.9803–2.6826 kW. Increasing the flow rate from 0.0417 m^3/s to 0.0834 m^3/s improved the exergy transfer rate for the drying cases that performed at 60°C, 70°C, and 80°C as 7.98%, 7.80% and 18.51%, respectively. The outcome from Figure 2 and Figure 3 is that various forms of exergy have the same evolution in the direction of solar drying conditions. They rise as the dry air temperature and dry air flow improve. In addition, the little amount of evaporation energy notably lowers the exergetic yield of the drying procedure. The greater output exergy value in the DC indicates that the exergetic yield of the DC is greater. These values agree with the results of the similar studies that have been published (Beigi et al., 2017; Akpinar et al., 2005).

Figure 2 Exergy loss of the DC of dandelion roots at different aerothermal conditions (see online version for colours)

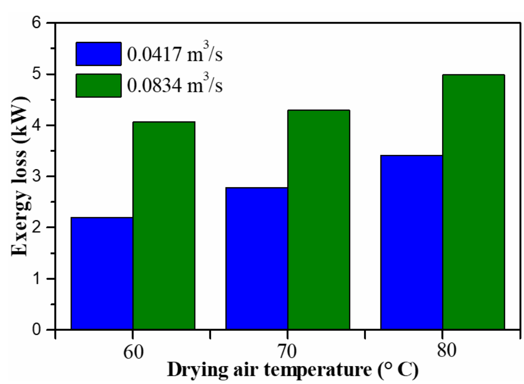
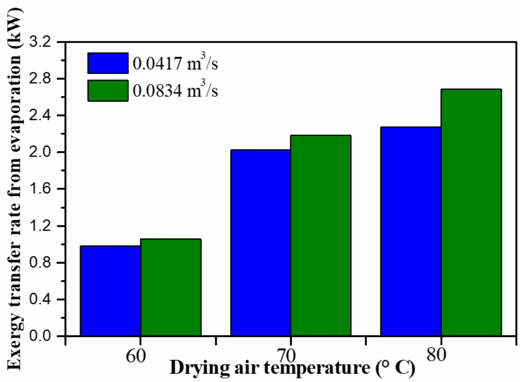


Figure 3 The rate of exergy transfer from the evaporation of dandelion roots drying (see online version for colours)



Figures 4 and 5 show different exergetic yield values for the DC and the drying process, respectively under different aerothermal conditions. Specifically, the present research considers three temperatures and two drying air fluxes. These figures can be employed to understand more about the drying process's and the DC's exergy efficiency. These results are critical to understanding and enhancing the effectiveness of solar drying devices for drying dandelion roots. The average exergy efficiency values of the drying process for the tests performed at lower flow rates at 60°C, 70°C, and 80°C were obtained as 12.4813%, 12.9647%, and 14.6951%, respectively. These values were obtained in the tests done at higher flow rates as 20.3590% (at 60°C), 21.0604% (at 70°C), and 23.0169% (at 80°C), respectively. Moreover, average exergy efficiencies of the DC for the tests performed at higher and lower flow rates were attained between ranges of 48.1141%–65.4054% and 52.0963%–68.2755%, respectively. From these figures, it was remarked that at fixed air-drying temperature and air flow rate, the value of the exergy efficiency for the drying process increases with an increase of the temperature and the air flow, whereas the value of the exergy yield for the DC decreases with a reduce in the temperature and the air flows. The obtained results and trends in the present work are in good line with similar studies available in the scientific literature that analysed the drying process of varying samples such as sardine waste (Bahammou et al., 2019) and carob pulp (Tagnamas et al., 2021).

The drying chamber has a higher exergetic efficiency compared to the drying process. This is caused by the fact that, as dry air conditions grow during the drying process, the exergy in the DC rises and the moisture content drops. Because of the low quality of the items utilised in the test and the high thermal energy carried by the SD, a smaller amount of evaporation heat and a bigger amount of useless energy were produced, leading to the lower exergetic efficiency value determined throughout the drying process. Similar to the exergetic efficiency of the drying process, increasing the flow rate and temperature led to improve the exergy efficiency of the DC. It should be noted that similar trends and increment rates were attained in some researches that analysed various types of drying systems like a spray dryer (Aghbashlo et al., 2012), a hybrid photovoltaic-thermal indirect solar dryer (Tuncer et al., 2023) and an ultrasonic-convective drying system (Wang et al., 2023).

Figure 4 Exergy efficiency for the drying process of the dandelion root at various drying configurations (see online version for colours)

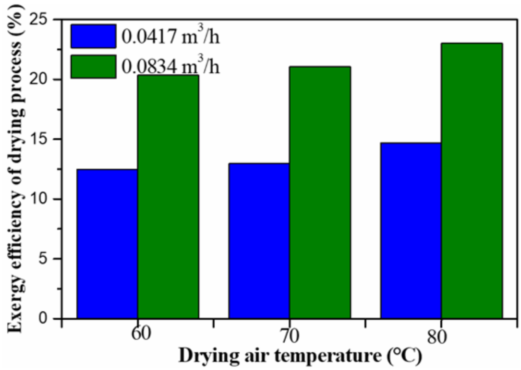
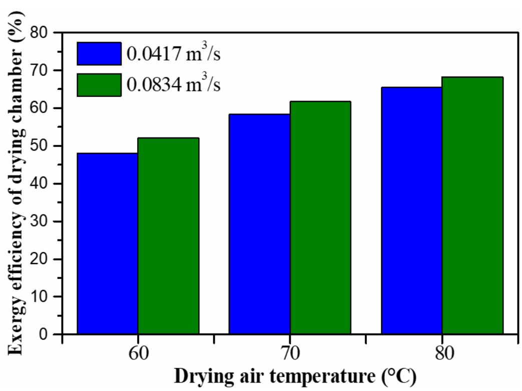


Figure 5 The exergy efficiency of DC of the dandelion root at various drying conditions (see online version for colours)



4 Conclusions

Drying agricultural crops using solar radiation is a very old preservation method practiced in many civilisations for increasing the shelf life of the crops. In this context, this experimental work presents a study of the solar drying of dandelion roots by a controlled forced convection indirect SD at three different temperatures and two air flow rates. This study seeks to the influence of different parameters (temperature of the drying air, air flow) on the drying process through the interpretation and analysis of the dryer. Since the energy loss of the DC fluctuates from 2.2003 kW to 4.9814 kW, the loss of the energy achieved from the DC is higher than the energy transfer rate of evaporation, according to the major outcomes of this work. Additionally, the evaporation capacity varies from 0.9803 kW and 2.6826 kW. Moreover, in all conditions of air heat, the exergetic yield of the DC is greater than the exergetic yield of the drying process; the exergy efficiency is between 12.4814% and 23.0170%, and the exergy efficiency of the dryer chamber varies from 48.1141% and 68.2755%. In further works, varying aerothermal conditions can be also experimentally analysed and machine learning and/or statistical approaches can be applied to optimise the operating parameters. Moreover, product quality analysis can be also done in future works and these outcomes can be utilised in the optimisation process.

References

Acar, C., Dincer, I. and Mujumdar, A. (2022) 'A comprehensive review of recent advances in renewable-based drying technologies for a sustainable future', *Drying Technology*, Vol. 40, No. 6, pp.1029–1050.

Aghbashlo, M., Mobli, H., Rafiee, S., Madadlou, A. (2012) 'Energy and exergy analyses of the spray drying process of fish oil microencapsulation', *Biosyst. Eng.*, Vol. 111, pp.229–241, https://doi.org/10.1016/j.biosystemseng.2011.12.001.

Akpinar, E.K., Midilli, A. and Bicer, Y. (2005) 'Energy and exergy of potato drying process via cyclone type dryer', *Energy Convers. Manag.*, Vol. 46, pp.2530–2552, https://doi.org/10.1016/j.enconman.2004.12.008.

Bahammou, Y., Lamsyehe, H., Kouhila, M., Lamharrar, A., Idlimam, A. and Abdenouri, N. (2019) 'Valorization of co-products of sardine waste by physical treatment under natural and forced convection solar drying', *Renew. Energy*, https://doi.org/10.1016/j.renene.2019.04.012.

Beigi, M., Tohidi, M. and Torki-Harchegani, M. (2017) 'Exergetic analysis of deep-bed drying of rough rice in a convective dryer', *Energy*., Vol. 140, pp.374–382, https://doi.org/10.1016/j.energy.2017.08.100.

Beigi, M., Tohidi, M. and Torki-Harchegani, M. (2017) 'Exergetic analysis of deep-bed drying of rough rice in a convective dryer', *Energy*, https://doi.org/10.1016/j.energy.2017.08.100.

Dinçer, İ. and Zamfirescu, C. (2016) *Drying Phenomena: Theory and Applications*, John Wiley & Sons, Hoboken, New Jersey, USA.

Idlimam, R., Chatir, K., Asbik, M., Bah, A. and Moussaoui, H. (2022) 'Thermokinetic study by solar convective drying of Argan press-cake', *International Journal of Heat and Technology*, Vol. 40, No. 1, pp.174–182.

Khanali, M., Aghbashlo, M., Rafiee, S. and Jafari, A. (2013) 'Exergetic performance assessment of plug flow fluidised bed drying process of rough rice', *Int. J. Exergy*, https://doi.org/10.1504/IJEX.2013.057357.

Khanlari, A. and Tuncer, A.D. (2023) 'Analysis of an infrared-assisted triple-flow prototype solar drying system with nano-embedded absorber coating: an experimental and numerical study', *Renewable Energy*, Vol. 216, p.119125, https://doi.org/10.1016/j.renene.2023.119125.

Kouhila, M., Moussaoui, H., Lamsyehe, H., Tagnamas, Z., Bahammou, Y., Idlimam, A. and Lamharrar, A. (2020) 'Drying characteristics and kinetics solar drying of Mediterranean mussel (mytilus galloprovincilis) type under forced convection', *Renew. Energy*, https://doi.org/10.1016/j.renene.2019.09.055.w.

Moussaoui, H., Idlimam, A. and Lamharrar, A. (2019) 'The characterization and modeling kinetics for drying of taraxacum officinale leaves in a thin layer with a convective solar dryer', *Lect. Notes Electr. Eng.*, pp.656–663, https://doi.org/10.1007/978-981-13-1405-6_75.

Moussaoui, H., Lamsyehe, H., Kouhila, M., Bahammou, Y., Tagnamas, Z., Idlimam, A. and Lamharrar, A. (2020) 'Adsorption measurements and study of temperature and humidity influences on the dandelion leaves' powder', *Moroccan J. Chem.*, Vol. 8, pp.147–156, https://doi.org/https://doi.org/10.48317/IMIST.PRSM/morjchem-v8i1.15545.

Rauwald, H.W. and Huang, J.T. (1985) 'Taraxacoside, a type of acylated γ-butyrolactone glycoside from taraxacum officinale', *Phytochemistry*, https://doi.org/10.1016/S0031-9422(00)81065-1.

Selimefendigil, F. and Şirin, C. (2022) 'Experimental investigation of a parabolic greenhouse dryer improved with copper oxide nano-enhanced latent heat thermal energy storage unit', *International Journal of Energy Research*, Vol. 46, No. 3, pp.3647–3662.

Şirin, C., Selimefendigil, F. and Öztop, H.F. (2023) 'Performance analysis and identification of an indirect photovoltaic thermal dryer with aluminum oxide nano-embedded thermal energy storage modification', *Sustainability*, Vol. 15, No. 3, p.2422.

Tagnamas, Z., Lamsyehe, H., Moussaoui, H., Bahammou, Y., Kouhila, M., Idlimam, A. and Lamharrar, A. (2021) 'Energy and exergy analyses of carob pulp drying system based on a solar collector', *Renewable Energy*, Vol. 163, pp.495–503, https://doi.org/10.1016/j.renene.2020.09.011

Tuncer, A.D., Khanlari, A., Afshari, F., Sözen, A., Çiftçi, E., Kusun, B. and Şahinkesen, İ. (2023) 'Experimental and numerical analysis of a grooved hybrid photovoltaic-thermal solar drying system', *Applied Thermal Engineering*, Vol. 218, p.119288, https://doi.org/10.1016/.applthermaleng.2022.119288.

Wang, H., Torki, M., Taherian, A., Beigi, M., Xiao, H.M. and Fang, X.M. (2023) 'Analysis of exergetic performance for a combined ultrasonic power/convective hot air dryer', *Renewable and Sustainable Energy Reviews*, Vol. 185, p.113607, https://doi.org/10.1016/j.rser.2023.113607.

Yogendrarajah, P., Samapundo, S., Devlieghere, F., De Saeger, S. and De Meulenaer, B. (2015) 'Moisture sorption isotherms and thermodynamic properties of whole black peppercorns (Piper nigrum L.)', *LWT – Food Sci. Technol.*, Vol. 64, pp.177–188, https://doi.org/10.1016/j.lwt.2015.05.045.