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Electrohydrodynamic drying versus conventional drying methods: A comparison of key performance indicators

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ABSTRACT

Preserving fruits and vegetables by drying is a traditional yet effective way of reducing food waste. Existing drying methods are either energy-intensive or lead to a significant reduction in product quality. Electrohydrodynamic (EHD) drying is an energy-efficient low-temperature drying method that presents an opportunity to comply with the current challenges of existing drying methods. However, despite its promising characteristics, EHD drying is yet to be accepted by industry and farmers. The adoption of EHD drying is hindered due to different reasons, such as uncertainties surrounding its scalability, quality of dried product, cost of operation, and sustainability compared to conventional drying methods. To address these concerns, this study quantifies and benchmarks the Key Performance Indicators (KPIs) of EHD drying compared to the standard conventional drying methods based on lab-scale experiments. These drying methods include hot-air, freeze, microwave, and solar drying. The results show that drying food using EHD is at least 1.6, 20, and 70 times more energy-efficient than the microwave, freeze, and hot-air, respectively. Similar results could be observed for exergy efficiency. EHD drying has superior product quality compared to other drying methods. For instance, it could retain 62% higher total phenolic content with 21% less color degradation than freeze-drying. Although microwave drying resulted in significantly higher drying kinetics than other techniques, EHD performed better than solar and freeze-drying but was comparable with hot-air drying. EHD drying also shows promising results in economic performance assessment. It is the cheapest drying method after solar drying and has the highest estimated net present value (NPV) after hot-air drying. Overall, compared to the currently used drying methods for small to medium-scale drying, EHD was found to be a more exergy and energy-efficient, cost-effective, and sustainable alternative that can provide higher-quality dried products. However, its drying kinetics should be improved for industrial applications.

1. Introduction

A substantial increase of about 70 % in global food demand is expected by 2050 due to the growing human population together with income growth [1,2]. Yet, the currently available food production and supply cannot meet this growing demand. This is a serious threat to global food security and is a key obstacle to sustainable development [3]. Appropriate pre- and post-harvest measures are required to prevent probable food crises in the future, and reducing food loss is one of the essential post-harvest actions. About 33 % of the total food produced for human consumption is wasted yearly along food supply chains mainly because of inadequate storage and improper processing [4,5]. Such a remarkable level of food loss contributes to 5–10 % of global greenhouse gas emissions and amounts to an enormous loss in resources, including labor, water, and investment [6]. One of the oldest and most reliable techniques to reduce food loss is preserving food as dried material [7].

Nevertheless, drying is an energy-intensive process. On the one hand, industrial techniques employed in developed countries are either energy-inefficient or lead to a significant loss of product quality due to

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Nomenclature

Symbols

A_s	total area of the drying material [m^2]
C_a	annualized investment cost [USD]
C_{ac}	annual maintenance costs [USD]
C_e	annual cost of energy [USD]
C_{ic}	initial capital investment [USD]
C_m	annual maintenance costs [USD]
C_n	operating cost of dryer [USD]
C_P	specific heat capacity [kJ $kg^{-1}C^{-1}$]
C_1	reference cost [USD]
C_2	adjusted cost [USD]
CEPCI	chemical engineering plant cost index
CF	carbon footprint [kg_{CO2eq}]
CRF	capital recovery factor
DF	drying flux [g m^{-2} s^{-1}]
DR	average drying rate [kg_{H2O} h^{-1}]
E	energy [kJ]
ex	specific exergy [J kg^{-1}]
$\dot{E}x$	exergy rate [kW]
$\dot{E}x_1$	supplied exergy rate to the system [kW]
g	gravitational acceleration [m s^{-2}]
g_c	Newton's law constant
h	specific enthalpy [kJ Kg^{-1}]
I	current [A]
i	interest rate [%]
J	Joule law constants
LD	loading density [$kg_{drying\ matter}$ $m^{-2}_{of\ tray}$]
L_{eva}	latent heat of evaporation [kJ Kg^{-1}]
m_{eva}	evaporated water mass [kg]
m_t	total mass of drying materials at critical drying time [kg]
m_0	total mass of the fresh-cut drying matter before drying [kg]
MC_{wb}	wet basis moisture content [g g^{-1}_{wb}]
P	power [kW]
P	pressure [Pa]
P_s	estimated total annual sales [USD]
PR	production rate [kg_{dm} m^{-2} day^{-1}]
Q	evaporation energy [kJ]
R	gas constant [J mol^{-1} K^{-1}]
R_n	revenue of dryers [USD]
RH	relative humidity [%]
s	specific entropy [kJ kg^{-1}]
SDR	specific drying rate [g_{H2O} $kg^{-1}s^{-1}$]
SEC	specific energy consumption [J kg^{-1}_{H2O}]
SMER	specific moisture extraction rate [kg_{H2O} kWh^{-1}]
SPBP	Simple payback period [year]
SVF	salvage value factor
T	average surface temperature of drying samples [°*C*], [°K]
$\bar{T}_m$	average temperature of drying material [°K]
t_{crit}	critical drying time [h]
u	specific internal energy [kJ kg^{-1}]
V	applied voltage [V]
V	velocity [m s^{-1}]
V_s	salvage value [USD]
V_{as}	annualized salvage value [USD]
w_{crit}	critical moisture content [kg m^{-3}]

Greek symbols

Δ	difference indicator
η_{Drying}	drying efficiency
η_E	energy efficiency
η_{Ex}	exergy efficiency
μ	chemical potential [kg m^{-3}]
ν	specific volume [m^3 kg^{-1}]
ω	specific humidity [kg kg^{-1}]

Subscripts

crit	critical
db	dry basis
dest	destroyed
eva	evaporated
f	saturated liquid state
g	saturated vapor state
in	input/ inflow
out	output/outflow
s	sample
wb	wet basis
0	reference/dead state condition

Abbreviations

ANOVA	Analysis of variance
EHD	Electrohydrodynamic
GHG	Greenhouse gases
KPIs	Key performance indicators
LCA	Life cycle assessment
NPV	Net present value
PPO	Polyphenol oxidase

elevated drying temperatures [8]. On the other hand, traditional methods such as natural sun drying, which are widely used in developing countries, are not ideal either. Sun drying is cheap and easy to implement but is characterized by long-term processing, weather uncertainties, large drying area requirements, lack of process controllability, and product contamination [8]. Thus, the food industry and other value chain stakeholders are continuously looking for more energy-efficient drying methods that are cost-effective and can produce premium dried products.

Recently, electrohydrodynamic (EHD) drying has shown promising potential as an energy-efficient and low-temperature method [9]. Its simple configuration consists of a high-voltage power supply and repeated arrays of two electrodes (emitter and collector). Applying a high-voltage difference between the electrodes ionizes the air around the emitter. The motion of the ions from the emitter towards the collector induces a wind (0.1 to 10 m s^{-1}) that contains ions, called ionic wind. The generated wind stimulates convective dehydration on drying materials.

Extensive research has been conducted on lab-scale EHD drying in the past two decades. A significant part of the studies was allocated to investigating the drying kinetics, final product quality (sensorial appeal and nutritional content), and optimizing the electrical process parameters, electrode configuration, and environmental parameters. The commonly used electrode configurations are the needle-to-plate ([10]), wire-to-plate ([11]), the multiple wire-to-plate ([12]), and wire-to-mesh that has been introduced recently [13]. These design configurations have been used to dry different fruits and vegetables, such as tomato, carrot, kiwi fruit, banana, and apple. These studies have already evaluated the energy efficiency, drying kinetics, and product quality attributes of this novel technology. However, no comprehensive study is available that compares the overall performance of EHD drying with available drying techniques. Having a clear vision of the sustainability, scalability, and affordability aspects of EHD drying is crucial for future research directions and the diffusion of this clean technology [14]. As a result of lacking such a comprehensive study, large-scale EHD drying units have not been deployed, and only a limited number of working pilot-scaled EHD drying prototypes have been introduced [15].

This paper aims to provide a clear overview of the advantages and disadvantages of using EHD drying as an alternative to the current technologies. To this end, the Key Performance Indicators (KPIs) are quantified for EHD drying and standard drying methods. EHD drying is then benchmarked against the standard drying methods from different perspectives based on the quantified KPIs. The selected standard drying methods include hot-air, solar, microwave, and freeze-drying. The motivations to select these methods were being currently the most employed method in the food industry (i.e., hot-air drying), delivering the best product quality attributes (i.e., freeze-drying), having the best energy efficiency and drying kinetics (i.e., microwave drying), and being the most economical solution (i.e., solar drying) based on literature [7,16,17]. The thorough insight provided by this paper increases the prospects for investing in EHD drying as a step toward adopting this clean technology by farmers, industries, and other stakeholders. In this study, for the first time, conventional drying methods are analyzed simultaneously from energy, exergy, environmental impact, drying kinetics, economics, and final product quality points of view. The methods introduced and employed in this study can be used as a reference for future performance evaluation of the drying technologies.

2. Materials and methods

2.1. General considerations

EHD drying is benchmarked against four conventional drying methods based on their performance in drying apple slices. These methods include hot-air, freeze-drying, microwave, and solar drying. This benchmarking is done for lab-scale drying setups. The data for these analyses are obtained based on direct and indirect collection methods. The direct collection gathers raw data from experiments performed by the authors. Indirect collection obtains data from the literature. To this end, all the data collected for EHD, hot-air, and freeze-drying were based on experiments conducted by the authors and verified by the literature (Table 1). All the data collected for microwave and indirect solar drying are obtained from the literature (Table 1). Note that, to be able to compare the results with our experiments, the literature selected as the indirect data inventory has performed the experiments on apple slices with a thickness of 4 ± 1 mm and initial moisture content of 83 ± 3 % [g g_{wb}^{-1}] under test conditions close to our experiments. These conditions and the operating parameters are summarized in Table 1.

2.2. Sample preparation

The Pink Lady cultivar apples were used for the drying experiments. A total of 500 samples (i.e., apple slices) weight 1100 ± 42 g were selected based on a similar shape, color, and size. The initial moisture content of the samples was MC_{wb} = 85 ± 0.7 % [g g_{wb}^{-1}], which was measured according to the method approved by AOAC [35]. In this regard, the samples were dehydrated in a drying oven at 105 ± 1 ℃ until a constant weight was obtained. Drying experiments were conducted at 22 ± 1 ℃ air temperature and 54 ± 8 % relative humidity in a controlled room. The apple slices were cut with 3 ± 0.3 mm thicknesses using an electric food slicer (Domo DO1950S, LINEA 2000, Belgium). 30 mm × 30 mm square slices were cut for the experiments with an in-house designed square puncher. Between 20 and 25 slices were used for each drying run. The samples were placed in small labeled Petri dishes, weighed, and immediately put into the dryer to reduce enzymatic browning. For drying kinetics of EHD drying tests, the samples were weighted in continuous and intermediate modes using a suspended weighing system (Fig. 1a). In intermediate mode, the system was turned off every 10 min during the first two hours of drying and every 30 min after the first two hours to cancel out the air drag force and electrostatic effects measured in continuous mode when the dryer was on.

Table 1
Source of the collected data for the performance analyses.

Data collection approach	Drying method	Operating parameters	References
Direct*	EHD drying	Drying temperature = 20 ± 1 °C; Relative humidity = 40 ± 5 %; Applied power = 12.8 ± 0.3 W; Electrodes gap = 5 cm;	[9,10,18]
	Hot-air drying	Drying temperature = 50 – 80 °C; Air velocity: 0.6 – 2 m s^{-1}; Relative humidity = 35 – 50 %;	[19–23]
	Freeze-drying	Heating plate temperatures = 45 to 65 °C; Condenser temperature = −20 to −40 °C; Vacuum level = 80 to 100 Pa;	[19,24–26]
Indirect**	Microwave drying	Drying temperature≈ 70 °C; Applied power = 200 – 2000 W; Frequency = 2.45 GHz; Volume (Capacity) = 19 – 22 L;	[27–30].
	Indirect solar drying	Drying temperature = 30 – 60 °C; Relative humidity = 30 – 60 %; Average solar radiation = 800 – 1000 W m^{-2}; Mode of air flow = natural and forced (fan 0.37 kW); Airflow rate = 0.06 – 0.1 m^3 s^{-1}; Experiment time = April and May;	[17,31–34].

* Based on experiments conducted by authors and validated by the literature mentioned in the references column.
** Based on the data provided by the literature mentioned in the references column.

2.3. Drying experiments

EHD drying tests were performed using a lab-scale EHD drying setup (Fig. 1a) optimized based on the previous simulation and experimental studies [13,36]. This upscalable setup is composed of a convective chamber (40 × 40 × 70 cm), a digital weighing scale to record the weight of the samples on the computer every 60 s (0.1 g resolution, PG5001-S, Mettler-Toledo, Greifensee, Switzerland), discharge (emitter) and collecting electrodes, and two high-voltage power supplies of positive and negative polarity (Spellman_SL30PN10, 0 ~ 30 kV). The emitters were connected to the positive and the collectors to the negative polarity high-voltage power supplies. The apple slices were placed on the collector electrode. A suspended weighting system was used to avoid any disturbance in the airflow distribution close to the samples by the digital scale. The employed non-intrusive weighing method enabled us to measure the weight loss in real time. The total energy consumption (i.e., overall energy consumed by the dryer) was measured using a plug power meter (MegaPower™, Digiparts, Canada). The discharge energy consumption of the EHD dryer was calculated based on the current and voltage applied between electrodes and monitored using a multimeter (Keysight U1253B, Santa Rosa, CA, USA) and a 1000:1 high-voltage probe (Testec HVP-40, Testec Elektronik GmbH, Germany). More details about the EHD drying setup are available in [13].

For freeze-drying, the samples were frozen at −20 °C and freeze-dried using a freeze dryer (Alpha 1–4 LSC plus, Christ, Osterode, Germany) (Fig. 1b), connected to an oil pump. Hot-air drying was

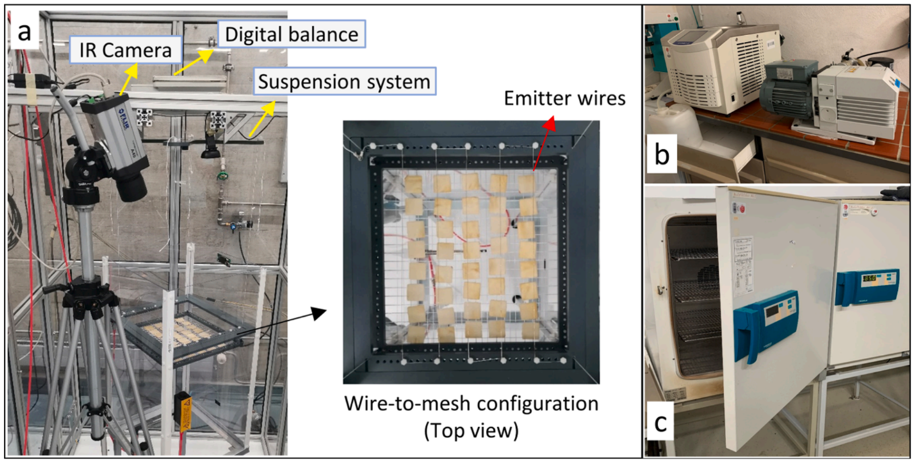

Fig. 1. Experimental setups used for drying tests; a) EHD drying setup together with the emitter–collector configuration, b) Freeze-dryer, c) hot-air dryer.

performed at 70 °C with a Function line Heraeus drying oven (Heraeus Deutschland GmbH, Hanau, Germany) (Fig. 1c).

2.4. Product quality assessment tests

The product quality of apple slices dried by EHD was compared with the other two drying methods: freeze-drying and hot-air drying. Freeze-drying was chosen because it has been extensively reported to be the best drying method in terms of overall product quality [16]. Hot-air drying was also chosen because it is the most used and adopted drying method in food industries [7]. The drying conditions and sample preparation procedures for quality assessment were similar to those described in previous sections. Since applying different drying methods leads to different equilibrium levels for the same material, the samples were dried to reach a certain moisture content in all the drying methods. This enables us to perform the quality test of the dried products under the same conditions. $MC_{wb} = 15$ % $[g\ g_{wb}^{-1}]$ was considered as the cut-off point, and the quality assessment tests on the dried products were performed at this moisture content. $MC_{wb} = 15$ % $[g\ g_{wb}^{-1}]$ was selected because it is below the critical moisture content (for apple slices ~ 23 % $[g\ g_{wb}^{-1}]$), which is the averaged moisture content in the sample that corresponds to an equilibrium water activity below which no spoilage occurs [36]. As such, the drying experiments for quality assessment were stopped at different times, depending on when this threshold was reached.

2.5. Statistical analysis

All experiments were repeated twice. The analytical methods and all measurements were repeated in triplicate. The results were expressed as average ± standard deviation. Data that did not follow a normal distribution were normalized before the analysis. Statistical differences among means of data obtained for samples were analyzed using a one-way analysis of variance (ANOVA) with the least significant difference comparison test (*t*-test) and accepted at a significance level of p-value < 0.05. Randomization was used in all the measurements to assure the independence of the error. All the statistical analyses were performed in R [37].

2.6. Performance indicators and metrics

The selected indicators for evaluating the performance of the drying technologies for drying apple slices are presented in this section. These indicators are divided into four categories: 1- drying kinetics, 2-environmental impact, energy, and exergy analyses, 3- quality of dried product, and 4- economics. The indicators in each category are listed in Table 2 and discussed below.

Table 2
Performance indicators for plant-based food drying methods.

Category	Indicator	Unit
Drying kinetics	Critical drying time	h
	Drying capacity (loading density)	$kg_{dm}\ m^{-2}$
	Throughput (Production rate)	$kg_{dm}\ h^{-1}\ m^{-2}$
	Specific drying rate (SDR)	$g_{H2O}\ kg^{-1}s^{-1}$
	Drying flux	$g_{H2O}\ m^{-2}\ s^{-1}$
Environmental impact, energy, and exergy analyses	Specific energy consumption (*SEC*)	$kJ\ kg_{H_2O}^{-1}$
	Specific moisture extraction rate (SMER)	$kg_{H_2O}\ kWh^{-1}$
	Energy efficiency	%
	Exergy efficiency	%
	Drying (system) efficiency	%
	Greenhouse gas (GHG) emission	$kg_{CO2\text{-}eq}\ kg^{-1}$
Product quality	Color change (CIE-LAB color parameters)	–
	Rehydration ratio	–
	Total phenolic content chlorogenic acid equivalent (CAE)	$\mu g_{CAE}\ g^{-1}$ fresh matter
	Trolox equivalent antioxidant capacity (TEAC)	$mmol_{TE}\ g^{-1}$ fresh matter
	Microstructural determination	–
Economics	Annualized investment cost of drying (C_a)	USD
	Cost of drying per kg of dried material (apple slices) (C_s)	USD
	Simple payback period (P_b)	Year(s)
	Net present value (NPV)	USD

2.6.1. Drying kinetics

(a) **Critical drying time**

The critical drying time (t_{crit}) was used as the reference drying time to compare different drying methods with different drying curves. It is defined as the needed drying time for the sample to reach the critical moisture content (w_{crit}). w_{crit} is the average moisture content of the sample that corresponds to an equilibrium water activity below which no spoilage occurs [38]. w_{crit} for the apple tissue is 37.8 kg m^{-3}, which corresponds to a dry-based moisture content of 0.29 $[kg_{H2O}\ kg_{dry\ based}^{-1}]$ [38].

(b) **Drying capacity (loading density)**

Drying capacity, or so-called loading density [$kg_{drying\ matter}\ m^{-2}_{of\ tray}$], is the total mass of the fresh-cut samples placed in the dryer to the total tray area.

(c) **Throughput (Production rate)**

Throughput or production rate [$kg_{dm}\ m^{-2}\ day^{-1}$] is defined as the amount of the fruit that can be loaded into the dryer per day, which can be formulated as follows:

$$PR = \frac{24}{t_{crit}} \times LD \tag{1}$$

(d) **Specific drying rate (SDR)**

The average drying rate (DR) [$kg_{H2O}\ h^{-1}$] over the drying period up to the critical drying time was derived from the moisture loss curves:

$$DR = \frac{evaporated\ \ water\ \ mass}{\Delta t} = m_t \frac{MC_{db,1} - MC_{db,2}}{t_{crit}} \tag{2}$$

where $MC_{db,1}$ and $MC_{db,2}$ are the moisture content in dry basis [$kg_{H2O}\ kg^{-1}_{dry\ \ based}$] at the beginning of the drying process and at the critical drying time, respectively. m_t [kg] is the total mass of the samples at the critical drying time. Since the drying rate depends on the mass of the wet sample, specific drying rate (SDR) was used in our comparative analysis to make the drying rate index independent of the amount of the loaded material. SDR is defined as the drying rate per unit mass of the loaded drying material [$g_{H2O}\ kg^{-1} s^{-1}$]:

$$SDR = \frac{DR}{m_0} \tag{3}$$

where m_0 [kg] is the total mass of the fresh-cut drying matter.

(e) **Drying flux**

Since the drying rate is proportional to the area of the wet sample, drying flux has been used for drying kinetics performance evaluation. Drying flux in a particular time window is defined as the drying rate per unit area of samples [$g\ m^{-2}\ s^{-1}$]:

$$DF = \frac{DR}{A_s} \tag{4}$$

where A_s [m^2] is the total area of the drying material at the beginning of drying. Note that the surface area of the samples will change over time as they shrink. This effect was not accounted for here. The time window was considered from the beginning of the drying up to the critical drying time.

2.6.2. Environmental impact, energy, and exergy analyses

(a) **Specific energy consumption (*SEC*)**

The specific energy consumption (*SEC*) [$kJ\ kg^{-1}_{H_2O}$] is a robust indicator for comparing the energy performance of the drying methods properly because it also incorporates quantities related to the drying kinetics. It is defined as the net energy E [kJ] consumed to evaporate a unit mass of water Δm [kg]. *SEC* can be calculated by dividing the dryer power *P* [kW] by the average drying rate:

$$SEC = \frac{E}{m_{eva}} = \frac{P}{DR(t_{crit})} \tag{5}$$

m_{eva} is the evaporated water mass. The energy consumption of the EHD drying method is calculated as $E = V.I.t_{crit}$, where V [V] is the applied voltage and I [A] is the current. Energy consumption of the other drying methods is calculated using the standard formulation provided by [7,39,40].

(b) **Specific moisture extraction rate (SMER)**

Specific moisture extraction rate (SMER) [$kg_{H_2O}\ kWh^{-1}$] is a performance indicator that is used to describe the effectiveness of the energy used in the drying process [41]. It is given by dividing the total moisture removed by the total energy input [17].

$$SMER = \frac{\Delta m(t_{crit})}{E_{in}} \tag{6}$$

(c) **Energy efficiency**

Energy efficiency (η_E) is defined as the minimum energy needed for water evaporation at the solid feed temperature (E_{eva}) to the total input energy of the dryer (E_{in}) [42];

$$\eta_E = \frac{E_{eva}}{E_{in}} = \frac{m_{eva} L_{eva}}{P \times t_{crit}} \tag{7}$$

where m_{eva} is the evaporated water mass [kg] and $L_{eva} = h_{fg}$ [$kJ\ Kg^{-1}$] is the latent heat of evaporation that was calculated from the following equation [22]:

$$L_{eva} = \begin{cases} h_{fg} = 2.503 \times 10^6 - 2.386 \times 10^3 T_s 0^\circ C < T_s \leq 65.56^\circ C \\ h_{fg} = (7.33 \times 10^{12} - 1.6 \times 10^7 (T_s + 273.16)^2)^{0.5} 65.56^\circ C < T_s < 280^\circ C \end{cases} \tag{8}$$

where subscripts g and f are saturated vapor and liquid states, respectively. Note that in freeze-drying, instead of L_{eva}, the latent heat of sublimation was used (2838 [$kJ\ kg^{-1}$] [43]).

(d) **Drying efficiency**

Energy efficiency indicates the fraction of the available energy used for water evaporation and only takes into account the latent heat of evaporation. Drying efficiency also accounts for the pre-heating energy used for the sample to reach the drying temperature in addition to the latent heat of evaporation.

$$\eta_{Drying} = \frac{E_{p,eva}}{E_{in}} = \frac{m_{eva}(C_P \Delta T + L_{eva})}{P(t_2 - t_1)} \tag{9}$$

C_P is the specific heat capacity of apple fruit which was considered as 3.64 $kJ\ kg^{-1}C^{-1}$ for above the freezing conditions and 1.76 $kJ\ kg^{-1}C^{-1}$ for below freezing [44]. ΔT [°C] is the difference between average surface temperature of the samples before and after starting the drying.

(e) **Exergy analysis: exergy efficiency and improvement potential**

Exergy analysis is one of the most powerful tools to improve the energy-efficient use of resources. It enables us to identify the locations and types of inefficiencies and quantify the magnitude of losses in energy systems. Exergy is the maximum amount of work a system can produce when it approaches equilibrium with a reference environment [34]. Therefore, the results of exergy analyses are always relative to the reference environment, which is characterized by specific temperature, pressure, and chemical composition.

Exergy is energy available from any source, including with mass flow (e.g., hot air) or without mass flow (e.g., radiation). It is usually expressed per unit system mass and is called specific exergy, which can be written as follows:

$$Exergy = \underbrace{(u-u_0)}_{\text{internal energy}} \underbrace{-T_0(s-s_0)}_{\text{entropy}} + \underbrace{\frac{P_0}{J}(v-v_0)}_{\text{work}} + \underbrace{\frac{V^2}{2gJ}}_{\text{momentum}} + \underbrace{\frac{g}{g_cJ}(z-z_0)}_{\text{gravity}} + \underbrace{\sum_C(\mu_c-\mu_0)N_c}_{\text{chemical}} + \underbrace{E_iA_iF_i(3T^4-T_0^4-4T_0T^3)}_{\text{radiation}} + \underbrace{\cdots}_{\text{other sources}} \quad (10)$$

where the subscript 0 denotes the reference conditions.u [kJ kg^{-1}] is specific internal energy, s [kJ kg^{-1} K^{-1}] is specific entropy, P [Pa] is pressure,ν [m^3 kg^{-1}] is specific volume, J and g_c are Joule and Newton's law constants, respectively. V [m/s] is velocity, g [m s^{-2}] gravitational acceleration, z [m] altitude coordinate, μ [kg m^{-3}] is chemical potential, N number of species. E, A [m^2],F, and T [K] are emissive power, area, shape factor, and temperature, respectively.

To purposefully conduct an exergy analysis, the following are the assumptions made for the control volume defined in Fig. 2:

- Since the drying chamber is the common part for the drying methods, it was considered as the control volume.
- All processes are steady-state and steady flow with negligible changes in potential and kinetic energy of the control volume.
- Air and vapor are ideal gases.
- Equation (10) is simplified by substituting enthalpy for the internal energy and $P\nu$ terms under steady flow assumption [45].
- The reference dead state conditions are assumed to be $T_0 = -50$ °C (to respect freeze-drying temperature), $P_0 = 101.325$ kPa (1 atm), and relative humidity (RH) = 50 % for all the analyzed drying methods.
- The product temperature during drying is assumed to be equal to the drying temperature.
- The energy transfer to the system and the work transfer from the system are positive.

The general exergy balance states that exergy destroyed (loss) is equal to the difference between exergy inflow and exergy outflow. The general mathematical formulation of exergy balance is written in Equation (11).

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \quad (11)$$

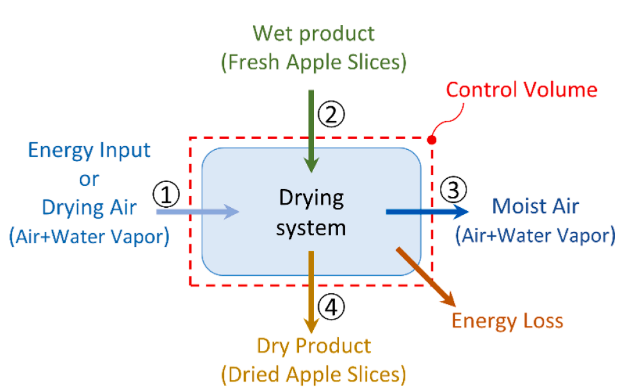

Fig. 2. Schematic of control volume representing drying process with inputs and outputs.

for the dryer shown in Fig. 2, Equation (11) is as written in Equation (12).

$$\dot{E}x_1 + \dot{E}x_2 - \dot{E}x_3 - \dot{E}x_4 = \dot{E}x_{dest} \quad (12)$$

Dincer and Sahin [45] defined the exergy efficiency of the drying process as the exergy used in the drying to the supplied exergy to the system:

$$\eta_{Ex} = \frac{\dot{E}x_{eva}}{\dot{E}x_1} = \frac{\dot{Q}_{eva}\left(1-\frac{T_0}{\overline{T}_m}\right)}{\dot{E}x_1} = \frac{\dot{m}_{eva}L_{eva}\left(1-\frac{T_0}{\overline{T}_m}\right)}{\dot{E}x_1} \quad (13)$$

where $\overline{T}_m$ [K] is the average drying material temperature, considered as drying temperature. In freeze-drying, instead of L_{eva}, the latent heat of sublimation was used (2838 [kJ kg^{-1}] [43]). Depending on the drying method, the relevant terms in equation (10) are used to calculate $\dot{E}x_1$ which are specified in Table 3. Note that average value of η_{Ex} over drying time (up to t_{crit}) is reported here.

Where ΔV [V] is the applied voltage and I [A] is the applied. T_i, T_{freeze}, and $T_{cooling}$ [K] denote the product temperature at the sublimation interface, after freezing, and temperature of the cooling source, respectively.$\dot{E}x_{in,h}^{pd}$, $\dot{E}x_{in,m}^{pd}$,$\dot{E}x_{in}^{cond}$ and, $\dot{E}x_{in}^{pump}$ [W] are the exergy input due to heat transfer during primary drying, exergy input due to mass transfer during primary drying, exergy input to the condenser, and exergy input in the pump, respectively. ΔH_s [J kg^{-1}] is the sublimation enthalpy, $\dot{Q}_{cond}$ [W] is the vapor condenser power and P_{vp} [W] is the vacuum pump power, and P_{MW} [W] is the microwave oven input power. In Table 3, ex_{air} [J kg^{-1}] is the inflow air specific exergy, which is defined below

Table 3
The mathematical formulation of the supplied exergy in different drying methods.

Drying method	$\dot{E}x_1$	References
EHD	$=\dot{m}_{air}(ex_{air})_1 + \Delta VI$	[45,46]
Freeze	$= \dot{E}x_{in,h}^{pd} + \dot{E}x_{in,m}^{pd} + \dot{E}x_{in}^{cond} + \dot{E}x_{in}^{pump}$ $= T_0m_0C_{P,frozen}\left[ln\left(\frac{T_i}{T_{freeze}}\right) - \frac{T_i-T_{freeze}}{T_0}\right] +$ $m_0\Delta H_s\left(\frac{T_0}{T_i}-1\right)$ $+ T_0\left(\dot{m}_{eva}\right)C_{P,dried}\left[ln\left(\frac{T_0}{T_i}\right) - \frac{T_0-T_i}{T_0}\right]$ $+ \dot{Q}_{cond}\left(\frac{T_0}{T_{cooling}}-1\right)$ $+ P_{vp}$	[47,48]
Hot air	$=\dot{m}_{air}(ex_{air})_1 + P_{fan}$	[45,46]
Solar	$=\dot{m}_{air}(ex_{air})_1 + P_{fan}$	[49,50]
Microwave	$=P_{MW}$	[51,52]

$$ex_{air} = (C_{p,a} + \omega_{in}C_{p,v})\left[T_{in} - T_0 - T_0 ln\left(\frac{T_{in}}{T_0}\right)\right] + T_0(R_a + \omega_{in}R_v)ln\left(\frac{P_{in}}{P_0}\right) + T_0\left[(R_a + \omega_{in}R_v)ln\left(\frac{1+1.6078\omega_0}{1+1.6078\omega_{in}}\right) + 1.6078\omega_{in}R_a ln\left(\frac{\omega_{in}}{\omega_0}\right)\right] \quad (14)$$

where $C_{p,a}$ and $C_{p,v}$ [kJ kg^{-1} K^{-1}] are the specific heat capacities of air and water vapor, respectively. ω_{in} and ω_0 [kg kg^{-1}] are specific humidity of air at the inlet and reference dead state, respectively. R_a and R_v are gas constant of air and water vapor, respectively.

(f) **Greenhouse gas (GHG) emission**

Greenhouse gases (GHGs) include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). In EHD drying, ozone is produced as a side-product of corona discharge. Carbon footprint (CF) expressed in carbon dioxide equivalent (CO_2-eq) is a general term for GHG emissions. It is equal to the amount of GHG emissions over the life stages of a product. This study calculates the carbon footprint of the drying processes based on life cycle assessment (LCA) principles. In this regard, calculating the carbon footprint of apple fruit drying by different drying methods is considered as the *goal and scope*. *Functional unit* is 1 kg of water evaporated from apple slices. The *system boundary* was limited to the drying process (gate-to-gate), starting after loading the sliced apples into the dryer and ending by drying the slices up to the moisture content of 0.29 [$kg_{H2O}\ kg^{-1}_{dry\ based}$]. Electricity [kWh] and dried materials [kg] were considered as the input and output, respectively. The *inventory* was based on lab-scale experiments (foreground data). The carbon footprint of the auxiliary devices is neglected in our evaluation.

The amount of CO_2eq produced per kWh of electric energy depends on how it is generated. Typical values are 0.4–0.6 kg_{CO2eq} kWh^{-1} for Europe, 0.6 kg_{CO2eq} kWh^{-1} for North America, 0.8–1.0 kg_{CO2eq} kWh^{-1} for developing countries [40]. A worldwide average of 0.475 kg_{CO2eq} kWh^{-1} [53] was considered for this study. The results are reported as kg_{CO2eq} per kg_{H_2O} which indicates the carbon footprint for evaporating a unit mass of water from apple slices:

$$CF = \frac{0.475}{SMER} \quad (15)$$

2.6.3. Product quality

(a) **Color change measurements (CIE-LAB color parameters)**

The surface color of apple slices was measured prior to and after the drying with CIELab system using a Minolta chroma meter (CM-2600D, Konica Minolta Inc., Japan), with SCE (specular component excluded) mode, illuminant D_{65} (daylight), and 10° observer angle. Before the color acquisition, the colorimeter was calibrated using a standard white plate. After color measurement, all samples were temporarily stored in the desiccator for further quality measurement.

The overall color change, ΔE, was calculated using the following equation [54]:

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (16)$$

where L^*, a^*, and b^* are the parameters of the CIE color coordinate system defined by the Commission Internationale de l'Eclairage (CIE). L^* indicates the light–dark spectrum ranging from 0 (black) to 100 (white),a^* indicates the red-green spectrum ranging from −60 (green) to 60 (red) and b^* indicates the yellow–blue spectrum ranging from −60 (blue) to 60 (yellow) of the samples. L_0^*, a_0^*, and b_0^* are the color measurements of the fresh-cut slices and L^*, a^*, and b^* are the color measurements of the same slices after drying. The surface color of 12 samples per drying run was tested with three repetitions for each sample, and the mean value and standard deviation are reported in this paper.

(b) **Rehydration measurements**

Rehydration is defined as the percentage of the weight gained by dried samples during rehydration for a given time at a given temperature in distilled water. For rehydration measurements, the samples were first weighed, then 10 mL of hot tap water at 75° C was pipetted into the apple samples in their Petri dishes. They were then placed in an oven at 75° C for 90 min. The samples were drained for two minutes, followed by blotting with a paper tissue to remove the surface water and then reweighed to calculate the water absorption. Triplicate experiments were carried out for each setting. Different rehydration indices have been introduced. The most common one is the rehydration ratio which is defined as the drained weight of the rehydrated sample to the weight of the dry sample W_d [g].

(c) **Total phenolic content measurements**

To determine antioxidant capacity and total phenolic content (TPC), the amount of water previously lost during drying was added to the samples. This allowed us to treat our samples as fresh-weight samples. 1 mL of deionized water was added to the samples in order to obtain sufficient supernatant for the measurements. The samples were centrifuged at 14000 rpm for 20 min and the supernatant was collected. Folin-Ciocalteu method [55] using chlorogenic acid as a standard was used for the TPC analysis. To this end, 1 mL of extract was mixed with 5 mL Folin reagent (1 N) and after 5 min, 4 mL of Na_2CO_3 solution (3 %) was added to stop the reaction and let for 1 h at room temperature in the dark. Then the absorbance was measured at 765 nm. Twenty-four samples from two different drying batches were tested for each drying method. TPC was calculated and expressed as μg chlorogenic acid equivalent (CAE) equivalent per 1 g of apples.

(d) **Trolox equivalent antioxidant capacity (TEAC)**

The obtained extract from the dried samples described in section 2.6.3c was used for estimating the antioxidant activity. Twenty-four samples from two different drying batches were tested for each drying method. To evaluate the total antioxidant capacity of the dried products, Trolox Equivalent Antioxidant Capacity (TEAC) assay described by [56] has been used.

(e) **Microstructural determination**

Six apple slices were randomly chosen from fresh, EHD dried, hot-air dried, and freeze-dried apple slices for microstructural determination. Scanning Electron Microscope (SEM) (Phenom Elektronenmikroskop, Phenom-World BV, NL-5652 AM Eindhoven, Netherlands) was used to determine the structural changes of apple slices during drying qualitatively. In order to examine the impact of different drying methods on the structure of dried apple slices, small portions were taken from each sample, placed in a sample holder, and analyzed directly. SEM pictures were taken using magnification from 59 × to 2150 ×.

2.6.4. Economics

The economic performance was analyzed to evaluate the commercial sustainability of the drying methods from the business feasibility perspective. Based on [57], the key performance indicator for economic performance analysis of the dryers are annualized investment cost of drying (C_a [USD]), cost of drying per kg of dried material (apple slices) (C_s [USD]), payback period (P_b [years]), and net present value (NPV [USD]). The economic key performance indicators were estimated based

Table 4
Input data and assumptions made for estimation of the economic performance of the dryers.

Item [unit]	Drying method				
	EHD	Hot-air	Freeze-drying	Solar	Microwave
Reference year	2022	2022	2020	2020	2020
$CEPCI_1$	289.4	289.4	235.5	235.5	235.5
Desired capacity [kg]	100	100	100	100	100
Life span of dryer [year]	10	10	10	10	10
Reference capacity [kg batch^{-1}]	1	48	18	1050	2500
Capital cost of dryer per kg of drying capacity ($C_{ic}/capacity$) [USD/kg] at the reference year	1′130	134	3′000	2	440
Salvage value [USD]	$0.1\times C_{ic}$	$0.1\times C_{ic}$	$0.1\times C_{ic}$	$0.1\times C_{ic}$	$0.1\times C_{ic}$
Maintenance cost [USD]	$0.02\times C_{ic}$	$0.1\times C_{ic}$	$0.05\times C_{ic}$	$0.01\times C_{ic}$	$0.05\times C_{ic}$
Salvage value factor (SVF)	0.069	0.069	0.069	0.069	0.069
Capital recovery factor (CRF)	0.149	0.149	0.149	0.149	0.149
Discount or Interest rate [% year^{-1}]	8	8	8	8	8
Energy price per unit [USD kWh^{-1}]	0.133	0.133	0.133	0.133	0.133
Operation period [days per year]	320	320	320	320	320
Quantity of dried apple slices [kg per year] *	1469.7	2415.4	1018.9	253.7	7804.6
Sales price per kg of dried apple slices [USD]	10	10	10	10	10
References	[13]	[59]	[60,61]	[62]	[30,63]

*Based on critical drying time obtained from the drying kinetics section

on the fiscal situation in Switzerland. To our best knowledge, there is no scaled-up EHD dryer available. Therefore, capital costs of lab-scale dryers were considered, and economics of scale principles based on [58] were used to estimate the costs of the scaled-up dryers.

(a) **Annualized investment and operation cost of drying**

The annualized cost method compares the relative drying cost for a unit amount of drying product among the different dryers. The annualized investment cost (C_a) of the dryers was estimated using parameters in Equation

$$C_a = C_{ac} + C_m - V_{as} + C_e \tag{17}$$

where, V_{as} [USD] and C_{ac} [USD] are the salvage values of the dryers and annualized capital cost, respectively. C_m [USD] is the annual maintenance costs and C_e [USD] refers to the annual cost of energy (electricity) required for the drying process. Annual capital cost and annual salvage value are calculated using initial capital investment (C_{ic}) and salvage value (V_s):

$$C_{ac} = C_{ic} \times CRF \tag{18}$$

$$V_{as} = V_s \times SFF \tag{19}$$

The capital recovery factor (CRF) and salvage value factor (SVF) were calculated using the following equations:

$$CRF = \frac{i(i+1)^n}{(i+1)^n - 1} \tag{20}$$

$$SVF = \frac{i}{(i+1)^n - 1} \tag{21}$$

where n is the number of operation years (10 years are assumed for all equipment), and i is the interest rate of the dryers (8 % is used in this paper). The initial capital investment (C_{ic}) was calculated based on itemized cost estimation and economics of scale methods [7,58]. Accordingly, C_{ic} can be calculated to scale up based on the relationship between equipment cost and equipment attribute as shown in equation (22)

$$C_2 = C_1 \times \left(\frac{A_2}{A_1}\right)^{n_e} = Original\ cost \times \left(\frac{desired\ capacity}{original\ capacity}\right)^{n_e} \tag{22}$$

where C_1 is a reference cost (capital cost for a lab-scale dryer), C_2 is the adjusted cost for the scaled-up process, A_1 is a reference production capacity, and A_2 is the scaled-up production capacity. n_e is the cost exponent which varies based on type of equipment and process (see typical values for different drying component in [7]). The common value of n is 0.6, referred to as the six-tenths rule, which can be used when no information on the cost exponent to scale up equipment is available [58]. To calculate the reference capital cost of dryers, i.e., the capital cost of a lab-scale dryer, the capital cost of the main components of the dryer was considered. Note that dryers at a larger scale will have, to some extent, different cost per item. Details of assumptions made for the estimation of the economics are given in Table 4. To consider the change in equipment cost over time, the chemical engineering plant cost index (CEPCI) [58] is used to reflect the value of money over time:

$$C_2 = C_1 \times \frac{CEPCI_2}{CEPCI_1} = Original\ cost \times \frac{CEPCI\ at\ updated\ time}{CEPCI\ at\ the\ time\ of\ original\ cost} \tag{23}$$

where C_1 is equipment cost in the reference year, C_2 is adjusted equipment cost in 2022, $CEPCI_1$ is chemical engineering plant cost index at the reference year, and $CEPCI_2$ is 289.4 for 2022 [7]. More details about predicting the fixed capital investment cost of drying can be found in [7]. Note that the cost of related raw materials, labor, production, and other related factors are assumed to be the same for all the dryers and neglected in these calculations.

(b) **Other economic performance indicators**

Cost of drying 1 kg of the fruits (apple slices) (C_s [USD]) was calculated by dividing the estimated total annual investment and operation costs of the drying methods by the kg of dried products.

Simple payback period (SPBP) [year] refers to the shortest amount of time for the invested money to be recovered by the accrued income. SPBP is calculated using the formula below

$$SPBP = \frac{C_a}{P_s} \tag{24}$$

Where P_s [USD] is the estimated total annual sales from products dried by each drying method.

Net present value (NPV) [USD] is used to quantify the expected profitability of an investment after a specific period of time. It is defined as the difference between the present value of cash inflows and the present value of cash outflows over a specific period of time.

$$NPV = \sum_{n=0}^{N} \frac{R_n - C_n}{(1+i)^n} - C_{ic} \quad (25)$$

Where R_n [USD] indicates the benefit revenue of dryers, C_n [USD] is the operating cost of dryers based on energy cost and maintenance, N denotes the total number of years of investing, which was assumed to be 10 years in this study, and n is the specific year of investing.

3. Results

3.1. Drying kinetics

This section compares the drying kinetics indicators of the five different drying methods. The results are shown in Fig. 3. For a more straightforward visual interpretation, the indicators are represented so that the larger the colored area of the spider web charts, the better the dryer's performance. For this reason, the inversed critical drying time values are plotted since the lower the drying time, the better the performance of the dryer in drying kinetics. Fig. 3 and the other graphs presented in this paper can be interpreted in several ways by giving different weights to each indicator based on the needs and priorities of the reader. Accordingly, the surface area of the spider web charts can be considered as a simple tool to compare the overall drying kinetics performance of the drying methods relative to each other. The drying kinetics are significantly affected by the drying methods. Microwave drying performs significantly better than other drying methods ($p < 0.05$). Its specific drying rate is up to 10 times higher than hot-air, EHD, and freeze-drying. The specific drying rate of EHD is less than hot-air and higher than freeze-drying, but the difference is not significant ($p > 0.05$). The solar dryer performs poorly in drying kinetics compared to the other methods. Esehaghbeygi and his colleagues [64] also observed similar differences in the drying kinetics of banana slices by microwave and EHD. Based on their results, drying banana slices with a microwave was 7 to 27 times faster than EHD, depending on the specific power levels.

3.2. Energy consumption and environmental impact

Energy consumption, exergy efficiency, and environmental impact performance indicators of the five different drying methods are compared in this section. The results are shown in Fig. 4. The inversed carbon footprint values are plotted in the spider web charts because the lower the GHG emission, the better the dryer's performance. Similar to the previous section, the surface area of the spider web charts can be considered as a simple tool to compare the overall performance of the drying methods relative to each other. Based on the results, energy consumption, exergy efficiency, and environmental impact performances are significantly affected by the drying methods ($p < 0.05$). EHD drying performs significantly better than other drying methods from energy, exergy, and environmental impact perspectives ($p < 0.05$). Compared to indirect solar and microwave drying, which are considered as energy-efficient methods, EHD has up to 70 % higher energy efficiency and 66 % less carbon footprint. Drying food using EHD is 1.6, 33, and 180 times more energy efficient than the microwave, freeze, and hot-air, respectively. Similar results were reported in previous studies for EHD versus hot-air drying. [65,66], and [67] reported, respectively, 115, 160, and 200 times higher energy efficiency of EHD drying compared to thermal drying methods for different drying materials.

Exergy analysis can help in selecting drying systems with less envi-

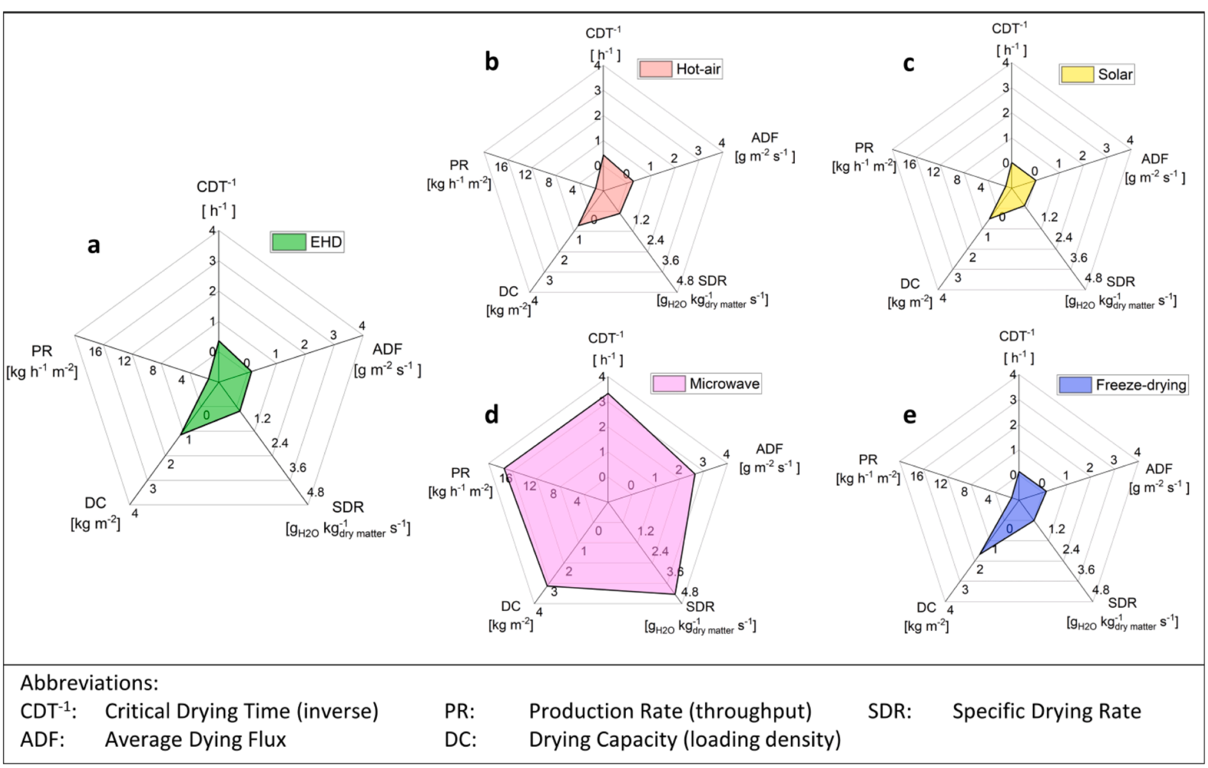

Fig. 3. Comparison of the drying kinetics of apples drying using a) EHD, b) Hot-air, c) Solar, d) Microwave, and e) Freeze-drying methods.

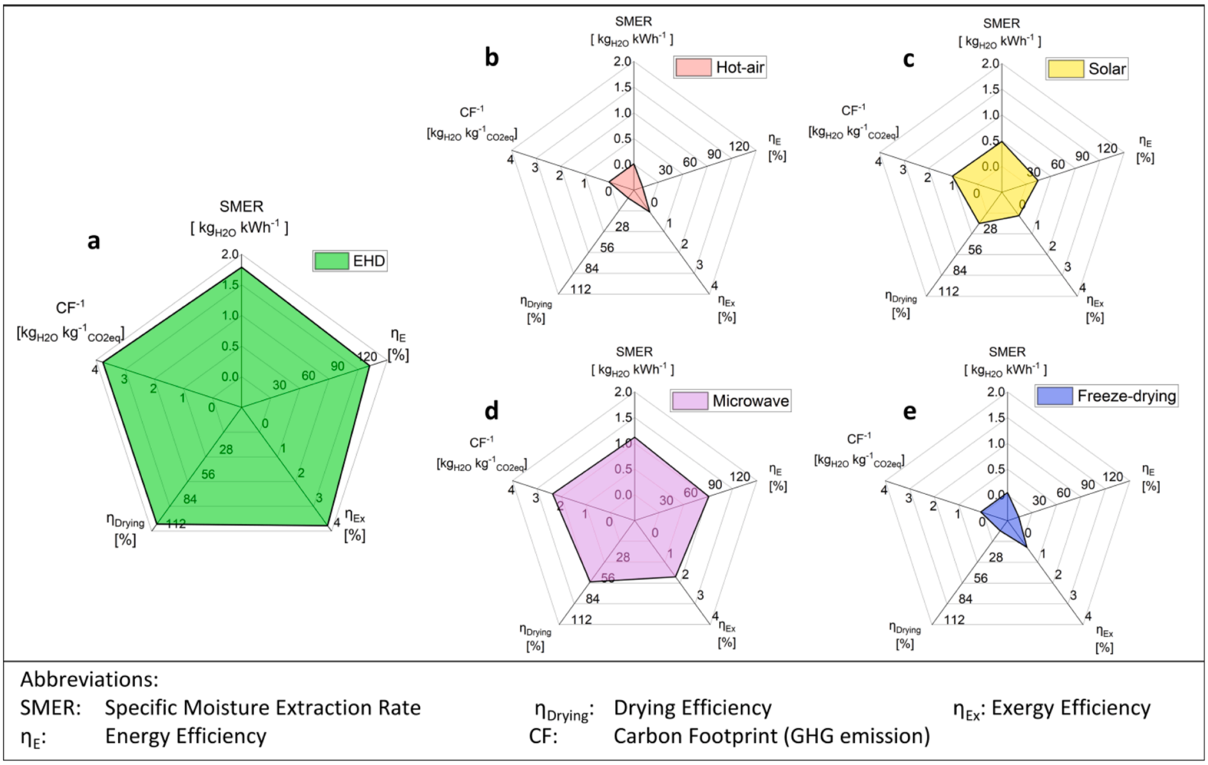

Fig. 4. Comparison of the energy consumption, exergy efficiency, and environmental impact performance of apples drying using a) EHD, b) Hot-air, c) Solar, d) Microwave, and e) Freeze-drying methods.

ronmental impact and more energy-efficient use of the resources. The exergy efficiency of EHD drying is 2.2 and 72.7 times higher than microwave and hot-air drying, respectively. This difference shows a better use of the energy resources by EHD compared to the conventional thermal drying methods.

3.3. Product quality

Overall product quality performance indicators of different drying methods are compared in this section. Only EHD, freeze and hot-air drying were considered for quality tests to reduce the experiment time and cost. The results are shown in Fig. 5 and Table 5. The product quality significantly depends on the drying method ($p < 0.05$). EHD drying is significantly better than other standard methods in preserving the nutritional content and sensory appeal of dried fruits ($p < 0.05$). Phenolic content is usually linked to a higher antioxidant activity of food products [68], which is also confirmed by the present study (Fig. 5 and Table 5). Antioxidant capacity and total phenolic content of fruits dried

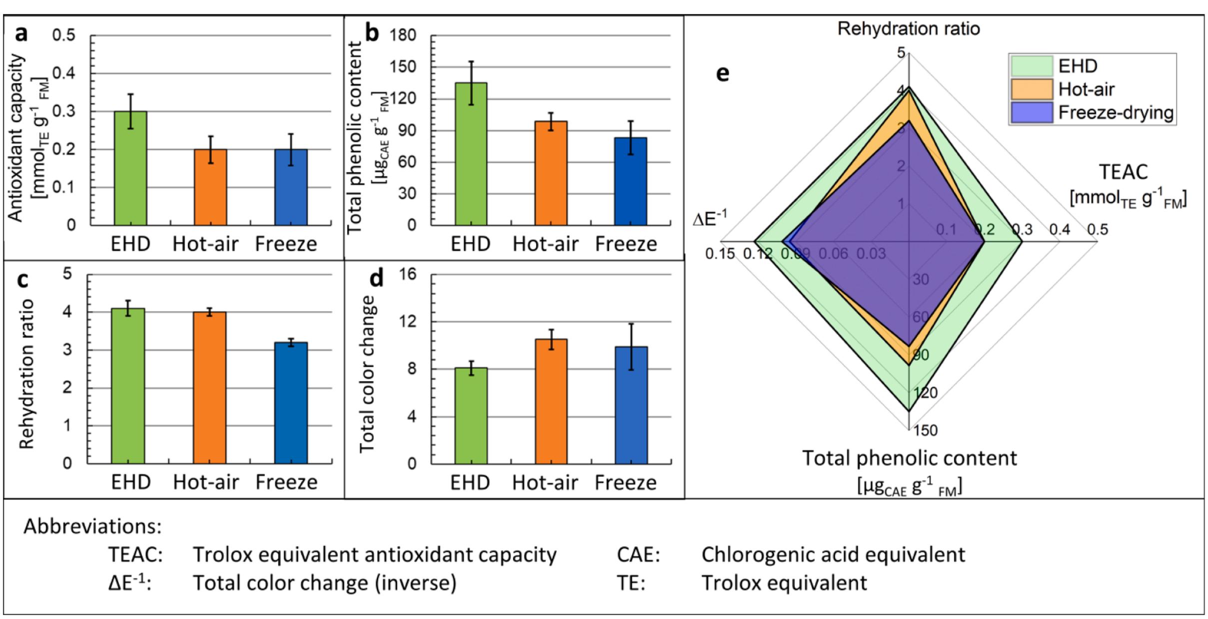

Fig. 5. Comparison of the final product quality performance of apples drying using EHD, Hot-air, and Freeze-drying methods; a) antioxidant capacity, b) total phenolic content, c) rehydration ratio, d)total color change, e) overall results on a spider web graph.

Table 5
Physicochemical quality attributes for apple slices dried by EHD drying, Freeze-drying, and Hot-air drying*,**.

Method	Quality indices			
	Rehydration ratio	Antioxidant capacity [$mmol_{TE}$ g^{-1} $_{fresh\ matter}$]	Total phenolic content [μg_{CAE} g^{-1} $_{fresh\ matter}$]	ΔE
Reference	–	0.13[b]	64.32[b]	–
EHD drying	4.09 ± 0.24[a]	0.27 ± 0.04[a]	135.04 ± 20.32[a]	8.11 ± 0.58[a]
Freeze-drying	3.21 ± 0.06[b]	0.19 ± 0.03[b]	83.20 ± 8.18[b]	9.89 ± 0.83[b]
Hot-air drying	3.96 ± 0.13[a]	0.20 ± 0.03[b]	98.41 ± 15.66[b]	10.52 ± 1.9[b]

*The values indicate mean ± standard error of ten measurements in two different sets of experiments.
**Values within the same column with similar letters are not significantly different (statistically $p > 0.05$).

using EHD are 50 % and 37 % higher than fruits dried using hot-air dryer. The same results were also observed by [69] for quince slices. Compared to freeze-drying, known as a method of delivering high-quality dried fruits, the antioxidant capacity and total phenolic content of EHD dried fruits are 50 % and 62 % higher. This difference could be attributed to different reasons, including the liberation of phenolic compounds due to structural changes at the cellular scale or the breakdown of large molecular weight phytochemicals into smaller compounds [70,71]. Nevertheless, more investigation is required to unravel the actual reasons for these observations.

Consumers prefer visible quality; therefore, color degradation is a major quality attribute in dried food products. During drying, color may change due to several chemical and biochemical reactions. The results of the measured color parameters (L*, a*, and b*) of the samples are shown in Table 6. The total color degradation ΔE, indicates the ability of human eyes to differentiate between the colors of a sample. Theoretically, if ΔE between two samples is<1, the difference is not noticeable [72]. The lower the values of ΔE, the smaller the total color difference between the fresh and dehydrated samples and the better the preservation of natural color. The total color degradation of apple slices dried by EHD is significantly less than the other two methods ($p < 0.05$). EHD reduced the total color degradation of fruits and vegetables by up to 29 % compared to fruits dried using hot-air and freeze-drying (Table 6). Note that enzymatic browning reactions and color change in fruits and vegetables are often caused by the PPO (polyphenol oxidase) activity which initiates the oxidation of phenols into quinones. The less color degradation by EHD could be attributed to the lower PPO activity, which could also justify the higher antioxidant activity. Other studies, such as [64], reported similar differences in the total color change of banana slices dried by microwave and EHD. Based on the results presented in [64], the total color change of the EHD-dried samples was 45 % less than

Table 6
CIE L*a*b* color coordinates for apple slices dried by EHD drying, Freeze-drying, and Hot-air drying. EHD changes the color the least, which makes the products more appealing to consumers.

Method	Color coordinates					
	L_0*	a_0*	b_0*	L*	a*	b*
Reference	75.5 ± 0.70	−0.4 ± 0.12	18.5 ± 1.70	–	–	–
EHD drying	77.1 ± 0.94	−0.6 ± 0.15	17.1 ± 1.73	82.4 ± 0.37	2.3 ± 0.42	22.4 ± 1.28
Freeze-drying	76.7 ± 0.62	−0.6 ± 0.15	17.9 ± 1.70	84.4 ± 1.10	2.3 ± 0.74	22.9 ± 0.99
Hot-air drying	76.3 ± 1.19	−0.4 ± 0.15	18.6 ± 1.30	81.8 ± 1.12	2.8 ± 0.97	26.7 ± 1.72

the microwave-dried samples.

Rehydration can be considered a measure of the injuries to the material caused by drying and processing. The higher the rehydration ratio, the lower the structural damage caused by the drying process [73]. Fig. 5 and Table 5 show that the rehydration ratio of EHD and hot-air drying is significantly higher ($p < 0.05$) than freeze-drying. This can be explained by microstructural changes in samples after drying, which are presented in Fig. 6. The microstructure of fresh and dried samples was observed under a scanning electron microscope (SEM), as shown in Fig. 6. Drying through sublimation and freezing leads to larger pores and cavities due to the growth of the ice crystals during freezing [74]. However, it also resulted in broken cells and devastating disruption of the microstructure at the same time. This could be the reason for the difference between the microstructures of samples dried by freeze-drying and the other methods.

Similar differences in the rehydration ratio of other drying materials dried by different methods are reported by other studies. For instance, [64] reported up to 13 % higher rehydration ratio in EHD-dried banana slices compared to the microwave-dried samples. Note that the impact of EHD drying on other heat-sensitive compounds like vitamin C is not investigated here as other studies have already proved the superiority of EHD for preserving these compounds [69,75].

3.4. Economics

This section compares the overall economic performance indicators of the five different drying methods. The results are tabulated in Table 7. Solar drying has the lowest investment cost, operational cost, and payback time, followed by EHD drying. However, due to the long process time of the solar dryers, the net present value (NPV) of EHD drying is significantly higher than solar drying. NPV assessment indicates that freeze-drying for the assumed sales price (i.e., 10 USD per kg of dried apple) is unreasonable. To have a positive NPV for freeze-drying, the sales price of dried apple slices should be higher than 51 USD. Therefore, freeze-drying should only be considered as the preservation process of high-value biomaterials. Hot-air and EHD drying methods are the most reasonable methods to dry low-value, high-volume products like apples from an NPV point of view. It is worth noting that due to the future strict environmental measures taken by the countries and increasing energy prices, the NPV value for hot-air dryers will most likely decrease in the future. This decrease in NPV of hot-air dryers demands process optimization or proper alternatives like EHD drying. Note that the sales price of dried products was considered the same for all the drying methods (i.e., 10 USD per kg, as shown in Table 4). Nevertheless, based on the higher product quality obtained by EHD drying discussed in section 3.3, the sales price for EHD-dried products could be considered higher than other methods, which results in higher profitability (higher NPV).

4. Discussion

Fig. 7 represents the overall key performance indicators (KPIs) assessment of the different drying methods investigated in this study. Note that for each category, one of the indicators which incorporates the highest information of that category is selected as the representative for the category. Accordingly, specific drying rate (SDR), specific moisture extraction rate (SMER), and net present value (NPV) are chosen as the representatives of drying kinetics, energy consumption and environmental impact, and economics, respectively. The representative for product quality is the surface area of the spider web charts presented in Fig. 5e because the indicators of this group do not share the same units. The information provided in Fig. 7 is essential in the decision-making process of different stakeholders to select a proper dryer. It should be noted that although a comprehensive study has been performed, as in any other research, this study has its limitations and boundaries and the results should be interpreted in this context. For instance, this study focussed on lab-scale drying facilities. Despite the fact that attempts

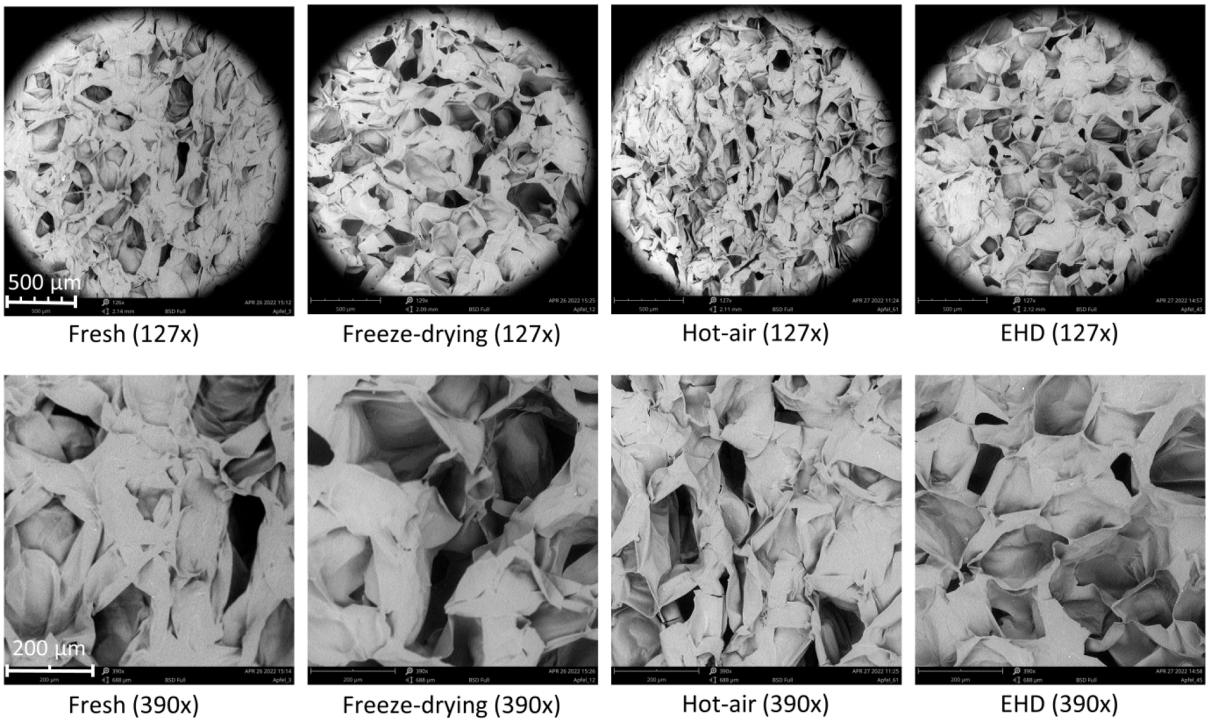

Fig. 6. Scanning electron microscopy (SEM) images of apple slices, fresh and dried by EHD, hot-air, and freeze-drying methods at different magnifications (127X and 390X).

Table 7
key performance indicators for economic performance analysis of the dryers.

KPI	Drying method				
	EHD	Hot-air	Freeze-drying	Solar	Microwave
Annualized investment cost [USD]	751	2774	18,812	97	74,214
Cost of drying per kg of dried material (apple slices) [USD]	1.12	4.13	28.04	0.14	110.60
Simple payback period [Year]	0.34	0.77	Never	0.26	6.38
Net present value (NPV) [USD]	7776	9189	−48364	1998	1692

have been made to use dimensionless performance indicators, it is possible that the values change to some extent for scaled-up dryers. This needs to be explored later.

Farmers, food processing industry, and consumers are the main stakeholders in the dried product supply chain. These stakeholders have different concerns; Consumers are concerned about product quality and price, while the industry is concerned about production rate in addition to the consumers' concerns. From the farmers' side, the main concerns are employing low-cost and simple methods for reducing the loss of fresh produce and storage for off-season availability when the market demand is higher.

One of the challenges for farmers in developing countries, especially in Sub-Sahara Africa, is the issue of electric power supply and little access to cold storage rooms. Their current drying solutions are traditional open sun drying used by rural farmers or indirect solar and convective fan-driven dryers used by urban and semi-urban farmers. Although these solutions are more affordable than EHD, they consume more time and result in dried products of lower nutritional and sensory quality than EHD (Fig. 7). This issue conflicts with one of the main concerns of the consumers, namely product quality. Moreover, they lead to high product loss due to inadequate drying environments and do not completely satisfy the farmers' concerns either [15]. Faster drying kinetics and higher product quality offered by EHD make this technology a viable alternative to satisfy the concerns of both stakeholders. To overcome the electricity issue in rural farms, a solar-powered EHD dryer, i.e., an EHD dryer coupled to a solar photovoltaic (PV) system, can be employed. Due to the low energy consumption of EHD drying, solar-powered EHD dryers can be very effective for rural areas. Nevertheless, it increases the dryer's capital cost, requiring governmental support like clean technologies subsidies.

For the large-scale drying industry, EHD would still need improvement in drying kinetics to satisfy the high production rate concern of the industry. To improve the drying kinetics, increasing the airflow rate by successive EHD stages, pretreatment, or intermediate methods combined with EHD drying could be effective but still needs further investigation. However, current EHD drying technology can be a more sustainable alternative to the currently used drying methods for heat-sensitive materials on an industrial scale. Drying methods based on elevated temperature (e.g., hot-air and microwave) are less suitable for drying such materials as they destroy the heat-sensitive compounds. Low-temperature methods such as freeze-drying are widely used in this case. Nevertheless, as shown in Fig. 7, freeze-drying has the same drying kinetics as EHD but with significantly higher energy consumption and lower product quality (Fig. 7). Therefore, this study suggests that, wherever possible, freeze-drying can be replaced by EHD, even at an industrial scale. When high throughputs are important, the number of batch dryers can just be increased since the capital cost of EHD dryers is not very high.

5. Conclusion

The key performance indicators (KPIs) of the different drying methods for small to medium-scale drying of fruits and vegetables are studied in this paper based on lab-scale setups. The drying methods include EHD, hot-air, microwave, indirect solar, and freeze-drying. The main conclusions are listed below.

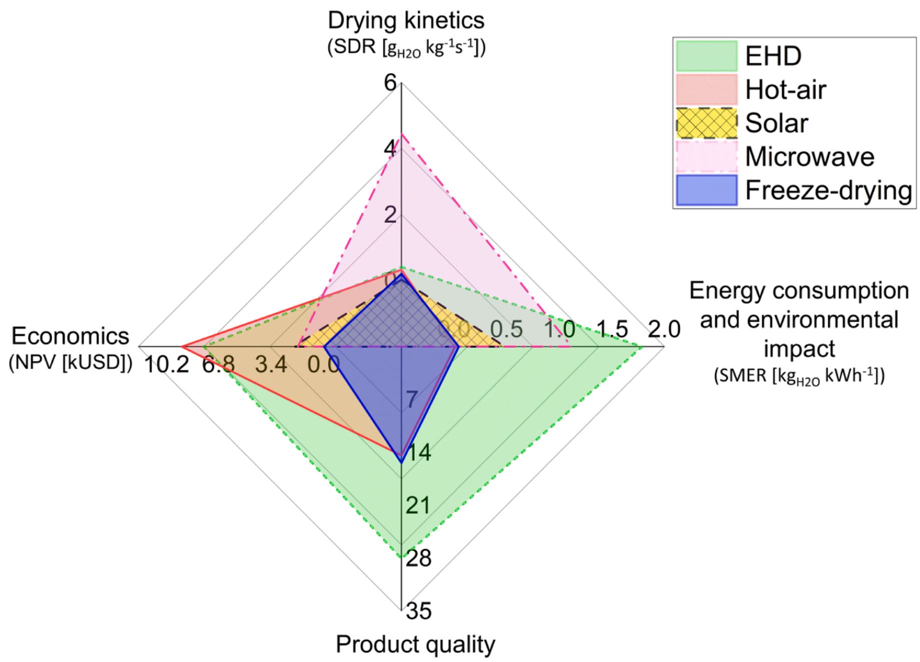

Fig. 7. Overall key performance indicators (KPIs) assessment of the different drying methods for small to medium-scale drying of fruits.

- EHD drying performs significantly better than other studied drying methods in environmental impact, energy, and exergy efficiencies by at least 60 % higher energy efficiency, 220 % higher exergy efficiency, and 66 % less carbon footprint.
- EHD drying was compared with hot-air and freeze-drying from the product quality perspective. Compared to those two methods, EHD could retain at least 50 % higher antioxidant capacity and 37 % higher total phenolic content with 21 % less color degradation.
- Solar dryers have the lowest capital and operation costs, but their net present value (NPV) is significantly less than hot-air and EHD drying due to the long-term drying process. Economics performance results show that EHD is the most economical solution as a trade-off between costs and NPV.
- EHD drying still needs improvement in terms of drying kinetics to satisfy the high throughput demand of the large-scale food processing industry. For large-scale drying, if energy consumption and the elevated drying temperature are not the main concerns, hot-air drying is the best method regarding drying kinetics and economics. However, when preserving heat-sensitive compounds is a priority, EHD is a more sustainable and economical solution than freeze-drying. It can deliver products of higher nutritional content and sensory appeal with a higher production rate than freeze-drying.

CRediT authorship contribution statement

Kamran Iranshahi: Conceptualization, Methodology, Investigation, Project administration, Writing – original draft, Writing – review & editing. **Donato Rubinetti:** Writing – review & editing. **Daniel I. Onwude:** Methodology, Writing – review & editing. **Marios Psarianos:** Writing – review & editing. **Oliver K. Schlüter:** Methodology, Writing – review & editing. **Thijs Defraeye:** Conceptualization, Methodology, Supervision, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] Montesclaros JML, Teng PS. Agriculture and Food Security in Asia, Springer, Singapore; 2021, p. 137–68. https://doi.org/10.1007/978-981-15-8852-5_7.
[2] UN FAO. How can we feed the world in 2050? FAO WSFS 2019:1–35. http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf.
[3] UN. The Millennium Development Goals Report 2015; 2015. https://doi.org/10.1016/0025-326x(71)90021-x.
[4] Chaboud G. Assessing food losses and waste with a methodological framework: Insights from a case study. Resour Conserv Recycl 2017;125:188–97. https://doi.org/10.1016/j.resconrec.2017.06.008.
[5] Hasan Masud M, Karim A, Ananno AA, Ahmed A. Sustainable Food Drying Techniques in Developing Countries: Prospects and Challenges. Cham: Springer International Publishing; 2020. https://doi.org/10.1007/978-3-030-42476-3.
[6] Onwude D, Bahrami F, Shrivastava C, Berry T, Cronje P, North J, et al. Physics-driven digital twins to quantify the impact of pre- and postharvest variability on the end quality evolution of orange fruit. Resour Conserv Recycl 2022;186:106585. https://doi.org/10.1016/J.RESCONREC.2022.106585.
[7] Mujumdar AS. Handbook of Industrial Drying. CRC Press; 2014. https://doi.org/10.1201/b17208.
[8] Lamidi RO, Jiang L, Pathare PB, Wang YD, Roskilly AP. Recent advances in sustainable drying of agricultural produce: A review. Appl Energy 2019;233–234:367–85. https://doi.org/10.1016/j.apenergy.2018.10.044.
[9] Martynenko A, Zheng W. Electrohydrodynamic drying of apple slices: Energy and quality aspects. J Food Eng 2016;168:215–22. https://doi.org/10.1016/j.jfoodeng.2015.07.043.
[10] Martynenko A, Iranshahi K, Defraeye T. Plate versus mesh collecting electrode for electrohydrodynamic (EHD) drying. Https://DoiOrg/101080/0737393720211962338 2021. https://doi.org/10.1080/07373937.2021.1962338.
[11] Defraeye T, Martynenko A. Electrohydrodynamic drying of multiple food products: Evaluating the potential of emitter-collector electrode configurations for upscaling. J Food Eng 2019;240:38–42. https://doi.org/10.1016/j.jfoodeng.2018.07.011.

[12] Taghian Dinani S, Hamdami N, Shahedi M, Havet M, Queveau D. Influence of the electrohydrodynamic process on the properties of dried button mushroom slices: A differential scanning calorimetry (DSC) study. Food Bioprod Process 2015;95:83–95. https://doi.org/10.1016/j.fbp.2015.04.001.
[13] Iranshahi K, Onwude DI, Rubinetti D, Martynenko A, Defraeye T. Scalable electrohydrodynamic drying configuration for dehydrating biological materials at industrial scale. Engrxiv 2022. https://doi.org/10.31224/2328.
[14] Soltanali H, Khojastehpour M, Torres FJ. Measuring the production performance indicators for food processing industry. Measurement 2021;173:108394. https://doi.org/10.1016/j.measurement.2020.108394.
[15] Onwude DI, Iranshahi K, Martynenko A, Defraeye T. Electrohydrodynamic drying: Can we scale-up the technology to make dried fruits and vegetables more nutritious and appealing? Compr Rev Food Sci Food Saf 2021;20:5283–313. https://doi.org/10.1111/1541-4337.12799.
[16] Bhatta S, Stevanovic Janezic T, Ratti C. Freeze-Drying of Plant-Based Foods. Foods 2020;9:87. https://doi.org/10.3390/foods9010087.
[17] Menon A, Stojceska V, Tassou SA. A systematic review on the recent advances of the energy efficiency improvements in non-conventional food drying technologies. Trends Food Sci Technol 2020;100:67–76. https://doi.org/10.1016/j.tifs.2020.03.014.
[18] Li B, Li X, Zhao Y, Xiong X, Ding X. Characteristics and mathematical modeling of apple slice drying in an electrohydrodynamic system with a needle-plate electrode. J Food Process Eng 2022::e14049.
[19] Baysal T, Ozbalta N, Gokbulut S, Capar B, Tastan O, Gurlek G, et al. Investigation of effects of various drying methods on the quality characteristics of apple slices and energy efficiency. J Therm Sci Technol 2015;35:135–44.
[20] Royen MJ, Noori AW, Haydary J. Experimental Study and Mathematical Modeling of Convective Thin-Layer Drying of Apple Slices. Processes 2020;8:1562. https://doi.org/10.3390/pr8121562.
[21] Hazervazifeh A, Nikbakht AM, Moghaddam PA. Novel hybridized drying methods for processing of apple fruit: Energy conservation approach. Energy 2016;103:679–87. https://doi.org/10.1016/j.energy.2016.03.012.
[22] Beigi M. Energy efficiency and moisture diffusivity of apple slices during convective drying. Food Sci Technol 2016;36:145–50. https://doi.org/10.1590/1678-457X.0068.
[23] Antal T, Kerekes B, Sikolya L, Tarek M. Quality and Drying Characteristics of Apple Cubes Subjected to Combined Drying (FD Pre-Drying and HAD Finish-Drying). J Food Process Preserv 2015;39:994–1005. https://doi.org/10.1111/jfpp.12313.
[24] Huang L, Zhang M, Mujumdar AS, Sun D, Tan G, Tang S. Studies on Decreasing Energy Consumption for a Freeze-Drying Process of Apple Slices. Dry Technol 2009;27:938–46. https://doi.org/10.1080/07373930902901844.
[25] Antal T, Kerekes B. Investigation of Hot Air- and Infrared-Assisted Freeze-Drying of Apple. J Food Process Preserv 2016;40:257–69. https://doi.org/10.1111/jfpp.12603.
[26] Li R, Huang L, Zhang M, Mujumdar AS, Wang YC. Freeze Drying of Apple Slices with and without Application of Microwaves. Dry Technol 2014;32:1769–76. https://doi.org/10.1080/07373937.2014.934831.
[27] Zarein M, Samadi SH, Ghobadian B. Investigation of microwave dryer effect on energy efficiency during drying of apple slices. J Saudi Soc Agric Sci 2015;14:41–7. https://doi.org/10.1016/j.jssas.2013.06.002.
[28] Çelen S, Kahveci K. Microwave drying behaviour of apple slices. Proc Inst Mech Eng Part E J Process Mech Eng 2013;227:264–72. https://doi.org/10.1177/0954408912464729.
[29] Selvanayaki S, Sampathkumar K. Techno-economic Analysis of Solar Dryers. In: Prakash O, Kumar A, editors. Sol. Dry. Technol. Concept, Des. Testing, Model. Econ. Environ., Singapore: Springer Singapore; 2017, p. 463–93. https://doi.org/10.1007/978-981-10-3833-4_16.
[30] Hazervazifeh A, Moghaddam PA, Nikbakht AM. Microwave dehydration of apple fruit: Investigation of drying efficiency and energy costs. J Food Process Eng 2017;40:e12463.
[31] Prakash O, Kumar A. Solar Drying Technology 2017;vol. 4. https://doi.org/10.1007/978-981-10-3833-4.
[32] Singh S, Kumar S. Solar drying for different test conditions: Proposed framework for estimation of specific energy consumption and CO2 emissions mitigation. Energy 2013;51:27–36. https://doi.org/10.1016/J.ENERGY.2013.01.006.
[33] Lingayat A, Chandramohan VP, Raju VRK, Kumar A. Development of indirect type solar dryer and experiments for estimation of drying parameters of apple and watermelon. Therm Sci Eng Prog 2020;16:100477. https://doi.org/10.1016/j.tsep.2020.100477.
[34] Hassan A, Nikbahkt AM, Welsh Z, Yarlagadda P, Fawzia S, Karim A. Experimental and thermodynamic analysis of solar air dryer equipped with V-groove double pass collector: Techno-economic and exergetic measures. Energy Convers Manag X 2022;16:100296. https://doi.org/10.1016/j.ecmx.2022.100296.
[35] Horwitz W, Chichilo P, Reynolds H. Official methods of analysis of the Association of Official Analytical Chemists. Washington - D.C: AOAC; 1970.
[36] Iranshahi K, Martynenko A, Defraeye T. Cutting-down the energy consumption of electrohydrodynamic drying by optimizing mesh collector electrode. Energy 2020;208:118168. https://doi.org/10.1016/j.energy.2020.118168.
[37] R Core Team. R: A Language and Environment for Statistical Computing 2021.
[38] Defraeye T, Verboven P. Convective drying of fruit: Role and impact of moisture transport properties in modelling. J Food Eng 2017;193:95–107. https://doi.org/10.1016/j.jfoodeng.2016.08.013.
[39] Motevali A, Minaei S, Khoshtagaza MH. Evaluation of energy consumption in different drying methods. Energy Convers Manag 2011;52:1192–9. https://doi.org/10.1016/J.ENCONMAN.2010.09.014.
[40] Kemp IC. Fundamentals of Energy Analysis of Dryers. In: Tsotsas E, Mujumdar AS, editors. Mod. Dry. Technol., Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA; 2011, p. 1–45.
[41] Şevik S, Aktaş M, Doğan H, Koçak S. Mushroom drying with solar assisted heat pump system. Energy Convers Manag 2013;72:171–8. https://doi.org/10.1016/j.enconman.2012.09.035.
[42] Motevali A, Minaei S, Banakar A, Ghobadian B, Khoshtaghaza MH. Comparison of energy parameters in various dryers. Energy Convers Manag 2014;87:711–25. https://doi.org/10.1016/j.enconman.2014.07.012.
[43] Datt P. Latent Heat of Sublimation. Encycl. Earth Sci. Ser., vol. Part 3, Springer, Dordrecht; 2011, p. 703–703. https://doi.org/10.1007/978-90-481-2642-2_329.
[44] Mykhailyk V, Lebovka N. Specific heat of apple at different moisture contents and temperatures. J Food Eng 2014;123:32–5. https://doi.org/10.1016/J.JFOODENG.2013.09.015.
[45] Dincer I, Sahin AZ. A new model for thermodynamic analysis of a drying process. Int J Heat Mass Transf 2004;47:645–52. https://doi.org/10.1016/j.ijheatmasstransfer.2003.08.013.
[46] Bardy E, Hamdi M, Havet M, Rouaud O. Transient exergetic efficiency and moisture loss analysis of forced convection drying with and without electrohydrodynamic enhancement. Energy 2015;89:519–27. https://doi.org/10.1016/j.energy.2015.06.017.
[47] Fissore D, Pisano R, Barresi AA. Applying quality-by-design to develop a coffee freeze-drying process. J Food Eng 2014;123:179–87. https://doi.org/10.1016/J.JFOODENG.2013.09.018.
[48] Liu Y, Zhao Y, Feng X. Exergy analysis for a freeze-drying process. Appl Therm Eng 2008;28:675–90. https://doi.org/10.1016/j.applthermaleng.2007.06.004.
[49] Bennamoun L. An Overview on Application of Exergy and Energy for Determination of Solar Drying Efficiency. Int J Energy Eng 2012;2012:184–94. https://doi.org/10.5923/j.ijee.20120205.01.
[50] Chowdhury MMI, Bala BK, Haque MA. Energy and exergy analysis of the solar drying of jackfruit leather. Biosyst Eng 2011;110:222–9. https://doi.org/10.1016/J.BIOSYSTEMSENG.2011.08.011.
[51] Darvishi H, Zarein M, Farhudi Z. Energetic and exergetic performance analysis and modeling of drying kinetics of kiwi slices. J Food Sci Technol 2016;53:2317–33. https://doi.org/10.1007/s13197-016-2199-7.
[52] Prommas R, Rattanadecho P, Jindarat W. Energy and exergy analyses in drying process of non-hygroscopic porous packed bed using a combined multi-feed microwave-convective air and continuous belt system (CMCB). Int Commun Heat Mass Transf 2012;39:242–50. https://doi.org/10.1016/j.icheatmasstransfer.2011.10.004.
[53] IEA. Global Energy & CO2 Status Report 2019. Paris: 2019.
[54] Abbott JA. Quality measurement of fruits and vegetables. Postharvest Biol Technol 1999;15:207–25. https://doi.org/10.1016/S0925-5214(98)00086-6.
[55] Singleton VL, Orthofer R, Lamuela-Raventós RM. [14] Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent. Methods Enzymol., vol. 299, Academic Press; 1999, p. 152–78. https://doi.org/10.1016/S0076-6879(99)99017-1.
[56] Re R, Pellegrini N, Proteggente A, Pannala A, Yang M, Rice-Evans C. Antioxidant activity applying an improved ABTS radical cation decolorization assay. Free Radic Biol Med 1999;26:1231–7. https://doi.org/10.1016/S0891-5849(98)00315-3.
[57] Sodha MS, Chandra R, Pathak K, Singh NP, Bansal NK. Techno-economic analysis of typical dryers. Energy Convers Manag 1991;31:509–13. https://doi.org/10.1016/0196-8904(91)90085-W.
[58] Turton R, Bailie RC, Whiting WB, Analysis SJA. synthesis and design of chemical processes. Pearson Education; 2008.
[59] Kingphadung K, Kurdkaew P, Siriwongwilaichat P, Kwonpongsagoon S. Comparison of Performance and Economic Efficiency for Greenhouse Solar versus Hot Air Drying: A Case of Crispy Mango Production. Processes 2022;10:311. https://doi.org/10.3390/pr10020311.
[60] Stratta L, Capozzi LC, Franzino S, Pisano R. Economic Analysis of a Freeze-Drying Cycle. Processes 2020;8:1399. https://doi.org/10.3390/pr8111399.
[61] Liapis AI, Bruttini R. Freeze Drying. Handb Ind Dry 2020:309–43. https://doi.org/10.1201/9780429289774-10.
[62] Mohammed S, Fatumah N, Shadia N. Drying performance and economic analysis of novel hybrid passive-mode and active-mode solar dryers for drying fruits in East Africa. J Stored Prod Res 2020;88:101634. https://doi.org/10.1016/j.jspr.2020.101634.
[63] Radoiu M. Microwave drying process scale-up. Chem Eng Process - Process Intensif 2020;155:108088. https://doi.org/10.1016/J.CEP.2020.108088.
[64] Esehaghbeygi A, Pirnazari K, Sadeghi M. Quality assessment of electrohydrodynamic and microwave dehydrated banana slices. LWT - Food Sci Technol 2014;55:565–71. https://doi.org/10.1016/j.lwt.2013.10.010.
[65] Ramadhanty S, Amirullah MH, Faturrahman MH, Dhelika R, Abuzairi T. Development of Small Scale Electrohydrodynamic Drying Device for Rough Rice Using DC Plasma Generator. Evergreen 2019;6:103–7. https://doi.org/10.5109/2321000.
[66] Martynenko A, Kudra T. Alternating versus direct current in electrohydrodynamic drying. Dry Technol 2022;40:2382–95. https://doi.org/10.1080/07373937.2021.1942899.
[67] Esehaghbeygi A, Basiry M. Electrohydrodynamic (EHD) drying of tomato slices (Lycopersicon esculentum). J Food Eng 2011;104:628–31. https://doi.org/10.1016/j.jfoodeng.2011.01.032.
[68] Aryal S, Baniya MK, Danekhu K, Kunwar P, Gurung R, Koirala N. Total Phenolic Content, Flavonoid Content and Antioxidant Potential of Wild Vegetables from Western Nepal. Plants 2019;8:96. https://doi.org/10.3390/plants8040096.

[69] Elmizadeh A, Shahedi M, Hamdami N. Quality assessment of electrohydrodynamic and hot-air drying of quince slice. Ind Crops Prod 2018;116:35–40. https://doi.org/10.1016/j.indcrop.2018.02.048.
[70] Harguindeguy M, Fissore D. On the effects of freeze-drying processes on the nutritional properties of foodstuff: A review. Dry Technol 2020;38:846–68. https://doi.org/10.1080/07373937.2019.1599905.
[71] Vega-Gálvez A, Di Scala K, Rodríguez K, Lemus-Mondaca R, Miranda M, López J, et al. Effect of air-drying temperature on physico-chemical properties, antioxidant capacity, colour and total phenolic content of red pepper (Capsicum annuum, L. var. Hungarian). Food Chem 2009;117:647–53. https://doi.org/10.1016/J.FOODCHEM.2009.04.066.
[72] Šumić Z, Tepić A, Vidović S, Jokić S, Malbaša R. Optimization of frozen sour cherries vacuum drying process. Food Chem 2013;136:55–63. https://doi.org/10.1016/j.foodchem.2012.07.102.
[73] Wiktor A, Nowacka M, Dadan M, Rybak K, Lojkowski W, Chudoba T, et al. The effect of pulsed electric field on drying kinetics, color, and microstructure of carrot. Dry Technol 2016;34:1286–96. https://doi.org/10.1080/07373937.2015.1105813.
[74] Voda A, Homan N, Witek M, Duijster A, van Dalen G, van der Sman R, et al. The impact of freeze-drying on microstructure and rehydration properties of carrot. Food Res Int 2012;49:687–93. https://doi.org/10.1016/j.foodres.2012.08.019.
[75] Xiao A, Ding C. Effect of Electrohydrodynamic (EHD) on Drying Kinetics and Quality Characteristics of Shiitake Mushroom. Foods 2022;11:1303. https://doi.org/10.3390/foods11091303.