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Sustainability of drying technologies: system analysis

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Sustainability is a multi-dimensional indicator of the impact of current human activities on future generations. The concept of sustainability could be extended to food drying, reflecting the impact of current drying technologies on energy and resource use, as well as social and food security. The objective of this review is a sustainability assessment of drying, based on the so-called 4E system analysis considering energy, exergy, environmental and economic aspects. For energy analysis, instead of the ambiguous term "efficiency", it is proposed to use specific energy consumption as a measure of the energy efficiency of drying. For exergy analysis, it is proposed to use specific exergy consumption as a measure of the efficiency of non-renewable resource usage. Both metrics, expressed in kilojoules per kg of extracted water, are good indicators of the sustainability of the drying process and their minimization is the objective of future research in drying technologies. The environmental impact of drying is evaluated as a potential carbon footprint and associated carbon tax rate. Economic analysis characterizes the sustainability of drying technology with the payback period and net present value, which are specific to the dried material. The insight into the effect of drying on the social aspects of sustainability, *i.e.* malnutrition and food insecurity is also presented. All aspects of sustainability are linked to each, showing how drying processes/technologies can contribute to a more sustainable world.

Sustainability spotlight

Food drying technologies are in general not energy-efficient and create significant environmental impacts. The review touches on an important topic of the sustainability of drying technologies, proposing metrics to compare drying technologies on a common basis scale. The benefits of renewable energy use for drying are discussed. The sustainability of drying technologies was evaluated based on the so-called 4E system analysis, considering energy, exergy, environmental and economic aspects.

Introduction

Recent climate changes, pandemics, and globalization of food markets present new challenges for human society. Because of increased demands for food preservation, new drying technologies are constantly being developed for a common objective: the removal of a solvent (most commonly water) from materials for obtaining dry matter as the final product.[1] With the great variety of drying technologies, their assessment should include the impact on future generations or sustainability.[2] According to Betoret *et al.*,[3] the sustainability of drying technology can be assessed by environmental, social, and economic analyses. Also, since drying is one of the most energy-intensive operations,[4] the assessment should include energy and exergy analysis. More recently, the sustainability of drying technology was evaluated based on the so-called 4E system analysis, considering energy, exergy, environmental and economic aspects.[5,6] This multi-dimensional analysis is complicated because of the correlations between all aspects of sustainability. For example, different energy sources used in drying might negatively affect the environment. In addition, different drying technologies require labor with a very specific skill set, which is in turn related to training and employment issues. Furthermore, drying is one of the most common postharvest technologies for food preservation, providing food and consequently societal security, one of the most important human rights. Lastly, every drying process – as any industrial process – aims to increase product value, requiring thus a thorough cost–benefit analysis of drying technology.

To establish a plan of action for sustainable growth for humanity, the United Nations adopted the 2030 Agenda for Sustainable Development, which lists commitments from UN members for attaining 17 Sustainable Development Goals (SDG) with 169 associated targets.[7] The Agenda took effect on January 2016 and since then guided the worldwide community toward sustainability. The trends in achieving these goals are reflected

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in the recent report.[8] This report presents a set of performance indices of sustainability but the analysis is limited to the score-based ranking of different countries.

Drying technologies are intimately related to some of these goals, reflecting the importance of food drying for the economy, employment, energy saving, and food security. Unfortunately, performance indices for drying technologies are still missing. The current review aims to discuss some indicators of sustainability in drying technologies, based both on their technical details and the aforementioned aspects of sustainability. The relationship between those and Sustainable Development Goals will be discussed throughout the text accordingly, even though they are considered indissociable from each other. The first aspect to be discussed is the energy analysis, which will present a technical discussion on the most informative indicators of energy efficiency. An additional tool is the exergy analysis, reflecting the efficiency of non-renewable resource usage. These analyses will be followed by environmental and economic assessments of the drying process and its impact on social aspects. At the end of this review, we will discuss how these separate aspects are linked to each other as a whole concept of sustainability, and how drying processes/technologies can contribute to a more sustainable world.

Energy analysis

It is difficult to overestimate the strategic importance of energy sources used in drying. In the context of the 2030 Agenda for Sustainable Development, one can say that a suitable energy analysis in drying processes directly contributes to Goals 7, 13, and 15 and their targets, namely:

- Goal 7: ensure access to affordable, reliable, sustainable, and modern energy for all.
- Goal 13: take urgent action to combat climate change and its impacts.
- Goal 15: protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation and halt biodiversity loss.

It is known that drying is a major energy-consuming process, but the exact fraction of energy usage related to drying processes is not consistent, as different sources mention different percentages.[1,4,9–11] However, the motivation for the reduction of energy consumption in drying processes is still strong. It is expected that a suitable energy analysis of drying technology will provide information on the sustainable usage of natural resources, contributing thus to environmental preservation, which will be discussed later in this review.

To evaluate how energy is spent in drying equipment, many indexes were proposed. A comprehensive description and physical meaning of these indexes are available in the papers by Kudra,[4] Raghavan *et al.*,[12] and Chapter 54 of the fourth edition of the Handbook of Industrial Drying.[9] Part of these indexes will be described briefly.

Energy analysis is based on the principle of energy conservation. For example, the general energy balance of thermal convective drying[13] is expressed as:

$$\dot{Q}_{\rm in} + \dot{m}_{\rm a}h_{\rm in} = \dot{m}_{\rm a}h_{\rm out} + \dot{Q}_{\rm h} + \dot{Q}_{\rm evap} \tag{1}$$

where $\dot{Q}_{\rm in}$ is the heat energy inflow, $\dot{m}_{\rm a}$ is the mass flow rate of drying air, h is the specific enthalpy of drying air, $\dot{Q}_{\rm h}$ and $\dot{Q}_{\rm evap}$ represent the heat flow, required for the heating product and water evaporation, respectively.

The term "energy efficiency" can be ambiguous. One might define energy efficiency as the ratio of net energy used for drying (*i.e.*, moisture evaporation) to the total energy input supplied by the drying air.[14] In the case of continuous drying, it is calculated considering the mass flows of the product $\dot{m}_{\rm p}$, water $\dot{m}_{\rm w}$ and hot air $\dot{m}_{\rm a}$, as well as corresponding enthalpies:

$$\eta_{\rm E} = \frac{\dot{m}_{\rm p}\left(h_{\rm p,out} - h_{\rm p,in}\right) + \dot{m}_{\rm w,out}h_{\rm w,out} - \dot{m}_{\rm w,in}h_{\rm w,in}}{\dot{m}_{a}\left(h_{\rm a,in} - h_{\rm a,out}\right)} \tag{2}$$

In the case of batch drying, eqn (2) is simplified to:

$$\eta_{\rm E} = \frac{\dot{m}_{\rm w}h_{\rm lv}}{\dot{m}_{\rm a}\left(h_{\rm a,in} - h_{\rm a,out}\right)} \tag{3}$$

where $h_{\rm lv}$ is the enthalpy of vaporization at a given temperature (kJ kg^{-1}).

The cumulative energy efficiency is calculated for the entire drying cycle as the ratio of the energy required to evaporate water $m_{\rm w}$ to the total energy provided to drying equipment ΣE:[4]

$$\eta_{\rm E} = \frac{\sum m_{\rm w}h_{\rm lv}}{\sum E} \tag{4}$$

It is important to note that energy efficiency is variable in the different stages of drying because of the various heat and mass transfer mechanisms involved. This variability can be accounted for by introducing instantaneous energy efficiency. Instantaneous energy efficiency is calculated using time increments of energy used for evaporation and the total input energy:[4,9]

$$\eta_{\rm E}(t) = \frac{\Delta m_{\rm w}(t)h_{\rm lv}}{\Delta E(t)} \tag{5}$$

The instantaneous energy efficiency is useful for the real-time (dynamic) optimization of the drying process conditions, for example in batch dryers. Maximizing $\eta_{\rm E}(t)$ will eventually lead to better sustainability of the drying process.

In eqn (2)–(5), the energy efficiency is expressed as a dimensionless value ranging from 0 to 1, indicating how close the process is to ideal thermodynamical conditions of evaporation. This index is the closest to the definition of the so-called first law efficiency, giving a general idea about the overall efficiency of drying technology and its suitability for the future sustainable world.

Another indicator of the thermodynamic efficiency of drying technology is thermal efficiency, which can be found in the literature, especially for continuous drying equipment.[4] Thermal efficiency is defined as the ratio of two temperature differences: temperature drop between the inlet T_1 and outlet T_2 temperatures, over the difference between the inlet and ambient temperatures T_∞, as stated in eqn (6):

$$\eta_T = \frac{T_1 - T_2}{T_1 - T_\infty} \quad (6)$$

Thermal efficiency is also a dimensionless value in the range of 0 to 1. It shows how close the outlet air is to saturation conditions. In an ideal case, thermal efficiency approaches unity when the outlet air temperature tends to its minimum value, that is, the wet bulb temperature.

It should be pointed out that both "energy efficiency" and "thermal efficiency" indices are only relative indicators of the thermodynamic efficiency of the drying process. They are specific for the particular drying equipment and drying material. They could be used for process improvement/optimization but could not be used for the comparison of different drying technologies.

The energy efficiency of different drying technologies could be fairly compared only with absolute indicators, such as specific energy consumption (SEC). SEC is defined by the ratio of total energy provided to drying equipment in all its forms (thermal, electrical, *etc.*) to the mass of extracted water, as shown in eqn (7):

$$\mathrm{SEC} = \frac{\sum E}{\sum m_{H_2O}} \quad (7)$$

Specific energy consumption is measured in absolute units of energy (kJ) per kg of extracted water. The commonly used description of SEC corresponds to the average value, calculated for the entire process of drying. However, the real drying process is non-stationary, and SEC is not constant throughout drying. In this case, we should use instantaneous estimates of SEC, which could be calculated similarly to eqn (5) for the specific time window. Continuous monitoring of SEC in the process of drying allows real-time optimization of drying conditions. The objective function is the minimization of SEC, which improves the sustainability of the drying process.

As described by Raghavan *et al.*[12] and Martynenko *et al.*,[15] thermal drying is characterized by higher energy consumption compared to non-thermal drying technologies. This happens due to the significant thermal losses, inevitable during the heat transfer to the material. Even though hot air is the most common drying medium due to its cost-effectiveness, its thermal conductivity is very low (approximately 0.02 W m^{-1} K^{-1} under ambient conditions), thus air is not the best drying medium. In this sense, conductive heat transfer in a solid (drum drying) or liquid (RW drying) medium could be more efficient, because it directly transfers thermal energy to the material. Also, exploration of other non-thermal sources of energy, such as electromagnetic radiation, pressure gradients (either in vacuum drying or ultrasound-assisted drying), power cycles (heat pump drying), or ionic wind in electrohydrodynamic drying could lead to more sustainable technologies compared to hot-air drying.

Additionally, as discussed later in this article, thermal drying is associated with the inevitable loss of available energy according to the second law of thermodynamics. Therefore, energy analysis should be complemented by an evaluation of the thermodynamic efficiency of energy use or exergy analysis. In this context, the next section presents an introduction to the exergy analysis and its consequences for the drying process efficiency and sustainability.

Exergy analysis

Exergy analysis of drying technology is intimately tied to the concept of sustainability. The problem is that not all energy in the system could be efficiently used for drying. For example, low-quality energy like sensible heat in the saturated vapor does not help with drying but rather negatively affects drying performance. Therefore, the evaluation of the process performance should consider only a fraction of the total energy, which is available for drying, or exergy.

The term "exergy" was coined in 1956 by Zoran Rant,[16] but the concept had been earlier developed by Willard Gibbs and known as Gibbs's free energy.[17] Exergy analysis is based on the second law of thermodynamics, which states that exergy is destroyed due to process irreversibility, for example, heat losses to the environment. This law also states that all-natural processes occur in the direction of increasing system entropy until thermodynamic equilibrium is reached. More recently, the second law of thermodynamics has been stated differently: when there are no barriers to energy flow, it will spontaneously spread out of a system, decreasing the amount of exergy to zero.

The amount of exergy is quantified compared to the reference conditions of the environment in which the system is immersed.[18] For example, the exergy of the drying chamber is quantified compared to the ambient air surrounding the drying chamber. Hence, describing the reference conditions is essential for exergy analysis, as they are quite different around the world or along different seasons of the year. Exergy is thus a function of the state of the material and environment.[19,20]

Exergy exchange between the open steady-state drying system and the environment could be graphically illustrated.[20,21] Fig. 1, also known as a Sankey diagram, represents the exergy flow balance in the system.[22,23] This diagram is a useful tool for identifying and reducing exergy losses, thus improving system sustainability. The exergy analysis is particularly useful for thermal drying technologies with irreversible heat transfer. The practical interest in exergy analysis of drying processes and systems has been increasing in the last decade.[24] The starting point of exergy analysis is the exergy balance equation, which is determined by specific exergies at the input/output and internal heat/mass transfer:[24]

$$\sum_k \left(1 - \frac{T_o}{T_k}\right)\dot{Q}_k + \sum_{\mathrm{in}} \dot{m}_a \mathrm{ex}_{\mathrm{in}} = \dot{W} + \sum_{\mathrm{out}} \dot{m}_a \mathrm{ex}_{\mathrm{out}} + \dot{\mathrm{E}}\mathrm{x}_{\mathrm{dest}} \quad (8)$$

In this equation, the first term represents the exergy related to the internal heat transfer in the system from each of k sources/sinks at a certain temperature T_k; $\dot{W}$ represents the exergy used for water evaporation; ex indicates the specific exergy (kJ kg^{-1}) of hot air at the input or output of the system; and $\dot{\mathrm{E}}\mathrm{x}_{\mathrm{dest}}$ is exergy destroyed internally in the process of drying. The specific exergy of the input and output air streams could be calculated

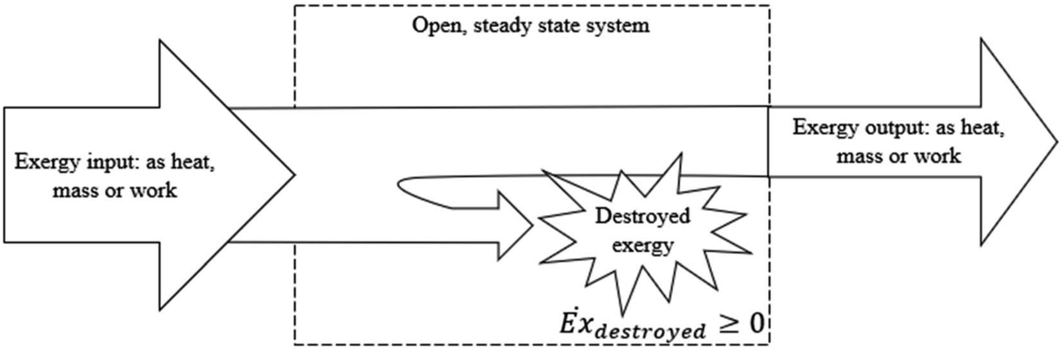

Fig. 1 Schematics of an exergy flow in an open steady-state system.

by knowing enthalpy and entropy changes, provided by temperatures of each medium:[19]

$$\mathrm{ex_{in}} = c_\mathrm{p}\left[(T_\mathrm{in} - T_\mathrm{o}) - \frac{T_\mathrm{o} \ln T_\mathrm{in}}{T_\mathrm{o}}\right] \tag{9}$$

$$\mathrm{ex_{out}} = c_\mathrm{p}\left[(T_\mathrm{out} - T_\mathrm{o}) - \frac{T_\mathrm{o} \ln T_\mathrm{out}}{T_\mathrm{o}}\right] \tag{10}$$

On the right-hand side of eqn (9) and (10), the first term corresponds to enthalpy change, and the second term corresponds to entropy change. The calculation of specific exergies makes it possible to quantify how reversible is a process by evaluating how much exergy is destroyed.

The exergy efficiency of the drying chamber is defined as the ratio of the total output exergy to the total input exergy supplied in the absence of product:[25]

$$\psi_\mathrm{equip} = \frac{\mathrm{ex_{out}}}{\mathrm{ex_{in}}} \tag{11}$$

The exergy efficiency of the drying process could be defined as the fraction of input exergy used for evaporation:[20]

$$\psi_\mathrm{drying} = \frac{\dot{W}}{\dot{W}_\mathrm{max}} = \frac{\dot{W}}{\dot{m}_\mathrm{a}\mathrm{ex_{in}}} \tag{12}$$

It is important to note the effect of process variables on exergy efficiency. The comparison of energy and exergy efficiency in convective drying shows that the energy efficiency of a thermal convective dryer ranges from 5 to 45%, while exergy efficiency does not exceed 14%.[18] Providing a dryer with warmer inlet air leads to a higher rate of heat loss, thereby decreasing the energy and exergy efficiencies. Any increase in drying temperature results in higher exergy losses.[25] Similarly, a higher air mass flow rate results in lower energy and exergy efficiencies. In continuous drying of material supplied at a constant rate and constant moisture content, the exergy efficiency is relatively constant over time. In batch drying, the exergy efficiency increases towards the end of the process due to the smaller exergy losses.[26] This fact can be attributed to the reduced driving force in the vicinity of thermodynamic equilibrium, which is, by definition, the condition of minimal exergy destruction. It follows that the slower the drying rate, the smaller will be the exergy losses, and the better the process reversibility, as stated by the second law of thermodynamics. Also, the additional advantage of low-temperature drying is the better quality (added value) of the dried product, which contributes to process economics.

In general, higher exergy efficiency could be obtained with lower temperatures and lower initial moisture content,[27] or when the air outlet temperature of the dryer is close to ambient conditions.[28] These conditions improve the usage of the available energy but at the expense of increased drying time and operational costs. For example, recirculation of the drying air and removal of air humidity at low temperatures improves exergy efficiency. This strategy is used in heat pump drying.[29] Introducing a heat pump can decrease energy losses and improve energy efficiency. Interesting that the exergy efficiency of a heat pump dryer increases with the temperature of drying air.[30] This trend is the opposite compared to convective drying. It reduces drying time and therefore, is beneficial from the industry perspective. The efficiency of a heat pump is evaluated with the coefficient of performance (COP), usually from 2.3 to 3.5, which shows that it saves more thermal energy than consumed. Heat pumps, however, are driven by electricity and thus COP should be multiplied by the primary energy factor (PEF). Also, considering a significant increase in capital and operational costs, the sustainability of heat pump drying should be evaluated *via* thorough economic analysis.

The general methodology of exergy analysis in drying is presented by Dincer and Sahin.[19] With small modifications, it could be applied to any batch or continuous drying technology. Exergy analysis proved to be a useful tool for the optimization of renewable energy systems,[31] such as solar dryers,[32–35] heat pump dryers,[36,37] and electrohydrodynamic dryers.[38] Atalay[39] used exergy analysis for a comparative assessment of solar and heat pump dryers. The review article by Aghbashlo *et al.*[24] and the book by Dincer and Rosen[25] are also recommended for further reference on the exergy analysis of drying processes.

To compare different drying technologies, we can introduce an index similar to specific energy consumption, that is, a specific exergy consumption (SexC), defined as cumulative exergy consumption per unit mass of evaporated water, as proposed using eqn (13):

$$\mathrm{SExC} = \frac{\sum_k \left(1 - \frac{T_\mathrm{o}}{T_{k,\mathrm{nr}}}\right)\dot{Q}_{k,\mathrm{nr}} + \sum \dot{m}_\mathrm{a}\mathrm{ex}_\mathrm{in} - \sum \dot{m}_\mathrm{a}\mathrm{ex}_\mathrm{out}}{\dot{m}_{\mathrm{H_2O}}} \quad (13)$$

Even though heat transfer-related exergy loss is predominant in the drying process, it seems to be theoretically possible to consider electricity exergy losses whenever relevant. These losses are a function of how electricity is generated, hence being also a function of the location where the dryer is operated. A simple proposal might be to ponder the exergy destruction due to electricity with the fraction of the electrical energy originating from non-renewable sources (for example based on data published by the International Energy Association,[42] or other statistical data), by multiplying this value to exergy destruction in a drying process.

Exergy derived from renewable sources is a more sustainable option, while non-renewable energy sources increase the thermo-economical cost and environmental impact of drying.[20] Commonly used non-renewable energy sources such as fossil fuel combustion are major exergy destructors.[21] In contrast, the usage of renewable sources of energy, for example, solar, geothermal energy, or biogas, will increase exergy efficiency. In this scenario, part of the exergy will be delivered by a renewable source, which will decrease the requirement in inlet exergy flow $\sum_{\mathrm{in}} \dot{m}\psi$, and consequently increase exergy efficiency. Increased exergy efficiency is associated with less resource degradation and waste exergy emissions.[40]

Optimization of energy use by exergy analysis is the first and the most important step towards the sustainability of the drying process. The concept of exergy efficiency turned out to be a very useful and powerful tool for the analysis of drying processes and systems.[25] Since exergy efficiency in drying correlates with better utilization of input energy for evaporation, it could be used for the optimization of energy use in the drying process. For example, in convective drying, increasing air temperature or air mass flow rate would reduce energy efficiency. On the other hand, the exergy efficiency increases linearly with product mass and moisture content, which shows better utilization of input energy. This effect is more pronounced as the evaporation rate increases.

The exergy efficiency could not reach 100% because of the irreversible nature of water evaporation, however, it could be maximized by matching the energy supply with the energy used for evaporation.[25] For thermal drying, this statement implies that the temperature of a heating fluid should be slightly above the temperature of the dried material. For non-thermal technologies, for example, vacuum drying, the gradient of vapor concentration should be enough to provide a reasonable evaporation rate, but not too high to justify energy expenses on maintaining a vacuum. The same is observed in heat-pump drying, where the extraction of water vapor requires additional energy.

The variables, used in the calculation of exergy efficiency, are measurable in real time. It makes it possible to use exergy efficiency (not energy efficiency, as was proposed by Kudra[4]) as an objective function for the optimization of energy use in the drying process. Exergy-based optimization offers an advantage over energy-based optimization because it shows the potential for efficiency improvement. In summary, we can conclude that exergy analysis is closely tied to the environmental impact of drying, which motivates the next section of this article.

Environmental analysis

In the context of the 2030 Agenda for Sustainable Development, one can say that a suitable analysis of the environmental impact of drying processes directly contributes to Goals 7, 13, and 15 (already described), and specifically Target 11.b, namely:

• Target 11.b: "By 2020, substantially increase the number of cities and human settlements adopting and implementing policies and plans towards […] resource efficiency, mitigation, and adaption to climate change […]".[7]

The resource efficiency of drying is evaluated in two previous sections, while the impact of drying on climate change could be quantified using global statistics on CO_2 emissions. Data from the International Energy Agency (IEA) show that energy-related CO_2 emissions grew by 0.9% to over 36.8 Gt in 2022, a level exceeding the range of 25–30 Gt per year considered to be in line with containing global warming to 1.5 °C above pre-industrial era, as aligned with the objectives of the 2015 Paris Agreement. On average, energy industries generate 28% of greenhouse gas emissions in OECD countries, followed by transport (23%), manufacturing industries (12%), agriculture (10%), industrial processes (7%), and waste (3%).[41] These indicators show that there is a long way to the reduction of greenhouse gas emissions and mitigating the effects of global warming.

Specifically for drying processes, environmental analysis of the environmental impact of different energy sources used must be considered. The following numbers of CO_2 emissions per kg of evaporated water have been obtained for typical fossil fuels used in air heaters: 0.074 $\mathrm{kg_{CO_2}/kg_{water}}$ for natural gas, 0.11 $\mathrm{kg_{CO_2}/kg_{water}}$ for heavy fuel oil, and 0.13 $\mathrm{kg_{CO_2}/kg_{water}}$ for anthracite coal.[15] The use of biomass or any organic fuel instead of electricity decreases overall sustainability due to smaller energy efficiency and larger carbon footprint (CF).

If the major source of energy for drying is electricity, we need to consider the CO_2 emissions on the generation site. The amount of CO_2 produced per kW h of electric energy on the generation site depends on the way electrical energy is generated. According to the IEA report, the average values for Europe are 0.4–0.6 $\mathrm{kg_{CO_{2eq}}}$ kW h^{-1}, about 0.6 $\mathrm{kg_{CO_{2eq}}}$ kW h^{-1} for North America, and 0.8–1.0 $\mathrm{kg_{CO_{2eq}}}$ kW h^{-1} for developing countries. For Turkey, this value was estimated as 0.98 $\mathrm{kg_{CO_{2eq}}}$ kW h^{-1}.[39] The worldwide average carbon footprint (CF) is reported as 0.475 $\mathrm{kg_{CO_{2eq}}}$ kW h^{-1}.[42]

It follows that the CF of drying technology could be tied to specific energy consumption (SEC). This approach for the evaluation of the environmental impact of drying technology is in agreement with the commonly used methodology.[39,46] Based on the average carbon footprint of 0.475, the CF of any drying technology in $\mathrm{kg_{CO_{2eq}}/kg_{H_2O}}$ can be calculated as:

$$\mathrm{CF} = 0.475 \times \mathrm{SEC}$$

where SEC is expressed in kWh per kg of evaporated water. The estimates of SEC for different drying technologies are presented in Table 1.

CO_2 and thermal emissions on the consumer site depend on the energy efficiency of drying equipment. Most of the energy is lost in the convective dryer in the form of thermal emissions, which could reach up to 85% of all energy input.[4] In a highly efficient thermal convective dryer, the ratio between evaporated water and emitted CO_2 is 8 : 1. Considering that some of the currently used convective dryers are using fossil fuels, the real carbon footprint could be much higher.

We can conclude that the high carbon footprint of traditional thermal drying technologies is related to the extremely high SEC of thermal drying. For example, in Canada drying accounts for approximately 330 PJ per year, which is equivalent to 10.4 Mt of CO_2 emissions, currently discharged into the atmosphere.[15] A more sustainable solution would be the implementation of renewable and non-thermal drying technologies.

Opting to use local renewable energy sources is a way to reduce specific exergy consumption[20] and consequently reduce environmental impact. Novel drying technologies based on renewable energy sources have already been pointed out as to be the key to cleaner, more affordable, and more efficient drying processes for different kinds of products.[43]

The negative effect of drying technologies on the environment could be quantified as an opportunity cost.[44] In this context, the environmental impact of drying should be evaluated by thorough economic analysis, which motivated the next section of this article.

Table 1 Specific energy consumption of thermal and non-thermal drying technologies

Drying technology		SEC, kW h kg^{-1}	Source
Thermal	Convective hot-air	2.2–22.2	12
	Infrared	3.68–10.8	66
	Solar + infrared	1.79–4.35	66
	Solar + heater	3.0	67
	Solar + desiccant	0.65–1.45	68
	Fluidized bed drying	1.36	69
	Direct-heat rotary drying	1.33	69
	Flash drying	1.3	69
	Spray drying	1.58	69
	Conveyor drying	1.06	69
	Agitated contact drying	0.8	69
Hybrid	Microwave + convective	1.94–6.75	12
	Microwave + vacuum	0.83–1.94	12
	Microwave + vacuum	1.0–1.4	70
	MW + vacuum + freeze	21.3	71
	MW + vacuum + convective	10.75	71
Non-thermal	Freeze/sublimation	4.72–11.67	72
	Vacuum	0.83–1.39	12
	Ultrasound-vacuum	2.0–3.8	73
	Heat pump	0.25–0.44	12
	Heat pump	0.2	74
	Heat pump + ultrasound	3.37	74
	EHD drying	0.004–0.75	69
	EHD drying	0.03–0.25	75

Economic analysis

The system approach to the analysis of sustainability requires the evaluation of economic aspects of drying, such as the cost *vs.* potential economic benefits from drying. The cost-estimation methods for dryers and drying processes could be found in ref. 11 and 76. The cost components of drying are usually divided into two categories:

(1) Fixed costs or long-term investments, which are not affected by fluctuations in the level of production activity. They include initial capital cost for manufacturing and installation of the dryer, depreciation of equipment and buildings, interest charges for the investment capital, insurance, fixed part of taxes and rents, fixed part of the maintenance cost, and executive salaries (administration, overhead).

(2) Variable costs or operating expenses, which vary with the production level. They include the cost of raw materials, costs of energy and utilities, direct labor (operating, transportation, supervision, and laboratory control), bank interest on working capital, royalties, day-by-day maintenance, and other direct costs.

The key performance indicator for economic analysis is the annualized cost of drying $C_{a,}$ which accounts for all cost components of drying on an annual basis:

$$C_a = C_{ac} + C_e + C_m + C_l + C_{CO_2} - V_{as}$$

where C_{ac} is annualized capital cost, C_e is energy cost, C_l is labor cost, C_{CO_2} is the carbon tax rate and V_{as} is a salvage value (all in USD). The salvage value is often neglected since dryers are typically used in one location until they fall apart.

Annual capital cost C_{ac} is calculated using initial capital investment C_{ic}:

$$C_{ac} = C_{ic} \times \mathrm{CRF}$$

where CRF is the capital recovery factor, calculated from the number of operation years (usually $n = 10$–15) and the interest rate on the investment capital (i):

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

In the absence of recent data, the projected initial capital investment C_{ic} could be evaluated, using methodology (Kudra[76]). The cost of a dryer could be calculated based on the cost of similar dryers in the previous year. Indexing of dryer capital cost could be done using Marshall and Swift (M&S) Index or Chemical Engineering (CEPCI) plant cost index:[11]

$$C_{ic} = C_{ic}^{\mathrm{original}} \frac{\text{CEPCI index}}{\text{CEPCI index at the time of original cost}}$$

The cost of a scaled-up drying system can be predicted approximately from the empirical ratio:

$$C_{ic} = C_{ic}^{\mathrm{original}} \frac{\text{desired capacity}}{\text{original capacity}}$$

Cost of energy, maintenance, labor, and CO_2 emissions could be considered as the variable cost of drying (COD):

$$\text{COD} = C_e + C_m + C_l + C_{CO_2}$$

The cost of energy is calculated based on the power consumed P (kW), drying time t (h), and specific energy price C_e^o in USD per kW h:

$$C_e = C_e^o \times Pt$$

It should be noted that specific energy consumption (given in Table 1) depends on the type of dryer and, in general, is not constant during drying.

Maintenance cost depends on the complexity of the dryer and usually varies from 2 to 10% of investment cost:

$$C_m = (0.02\cdots0.1) \times C_{ic}$$

Labor cost C_l depends on the number of operators n, their qualifications, and hourly wage. In general, it is proportional to the time of operation t:

$$C_l \sim nt$$

Carbon tax rates C_{CO_2} are variable around the world and in general tend to increase. For example, Sweden levies the highest carbon tax rate at €117.30 (US \$129.89) per ton of carbon emissions, followed by Switzerland and Liechtenstein (€117.27, \$129.86) and Norway (€79.12, \$87.61).[45] In Canada, it is currently \$50 per ton but will rise by \$15 per ton annually to reach \$170 per ton in 2030. As it was stated before, carbon emissions are linked to the quantity/quality of energy used and the amount of water evaporated (see previous section):

$$C_{CO_2} = \$0.050 \times 0.125QX$$

where Q is the annual volume of the dry product (kg per year) and X is the average moisture content (kg kg^{-1} dry basis).

The benefit of drying technology is calculated as the increased value of the final product. The main added value to drying products is related to an increase in its market price, shelf life, availability out of the harvest season, and other characteristics, such as a decrease in bulk volume and weight that reduce storage and transportation costs. All these factors could be summarized in the monetary form as annual sales S_a. Neglecting marketing expenses, the projected value addition per kg of dry product could be calculated as:

$$S = C_d - C_f(X + 1)$$

where C_f and C_d are the cost of fresh and dry products (per kg dry weight). For example, if the average cost of fresh fruit (X = 9.0 kg kg^{-1}) at the farm gate is \$0.4 per kg and the market value of dried fruits is \$10 (apples) and \$40 (peaches), the value-addition is from 6 for apples to 36 for peaches dollars per kg dry weight. Annualized revenue R_a could be calculated as a difference between annual sales SQ and annual variable cost of drying COD:

$$R_a = \text{SQ} - \text{COD}$$

The payback period (PBP) is defined as the time required to recover an initial investment with future predicted annual revenue R_a, assuming it is the same each year:

$$\text{PBP} = \frac{C_{ic}}{R_a}$$

The payback period is a quick and easy way to assess investment risks. The shorter the payback period, the more attractive the investment would be. It is also a convenient way to compare two or more drying technologies by comparing time to break even. Despite being a quantitative measurement of investment efficiency, its interpretation is rather subjective, since it does not show specific profitability. In contrast, capital budget estimates, such as net present value (NPV) or internal rate of return (IRR) reflect opportunity cost, which is a more accurate indicator of sustainability.

Net present value (NPV) is the indicator of the expected profit from an investment over a specific period. It is a cumulative indicator, allowing us to find the breakeven point:

$$\text{NPV} = \sum_{n=1}^{N} \frac{R_{an} - C_{an}}{(1+i)^n} - C_{ic}$$

where R_{an} and C_{an} are annualized revenue and capital cost for the n-th year.

These economic metrics are used as key performance indicators of sustainability. The compounded values for six different drying technologies for the case of apple drying are presented in Table 2.

Table 2 shows the highest NPV for microwave and heat-pump drying, while the lowest NPV is for hot air drying. However, significant investments in MW drying and high risks of product overheating limit the adoption of this technology by the industry. The NPV of solar and EHD drying is approximately the same; however, EHD requires more capital investment and a longer payback period. Negative values of NPV for freeze drying concur with Iranshahi *et al.*,[46] that it is not a feasible option for apple slice drying.

Another instrument for comparative economic analysis of drying technologies is a life-cycle analysis (LCA), which is based on the assumption that the majority of the drying expenses are related to operational costs, rather than installation or maintenance. Therefore, it is reasonable to compare the operational cost of different drying technologies producing the same product(s) at the same rate. The comparison of the life-cycle savings (cash per unit mass) might provide the quantitative criterium for the most economically viable drying process/technology within the available choices. Some of the recent

Table 2 Key performance indicators of economic sustainability of drying technology[46]

	Hot air	Solar	EHD	Freeze	Microwave
Investment cost, $	18 600	650	5000	126 000	500 000
Annual investment cost, $	2774	97	751	18 812	74 214
Annual cost of drying, $	7016	6008	12 016	11 075	90 320
Annual sales, $	9600	16 000	24 000	1920	720 000
Annual revenue, $	2584	9992	11 984	−9155	629 680
PBP	1.16	0.38	0.83	−0.52	2.62
NPV	11 339	59 448	60 416	−71 021	92 553

applications of economic analysis of drying technologies will be presented briefly.

For example, Chavan and Thorat[47] evaluated the economic sustainability of solar dryers by annualized cost, life-cycle savings, payback period, and internal rate of return. Different configurations of solar dryers utilized different mechanisms of heat and mass transfer, consequently affecting energy costs and hence their economic viability. Lamrani and Draoui[48] analyzed the economic indices of an indirect solar dryer with a thermal storage system. They reported the effect of the thermal storage system on the annual cash flow and the payback period at different locations within Morocco. Myllymaa *et al.*[49] carried out an economic analysis of the moving bed dryer for wood bark, wood chips, and a mixture of soot sludge and sawdust. As a performance indicator, they used variable cost of drying (COD) per unit mass. They found that COD depends on the material and conditions of heat and mass transfer. For example, when the mass transfer was controlled by diffusion, an increase in air velocity did not improve drying, but significantly increased drying cost. Also, the analysis of the sustainability of drying technology is very specific to the material under drying. Iranshahi *et al.*[46] used three performance indicators (COD, PBP, and NPV) to compare five drying technologies for the case of apple slice drying. These indicators would be different for drying high-value biomaterials, like medicinal herbs or pharmaceuticals. These examples show the importance of preliminary engineering analysis of drying technology and optimization of drying conditions. Many engineering tools are available for economic analysis of the drying process/technology.[11,50]

The ultimate choice of drying technology should be based not only on the direct cost elements, such as equipment, assembly, labor, and maintenance cost, but also on the opportunity costs, related to perceived risks, environmental impact, and waste utilization.[44] Opportunity cost is a monetary evaluation of lost benefits due to the depletion of natural resources or pollution of the atmosphere. It could be calculated as the difference in profit between innovative and conventional drying technology. When calculating opportunity cost, it is also essential to consider the following factors:

• risk of making predictions about future investment returns;

• sunk costs, or money that has already been spent and cannot be recovered;

• explicit costs, or costs that are direct and visible;

• implicit costs, which refer to lost opportunities for wealth creation through the use of owned resources.

The opportunity cost is another index of sustainability, that allows for comparison of different drying technologies. This topic is discussed in detail as a part of the cost–benefit analysis.[44]

A brainstorm: how can drying R&D improve social indicators?

Food insecurity and malnutrition

The most recent report on food security and nutrition by the Food and Agriculture Organization (FAO) states that 3.1 billion people are unable to afford a healthy diet, a number which grew by 112 million in comparison to 2021.[51] According to FAO, the major factors behind such alarming figures are conflicts, climate extremes, economic shocks, and growing inequalities. The COVID-19 pandemic and the recent war in Ukraine worsened the scenario by disrupting supply chains of grain, fertilizers, and energy, which caused price hikes for final consumers.[51]

Most of the drying processes aim to enhance food preservation and decrease food losses, thus one can say that the drying process directly impacts Goal number 2 and Target 12.3 of the 2030 Agenda for Sustainable Development, namely:

• Goal 2: end hunger, achieve food security and improved nutrition, and promote sustainable agriculture;

• Target 12.3: by 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses.[7]

Of course, drying will not be the only factor responsible for ending world hunger: after all, there are other major drivers of food insecurity and malnutrition. On the other hand, the importance of drying processes in food waste reduction and consequently providing food security is unquestionable. The approach to drying operations should correlate to the level of overall economic development. For example, the establishment of simple drying practices, especially in developing countries, will not only reduce postharvest food loss but also increase the job creation rate and social security of people, involved in drying operations. At the same time, the improvement of drying operations in developed countries will reduce losses in the food distribution chain, creating the opportunity to fully utilize unmarketed produce in the form of natural flavors or ingredients.

An interesting and thorough analysis of the food industry and agricultural waste management by drying processes was carried out by Routray *et al.*[52] Based on many reports from FAO and a literature review, the authors discussed how drying processes can help with the conversion of agro-industrial residues into useful products.

Solutions under development for food insecurity in relationship to drying

As pointed out by Balderman *et al.*[53] and Sturm *et al.*,[54] global urbanization at the expense of farming caused a decline in the variety of edible plants with high nutritional value, which seems to be correlated to the increase in diet-related chronic diseases. On the other hand, many of the crops which used to be cultivated by traditional rural communities are better adapted to local climate and soil conditions, when compared to some of the most cultivated and consumed cereals around the world. These underutilized crops are known in North America as "special crops". Usually, they have a short shelf life; therefore, drying would improve their stability and storage ability. Hence, agricultural and horticultural research should also consider better handling and processing of these special crops, so that they become more accessible to an increasing and ironically malnourished urban population.

The decrease in the variety of edible plants is closely related to animal production: in fact, a great deal of grain production is used for feeding livestock. Unfortunately, traditional livestock production could not satisfy global protein needs.[55] Simple exergy analysis shows that producing grains for feeding livestock is just an additional step to a whole process chain, being thus more exergy destructive and less environmentally friendly, so it could not be considered a sustainable practice.

Of course, reducing animal protein consumption has been proposed as a solution to improve sustainability; on the other hand, there are cultural issues related to dietary changes. One of the roads to improve sustainability is insect farming, which has a lesser environmental impact.[56] Even though it seems polemic at first glance, insects have already been used as food additives for a long time (such as carmine food colorant). Hernández-Alvarez *et al.*[56] and Parniakov *et al.*[55] carried out a literature review of insect processing for food production, including the application of different drying technologies.

These and other proposals for solving food insecurity converge to the importance of rural production, not only for large-scale producers but mainly for small and medium-scale farmers, increasing their competitiveness in the globalized, large employer-based world.[57] Rural production could be increased by providing access for small-scale producers to innovative drying and other food processing technologies. The increase in rural input will contribute to the dampening effect of massive urbanization and its consequences.

The 4E analysis: sustainability as an indissociable concept

It follows that any drying technology should be thoroughly analyzed, considering all the above mentioned aspects of sustainability. A 4E system analysis has been already applied to some processes such as water desalination[6] and photovoltaic thermal (PVT) solar collection.[58–60]

All attempts to aggregate all economic, environmental, and social indicators of sustainability in a so-called sustainability index as a universal comparative measure of progress are failed. For example, a set of performance indices of sustainability are presented in the recent UN report.[8] It includes 120 indicators, which could be barely combined into one formula.

Technology is one of the core factors in the sustainability agenda,[61,62] but how we can evaluate its sustainability? If we look at the technology from a utilitarian viewpoint, the most suitable index for drying technology could be exergy efficiency (ψ), calculated through eqn (11) or (12). This sustainability index ranges from unity (totally irreversible process, zero exergy efficiency) to infinity (ideal reversible process, 100% exergy efficiency). As discussed, a process is more exergy efficient if most of the available energy is used in the process, and not dissipated instead. Hence, this index could be used to improve process efficiency. The comparison of drying technologies is possible based on absolute measures, such as specific exergy consumption (SExC), calculated through eqn (13). Atalay and Cankurtaran proposed an exergoeconomic assessment of drying technologies, which allows us to compare them based on the exergy destruction cost.[39]

On the other hand, a perfectly reversible drying process would be possible at an unviable low drying rate, hence not being economically sustainable (extremely large equipment or long operation times for batch processes). In this context, it seems that exergy efficiency and economic feasibility should be analyzed as a conjunct – or, as a part of the so-called 4E analysis.

Articles that carry out a 4E analysis, in general, present four separate analyses, with a discussion based on four parameters, mainly energy efficiency, exergy efficiency (or the sustainability index or improvement potential), CO_2 mitigation, and at least one of the aforementioned economic indexes. Examples of 4E analyses are described by Mishra *et al.*[63] and Atalay and Cankurtaran[39] for solar dryers. Mishra *et al.*[63] proposed a 4E methodology to evaluate the thermodynamic performance, environmental impact, and economic viability of greenhouse dryers under the humid climate conditions of North East India. The exergetic efficiency of the solar dryer was 4.5%, dropping to 4.1% under forced convection. They pointed out the economic and environmental advantages of solar dryers compared to hot air dryers but concluded that additional thermal energy storage, part drying, or hybrid drying could improve overall sustainability. In any case, the increase of renewable energy share in the overall energy balance is beneficial for sustainability indices of drying technology. To differentiate renewable and non-renewable sources used for drying, they proposed the Renewability Index (RI) as a fraction of exergy, derived from renewable sources in total exergy input:

$$\mathrm{RI} = \mathrm{ex}_{\mathrm{in}}^{\mathrm{renew}}/\mathrm{ex}_{\mathrm{in}}$$

The environmental impact of drying technology they proposed to estimate with the Sustainability Index (SI) linked to exergetic efficiency ψ is:

$$\mathrm{SI} = (1 - \psi)^{-1}$$

A higher value of SI indicates smaller harm to the environment and better sustainability of drying technology.[63]

Atalay and Cankurtaran[39] used the 4E methodology for the exergoeconomic assessment of large-scale solar dryers. They concluded that fans consume most of the energy in the solar dryer with an exergy destruction cost of $0.2286 per h and an exergy efficiency of 55.28%. When the solar dryer was examined in terms of environmental sustainability, the energy payback period and CO_2 mitigation amount were determined as 6.82 years and 99.60 tons, respectively. It was indicated that the obtained results had quite reasonable values for a large-scale solar dryer compared to small-scale systems in the literature.

For now, it seems that the discussion for the proposal of a single index that reunites these four aspects of sustainability is still open. It is desirable for drying to have minimum specific energy consumption, minimum specific exergy destruction, high profitability (low payback period, high internal rate of return, *etc.*), and low emissions of greenhouse gases. Sometimes, these objectives point in opposite directions.[64,65] For example, as aforementioned, a high exergy efficiency might lead to increased capital cost, consequently leading to an increase in installation and maintenance costs and payback time.

Conclusions and recommendations

The fact that drying processes have been playing a major role in humanity's development is unquestionable. According to the discussion in this review, we conclude that the relationship between the 2030 Agenda for Sustainable Development and the impacts of drying technologies is clear. From the discussion in this article, it can be concluded that:

• An energy analysis is only one of the aspects considering the sustainability of a drying process. Specific energy consumption and specific exergy consumption seem to be the most suitable indices of sustainability.

• One way to assess the sustainability of the drying process is the exergoeconomical assessment, which is the exergy destruction cost per unit mass of [dried] product.

• Even though the energetic and exergetic performance of solar and EHD dryers are low, they are more sustainable than hot air convective dryers. The increase of renewable energy share in the overall energy balance is beneficial for sustainability indices of drying technology.

• The exergetic performance of the dryer could be increased by increasing the difference between chamber and ambient temperature as well as decreasing humidity inside of the drying chamber.

• The environmental impact of drying technology could be evaluated as Sustainability Index (SI) and Renewability Index (RI).

• Different tools for the evaluation of the sustainability of drying processes are available. The comprehension of the fundamental mechanisms of how a drying process occurs might anticipate the results of economic analysis.

• In the long run, it would be possible to relate how drying affects social aspects. Of course, it will not be possible to propose a cause-effect relationship between investments in rural innovation and famine reduction, however, stimulating R&D in drying technologies should also be considered as a guiding policy so that the 17 Sustainable Development Goals are attained.

This review represents the starting point for the quantitative evaluation of the sustainability of drying technology. It should recognize the difference between drying equipment and the drying process. The approaches to system analysis of each element of drying technology might differ.

Author contributions

The idea of this paper was conceived by Alex Martynenko. Both authors were responsible for the preparation, creation, and/or presentation of the published work, including writing the draft, and pre-or post-publication stages.

Conflicts of interest

There are no competing financial interests, personal relationships, or other conflicts of interest to declare.

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