

Prospective LCA-based optimisation of tomato waste drying for biorefinery purposes

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ARTICLE INFO

Dataset link: <https://doi.org/10.5281/zenodo.18433019>

Keywords:

Drying
Prospective LCA
Biorefinery
Tomato waste

ABSTRACT

Tomato waste is currently an untapped potential source of different bioactive compounds, including lycopene, polyphenols, polysaccharides, and proteins. Drying is an energy-intensive process with potentially significant environmental impacts. However, drying is a necessary pretreatment for tomato waste before lipid-soluble bioactive compounds can be extracted. This work attempts to optimise tomato waste drying from the point of view of minimising environmental impacts at an early stage of technology development by using prospective LCA as a tool for optimisation. A comprehensive approach is adopted, starting from experimental investigation, followed by modelling of process kinetics and extrapolating differences in resulting residence times into the size of equipment, which in turn influences LCA inventory, i.e., required size of equipment. Modelling showed that the modified Page model achieved the lowest square error when fitting to experimental data. The study determined that environmental impacts decreased with increasing drying temperature, owing to a decreased contribution from capital goods, which in extreme cases (drying at 75°C) could contribute as much as 36.9% of the climate change impact. The climate change impact could be decreased from 0.42 to 0.11 kgCO₂eq per functional unit (1 kg of evaporated water) by replacing natural gas with biogas for the generation of heat for drying. However, other impact categories (eutrophication, ecotoxicity) showed a reverse trend, highlighting the need for further improvement in digestate and feedstock management in anaerobic digestion plants supplying biogas for the production of heat for such dryers.

1. Introduction

Tomatoes are one of the most commonly grown fruits worldwide [1]. Among many different substances, tomatoes contain significant amounts of carotenoids, which are essential for the human body [2,3]. This includes compounds such as β-carotene or lycopene [1,4]. Carotenoids present in tomato are stored in chromoplasts, with lycopene stored mostly in crystalline chromoplasts [3–5]. Such morphology has a significant influence on lycopene bioavailability for humans. Food processing can also generally increase the bioavailability of lycopene by disrupting cellular membranes and helping to release lycopene from the tissue matrix [6]. Lycopene is soluble in lipids. Thus, consumption of food containing lycopene with fats also increases its bioavailability [6]. Therefore, supercritical CO₂ extraction has been proposed as a lycopene

recovery method from tomato pomace [7,8], and tomato waste [9,10]. In general, the cascade approach to recovery of valuable compounds from tomato waste has been deemed to be a viable approach [10,11]. However, supercritical CO₂ extraction is typically performed with pre-dried feedstock [12,13]. Drying is a very energy-intensive process, so its optimisation requires special attention, and its impact should always be carefully assessed from an environmental perspective.

Life cycle assessment (LCA) is a tool with a coherent and standardised methodology which enables the evaluation of the environmental impact of various products and processes [14–17], including innovations [18]. Numerous examples show the possibility of implementing LCA in assessing the sustainability of novel solutions in various, distinctly different fields [19–22], decision-making at a regional scale [23], or even applying this tool for policy evaluation [24]. LCA has been

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<https://doi.org/10.1016/j.jaecs.2026.100514>

Received 31 January 2026; Received in revised form 9 May 2026; Accepted 18 May 2026

Available online 19 May 2026

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used extensively for many different biobased processes and products, including the production of bio-based growing media [25], seaweed cultivation [26], production of biochar [27], duck-rice co-culture systems for enhanced agricultural production [28], or wood-based heating systems [29].

Prospective LCA is deemed a viable tool to assess the environmental implications of technological innovations [30,31]. In many cases, it is applied on a macro-scale, e.g., to early pinpoint potential unintended consequences while designing policies [32]. However, in the case of the early stage of technology development, such an ex-ante type of LCA is not used to predict the future but rather to explore the range of possible scenarios within which an investigated process could operate [30]. This principle has been applied to detect potential environmental hot spots at early stages of developing technologies, including the production of biohydrogen [33] or hydrothermal pretreatment of brewers' spent grain for increased biomethane potential [34].

LCA has already been pointed out as a good tool for optimisation of drying, selection of energy sources, and reduction of potential environmental impacts of this unit process [35]. The majority of works on LCA of drying process have been performed for drying of different agricultural products at commercial scale, with not so many works available in total. Salgado-Aristizabal [36] determined that in the case of drying of food crops such as Açaí (*Euterpe oleracea*) fruit, drying contributes nearly 40% of its climate change impact. Bosona [37] reported the global warming impact of apple drying ranging between 120 and 130 kgCO_{2eq} per tonne of fresh apples. LCA performed by van Oirschot et al. [38] highlighted the importance of energy consumption during drying in the global warming impact determined for proteins recovered from seaweed. Kumar et al. [39] compared the performance of a small-scale heat-pump dryer with a laboratory-scale microwave dryer, reporting global warming impact of 3.3 and 7.5 kgCO_{2eq} per 1 kg of dried tomatoes for heat-pump-based and microwave drying, respectively.

This work uses prospective LCA as a tool for optimisation of tomato waste drying, looking from the point of view of environmental performance, for the purpose of its subsequent utilisation in a novel cascade biorefinery described in other works, which required drying of tomato waste for subsequent supercritical CO₂ extraction of oil and lycopene [9]. Such biorefineries can recover oil, lycopene, and proteins [9,11]. Drying is necessary to preserve the nutritional properties of tomato waste once produced, which could otherwise deteriorate (mold, etc.), and also because extraction with supercritical CO₂ is more effective if conducted on substrates with a low humidity content and more permeable to the passage of CO₂. In order to assess possible contribution from the capital goods, a comprehensive approach is adopted, starting from experimental investigation, followed by modelling of process kinetics and extrapolating differences of resulting residence times into the size of equipment, which in turn influences LCA inventory, i.e., required size of equipment. Moreover, this work takes into account the possible influence of the use of different fuels, i.e., natural gas and biogas produced using a fraction of the tomato waste stream as a feedstock.

2. Materials and methods

2.1. Thin-layer drying – experimental investigation

Dried tomato waste consisted of tomato peels and seeds. Experimental investigation was performed using an ATS60 gravimetric analyser (Axis Sp. z o.o., Gdańsk, Poland), equipped with two Kanlux J-100W halogens as a radiative source of heat. A 20 mL sample was spread evenly on an aluminium tray with a diameter of 7 cm, creating an even flat layer with a thickness not exceeding 5 mm. Initial moisture of the samples was 78 ± 0.3%. The tray with the sample was placed on a tared balance, the temperature was set on the controller, and the drying experiment started, along with data collection, using a laptop connected to the thermobalance using a USB port. The weight of the sample was recorded every 20 s, and drying took place until the mass of the sample

remained constant for 5 consecutive cycles (100 s). Resolution of the thermobalance was 1 mg. Drying was performed at temperatures of 120, 105, 90, and 75°C. Experiments were performed in triplicate. Drying was performed in the laboratory with an ambient temperature of 24 ± 1°C and relative humidity of 36 ± 5%, as measured by SP92 weather station (Metrex, Poznań, Poland).

2.2. Kinetics of thin-layer drying

Drying kinetics for thin-layer drying has been determined using several models reported in the literature for the drying of thin layers [40–42]. Thin-layer drying models describe the relationship between moisture ratio and drying time [41]. The moisture ratio (*MR*) can be described using the following equation:

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (1)$$

where:

M – instantaneous moisture content (on wet basis), %

*M*₀ – initial moisture content (on wet basis), %

*M*_{*e*} – equilibrium moisture content, %

In many applications of thin-layer drying, especially concerning the typical temperature range and various food industry feedstocks, *M*_{*e*} is assumed to be equal to zero [41,43,44], especially taking into account that relative humidity is not constant during such a process [41,44]. Thus, the equation for *MR* can be simplified, without significant errors [41], into the following form:

$$MR = \frac{M}{M_0} \quad (2)$$

Within the scope of this project, several different models will be used for fitting the experimental data on mass loss from thin-layer drying. One of the simplest models is the Lewis model, based on Newton's law of cooling, which assumes that the drying rate is proportional to the difference between actual and equilibrium moisture content. In such a model, *MR* is described with the following equation [40]:

$$MR = e^{-k \cdot t} \quad (3)$$

where:

k – drying constant, 1/s

t – drying time, s

The Lewis model has been criticised for underestimating drying rates at the higher *MR* values (early stage of drying) and overestimating drying rates at the lower end of *MR* (late stage of drying) [40]. Therefore, a different model was proposed by Page [40,41,44], described by the following equation:

$$MR = e^{-k \cdot t^n} \quad (4)$$

where:

k – drying constant, 1/s

t – drying time, s

n – empirically obtained parameter, -

Some researchers proposed the Page model with slight modifications [41], namely:

$$MR = e^{-(k \cdot t)^n} \quad (5)$$

Another empirical model of the drying process has been proposed by Midilli et al. [40,41,43,44], described by the following equation:

$$MR = a \cdot e^{-k \cdot t^n} + b \cdot t \quad (6)$$

where:

- k – drying constant, 1/s
- t – drying time, s
- a, b, n – empirically obtained parameters, -

Different empirical model has been proposed by Henderson and Pabis [41,43], described by the following equation:

$$MR = a \cdot e^{-k \cdot t} \quad (7)$$

where:

- k – drying constant, 1/s
- t – drying time, s
- a – empirically obtained parameter, -

Experimental data have been fitted to the models shown in equations (3) – (7). The quality of fitting has been assessed by calculating the root mean square error (RMSE), as shown in the following equation [45]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pred,i})^2}{N}} \quad (8)$$

where:

- $MR_{exp,i}$ – experimental moisture ratio for measurement i , -
- $MR_{pred,i}$ – moisture ratio predicted by a model for measurement i , -
- N – number of measurements recorded during drying experiment, -

Fitting was performed using non-linear regression, using the GRG Nonlinear solver engine from Excel Solver (MS 365), with a precision constraint of $1 \cdot 10^{-6}$ and convergence value of $1 \cdot 10^{-4}$. All fitting reports are included in the supplementary data files.

The model with the lowest average RMSE obtained for the series of drying experiments has been subsequently used for the calculation of the

required residence time in the dryer, using the assumed 15% final moisture content as an input.

2.3. Prospective LCA

2.3.1. Goal and scope definition

LCA was performed according to the methodology outlined in EN ISO 14040 and 14044. The functional unit was 1 kg of evaporated water. The intended application was pre-drying of tomato waste from an initial moisture content of 78% to a final moisture content of 15%, for the purpose of subsequent supercritical CO₂ extraction of lycopene (extraction was not included within the scope of investigation). The objective of the study was the determination of optimum drying temperature from the point of view of environmental performance of the dryer, as well as the selection of the heat source at an early stage of development of the envisaged biorefinery process scheme [9]. Moreover, the second objective of the study was to perform contribution analysis and assess whether the environmental impact of capital goods could indeed be meaningful for such a drying technology.

The scope (Fig. 1) included drying, along with the generation of the

Table 1

Different scenarios concerning fuel used for supplying the heat for drying (TW - tomato waste; AD - anaerobic digestion). The co-firing ratio indicates the ratio of biogas to the total volume of the gas mixture.

Scenario name	Label	TW to AD, %	Co-firing ratio, % _{vol}	Evaporated water, ton/y	qV biogas, m ³ /day	Boiler output, kW
100% Fossil fuel	F100	0	0.0	29 647	0	5 052
Predominantly fossil	FP	20	12.6	23 718	1 488	4 099
Baseline	B	40	29.7	17 788	2 977	3 147
Predominantly renewable	RP	60	54.1	11 859	4 465	2 195
100% renewable	R100	84	100.0	4 744	6 251	1 096

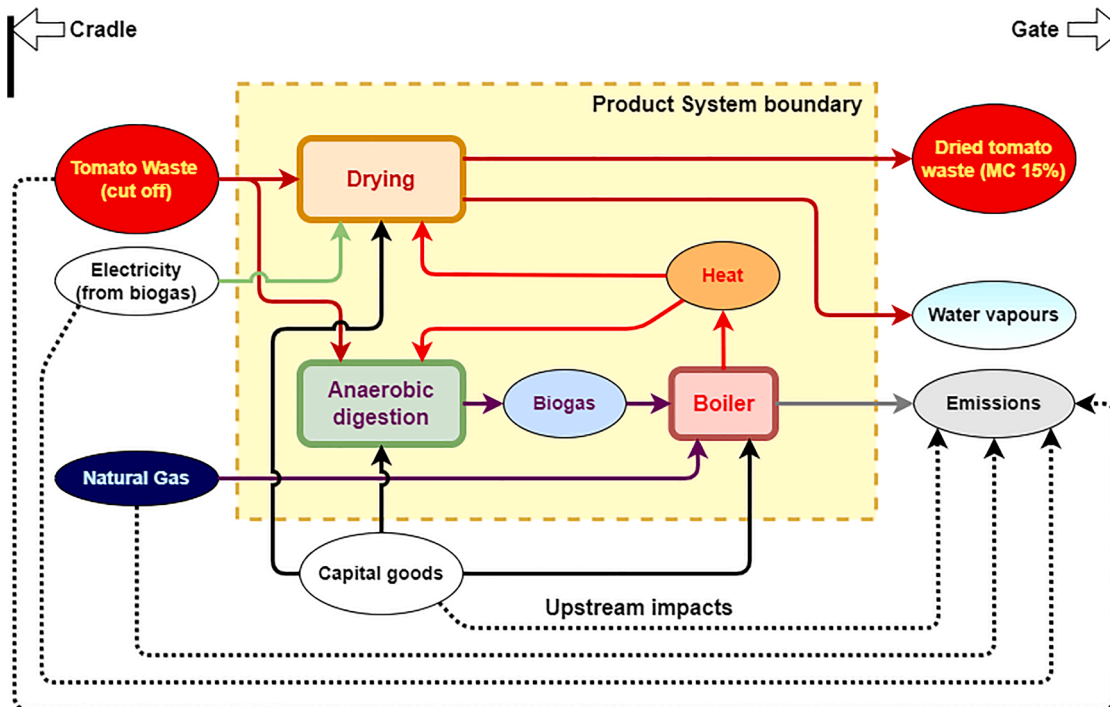


Fig. 1. Scope of the performed prospective LCA.

heat necessary for drying. Several different scenarios (Table 1) were investigated concerning the generation of heat needed for drying, i.e., scenarios considered combustion of natural gas, biogas produced using a part of the available tomato waste stream, or mixtures thereof with different co-firing ratios. The environmental impact of capital goods used by the dryer, anaerobic digestion installation, and a boiler was included within the scope (Fig. 1). The target audience of this ex-ante prospective LCA is the scientific community, as well as industrial professionals participating in research and development activities aiming at establishing novel biorefineries. Technological boundaries involve a cradle-to-gate approach (Fig. 1), and the study is geographically relevant for the EU, as intended for the application of the EF 3.1 database.

2.3.2. Inventory analysis

The tomato waste-based biorefinery, considered in this work, does not exist on a commercial scale. Thus, a prospective LCA was performed, using data from existing installations as proxies. Data regarding energy consumption and capital goods were taken from the Ecoinvent 3.11 database. Background data concerning rotary dryers, drying grass at 110–120°C [46], are provided by the process "Drying of grass {CH}| drying of grass | Cut-off, U", which outlines the energy consumption, the amount of iron used for the dryer, as well as m² of the building hall per 1 kg of evaporated water. Background data for the building hall is provided by "Building, hall {CH}| building construction, hall | Cut-off, U". A more detailed description is provided in section 3 of the supplementary materials. The dataset is based on common grass and maize drying plants, specifically 70 centralised plants in Switzerland that use rotary dryers, with a typical nominal power of 4–5 MW for drying air heaters [46], which is a similar scale to the system considered within the scope of this work. A conservative assumption of 4.79 MJ/kg_{H₂O} was made for the useful heat required per 1 kg of evaporated water, also based on the same dataset. Regarding capital goods, it was assumed that the data from a proxy dryer is relevant for drying at 120°C, whereas drying at 105, 90, and 75°C required increased size, implying increased environmental impact of capital goods. For each of the cases, the assumed scale was based on experimentally obtained drying kinetics, assuming that for the same inlet mass flow rate of the material to be dried, the size of the equipment and buildings increases linearly with the residence time in the dryer required for each of the investigated drying temperatures (scaling factors are provided in supplementary materials). Data concerning capital goods needed for anaerobic digestion were also taken using a proxy, based on Ecoinvent 3.11. Data concerning capital goods needed for the boiler were obtained based on the total dry mass of the boiler required for each scenario (Table 1), based on estimated heat duty and catalogue data from suppliers (see supplementary materials). Data for processes of different product systems were taken from EF 3.1, including upstream impacts of natural gas and biogas production, specified for EU+EFTA+UK locations. Due to the anticipated location of the tomato processing plant in a rural area, it was assumed that the electricity required for the process would be generated locally in a biogas plant. It was assumed that the electricity consumed by the dryer varies proportionally to the size of the equipment, using the same scaling factor as for capital goods data. Detailed Life Cycle Inventory for all analysed cases, including names of particular processes from databases, is provided in supplementary materials. LCA was performed using openLCA software (model graphs from openLCA provided in supplementary materials for each analysed case). Impacts from upstream processing of tomatoes were not included, i.e., a cut-off approach was adopted, and it was assumed that all impacts should be allocated to tomatoes, and tomato waste is burden-free.

Mass and energy balances were performed based on the assumption that the tomato pomace plant processes 20 t/h of tomatoes, with 25% waste to input ratio by mass [47]. Production of biogas from tomato waste in a continuous stirred tank reactor (CSTR) was assumed to be 290 mL/g_{VS}/day [48]. The share of the total biogas energy content (gross = boiler input, LHV-based) used for heating the digester was assumed to be

20% [49]. The methane content of biogas was assumed to be 47% [48]. The lower heating value of methane was taken as 35.80 MJ/Nm³, and it was also assumed that the heating value of biogas is proportional to its methane content. The boiler efficiency was assumed to be 90%. Mass and energy scenarios resulted in different amounts of evaporated water for each scenario (Table 1), due to different consumption of tomato waste for biogas production, which left less feedstock available for drying and subsequent use in the biorefinery. Inventory data uncertainty was assessed using a well-established pedigree matrix approach [50–53], in alignment with ILCD guidelines published by the European Commission [54].

2.3.3. Impact assessment

Impact assessment was performed using the Environmental Footprint 3.1 life cycle impact assessment method developed by the EU Joint Research Centre for the determination of the environmental footprint of products and organisations [55]. The impact categories and characterisation factors used in the method comply with Recommendation 2013/179/EU on the use of common models to measure and communicate the life cycle environmental performance of products and organisations [56]. The method was implemented in openLCA by the software developer (Green Delta GmbH), and the EF 3.1 process datasets (downloaded from Nexus) were fully compliant with the ILCD entry-level requirements [55]. Normalisation was performed after the calculations of impacts. Regarding the calculation type in openLCA, the eager/all setting was selected.

3. Results and discussion

3.1. Kinetics of thin-layer drying and its influence on the size of the dryer

Parameters obtained for different empirical models considered within the scope of this study (Table 2) are comparable to other results for similar materials reported in the literature. Ruiz Celma et al. [45] investigated thin-layer infrared drying kinetics of industrial tomato residues from Spain, for drying temperatures between 100 and 160°C. The parameter (*k*) obtained for the Lewis model ranged between 3.6·10^{−4} and 9.5·10^{−4} for drying at 100 and 160°C, respectively [45]. For the modified Page model, the study obtained *k* ranging between 3.5·10^{−4} and 9.3·10^{−4} and power (*n*) ranging between 1.19 and 1.32. Small differences in obtained parameters within the overlapping temperature range could be attributed to differences in the feedstock, relative humidity in the laboratory, and respective fitting algorithms. Nonetheless, RMSE values obtained within the scope of this study correspond well with the values obtained by Ruiz Celma et al. [45], e.g., RMSE for the modified Page model, obtained within the scope of this study, ranged between 0.038 and 0.039 (Table 3), whereas for the same model, Ruiz Celma et al. [45] obtained RMSE ranging between 0.025 and 0.026. Considering that all the models predict the value of MR, which always starts at the value of 1, and the ratio between the initial moisture content of 78% and the target final moisture content of 15% (wet basis) results in an MR of 0.19, the obtained RMSE values indicate reasonably good fitting quality. Similar RMSE values are reported in the literature for thin-layer drying of different types of biomass. Ghazanfari et al. [40] investigated thin-layer drying of flax fibre at temperatures ranging between 30 and 100°C, with obtained RMSE ranges of 0.032–0.036, 0.007–0.013, and 0.039–0.116, for Lewis, Modified Midilli, and Wang & Singh models, respectively. Tiguh et al. [42] investigated solar drying of unthreshed teff crops and obtained RMSE ranging between 0.013 and 0.035 for the Midilli model. Patel and Panwar [44] investigated solar drying of *Cucumis callosus* and obtained RMSE of 0.091, 0.070, and 0.063, for Henderson & Pabis, modified Page, and Midilli models, respectively.

Overall, out of the empirical models investigated within the scope of this study, the Midilli model and the modified Page model resulted in the best agreement with experimental results, the Midilli model achieving

Table 2
Parameters for different empirical drying models, obtained by non-linear regression of experimental drying data for each drying temperature (Avg - average; $\pm$ - standard deviation of the sample; RSD - average standard deviation relatively to the result).

Model	Param.	T drying 75°C			T drying 90°C			T drying 105°C			T drying 120°C		
		Avg.	$\pm$	RSD, %	Avg.	$\pm$	RSD, %	Avg.	$\pm$	RSD, %	Avg.	$\pm$	RSD, %
Lewis Page	k	1.19·10 ⁻⁴	5.39·10 ⁻⁶	4.5	1.66·10 ⁻⁴	7.60·10 ⁻⁶	4.6	2.80·10 ⁻⁴	5.85·10 ⁻⁵	20.9	3.49·10 ⁻⁴	2.27·10 ⁻⁵	6.5
	k	2.65·10 ⁻⁷	4.83·10 ⁻⁷	182.0	4.25·10 ⁻⁵	7.84·10 ⁻⁵	184.5	4.17·10 ⁻⁹	2.23·10 ⁻⁹	53.6	2.37·10 ⁻⁹	9.55·10 ⁻¹¹	4.0
Midilli	n	1.88	2.31·10 ⁻¹	12.3	1.46	4.15·10 ⁻¹	28.3	2.38	2.66·10 ⁻²	1.1	2.50	1.92·10 ⁻²	0.8
	a	7.13·10 ⁻¹	1.85·10 ⁻²	2.6	7.06·10 ⁻¹	4.91·10 ⁻²	7.0	7.13·10 ⁻¹	5.75·10 ⁻²	8.1	8.90·10 ⁻¹	2.02·10 ⁻²	2.3
	b	-1.99·10 ⁻⁴	4.35·10 ⁻⁶	2.2	-2.51·10 ⁻⁴	4.13·10 ⁻⁵	16.4	-3.98·10 ⁻⁴	7.07·10 ⁻⁵	17.8	-3.45·10 ⁻⁴	5.10·10 ⁻⁶	1.5
	k	-5.34·10 ⁻²	4.11·10 ⁻³	7.7	-6.64·10 ⁻²	1.12·10 ⁻²	16.8	-7.34·10 ⁻²	8.27·10 ⁻³	11.3	-5.56·10 ⁻²	1.06·10 ⁻²	19.1
Henderson&Pabis	n	3.27·10 ⁻¹	3.92·10 ⁻³	1.2	3.06·10 ⁻¹	3.19·10 ⁻³	1.0	3.07·10 ⁻¹	1.33·10 ⁻²	4.3	2.59·10 ⁻¹	3.78·10 ⁻²	14.6
	a	1.23	7.95·10 ⁻³	0.6	1.26	2.52·10 ⁻³	0.2	1.34	2.26·10 ⁻²	1.7	1.53	2.41·10 ⁻²	1.6
Modified Page	k	1.53·10 ⁻⁴	8.33·10 ⁻⁶	5.4	2.17·10 ⁻⁴	1.10·10 ⁻⁵	5.1	3.88·10 ⁻⁴	8.59·10 ⁻⁵	22.2	5.30·10 ⁻⁴	3.97·10 ⁻⁵	7.5
	n	2.72	3.55·10 ⁻²	1.3	2.67	1.03·10 ⁻¹	3.8	2.74	5.65·10 ⁻²	2.1	2.80	3.61·10 ⁻²	1.3
	k	1.32·10 ⁻⁴	4.85·10 ⁻⁶	3.7	1.81·10 ⁻⁴	9.90·10 ⁻⁶	5.5	2.98·10 ⁻⁴	5.95·10 ⁻⁵	20.0	3.61·10 ⁻⁴	2.21·10 ⁻⁵	6.1

the lowest RMSE for drying at 75 and 90°C, and the modified Page model having the lowest RMSE for drying at 105 and 120°C (Table 3). However, the Midilli model has been shown to predict some non-physical values (artefacts) for a higher range of MR values, in some cases showing an increase of MR during the first thousand seconds of drying (Fig. 2). For this reason, the modified Page model has been selected for estimating the required residence times during drying (Table 4), subsequently used in the prospective LCA in order to take into account the increased impact with increasing size of the equipment.

3.2. LCA interpretation - selection of optimum drying conditions for minimising environmental impacts

As expected, the performed prospective LCA has shown the highest climate change impacts for 100% fossil fuels scenario, which decreased with increasing share of biogas (co-firing ratio), as shown in Fig. 3. It is definitely possible to achieve drying with a lower climate change impact. De Falco et al. [57] investigated drying of various medicinal plants and obtained climate change (CC) impacts ranging between 0.27 and 0.38 kg_{CO2eq} per kg of dried product in the case of open-air drying under a wooden structure. For the case of the results obtained within the scope of this study, recalculating impacts from the functional unit used (kg of evaporating water) to kg of dried product requires multiplying results shown in Fig. 3 by 2.86 (initial and final moisture content of 78 and 15%, respectively). This results in climate change impact per kg of dried product ranging between 0.31 and 1.21 kg_{CO2eq}, making the solution considered within the scope of this work attractive from a climate perspective. However, this should be treated with caution, as apart from the impact of capital goods of the open-air drier, De Falco et al. [57] also included impacts from cultivation of the plants and transportation, whereas this work assumed burden-free tomato waste that would be processed on-site at a tomato processing plant. Nonetheless, it should not be overlooked that for the electric drying system, also analysed by De Falco et al. [57], the global warming potential ranged between 18.22 and 30.63 kg_{CO2eq}. Global warming potential reported in the literature for drying of different products is typically in the range of a few kg_{CO2eq} per functional unit. Zhang et al. [58] obtained 9.3 kg_{CO2eq} per kg of milk powder dried from 50% to 3% moisture content. The scope included transportation, cleaning of the drying equipment, as well as the end-of-life of machinery [58]. De Marco et al. [59] reported a global warming potential of 0.17 kg_{CO2eq} per 1 kg of dried apple powder, with scarce information on initial moisture content and heat generation.

Overall, the obtained results show that impacts for drying of all tomato waste worldwide could vary greatly, ranging between 0.5 and 12.9 Mton_{CO2eq} (Fig. 3B), reaching an order of magnitude of a small state/region. The reason for such a stark difference between the impact per kg of evaporated water and total impact of drying of all tomato waste, between the considered scenarios, is the fact that some scenarios consume a portion of tomato waste for the production of biogas, which increases with increasing share of biogas in co-firing (see Table 1). This is mirrored by normalised CC impacts, i.e., impact normalised per person and (Fig. 3C) mirrors trends shown per kg of evaporated water (Fig. 3A), whereas impact normalised per single person share of produced tomatoes worldwide (Fig. 3D) mirrors trends for total impact for all tomato waste worldwide, for respective scenarios (Fig. 3B).

If drying installation is supposed to be optimised, aiming at minimising climate change impact, based on the results of this prospective LCA, it can be stated that increasing the drying temperature improves environmental performance. Nonetheless, it should be noted that a conservative assumption regarding the required heat of 4.79 MJ/kg_{H2O} was adopted equally for all drying temperatures. In the scaled-up installation, the required heat might be different for different drying temperatures. On one hand, less heat is needed per kg of air to heat the air up to 75°C, when compared to 120°C. On the other hand, relative humidity decreases with increasing temperature, for the same initial absolute humidity of the air, which would decrease the required amount

Table 3

Average root mean square errors (RMSE), standard deviations of the sample (absolute and relative to average values) for all considered models, for each drying temperature (Avg - average; $\pm$ - standard deviation of sample; RSD - average standard deviation relatively to the result).

Model	T _{drying} 75°C			T _{drying} 90°C			T _{drying} 105°C			T _{drying} 120°C		
	Avg.	$\pm$	RSD, %	Avg.	$\pm$	RSD, %	Avg.	$\pm$	RSD, %	Avg.	$\pm$	RSD, %
Lewis	0.1569	0.0014	0.9	0.1568	0.0050	3.2	0.1645	0.0014	0.9	0.1739	0.0020	1.2
Page	0.0741	0.0186	25.2	0.1249	0.0281	22.5	0.0461	0.0034	7.5	0.0454	0.0005	1.1
Midilli	0.0284	0.0030	10.6	0.0287	0.0014	4.8	0.0383	0.0034	8.9	0.0515	0.0029	5.6
Henderson&Pabis	0.1287	0.0043	3.3	0.1276	0.0051	4.0	0.1269	0.0032	2.5	0.1215	0.0023	1.9
Modified Page	0.0392	0.0020	5.0	0.0388	0.0035	8.9	0.0380	0.0020	5.2	0.0386	0.0013	3.3

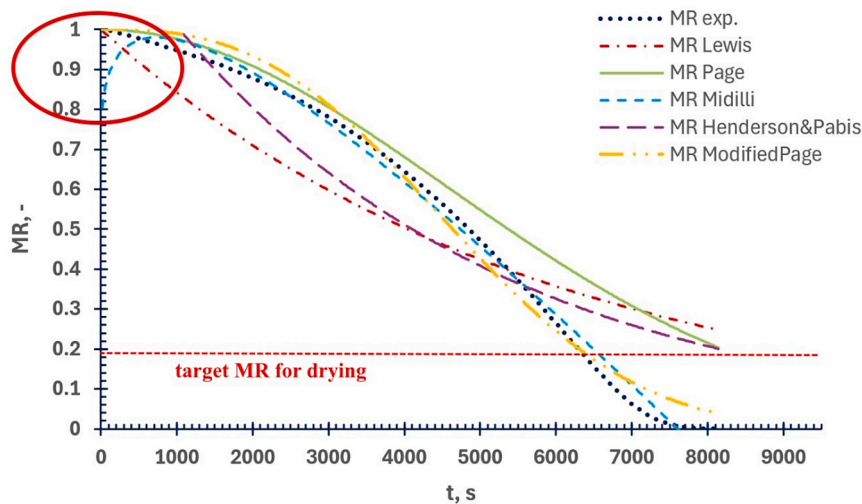


Fig. 2. Example of fitting of experimental data to different models for an experiment at drying temperature of 90°C. Non-physical behaviour predicted by the Midilli model for high moisture ratios marked with a red ellipse. Target MR for drying process marked with a red dashed line.

Table 4

Required residence time and normalised residence time based on the Modified Page model.

T _{drying} , °C	t _{drying} , s	normalised t _{drying}
120	3310	1
105	4030	1.216
90	6680	2.016
75	9110	2.749

of drying air. Less air required per kg of evaporated water would also reduce the electricity required by fans.

Decreasing the share of fossil fuel (natural gas) in heat generation for drying purposes overall provides more noticeable improvements in terms of climate change impact. However, this is not the case for other impact categories (Fig. 4). In the case of categories such as Eutrophication (Fig. 4 A and B) or Ecotoxicity (Fig. 4 C and D) of freshwater, the impact increases with increasing share of co-fired biogas. A similar observation could be made for acidification impact (Fig. 4 E and F). In the case of eutrophication impact, expressed in kg_{Peq}, analysis of the LCA model in openLCA has shown that processes related to the production of biogas are the main contributors. Aggregation of impacts, characteristic of EF 3.1 databases, makes it hard to pinpoint the source. However, since the elementary flows responsible for the impacts were phosphorus and phosphates, it seems plausible to suspect that this impact is related to digestate management.

Even though the data from EF 3.1 concern the production of biogas in the EU in general, the impact is likely to occur also for digestate from anaerobic digestion of tomato waste, since tomato peels and seeds were reported to contain 2.7 and 4.0 g_P/kg of dry product, respectively [60]. Thus, it seems sensible to anticipate a decrease in this impact category if

novel digestate management techniques are applied. Hydrothermal carbonisation (HTC) has been mentioned in the literature as a process that could provide support concerning controlled nutrient recovery, including phosphorus [61,62], from digestate. Moreover, organics solubilised in the process water from HTC could also be used as a substrate and produce additional biogas in anaerobic digestion [63–65], further decreasing the impacts. Furthermore, external use of hydrochars from digestate could provide additional savings across the life cycle, considering many different impact categories, including eutrophication, freshwater, as shown by Lombardi et al. [66].

In terms of ecotoxicity impact, the openLCA model has shown that among the elementary flows, H₂S was the biggest contributor. Generally, both biogas and natural gas can contribute to H₂S generation. Natural gas often contains between 1 and 10%_{vol} of H₂S, which is captured using amine absorption and subsequently treated using the Claus process, which accounts for 95% of sulphur production worldwide [67]. In terms of biogas plant operation, pre-storage of slurry (substrate) has been reported as the main source of H₂S emissions [68]. Since this gas is considered an odorant [68], abatement of its emissions would be beneficial not only from the point of view of environmental impact, but also from a public acceptance perspective. Also, in this case, thermal treatment processes could be expected to provide some effects of synergy, as HTC, as a pretreatment of anaerobic digestion substrates, was also shown to improve biogas yields [69]. However, Wang et al. [70] reported that HTC could produce H₂S by decomposition of sulphide and sulfone. This should be carefully assessed in future studies, concerning the potential influence on ecotoxicity impact for such a valorisation pathway. Nonetheless, tomato peels and seeds reportedly contain only 0.07 and 0.20%_{dry} of sulphur [71], which allows us to suspect that the ecotoxicity impact reported within the scope of this study provides a rather conservative estimate. Table 5 shows the results recalculated per

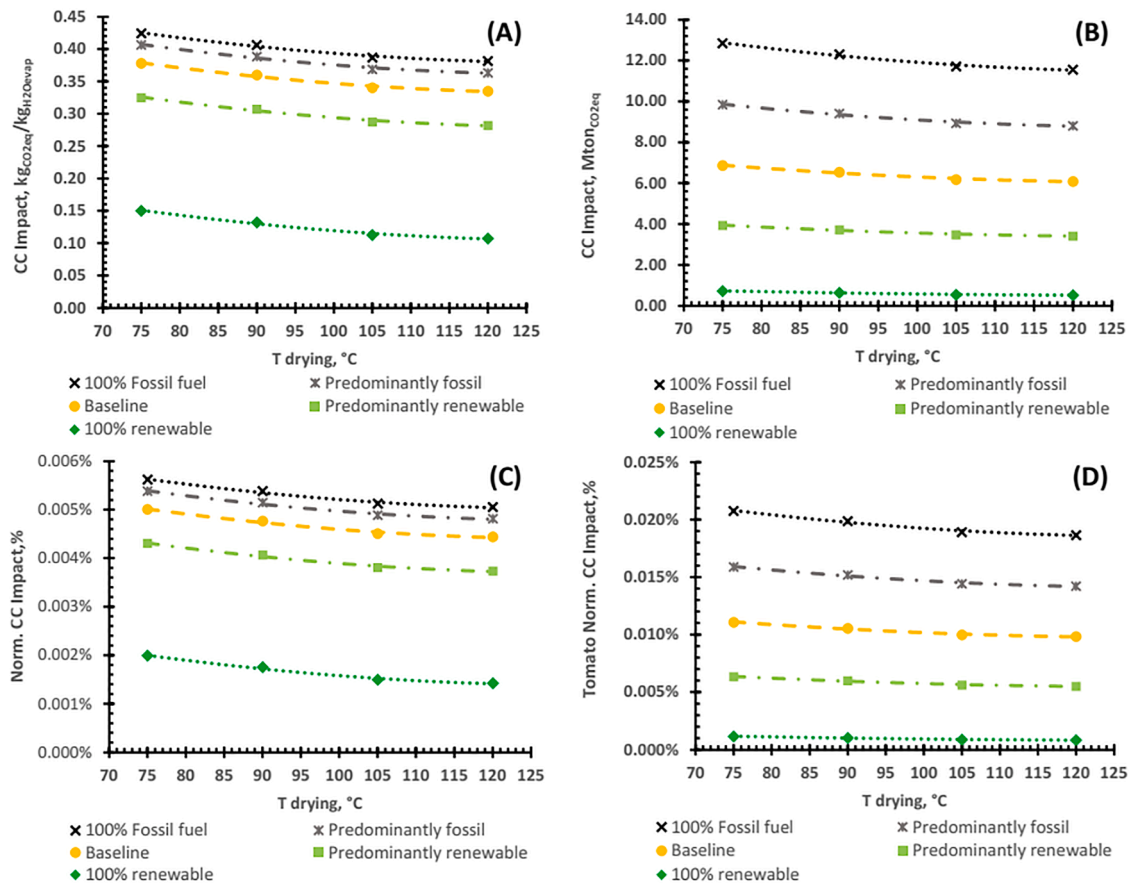


Fig. 3. Influence of drying temperature on climate change impact for different scenarios. A: Absolute Climate Change impact (kgCO_{2eq}) per functional unit; B: Absolute worldwide impact if all tomato waste was utilised this way; C: Climate Change impact normalised per person; D: Climate Change impact normalised per tomato production per person (23 kg per person, waste/tomato = 0.25).

kg of dried product.

3.3. LCA interpretation - contribution analysis for assessing impacts from capital goods

Results of the performed contribution analysis show that the environmental impacts of capital goods might be as high as 36.9% for the climate change category in the case of the scenario in which 100% of the required energy comes from renewable energy sources (Fig. 5). In terms of LCA studies on drying, the impact of infrastructure is often excluded [57]. This is understandable, as drying at higher temperatures, using fossil fuels, is associated with relatively smaller impacts, e.g., the contribution of infrastructure to climate change impact for drying tomato waste at 120 °C using natural gas for the generation of heat was only 3.1%. However, literature advises caution concerning excluding contributions of capital goods in LCA focused on renewable energy sources [72]. Indeed, in the case of the LCA results for open-air drying under a roof, reported by De Falco [57], infrastructure contributed roughly 15%. However, in the case of open-air drying, the generation of heat is not required. Indeed, the fact that infrastructure contributed only 15% was caused by a relatively high contribution from the cultivation of dried plants, which was included within the scope of LCA by De Falco [57]. In the case of this study, it was considered that tomato waste is burden-free, since its existence is a consequence of processing tomatoes to obtain the main marketable product (tomato sauce). Therefore, any allocation to tomato waste would decrease the burdens allocated to tomato sauce, which doesn't seem justified, since the waste is generated because of the sauce production.

Overall, in terms of climate change impact, it is possible to decrease

the contribution of capital goods from 36.9% for drying at 75 °C to 28.4% for drying at 120 °C using heat from the combustion of biogas (Fig. 5), owing to the decrease in the size of the required equipment. For the scenario with the highest contribution of capital goods (36.9%), the contribution of drying was the biggest (26.1% of the total), followed by the contribution of anaerobic digestion infrastructure (10.7% of the total), with boiler having a negligible share (<1% of the total).

Among the impacts of the consumed energy, the climate change impact of heat generation was dominant across scenarios, decreasing with increased share of biogas (Fig. 5). The impact could be considered significant even when supplying heat 100% from biogas, with shares in total impact being 44.4 and 62.1% for drying at 75 and 120 °C, respectively. Such a result could be attributed to the extensive scope of the background system from EF 3.1, providing data for biogas (process name in the inventory, in supplementary materials). The background data included transportation and handling of the substrate (sanitation, mechanical pretreatment), as well as digestate treatment (dewatering). This also suggests that the obtained results could be considered conservative. The contribution of electricity to climate change impact was relatively modest, reaching a maximum of 18.7% for the 100% renewable scenario with drying temperature of 75 °C. This is significantly different to contribution of electricity reported by Medeiros et al. [73] to be slightly higher than 60% for drying of polyphenol-rich acerola powder. However, in that case, spray drying was used instead of drum drying, and this particular drying technique requires high pressures for spraying the suspension. Spraying also turned out to involve a substantial contribution (approx. 90%) when steam was used for this purpose, as reported by Zhang et al. [58].

This shows that different drying principles might be a source of

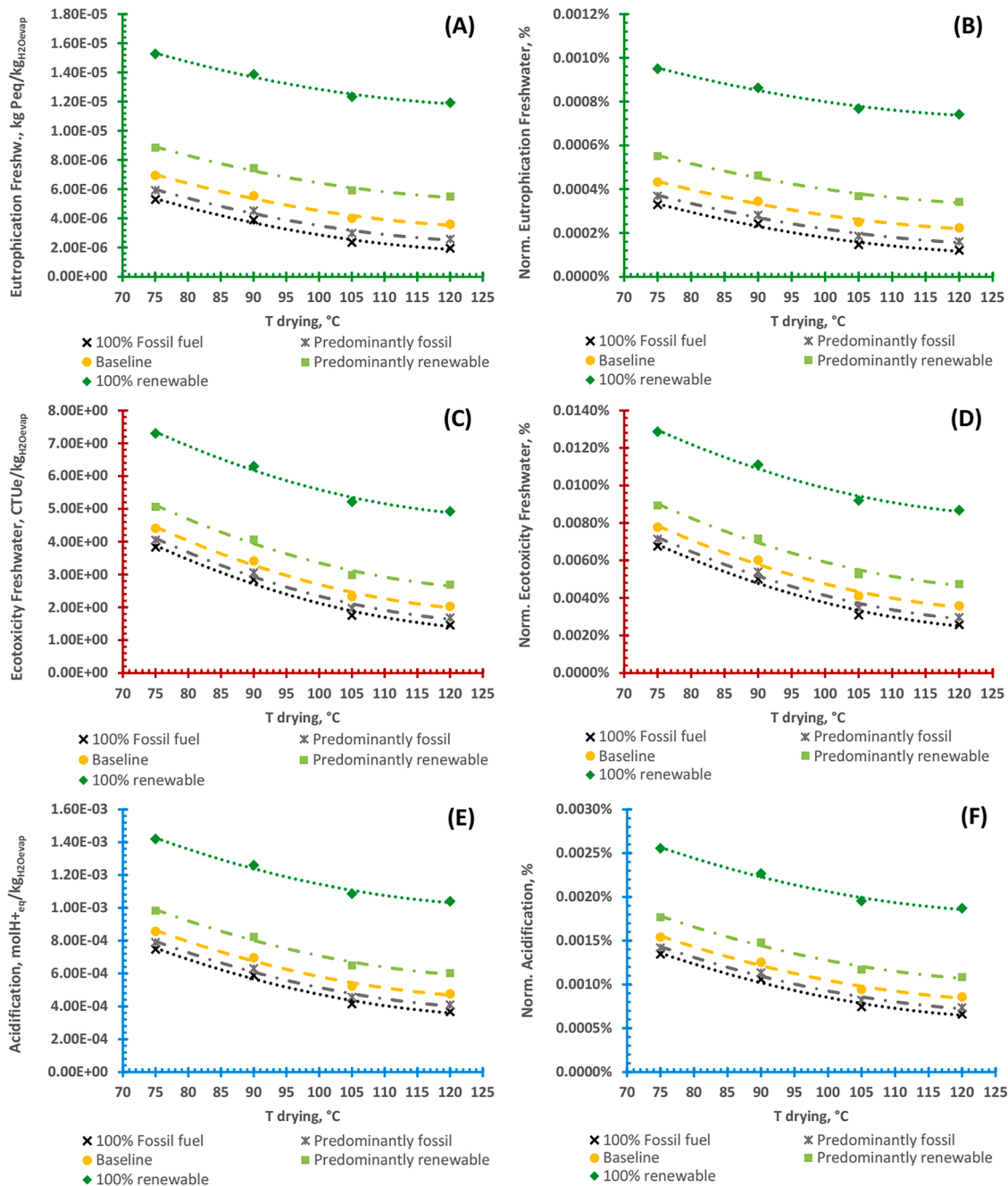


Fig. 4. Influence of drying temperature on Eutrophication (A&B), Ecotoxicity (C&D), and Acidification (E&F) impact for different scenarios.

different hot spots, and the results obtained within the scope of this study are specifically applicable to drum drying.

In the case of other impact categories, the contribution of the capital goods was relatively smaller. In terms of ecotoxicity impact, drying at 75 °C resulted in a relative contribution of capital goods ranging between 5.4 and 8.5% (Fig. 6), whereas drying at 120 °C ranged between 3.8 and 8.1% (Fig. 6). Electricity was the main contributor for 100% natural gas scenario, since local generation of electricity in the rural area (a sensible location of a tomato processing plant) was assumed to be based on biogas. As already mentioned in section 3.1, H₂S is the main contributor to ecotoxicity impact for biogas, and abatement of these emissions is likely in the future, as the gas is odorant, which significantly impacts public acceptance of biogas. It could be clearly seen in Fig. 6 that the share of heat is increasing with increasing co-firing share of biogas for heat generation. At first, it is tempting to state that the high contribution

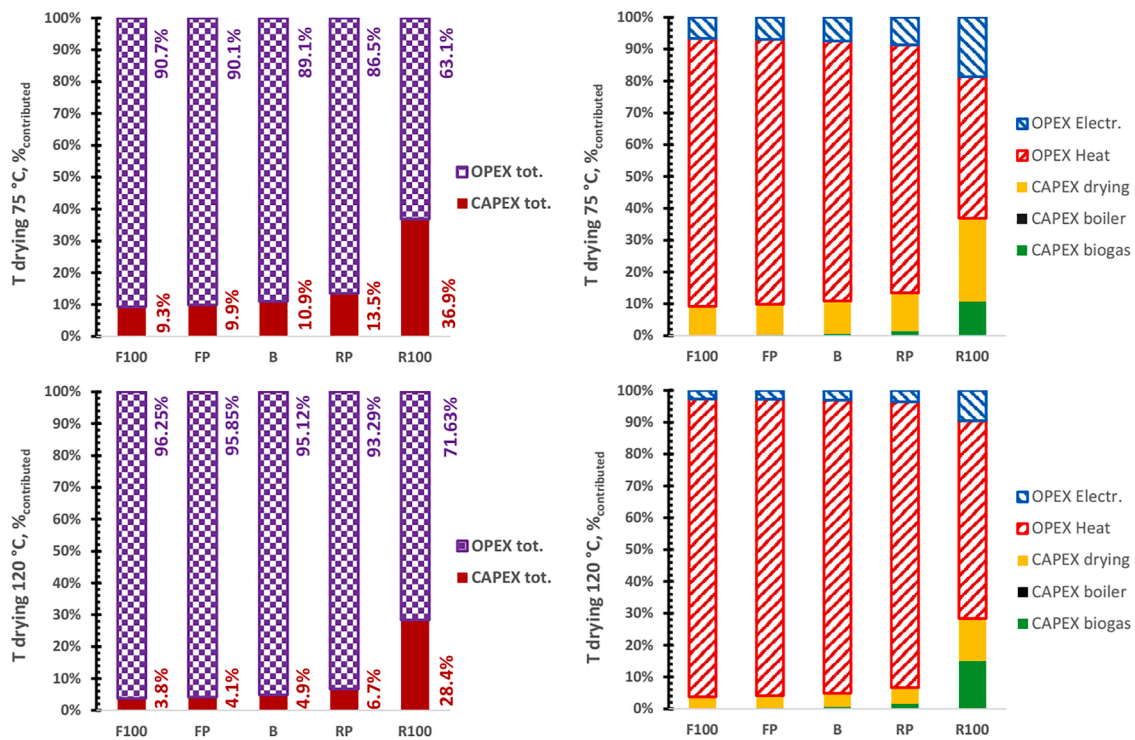
share of electricity is well in line with other studies, as Medeiros et al. [73] also reported the contribution of electricity to freshwater ecotoxicity impact for drying of polyphenol-rich acerola powder, slightly exceeding 50 and 60% for spray drying and foam mat drying, respectively. Moreover, Khosravi et al. determined the global warming contribution of electricity slightly exceeding 60% for spray drying of medicinal plant extracts [74]. However, such similarity should be treated with caution when different drying systems are considered [35].

Regarding eutrophication impact, drying at 75 °C resulted in a relative contribution of capital goods ranging between 3.6 and 1.4% (Fig. 7), whereas drying at 120 °C ranged between 3.6 and 0.8% (Fig. 7). It is not surprising that the results of contribution analysis for eutrophication follow the results obtained for ecotoxicity, as absolute values for both impacts exhibited similar trends (Fig. 4). Similarities suggest that impacts related to biogas exert a strong influence, which is confirmed by

Table 5

Results of the study for selected impact categories, recalculated for 1 kg of dried solid product (15% moisture content).

Scenario name	TW to AD %	Co-firing ratio % (vol)	T drying °C	Climate change kg CO _{2eq}	Eutrophication, freshwater kg P _{eq}	Ecotoxicity, freshwater CTU _e	Acidification mol H ₊ _{eq}
100% Fossil fuel	0	0.0	75	1.22E+00	1.52E-05	1.10E+01	2.14E-03
Predominantly fossil	20	12.6	75	1.16E+00	1.70E-05	1.16E+01	2.26E-03
Baseline	40	29.7	75	1.08E+00	1.99E-05	1.26E+01	2.45E-03
Predominantly renewable	60	54.1	75	9.31E-01	2.53E-05	1.45E+01	2.81E-03
100% renewable	84	100.0	75	4.30E-01	4.37E-05	2.09E+01	4.06E-03
100% Fossil fuel	0	0.0	90	1.16E+00	1.11E-05	8.15E+00	1.69E-03
Predominantly fossil	20	12.6	90	1.11E+00	1.30E-05	8.77E+00	1.81E-03
Baseline	40	29.7	90	1.03E+00	1.59E-05	9.78E+00	2.00E-03
Predominantly renewable	60	54.1	90	8.79E-01	2.13E-05	1.17E+01	2.36E-03
100% renewable	84	100.0	90	3.79E-01	3.97E-05	1.81E+01	3.61E-03
100% Fossil fuel	0	0.0	105	1.11E+00	6.75E-06	5.04E+00	1.19E-03
Predominantly fossil	20	12.6	105	1.06E+00	8.56E-06	5.66E+00	1.31E-03
Baseline	40	29.7	105	9.75E-01	1.15E-05	6.67E+00	1.50E-03
Predominantly renewable	60	54.1	105	8.23E-01	1.69E-05	8.56E+00	1.86E-03
100% renewable	84	100.0	105	3.23E-01	3.53E-05	1.50E+01	3.11E-03
100% Fossil fuel	0	0.0	120	1.09E+00	5.56E-06	4.20E+00	1.05E-03
Predominantly fossil	20	12.6	120	1.04E+00	7.38E-06	4.83E+00	1.17E-03
Baseline	40	29.7	120	9.60E-01	1.03E-05	5.83E+00	1.37E-03
Predominantly renewable	60	54.1	120	8.08E-01	1.58E-05	7.72E+00	1.73E-03
100% renewable	84	100.0	120	3.08E-01	3.41E-05	1.41E+01	2.98E-03

**Fig. 5.** Contribution of capital goods (denoted by CAPEX) and consumed energy (denoted by OPEX) to the climate change impact of tomato waste drying for different scenarios.

the observations made in Section 3.2 regarding the contributions from phosphorus and phosphates, attributed to digestate management.

Aside from optimisation of the dryer itself, it is interesting to notice that there are other spots for potential improvement, regarding the impact coming from capital goods. One such possibility would be offered by the development of the green steel sector in the EU, e.g., in the R100 scenario with drying at 75°C, the total contribution in the climate change category was 7.1 and 9.1% for cast iron and steel, respectively. For the same scenario, contributions from bricks, cement, and glass were 2.4, 2.2, and 4.5%, respectively (see supplementary materials). This shows some room for improvement in terms of the impact contributed by buildings [75]. A prospective LCA performed by Valentini et al. [76]

has shown that the selection of materials can exhibit a significant influence on the environmental impacts of buildings. Moreover, using solar heat for drying could become an interesting alternative [77]. Overall, Sankey diagrams in supplementary materials show the contribution of individual processes for selected impact categories, limited to 15 processes with the highest contributions and excluding all processes with contributions below 1%. Additionally, it should be noted that the system investigated within the scope of this study did not include the recovery of latent heat by using a condensing heat exchanger. Partial recovery of heat would decrease the overall fuel consumption (biogas / natural gas), thus decreasing the impacts from dryers' operation. However, in such a case, the impacts of capital goods associated with heat

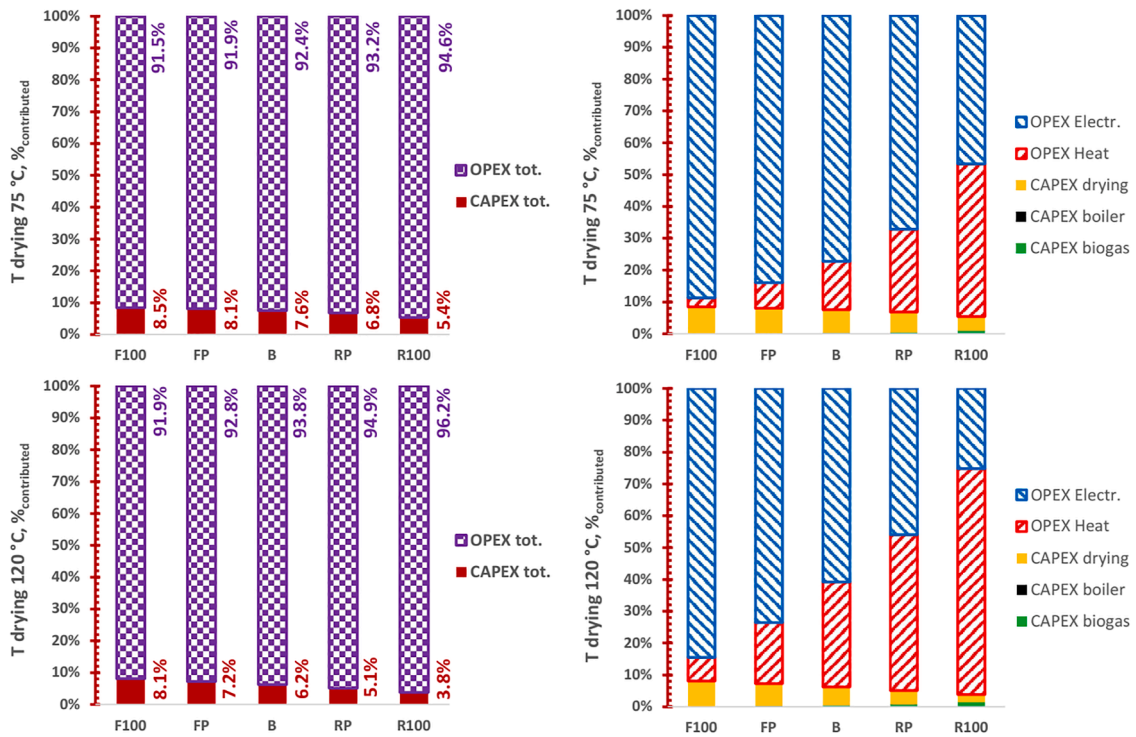


Fig. 6. Contribution of capital goods (denoted by CAPEX) and consumed energy (denoted by OPEX) to the ecotoxicity impact of tomato waste drying for different scenarios.

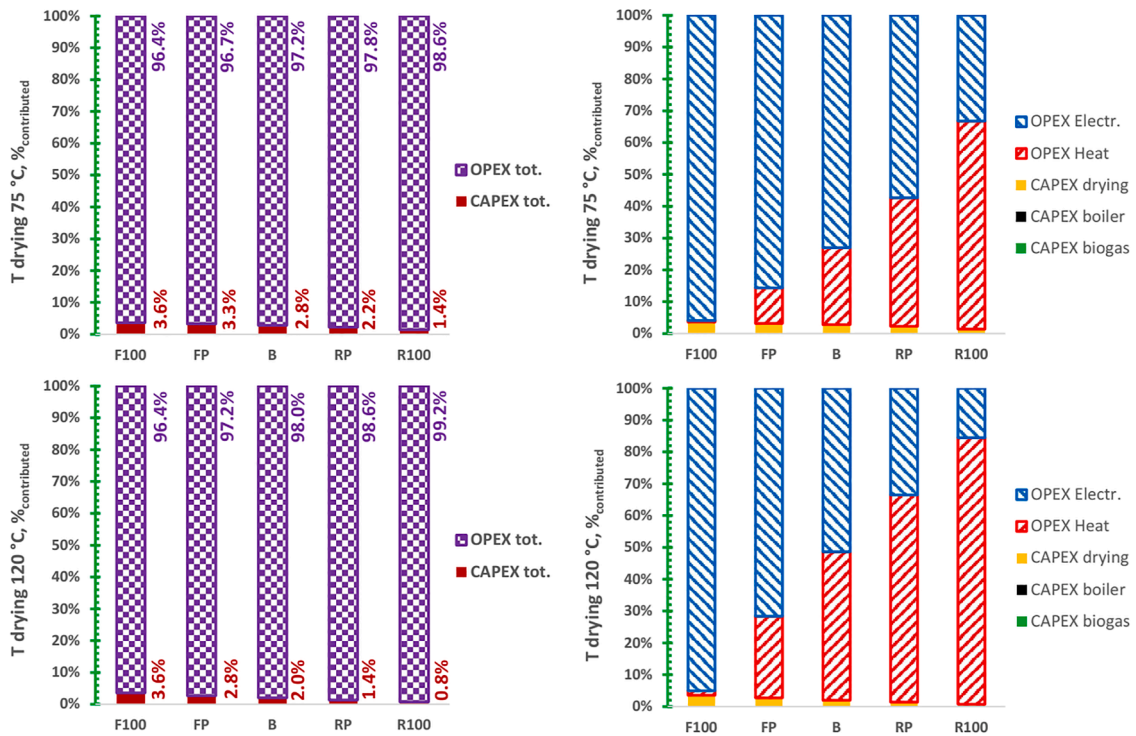


Fig. 7. Contribution of capital goods (denoted by CAPEX) and consumed energy (denoted by OPEX) to the eutrophication impact of tomato waste drying for different scenarios.

exchanger production should also be included. This is therefore recommended to be a subject of future investigations.

The quality of background data has been assessed using a pedigree matrix approach, according to ILCD guidelines [54]. As can be seen in Table 6, most of the background processes had an overall data quality

rating ($DQR \leq 3.0$), which can be considered basic quality [54]. None of the background processes had $DQR \leq 1.6$, which represents a limit for high-quality data according to ILCD [54]. ILCD classifies processes with $3.0 < DQR \leq 4.0$ as data estimates [54], and the only background data in this range was the proxy used for drying (Table 6). To some extent, this is

Table 6

Assessment of data quality using the ILCD pedigree matrix approach (DQR - data quality rating).

CAPEX/ OPEX	Used by	Process/Flow	Technological representativeness (TeR)	Geographical representativeness (GR)	Time-related representativeness (TiR)	Completeness (C)	Precision/ uncertainty (P)	Meth. appropriateness and consistency (M)	DQR
OPEX	Drying	Electricity from biogas, production mix, at power plant, mix of direct and CHP, technology mix regarding firing and flue gas cleaning, 1kV - 60kV	1	2	1	n.a.	2	n.a.	1.75
OPEX	Drying	Anaerobic fermentation, production mix, at plant, anaerobic fermentation of biowaste, 1 kg of waste fermented	2	3	3	n.a.	2	n.a.	2.75
OPEX	Drying	Natural gas mix, consumption mix, to consumer, technology mix, medium pressure level (< 1 bar)	1	1	3	n.a.	2	n.a.	2.38
CAPEX	Drying	Drying of grass {CH} drying of grass Cut-off, U	2	2	5	4	3	n.a.	4.00
CAPEX	Drying	Building, hall {CH} building construction, hall Cut-off, U	2	2	5	2	3	n.a.	3.78
CAPEX	Drying, Biogas plant	Cast iron, single route, at plant, electric arc furnace route, from steel scrap, secondary production, > 2,06 % carbon content - EU+EFTA+UK	2	2	2	n.a.	2	n.a.	2.00
CAPEX	Drying, Biogas plant, Boiler	Aluminium die-casting, single route, at plant, secondary production, aluminium casting, 2.7 g/cm ³ - EU+EFTA+UK	3	2	3	n.a.	2	n.a.	2.75
CAPEX	Drying	Portland cement, production mix, at plant, raw material extraction, production of clinker, and cement grinding, CEM I 32.5 - EU+EFTA+UK	2	2	2	n.a.	2	n.a.	2.00
CAPEX	Drying	Bricks vertically perforated, production mix, at plant, clay mining, processing and burning, vertically perforated - EU+EFTA+UK	3	3	3	n.a.	2	n.a.	2.88
CAPEX	Drying, Biogas plant	Concrete, production mix, at plant, production mix, at plant, aggregates mixing, C20/25 - GLO	3	2	3	n.a.	2	n.a.	2.75
CAPEX	Drying	Calcium aluminate cement, Production	3	3	3	n.a.	3	n.a.	3.00

(continued on next page)

Table 6 (continued)

CAPEX/ OPEX	Used by	Process/Flow	Technological representativeness (TeR)	Geographical representativeness (GR)	Time-related representativeness (TiR)	Completeness (C)	Precision/ uncertainty (P)	Meth. appropriateness and consistency (M)	DQR
CAPEX	Drying	mix, at plant, Technology mix - GLO Flat glass, uncoated, production mix, at plant, cut, Pilkington process, from sand and soda ash, 2500 kg/m ³ - EU+EFTA+UK	2	2	2	n.a.	2	n.a.	2.00
CAPEX	Drying	Polystyrene (PS), fossil fuel-based, production mix, at plant, polymerisation of styrene, petrochemical based - GLO	1	1	3	n.a.	2	n.a.	2.38
CAPEX	Drying, Biogas plant, Boiler	Steel production mix, at plant, production mix, at plant, technology mix, 72% primary, 28% secondary - GLO	2	3	3	n.a.	2	n.a.	2.75
CAPEX	Drying	Stainless steel hot rolled, production mix, at plant, hot rolling, stainless steel - ROW	2	3	2	n.a.	2	n.a.	2.63
CAPEX	Drying	Stone wool, production mix, at plant, technology mix - GLO	2	2	3	n.a.	2	n.a.	2.63
CAPEX	Drying	Zinc, recycled (pre consumer, remelting), single route, at plant, cleaning, melting, refining, 7.14 g/ cm ³ , 65.41 g/mol - EU+EFTA+UK	2	2	2	n.a.	2	n.a.	2.00
CAPEX	Drying	Diesel mix at refinery, production mix, at refinery, from crude oil, 10 ppm sulphur, 7.23 wt.% bio components - EU+EFTA+UK	1	1	1	n.a.	2	n.a.	1.63
CAPEX	Biogas plant	Aluminium extrusion, single route, at plant, primary production, aluminium extrusion, 2.7 g/ cm ³ - EU+EFTA+UK	3	2	3	n.a.	2	n.a.	2.75
CAPEX	Biogas plant	Copper Cathode, production mix, single route, at plant, technology mix, primary and secondary production, 8.92 g/ cm ³ - EU+EFTA+UK	2	2	2	n.a.	2	n.a.	2.00
CAPEX	Biogas plant	Gravel, production mix, at plant, wet and dry quarry, drying, grain size	2	2	2	n.a.	2	n.a.	2.00

(continued on next page)

Table 6 (continued)

CAPEX/ OPEX	Used by	Process/Flow	Technological representativeness (TeR)	Geographical representativeness (GR)	Time-related representativeness (TiR)	Completeness (C)	Precision/ uncertainty (P)	Meth. appropriateness and consistency (M)	DQR
CAPEX	Biogas plant	2/32 - EU+EFTA+UK Bitumen at refinery, production mix, at refinery, from crude oil, 38.7 MJ/ kg net calorific value -	1	1	1	n.a.	2	n.a.	1.63
CAPEX	Biogas plant	EU+EFTA+UK EPS Beads, production mix, at plant, from styrene polymerization and foaming, 0.96- 1.04 g/cm3 -	1	1	1	n.a.	2	n.a.	1.63
CAPEX	Biogas plant	EU+EFTA+UK Recycling plastic (PVC), waste management, technology mix, at plant, production mix, at plant, collection, sorting, transport, washing, granulation, pelletization, 90% recycling rate -	2	2	2	n.a.	2	n.a.	2.00
CAPEX	Biogas plant	EU+EFTA+UK Sand grading, production mix, at plant, grading, sand 0/2 - GLO	2	2	2	n.a.	2	n.a.	2.00
CAPEX	Boiler	Copper tube, single route, at plant, melting and mechanical treatment (fabrication), 8.92 g/cm3 -	2	2	2	n.a.	2	n.a.	2.00
Average:		EU+EFTA+UK							2.39
Max.:									4.00

a trade-off when it comes to prospective LCA of novel technologies, where proxies are often required due to the lack of data for commercial-scale devices. The relatively high shares of capital goods in overall impacts, in combination with the DQR of proxy data, point to the need to perform LCA in an iterative manner for different stages of technological development. It also shows that not only operational data, but also data on capital goods should be systematically collected when upscaling to a higher technology readiness level (TRL). Nonetheless, the possibility of identifying such a hot spot at an early stage also demonstrates the value of applying prospective LCA studies to technologies at low TRL.

Despite the fact that drying is estimated to account for 7–15% of industrial energy consumption [78], reaching 10% in the food sector, and 22% in the pulp and paper sector [79], only a scarce amount of background data is available for the drying process. When it comes to capital goods, the knowledge gap is even more substantial. More data with better overall quality will be needed in the future for a more accurate determination of environmental impacts in LCA studies of systems that include drying. This is especially important for prospective LCA studies aimed at guiding the development of novel technologies at low TRL. Due to the wide variety of dryer types with different applicability, a broad range of representative data for each technology is needed. Nonetheless, it should be noted that the data for individual construction materials (iron, steel, copper, concrete, etc.) shown in the

Sankey diagrams (see supplementary materials) as significant contributors had DQR values close to 2.0. This indicates that the main challenge is to quantify the amounts of these materials used in dryer construction. As renewable energy use for drying increases in the future, such data could also support the selection of less impactful dryers.

Overall, for prospective LCA performed at an early stage of technology development, it seems sensible to advise an iterative approach [80,81]. Next iteration of LCA with foreground data from operational installations, including energy consumption data as well as differences in efficiency between drying at different temperatures, could provide additional insight in terms of quantifying the environmental impacts of tomato waste drying. Moreover, performing LCA in such an iterative manner could show how prospective LCA could provide foundations for improving the environmental impacts of processes by being included at an early design stage.

4. Conclusions

The study has shown that the impact of capital goods cannot be easily neglected, without any analysis, as in some cases it might amount to as much as 1/3 of the total impacts, as was the case for the climate change impact of tomato waste drying at 75°C for 100% renewable heat scenario. However, what should be noticed is the fact that a higher proportion of capital goods in the total impact was caused by a decrease in

absolute value, overall. Prospective LCA seems to be a suitable technology optimisation tool, from the point of view of environmental performance, as various impact categories shown a clear trend regarding process temperature. Nonetheless, it should be noted that such optimisation would still depend on selected priorities, concerning environmental impacts that require mitigation. Specifically, the investigation has shown that increasing the share of renewable energy carrier (biogas) improves performance of the drying process in terms of climate change impact, while at the same time being potentially detrimental with respect to eutrophication or ecotoxicity impacts. This also identified a hot spot in terms of current practices in biogas production, signalling that future improvements in digestate treatment and feedstock pre-storage may bring improvements. This also highlighted the need for more accurate data, since the study used generalised data for biogas production across the EU, whereas relatively low sulphur content might in reality result in lower impacts, since ecotoxicity impact was attributed mostly to H₂S emissions.

This also highlights the need for an iterative approach to using prospective LCA at an early stage of technology development. New, more accurate data from a scaled-up installation would replace some rough assumptions. In this respect, also changing landscape in the area of biogas production, especially trends concerning digestate treatment and optimised utilisation of nutrients, might influence the values that could be observed in the future. More research is needed regarding the possible reduction in eutrophication impacts due to the recirculation of nutrients by the agricultural application of digestate (with and without valorisation).

Among the needs for future research, it seems sensible to recommend more extensive research on quantification of possible environmental impacts related to the recovery of latent heat, which would, on one hand, decrease fuel consumption leading to lower impact from heat production and on the other hand increase the impact of capital goods, due to additional materials required by heat exchangers. Moreover, it seems sensible to also take a more detailed look at the possible impact of using other sources of renewable heat, e.g., solar heat, which would also likely decrease the contribution from the process heat.

CRedit authorship contribution statement

Lukasz Niedzwiecki: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **David Kupka:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Jakub Čespiva:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Jan Skřínský:** Writing – review & editing, Validation, Supervision, Resources, Project administration. **Luca Fiori:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Conceptualization.

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.

Acknowledgements

This research is part of the Rapid project funded by PIANO NAZIONALE DI RIPRESA E RESILIENZA PNRR - Missione 4 "Istruzione e Ricerca" - Componente C2 - Investimento 1.1 "Fondo per il Programma Nazionale di Ricerca e progetti di Rilevante Interesse Nazionale (PRIN 2022 PNRR)".

This work was financially supported by the European Union under the REFRESH Research Excellence For REgion Sustainability and High-tech Industries project No CZ.10.03.01/00/22_003/0000048 via the Operational Programme Just Transition.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.jaecs.2026.100514](https://doi.org/10.1016/j.jaecs.2026.100514).

Data availability

<https://doi.org/10.5281/zenodo.18433019> ()

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