International Journal of Thermofluids 27 (2025) 101221

Contents lists available at ScienceDirect

International Journal of Thermofluids

journal homepage: www.sciencedirect.com/journal/international-journal-of-thermofluids

Mapping the most effective measures to optimize carrot slice tray drying using physics-based and Monte Carlo simulations

Jörg Schemminger [a,b,c,**], Sharvari Raut [b], Barbara Sturm [b,c], Thijs Defraeye [a,d,*]

[a] Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014, Switzerland

[b] Leibniz-Institut für Agrartechnik und Bioökonomie e.V. (ATB), Max-Eyth Allee 100, 14469, Potsdam, Germany

[c] Humboldt-Universität zu Berlin, Faculty of Life Sciences, Albrecht Daniel Thaer-Institute of Agricultural and Horticultural Sciences, Hinter der Reinhardtsstrasse 6-8, 10115, Berlin, Germany

[d] Food Quality and Design, Wageningen University & Research, P.O. Box 17, 6700 AA, Wageningen, the Netherlands

ARTICLE INFO

Keywords:
Optimization
Food
Modeling
Efficiency
Carotene
Vegetable

ABSTRACT

Optimizing convective tray drying for carrot slices requires addressing various process variables and objectives. Balancing quality, throughput, and energy consumption requires understanding mechanisms and considering the effort and effect of individual practical use cases. This study uses Monte Carlo simulations of a physics-based model to assess dehydration and identify ideal optimization measures from a base case. Reducing slice thickness from 5 mm to 2 mm cuts drying time by 62 % while preserving 220 % more β-carotene, making it the most effective optimization strategy. The effects on the throughput of fresh produce (+6 %) and energy consumption (+6 %) are negligible. To reduce energy consumption, it proves beneficial to reduce the airspeed from 1.8 m/s to 0.6 m/s - a 35 % reduction. However, this adjustment results in a 77 % drop in carotene retention and a 48 % reduction in throughput. Increased carotene retention (+39 %) and throughput (+28 %) can be achieved by increasing the airspeed from 1.8 m/s to 3 m/s. However, this improvement requires 30 % more energy. Given these trade-offs, it is essential to consider the constraints imposed by the production environment and situation. The results of this study support the identification of the ideal case-specific optimization strategies and thus help to avoid costly trial-and-error approaches in the future.

1. Introduction

Convective drying is widely used in food processing because it is a crucial part of many processing chains. The necessary phase change of water in this process significantly contributes to energy consumption in the food processing industry [1]. The nutritional quality of the end product is affected by the thermal drying process. Yet, the potential for nutrient retention versus energy consumption and drying time optimization through adjusted process control has yet to be fully realized [2,3].

The intricate interplay between process, design, and produce parameters, along with the resultant properties of the end product, makes batch tray drying a highly case-specific process. Investigations typically employ limited parameter spaces, which constrains the generalizability of the results. Furthermore, the heterogeneity in drying between the individual dried products is mostly not considered, complicating risk assessments and necessitating safety margins, particularly regarding the drying time necessary to ensure a microbially safe product [4].

Physics-based numerical hygrothermal simulations are increasingly used to study convective tray drying processes of fruits and vegetables due to their ability to model complex interactions between heat and mass transfer [5–7]. These simulations provide detailed insights into the drying process, allowing for the optimization of drying parameters to improve product quality and energy efficiency. However, a significant challenge remains in accurately representing the heterogeneity of a produce particle population inside a dryer. Published work that considers this heterogeneity of agrifood products mainly applies the Monte Carlo technique to tackle this challenge by considering differences between individual products [4,8–10]. Monte Carlo simulation uses random sampling of input parameters. It reveals probability

* Corresponding author at: Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014, St. Gallen, Switzerland.

** Corresponding author at: Humboldt-Universität zu Berlin, Faculty of Life Sciences, Albrecht Daniel Thaer-Institute of Agricultural and Horticultural Sciences, Hinter der Reinhardtsstrasse 6-8, 10115, Berlin, Germany.

E-mail addresses: schemmij@hu-berlin.de (J. Schemminger), thijs.defraeye@empa.ch (T. Defraeye).

https://doi.org/10.1016/j.ijft.2025.101221

Available online 16 April 2025

Nomenclature

Symbols

a_w	water activity [-]
c_β	ß-carotene content c_β [kg/kg_{dm}]
c_p	specific heat capacity [J/(kg•K)]
$\Delta h_{v,0}$	latent heat of water [J/kg]
e	specific air heating energy consumption [J/kg]
h	specific enthalpy [J/kg]
$\dot{m}$	mass flow of fresh carrots [kg/s]
t_d	drying time [s]
Th_{rel}	relative throughput [%]
v_a	drying air velocity [m/s]
Y_a	specific humidity of air [kg_w/kg_{da}]
z	slice thickness [mm]

Greek symbols

ε	mesh tray porosity [-]
ϑ	temperature [°C]

Subscripts

a	air
β	β-carotene
i	process setting
ref	reference setting
v	water vapor
0	initial value at $t = 0$ s

Abbreviation

PTFE	Polytetrafluoroethylene
PEF	Pulsed electric field
CR	carotene retention

distributions through an increased number of simulation runs, each with a newly generated set of pseudo-random input parameters. This method was preferred over other uncertainty quantification techniques. Unlike Design of Experiments (DOE) and Bayesian methods, which often require specific assumptions or complex formulations, Monte Carlo simulations can handle high-dimensional problems with greater flexibility and simplicity. In addition to the underrepresentation of product heterogeneity, most publications on fruit and vegetable drying are limited to the effect of selected parameter sets such as air temperature/velocity or shape/temperature and rarely consider all technically relevant factors in a production environment at once. However, all influencing factors must be examined to find the best balance between the effort and effect of optimization measures and advise practitioners.

Applying a hybrid physics-based digital shadow - a Monte Carlo simulation of the physics-based hygrothermal model presented by Schemminger et al. [4] - can case-specifically reduce drying time, energy consumption, and nutritional quality losses. This can lead to upgrading existing production lines without high investment costs, thus increasing efficiency. These existing production lines, which were often designed through trial and error due to the long machine lifespans, have a potential for optimization [3,11]. However, drying processes that have been running stably for many years must be modified to exploit this potential. It is, therefore, necessary to provide operators with knowledge about the impact of changes in the process to provide consistent or improved product quality through an understanding of the physio-chemical mechanisms that take place and their interrelations. The confidence gained through these comprehensive insights allows for risk assessment in the given production environment and the implementation of optimization measures.

This study uses a hybrid physics-based digital shadow, a Monte Carlo simulation of a physics-based hygrothermal model, as Schemminger et al. [4] presented. This approach aims to reduce drying time, energy consumption, and nutritional quality losses in a case-specific manner. Using this hybrid model, the present work takes the next step by analyzing the factors of drying air flow speed, specific air humidity, tray porosity, slice thickness, and drying air temperature. The primary goal of this study is to provide operators with knowledge about the impact of process-, design-, and produce-parameter adjustments in the drying process, as well as their impact on the drying of each individual slice of food to be dried. This knowledge is crucial for maintaining and improving product quality by understanding the physio-chemical mechanisms and their interrelations. The insights gained will enable risk assessment and the implementation of optimization measures in existing production environments. Utilizing a hybrid physics-based digital shadow generates a comprehensive dataset by computing the parametric space of technically relevant parameter ranges. This study identifies and quantifies the factors with the most significant positive effects, depending on the case-specific targeted optimization goal. The approach presented here aims to process this design space so that concrete actions can be derived for the production engineering application of convective tray drying. As carrots are widely used and have one of the most significant agricultural production volumes of vegetables in the world, they represent an ideal subject for this study [12,13].

2. Materials and methods

2.1. Computational model, domain, and assumptions

A hygrothermal model of carrot slices, *Daucus Carota* L. *Laguna* variety, is applied as described by Schemminger et al. [4], using a 2D geometry (Fig. 1). Details on material properties and computational realization are adopted from Schemminger et al. [4]. Here, only the main characteristics and improvements are discussed. The model parameters used, more precisely the material and thermodynamic correlations and values, can be found in Appendix A. In this study, this model is used to (i) calculate the hygrothermal behavior of carrot slices exposed to different combinations of process-, design- and produce-parameters, see Table 1; (ii) understand the heterogeneity of the carrot slice population in the dryer and derive the termination of the drying process based on this. The latter is achieved with the help of Monte Carlo simulations. Here, the intra-batch variability of the carrot slice thickness, diameter, initial moisture content, initial β-carotene content, initial temperature, sorption behavior, effective diffusivity, and convective heat transfer coefficient is pseudo-randomly resampled for 700 consecutive simulation runs. Numerical values, parameter ranges,

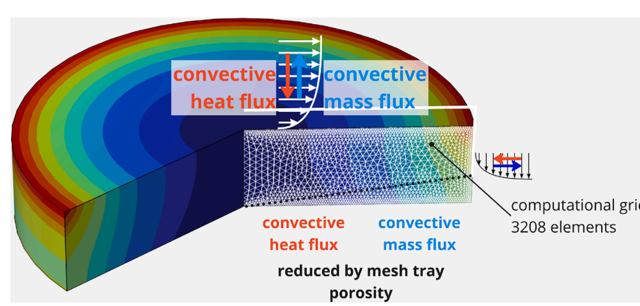

Fig. 1. Rotated illustration of the 2D geometry, the computation grid used, and the boundary conditions of the purely convective heat and mass transfer of the top and side surfaces, indicating a slice on a tray. The bottom heat and mass flux (dotted line) are reduced through multiplication with the mesh tray porosity ε. The color map shows the relative temperature distribution during drying, with red indicating higher and blue cooler temperatures.

Table 1
Parametric space and parameter increments examined.

	Lowest increment	Base case	Highest increment
Drying air flow speed v_a [m/s]	0.6	1.8	3
Specific humidity Y_a [g_w/kg_{dryAir}]	4	17	30
Tray porosity ε_{tray} [-]	0.2	0.5	0.8
Slice thickness z [mm]	2	5	8
Drying air temperature ϑ_a [°C]	50	65	80

and the type of random number generation are adapted from Schemminger et al. [4] and listed in Appendix A. A sensitivity analysis in the previous work has shown that, in addition to the thickness of the slice, the drying time is mainly influenced by the initial moisture content, the parameterization of the sorption isotherm, and the assumed effective moisture diffusivity [4]. The resulting data set is statistically analyzed concerning the metrics of drying time, throughput, β-carotene retention CR, and relative energy consumption for heating the drying air, which will be discussed in more detail later. Deformation and shrinkage of the carrot slices during the drying process are not considered in the present work.

Schemminger et al. [4] discuss the influence of the metal tray often used in experimental tray drying applications. The present work deviates from this but applies a common practice in producing dried fruit and vegetable slices: the carrot slices are positioned on a temperature-resistant perforated plastic mat. The purpose is to prevent sticking to the metal tray caused by juices released after cutting. This causes increased cleaning and labor costs when loading the drying unit and is avoided [14]. A typical material for these mats is heat-resistant PTFE, silicone, or polypropylene PP. Compared to a stainless steel mesh tray, the thermal conductivity is approximately 60 times lower for PTFE, 90 times lower for silicone, and 70 times lower for PP [15]. Therefore, the conductive heat flux from the perforated mat to the carrot slice can be neglected. Since the bottom surface area of the carrot slices exposed to airflow is reduced by the plastic mat and the tray, the convective heat and mass flux are decreased there. This reduction is implemented by multiplying the heat and mass flux at the bottom of the carrot slice by the porosity ε of the perforated mat, which is given by the ratio of the free area to the total area.

Depending on the design of the dryer and the way the drying air is guided, inhomogeneous distribution of drying air between drying trays can exist. This circumstance might also lead to crossflow effects: air does not optimally overflow the drying tray but flows vertically through the drying trays. In this study, longitudinal overflow of the drying trays is assumed.

To perform the simulations, COMSOL Multiphysics® software (version 6.1, COMSOL AB, Stockholm, Sweden) was used to solve the hygrothermal model and to perform Monte Carlo simulations using the Random function, see Schemminger et al. [4] for details. Sensitivity studies of the computation grid and the relative tolerance of the solver were performed to achieve acceptable minor errors (see Appendix A). The required number of Monte Carlo runs was determined by gradually increasing the number of runs and evaluating the relative change aiming at <5 % towards the moisture content and ratio, water activity, β-carotene content, and retention. Evaluations, statistical analyses, and graphical visualizations were performed using Python 3.11.4 script, Microsoft® Excel® 2016, and Origin® (Version 2022. OriginLab Corporation, Northampton, MA, USA).

2.2. Parametric space

Several measures can be taken to optimize an existing drying process. These measures can be categorized into process, design, and produce parameters. On the process parameters side, one can change the drying airspeed by either increasing the fan's rotational speed or changing the fan type and/or size entirely. Also, the drying air temperature can be influenced by adapting the air heater's design, operation, and/or settings. Dehumidification devices can influence the humidity of intake air. A design parameter that the producer can easily influence is the porosity of the drying tray: how fine a mesh is selected and the ratio of free to covered area. Finally, the produce characteristics can be adjusted by changing the slice thickness. In the use-case that a customer specifies a, for example, slice thickness requirement, it highlights a common limitation for broadly applicable optimization advice: what works for one producer may not suit another due to varying customer requirements. To address this challenge, the parametric space starting from a base case is explored and run through combinations of two parameters in technically common ranges, see Table 1. The parameter ranges were defined to optimally encompass the values compiled from a literature review on the convective drying of fruits and vegetables, see Appendix A. The base case represents the midpoint between the defined extreme values. It is thus possible to read directly from the results which optimization measures are best for the individual case at hand.

In addition to the influencing factors listed here, some technologies change the cell structure of the material to be dried and thus influence or accelerate the drying process. For example, cell walls are punctured by the formation of ice crystals during freeze-drying, (local) overheating damages the cell walls thermally during microwave and infrared drying, and by pre-treatments such as blanching. In addition, applying ultrasonic and pulsed electric field PEF treatments before and during drying impacts the cell wall permeability and potentially shortens the drying time [16,17]. These advanced methods are described and known but are rarely used for products with large production volumes and comparatively low product value, such as the carrot slices described here.

For each calculation set, two parameters are combined, resulting in 10 sets with nine calculations for each set. In a production environment, mainly when producing for customers, it is not advisable to implement multiple optimization measures simultaneously due to loss of causality and inefficient resource use. Typically, individual measures are taken, with up to two parameters changed at a time. Thus, combinations of two parameters are selected for this work. The effect of these combinations on drying time, throughput, air heating energy consumption, and carotene retention is calculated and plotted using the hybrid digital shadow. If the evaluation shows that a particular area needs to be more detailed, additional parameter increments are introduced and calculated.

Based on Onwude et al. [18] and additional studies, especially on carrots, the drying airflow speed, temperature, and humidity ranges were defined (see Appendix A). Typical thickness of carrot slices for tray drying applications can be found in the literature between 2 mm and 8 mm: Wang and Xi [19] and Doymaz [20] investigated ranges of 1.5 mm to 9 mm and 4 mm to 10 mm with multiple intermediate thicknesses. Other studies distinguish between two values of slice thickness, such as 3 mm and 6 mm, by Md Saleh et al. [21] and Cui et al. [22]. Single-defined slice thicknesses are in the range of 3 mm by Raut et al. [23], 3.5 mm by Md Saleh et al. [24], 4 mm by Frias et al. [25], Chen et al. [26], and Lin et al. [27], 5 mm by Kroehnke et al. [28], Aghbashlo et al. [29], and Zhao et al. [30], 6 mm by Kocabiyik and Tezer [31].

To avoid temperature dependency, air humidity is expressed in the specific form, not the more commonly used relative humidity form. The explored range spans from one realistic extreme case to another. A high humidity case corresponds with an intake air temperature of 35 °C and 85 % relative humidity (dew point 32.1 °C) that is then heated to the process temperature. The second extreme case representing the low humidity case is given by a specific humidity corresponding to 10 °C intake air with a relative humidity of 50 % (dew point 0.1 °C). This case also describes using a dehumidification device, such as a commonly applied condensation dehumidifier, to reduce relative humidity to approximately 40 % to 50 %.

In addition to these drying air-related parameters, design parameters can be used for optimization. Drying trays and applied non-sticky plastic mats can be found in different shapes and sizes on the market. A range of porosities of 0.2 to 0.8 was selected for this study. A porosity of 0.2 represents a dense mesh, whereas 0.8 represents a wide mesh, see Fig. 2.

2.3. Metrics to evaluate and optimize the drying process

2.3.1. Drying time

The drying time is crucial as it signifies the duration required to dry a single produce batch. In this study, the drying time is defined as when 99 % of carrot slices are dried to a volume averaged water activity of $a_w \leq 0.6$, as Schemminger et al. [4] described. Reducing drying time leads to decreased overall cycle time, enabling more cycles to be produced. Consequently, this results in more produce batches being dried, leading to an overall increase in particle production output. The time taken to charge the dryer, involving unloading dried produce and loading it with fresh produce particles, is assumed to be optimized for efficiency. Minimizing this time for charging is essential not only for productivity reasons but also for quality considerations, such as reducing oxidative discoloration. This charging procedure takes only a few minutes, which is negligible compared to drying times exceeding 150 min. It should be noted that a higher throughput and the associated increased number of loading and unloading the dryer correlates with increased workforce demands and the necessity of more shifts.

2.3.2. Throughput

Reducing the slice thickness has implications for the quantity of produce dried per unit of time. The mass of processed fresh carrots per time unit is compared with a base case to account for this. When comparing fresh produce, assuming constant density allows using volume ratios. In cases where the average diameter remains constant, as in the present scenario, a ratio factor based on the thicknesses of the slices is sufficient to define the relative throughput Th_{rel}:

$$Th_{rel} = \frac{\dot{m}_i}{\dot{m}_{ref}} \approx \frac{t_{d,ref} \cdot z_i}{t_{d,i} \cdot z_{ref}} \tag{1}$$

with the drying time t_d [min] and the slice thickness z [mm]. Index ref represents the base case, i for a different process setting. This relative throughput Th_{rel} is used for optimization in the present study.

2.3.3. β-carotene retention

The β-carotene retention CR is defined as the normalized concentration of β-carotene c_β [kg/kg$_{dm}$] at time t compared to the initial value $c_{\beta,0}$ [kg/kg$_{dm}$] at $t = 0$ s. The CR of a parameter setting that differs from the base case CR_i is compared to the CR value of the base case CR_{ref} to obtain a relative change CR_{rel}.

$$CR_{rel} = \frac{CR_i}{CR_{ref}} = \frac{c_{\beta,i} \cdot c_{\beta,ref,0}}{c_{\beta,i,0} \cdot c_{\beta,ref}} \tag{2}$$

The initial value $c_{\beta,0}$ is newly generated pseudo-randomly for each Monte Carlo run. The advantage of this relative approach is that it allows the effects and their significance to be evaluated despite possible systematic deviations.

2.3.4. Air heating energy consumption

The comparison of the absolute energy consumption of different drying processes is challenging because losses due to design are individual to each dryer design and the level of insulation. Relative comparison is a straightforward approach to understanding how different settings of process parameters impact energy consumption. Heating the drying air is the most energy-consuming part of the drying process. The energy required can be approached by calculating the specific enthalpy h_a [J/kg] of the drying air at different temperatures [15]:

$$h_a = c_{p,a} \cdot \vartheta_a + Y_a \left(\Delta h_{v0} + c_{p,v} \cdot \vartheta_a \right) \tag{3}$$

with the specific heat capacity of dry air $c_{p,a}$ [J/(kg•K)], the temperature ϑ [°C], specific humidity Y [kg$_w$/kg$_{air}$], latent heat of water Δh_{v0} [kJ/

Table 2
Thermodynamic properties.

Properties	Symbol	Value	Source
Specific heat capacity of water vapor	$c_{p,v}$	1932 J/(kg K)	[15]
Specific heat capacity of dry air	$c_{p,a}$	1007 J/(kg K)	[15]
Latent heat of water	Δh_v	2453.58 kJ/kg	[15]

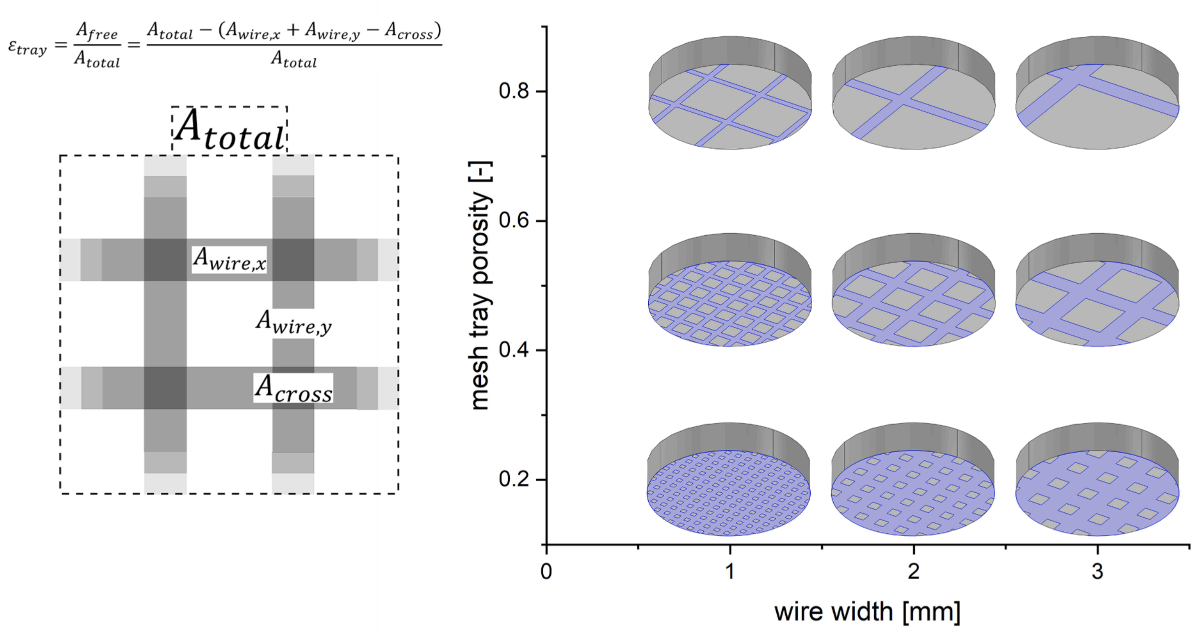

Fig. 2. Mesh tray porosity of different plastic mesh mats and trays is shown in the wire width and mesh tray porosity dimensions: a range of 0.2 to 0.8 covers all the technically applied mesh trays and mats (see Appendix A for details).

kg], specific heat capacity of water vapor c_{pv} [J/(kg•K)]. Values of the constants are shown in Table 2. To relatively compare drying settings i with the reference case ref, the ratio of airspeeds v_i/v_{ref}, drying times $t_{d,i}/t_{d,ref}$ and the reverse ratio of slice thicknesses z_{ref}/z_i are also considered for the relative energy consumption for air heating $e_{a,i}/e_{a,ref}$ which is used as the energy consumption determining metric in the current study:

$$\frac{e_{a,i}}{e_{a,ref}} = \frac{h_{a,i} \cdot v_{a,i} \cdot t_{d,i} \cdot z_{ref}}{h_{a,ref} \cdot v_{a,ref} \cdot t_{d,ref} \cdot z_i} \tag{4}$$

The fan's energy consumption also contributes to the total energy consumption, but the mechanical energy input only accounts for < 1 % of the total energy input (see Appendix A). The mechanical energy input is neglected in this work because of the low contribution to overall energy usage. Advanced drying processes use temperature and air velocity profiles, which are also not covered by this work [23]. Intermittent, infrared, and microwave-assisted drying has been found to improve the effectivity of drying processes, which is also not covered by the present work. Despite the limitations described, the results are relevant because a large proportion of the drying processes used in the industry are conventional tray drying processes [32–34].

3. Results

3.1. The impact of adjusted parameters on drying time and throughput

Shorter process cycles increase throughput, assuming that preparation times to load and unload the batch dryer cannot be shortened any further, as assumed in this work. Thus, shortening the drying time is an

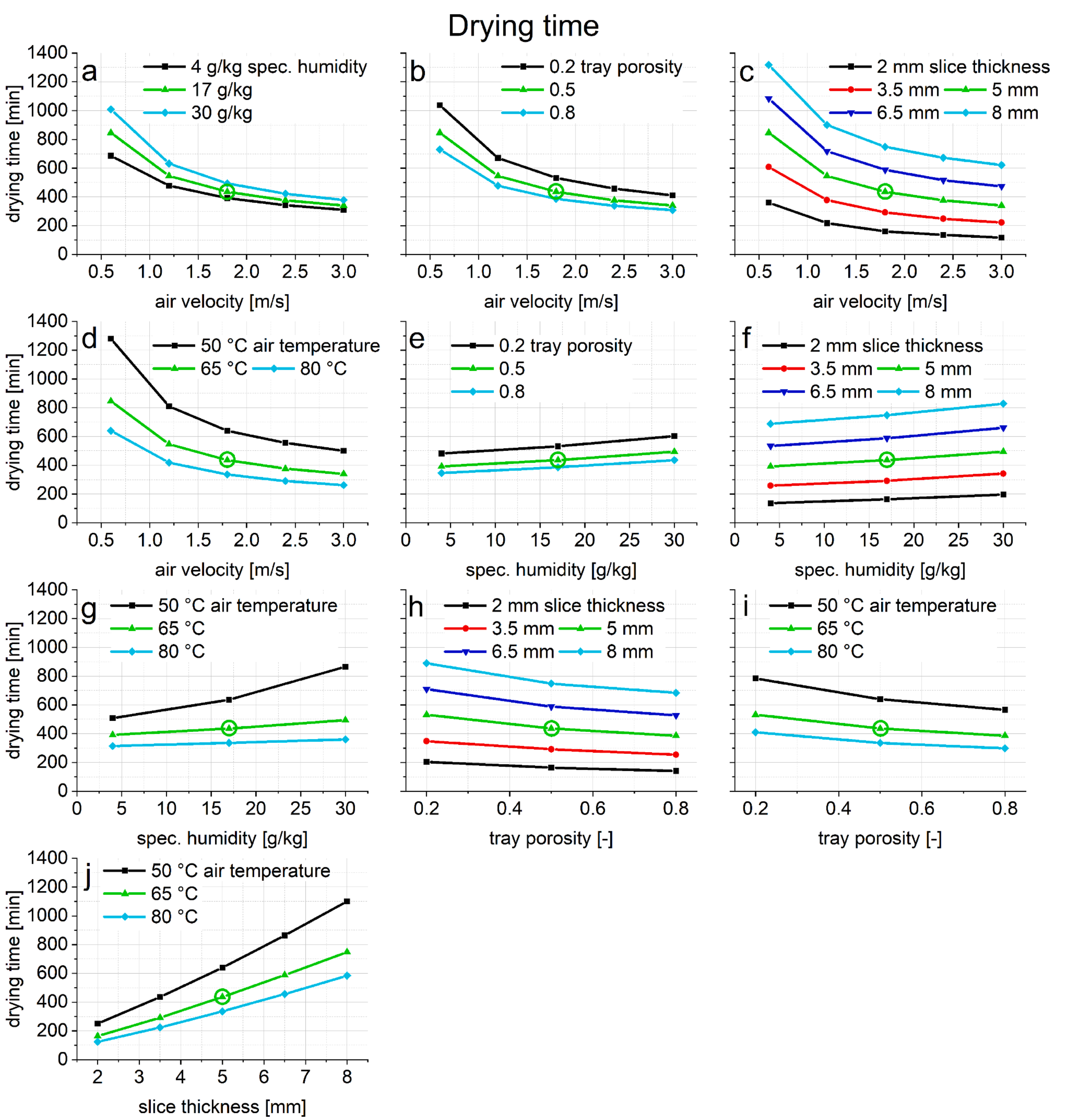

Fig. 3. Drying times resulting from varying two parameters for each diagram. A circle indicates the base case.

essential goal for optimization efforts in batch-wise tray drying. This section explores how adjustments in air velocity, specific humidity, tray porosity, slice thickness, and air temperature influence the metrics of drying time and throughput. The basis is the approach described by Schemminger et al. [4], where the drying process is terminated when 99 % of carrot slices have a volume averaged water activity of $a_w < 0.6$. This is the first time that the majority of carrot slices have a safe water activity level regarding microbial growth [13,35].

Air velocity. Fig. 3a, b, c, and d shows the impact of air velocity on drying time in combination with an adjusted specific humidity, tray porosity, slice thickness, and air temperature, respectively. Fig. 4 shows the equivalent for throughput. From the base case as a starting point, decreasing the air velocity from 1.8 m/s to 0.6 m/s strongly increases the drying time from 436 min to 846 min - 94 % more time required for drying. Increasing the airspeed to 3 m/s, on the other hand, has a less pronounced but still significant shortening effect from 436 min to 340 min - 22 % less time required. Derived from this, the relative throughput is reduced by 48 % at the lower airspeed described above. An increased airspeed leads to a 28 % higher relative throughput.

The drying time is shortened as the flow velocity increases, but this effect flattens out towards higher values. One reason for this is the increased vapor load of the air, which reduces the removal of moisture [14]. Airspeed has a significant influence on drying time and, therefore, relative throughput compared to the base case. Influencing the airspeed

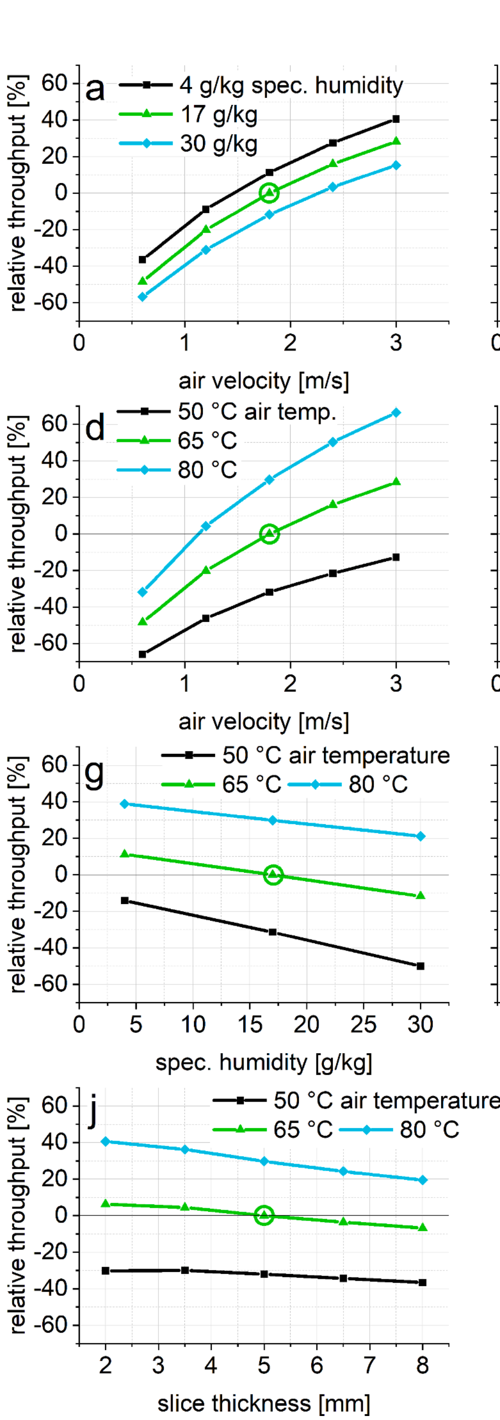

Fig. 4. Relative throughput toward the base case (marked with a circle) for different parameter combinations.

requires increased technical effort, either by using a frequency converter or replacing electrical or mechanical components. However, the potential for significant drying time reduction and throughput increases makes such investments worth considering.

Specific humidity. Fig. 3a, e, f, and g shows the impact of specific humidity on drying time in combination with an adjusted air velocity, tray porosity, slice thickness, and air temperature, respectively. Fig. 4 shows the equivalent for throughput. The influence of the specific humidity on the drying time and, thus, on the throughput is limited. If dehumidification is carried out to a specific humidity of 4 g/kg, starting from the base case, it is possible to reduce the drying time from 436 min to 392 min (10 % less) and thus increase throughput by 11 %.

Given the technical and energy-related dehumidification costs, adjusting air humidity is not a relevant drying time and throughput optimization option for most cases. Influencing the humidity impacts drying time and throughput but is negligible in the effort required compared to the effect and the other measures examined.

Tray porosity. Fig. 3b, e, h, and i shows the impact of tray porosity on drying time in combination with an adjusted air velocity, specific humidity, slice thickness, and air temperature, respectively. Fig. 4 shows the equivalent for throughput. Increasing the mesh porosity to 0.8, a throughput increase of 13 % can be achieved. If the porosity tends towards low values, a negative influence on the drying time and throughput can exist. Here, a throughput reduction of 18 % compared to the base case can result from a decrease of porosity from 0.5 to 0.2.

Reducing the tray porosity has a comparatively small effect on drying time and throughput. However, since restocking with wider-meshed mesh trays and/or plastic mats is comparatively cost-effective, this optimization measure should be considered for most cases.

Slice thickness. Fig. 3c, f, h, and j shows the impact of slice thickness on drying time in combination with an adjusted air velocity, specific humidity, tray porosity, and air temperature, respectively. Fig. 4 shows the equivalent for throughput. A 5 mm to 2 mm thickness reduction reduces drying time from 436 min to 160 min (63 %). This is presumably due to an increased surface-to-volume ratio [14]. If the slice is thickened from 5 mm to 8 mm, the drying time is prolonged to 846 min (94 %). Note that the throughput of fresh product is minimally affected by changes in slice thickness; the corresponding increase or decrease in the number of required batches offsets the variation in individual slice weight. Thus, reducing slice thickness from 5 mm to 2 mm increases the throughput by only 6 %.

The thickness of the slices represents the most impactful of the influencing parameters on the drying time investigated and should, therefore, be considered in optimization efforts. However, since customer requirements often dictate the required material thickness, the scope for customization may be limited. Altering the slice thickness to enhance fresh produce-based throughput is only marginally beneficial.

Drying air temperature. Fig. 3d, g, i, and j shows the impact of air temperature on drying time in combination with an adjusted air velocity, specific humidity, tray porosity, and slice thickness, respectively. Fig. 4 shows the equivalent for throughput. Lowering the temperature from 65 °C to 50 °C significantly increases drying time by 47 %. In contrast, raising the temperature by the same amount to 80 °C results in a less pronounced shortening effect on the drying time of 23 %. The corresponding changes in throughput are in positive and negative directions in a similar range. 32 % less throughput is achieved at 50 °C, and 30 % more throughput is reached at an elevated temperature of 80 °C due to the increased air heating requirement at elevated temperatures.

Increasing the air temperature is a preferred way of reducing drying times and increasing throughput. It is important to note that lowering the temperature disproportionately prolongs the drying process and should be avoided.

3.2. The impact of adjusted parameters on carotene retention

This section investigates how different parameters affect β-carotene retention (CR) during the convective drying of carrot slices. It examines the influence of air velocity, specific humidity, tray porosity, slice thickness, and air temperature on the relative change of CR compared to the base case. Based on this evaluation, the optimal conditions for maximizing CR are determined as a proxy for thermally degrading ingredients and evaluate the potential investment advantages in these areas.

Air velocity. Fig. 5a, b, c, and d shows the impact of air velocity on CR in combination with an adjusted specific humidity, tray porosity, slice thickness, and air temperature, respectively. The colored area represents the area between the 1 % and 99 % quantile. Reducing the air velocity from 1.8 m/s to 0.6 m/s results in a 77 % reduction in mean CR due to the prolonged drying time and, thus, longer exposure of the carrot slices to elevated temperatures and the associated increased thermal degradation of β-carotene. If the air velocity is increased and, therefore, the drying time is reduced, an increase in CR of 39 % is achieved compared to the base case.

An increase in airspeed leads to an improved retention of β-carotene due to the shortened drying time and thermal exposure of the carrot slices. The negative effect of lower airspeed is more pronounced than the effect of increased higher airspeed.

Specific humidity. Fig. 5a, e, f, and g shows the impact of specific humidity on drying time in combination with an adjusted air velocity, tray porosity, slice thickness, and air temperature, respectively. A reduction in the specific humidity from 18 g/kg to 4 g/kg and the associated drying time that is 10 % shorter results in a 32 % higher CR than the base case. In the investigated range, the specific humidity has an almost linear effect on the CR. Accordingly, an increase in the specific humidity and the associated drying time extension of 13 % results in a 30 % reduction in CR compared to the base case.

At lower air humidity, the evaporative cooling effect becomes more pronounced. This reduces the mean slice temperature. As a result, the β-carotene is less degraded. A reduction in humidity thus leads to a significant improvement in CR. If the aim is to optimize CR, a reduced humidity of the drying air should be considered.

Tray porosity. Fig. 5b, e, h, and i shows the impact of tray porosity on carotene retention in combination with an adjusted air velocity, specific humidity, slice thickness, and air temperature, respectively. If the tray porosity is reduced from 0.5 to 0.2, the CR is reduced by 33 % - a result from the longer drying time and the associated increased thermal exposure. Another reason is the reduced heat and mass transfer at the underside of the slice, which leads to less evaporation cooling and, thus, an increase in the average slice temperature, therefore, thermal degradation of β-carotene during drying. If the dryer is equipped with a wider mesh, an improvement in the CR of 21 % compared to the base case can be achieved by increasing the porosity to 0.8.

The potential for improving CR with increased tray porosity is slightly lower than reduced air humidity. The simpler and more cost-effective application nevertheless makes it a recommended optimization measure.

Slice thickness. Fig. 5c, f, h, j shows the impact of tray porosity on drying time in combination with an adjusted air velocity, specific humidity, tray porosity, and air temperature, respectively. A reduction from 5 mm to 2 mm can improve CR by 222 % thanks to a significantly reduced drying time, shorter diffusion paths for heat and mass transfer, and less moisture to evaporate and discharge by the drying air. However, when the slice thickens, the strong influence leads to a 77 % reduction in CR compared to the base case.

The slice thickness has the greatest influence on the CR of the parameters examined due to the reduced duration of heat exposure and shorter transport distances for heat and mass transfer. Thus, the possibility of reducing the slice thickness should be considered. Thickening the slices should be avoided: at 8 mm the CR deteriorates to such an

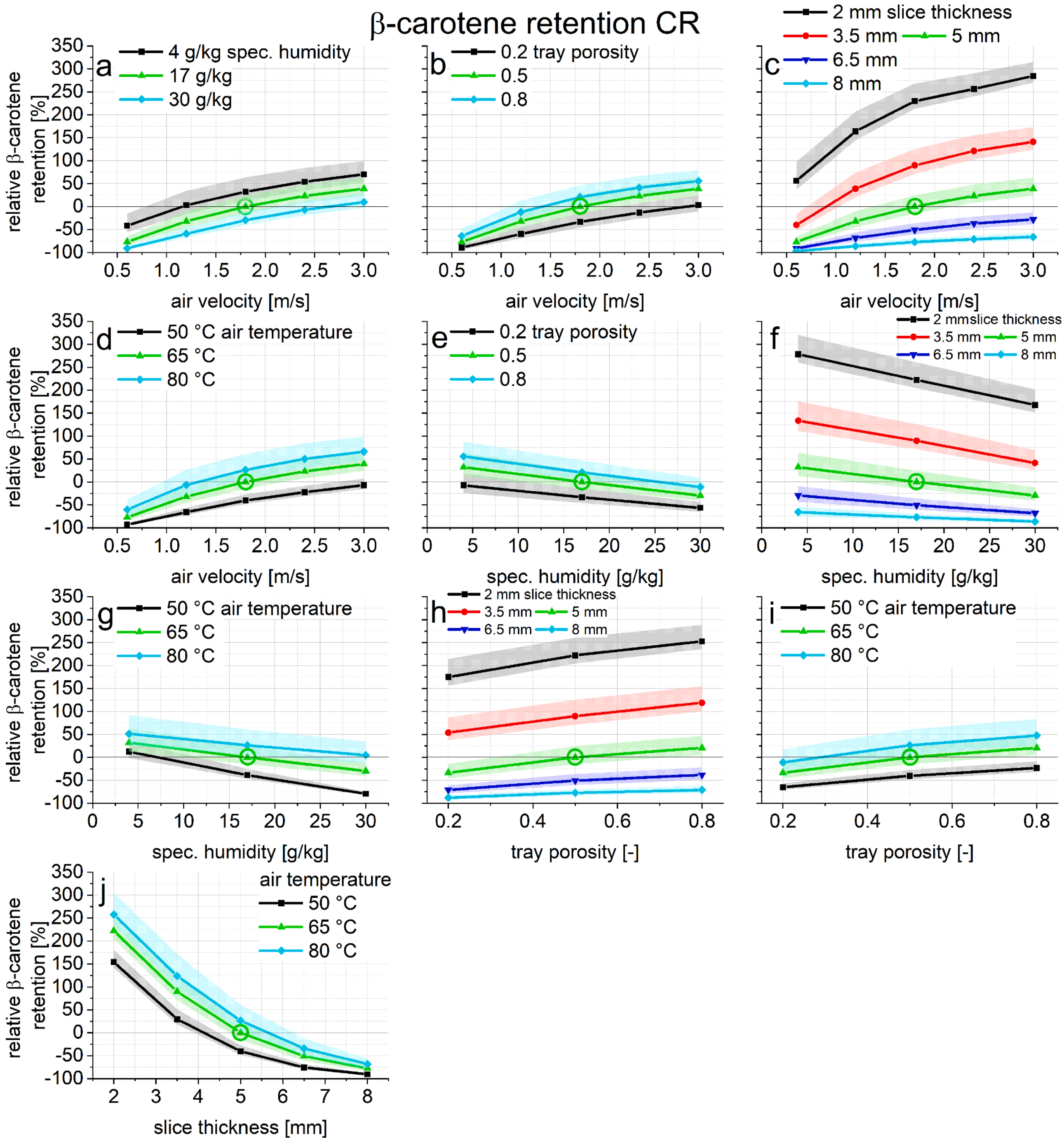

Fig. 5. Relative change of the β-carotene retention CR towards the base case (marked with a circle) for different parameter combinations. The colored areas show the range between the 1 % and 99 % quantile.

extent that practically no β-carotene is left without having a significantly positive effect on throughput.

Drying air temperature. Fig. 5d, g, i, j shows the impact of air temperature on the CR in combination with an adjusted air velocity, specific humidity, tray porosity, and slice thickness, respectively. If the temperature is increased, the temperature-dependent parameters such as the effective diffusivity, the saturation vapor pressure of the drying air, and thus the evaporation rate and evaporation cooling effect change, and with them, the temperature and its distribution in the carrot slice. A change in air temperature also has a strong effect on drying time and, thus, on the duration of thermal exposure. Subsequently, the CR improves by 26 % when the temperature increases from 65 °C to 80 °C, mostly caused by the corresponding reduction in drying time. However, if the temperature is reduced, the CR is 40 % lower compared to the base case, mainly due to the extended drying time. The variability of CR within a batch is noticeably higher at the elevated temperature of 80 °C.

An increase in air temperature also increases the CR, while drying at a cooler temperature worsens the CR. Since, in many cases, changing the air temperature is a relatively simple process intervention, a positive effect on drying time (-23 %), throughput (+30 %), and also CR (+26 %) can be achieved by increasing air temperature to 80 °C.

3.3. The impact of adjusted parameters on air heating energy consumption

This section aims to investigate how various operational parameters affect energy consumption in a drying process. The impact of adjusting air velocity, specific humidity, tray porosity, slice thickness, and air temperature on the energy requirements is assessed. Furthermore, it is assessed whether investments in changes to these parameters are cost-effective.

Air velocity. Fig. 6a, b, c, d shows the impact of air velocity on the relative energy consumption in combination with an adjusted specific humidity, tray porosity, slice thickness, and air temperature, respectively. An increased air velocity leads to increased airflow, so more air has to be heated per unit of time to operate the dryer, not considering potential downstream heat recovery here. This is counteracted by a shorter drying time due to improved heat and mass transfer. Together, both effects cause a 30 % increase in energy consumption when the airspeed is increased from 1.8 m/s to 3 m/s, resulting in a drying time reduction of 22 %. Reducing the airspeed to 0.6 m/s from the base case results in a 35 % reduction in energy consumption.

An increased airflow due to an increased airspeed requires more energy to be heated. This additional energy is partially compensated for by a shorter drying time. Thus, reducing airspeed is an important factor in saving energy.

Specific humidity. Fig. 6a, e, f, g shows the impact of specific humidity on the relative energy consumption in combination with an

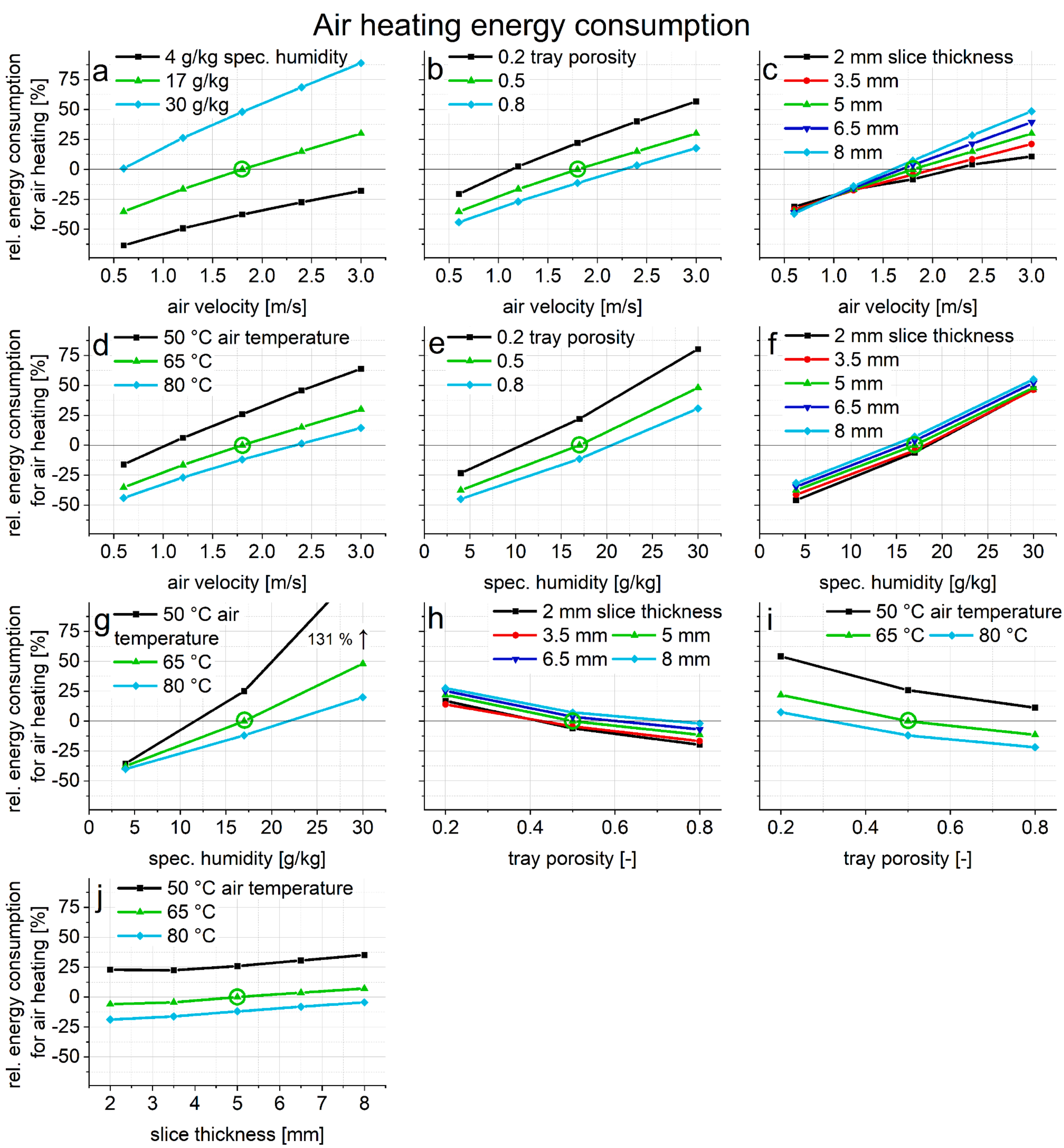

Fig. 6. Relative energy consumption towards base-case (marked with a circle).

adjusted air velocity, tray porosity, slice thickness, and air temperature, respectively. If the specific air humidity is reduced, this has an effect on the specific enthalpy of the air due to a reduced proportion of the sensible heat of the moisture contained (see Eq. (3)). The heating energy requirement is reduced by 38 % with reduced humidity. It should be noted that the energy for possible dehumidification is not taken into account here, which could nevertheless lead to an increased total energy requirement. If the specific humidity of the air is increased, this has a comparatively greater negative effect on the heating energy requirement of the air: an increase from 18 g/kg to 30 g/kg of the specific humidity results in an increased energy requirement of 48 %.

A decreased air humidity reduces the energy consumption of the drying process. Since influencing the air humidity is usually associated with increased technical and/or energy expenditure, this is not the first choice with regard to an energy optimization target. Increased air humidity, e.g. by recirculating the drying air inside the dryer, should be avoided due to increased energy requirements.

Tray porosity. Fig. 6b, e, h, i shows the impact of tray porosity on the relative energy consumption in combination with an adjusted air velocity, specific humidity, slice thickness, and air temperature, respectively. If the tray porosity is reduced from 0.5 to 0.2, the drying time and, thus, the heating requirement of the drying air increases by 22 %. A reduction of 11 % can be achieved by using a wider mesh with a porosity of 0.8.

Optimization towards a wider mesh can be a relatively simple to implement measure to improve energy consumption.

Slice thickness. Fig. 6c, f, h, j shows the impact of slice thickness on the relative energy consumption in combination with an adjusted air velocity, specific humidity, tray porosity, and air temperature, respectively. The slice thickness is a parameter that has a strong impact on the drying time. However, as the heating requirement discussed here is related to the fresh product throughput, this shorter drying time only has a minor effect on the energy requirement: only 6 % less energy is consumed per kg of fresh product to be dried with a reduced slice thickness. An increased slice thickness of 8 mm, on the other hand, increases energy consumption by 7 %.

Contrary to the strong influence of the slice thickness on the drying time and CR, it has little effect on the energy requirement. Changing the slice thickness is, therefore, not a relevant energy-saving measure.

Drying air temperature. Fig. 6d, g, i, j shows the impact of air temperature on the relative energy consumption in combination with an adjusted air velocity, specific humidity, tray porosity, and slice thickness, respectively. Air needs to be heated less to a lower temperature. However, at a lower temperature, the drying time is longer, so a larger volume of air must be heated. The latter predominates so that a reduction of the temperature from 65 °C to 50 °C increases the energy requirement by 26 %. On the other hand, an increase in temperature from 65 °C to 80 °C leads to a 12 % reduction in heating energy requirements compared to the base case.

The effect of reducing the drying time outweighs the additional energy required by the increased temperature. From an energy perspective, increasing the temperature is a reasonable measure.

Alternative approaches to reducing energy consumption in fruit and vegetable drying include using energy-efficient technologies such as heat pumps and heat recovery in general, as well as microwave- and infrared-assisted drying [36–38]. Improving insulation helps minimize waste heat, while renewable energy sources like solar and biomass can lower energy costs [39–41]. Additionally, machine learning, AI, and digital twin technologies can optimize process conditions in real time, further enhancing energy savings [42–44].

3.4. The trade-off between throughput, CR, and energy consumption

When a process, design, or production parameter is adjusted, it simultaneously affects the metrics of throughput, CR, and energy consumption to varying degrees. In this section, these interrelationships are examined.

Fig. 7 shows how throughput and air heating energy demand are correlated in their relative form, as used in this study. The bubble size, representing the relative carotene retention, shows that thin carrot slices have the best carotene retention. An increased airspeed is beneficial towards increased throughput and slightly better CR to the cost of increased energy demand. A reduced air humidity, increased tray porosity, thinning of carrot slice thickness, and increased air temperature support this effect.

A combination of increased airspeed with reduced humidity (a) can improve energy consumption by 18 % while also increasing throughput by ~40 % and increasing CR by 70 %. A combination of increased airspeed with also increased tray porosity (b) improves the throughput by ~40 % but requires ~20 % more energy at 56 % higher CR. Reduced slice thickness and increased air velocity (c) increase throughput by ~50 % and >280 % higher CR while the energy consumption slightly increases by 10 %. An increase in air temperature and velocity strongly increases the throughput to values >60 % compared to the base case, while energy consumption only increases to <15 % at a higher CR of 67 %. Lowering air humidity while increasing tray porosity (e) can reduce energy consumption by >40 % and, at the same time, increase throughput by >20 % with a CR improvement of 56 %. For thick carrot slices, a reduction of humidity (f) does have a limited effect, but for thinner slices, lowering humidity has a positive effect on throughput (>25 %) with a strongly positive effect on CR due to short drying times. The reduced energy requirement of 46 % towards the base case must be understood in the context of a potentially energy-intensive dehumidification process used. Increased humidity in combination with low temperatures (g) is a combination that should be avoided because the strong negative effect on energy consumption (131 % more energy use) is accompanied by 50 % less throughput. This amplification effect of the two parameters is less pronounced at higher temperatures. Increased tray porosity and thinner slices (h) result in >20 % more throughput and a 20 % lower energy consumption. Once again, the strong positive effect on CR is evident thanks to thin slices' much shorter drying time. An increase in tray porosity contributes to higher throughput when combined with increased drying temperatures (i). From a variation of drying temperature together with the slice thickness (j), an effect of increased fresh produce mass-related throughput by 41 % and decreased energy consumption by 19 % can be found. The temperature is the main factor responsible for the improved throughput, as it relates to the mass-related throughput.

A change in air temperature affects energy consumption, and different slice thicknesses influence the throughput through more batches necessary to achieve the production target. A combination of both of these factors shows that the temperature strongly influences the throughput while energy demand is not affected much. The effect of changes in slice thickness on throughput and energy demand is limited compared to the other factors examined in this study. Take-home messages are that

- Energy demand and throughput can be influenced significantly by optimizing the airspeed and temperature on a process condition level.
- If the slice thickness can be reduced, this will lead to vastly improved carotene retention while comparatively affecting the throughput only little, even reducing the energy demand to the cost of more labor necessary to deal with loading and unloading of the dryer for the increased number of batches required.
- Tray porosity - a simple design parameter that can be optimized - reliably leads to significantly better throughput and better energy efficiency
- Air humidity is especially critical at low temperatures: this combination should be avoided

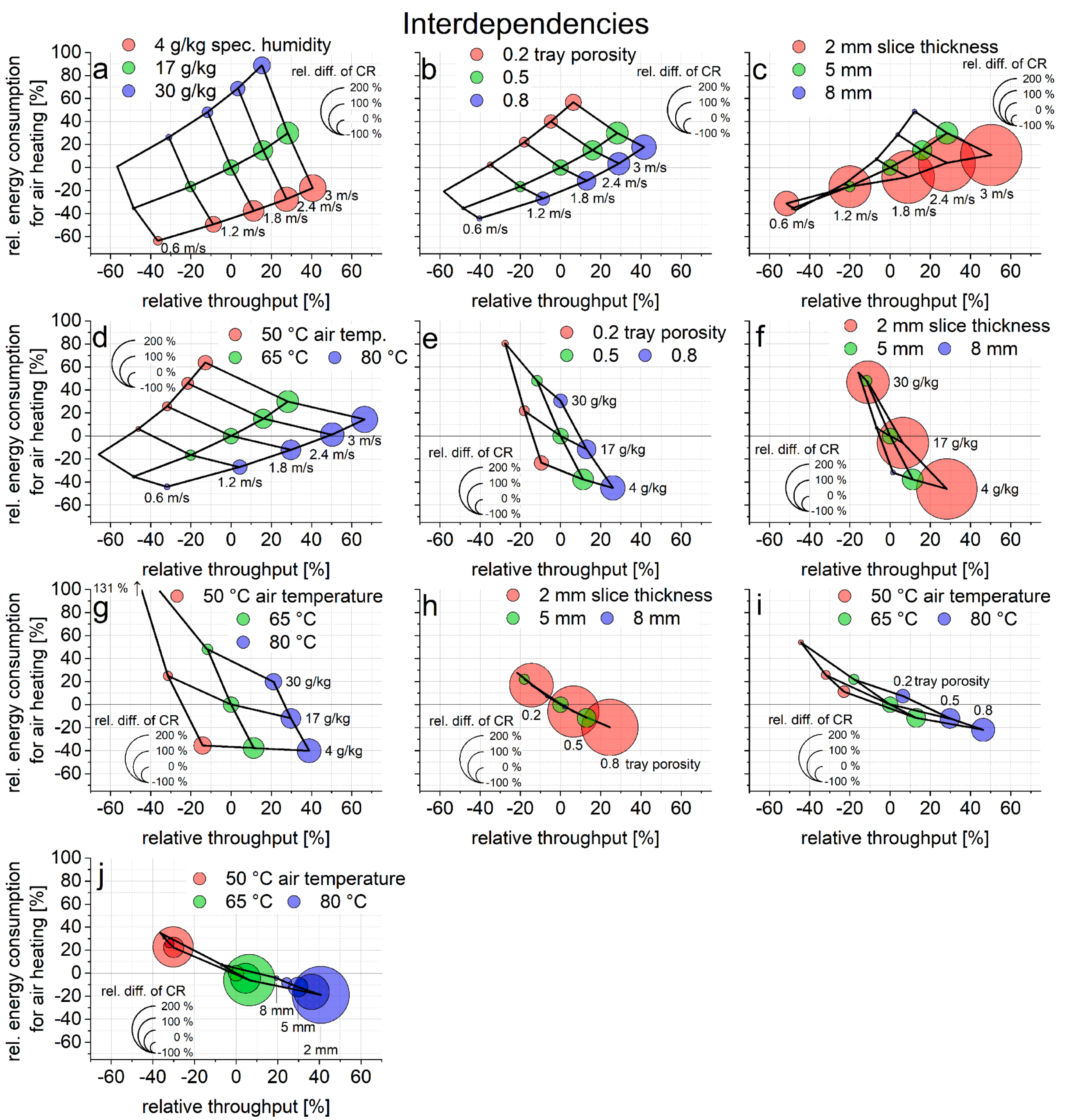

Fig. 7. Correlation of relative throughput and relative air heating energy demand. The bubble size represents the relative difference of the CR towards the base case. a: airspeed/humidity; b: airspeed/tray porosity; c: airspeed/slice thickness; d: airspeed/air temperature; e: humidity/tray porosity; f: humidity/slice thickness; g: humidity/air temperature; h: tray porosity/slice thickness; i: tray porosity/air temperature; j: slice thickness/air temperature.

4. Discussion

The approach described in this study utilizes physics-based simulation combined with statistical modeling. Consequently, the results should be compared with those from other experimental studies, as detailed in this section.

In most published experimental work, the mean moisture content of random samples is used as the criterion for terminating the drying process. As soon as a threshold value of moisture content is undershot, drying is terminated. This threshold can be different, such as at 0.14 g_w/g_{dm} for Md Saleh et al. [21] and 0.11 g_w/g_{dm} for Doymaz [20]. In more practice-oriented sources, lower final moisture contents of 0.06 g_w/g_{dm} are described [13]. This study uses the 99 % quantile to find 99 % of particles to have $a_w < 0.6$ as the termination criterion. This corresponds to an overall mean dry-based moisture content of 0.11 g_w/g_{dm}, see Appendix A. The approach of the current work thus confirms the termination criterion described in the literature.

A reduction of carrot slice thickness from 6 mm to 3 mm led to a reduction in drying time from 240 min to 195 min (19 % reduction at 65 °C, 2 m/s), as found by Sonmete et al. [45]. This 6 mm to 3 mm thinning leads to a reduction of 480 min to 360 min (25 % reduction at 60 °C, 2 m/s) as found by Md Saleh et al. [21]. Doymaz [20] found for a reduction from 7 mm to 4 mm a reduction of drying time from 403 min to 314 min (22 % reduction). The current study finds for 6.5 mm to 3.5

mm slice thinning at 65 °C and 1.8 m/s air velocity a reduction from 588 min to 292 min (50 %). For an increased air velocity of 2.4 m/s the reduction ranges from 516 min to 248 min (52 %). We, therefore, find generally longer drying times and a stronger drying time shortening effect due to slice thinning.

The extended drying times observed in this study are primarily attributed to the assumption of diminished heat and mass transfer along the overflown drying plate. In most experimental setups, individual slices are exposed to the drying air. When a fully loaded tray is subjected to the drying air, the heat and mass transfer along the plate's overflown length is reduced. This reduction is described by the Nusselt number correlation for an overflown flat plate under turbulent flow conditions, as detailed by Schemminger et al. [4]. Consequently, the drying time varies depending on the overflow length of the tray. For a randomly selected 3 mm thick slice at base case settings, after a tray length of 30 mm, the drying time is 142 min for $a_w < 0.6$, details see Appendix A. At the downstream end of the plate, after 510 mm, the drying time for the exact same slice increases by 70 % to 242 min. For a 5 mm thick slice, the corresponding drying times increase by 57 % from 264 min to 414 min. In addition, the influence of the tray porosity is taken into account, which also leads to a reduction in heat and mass transfer and, thus, to an increase in drying time. Under production conditions, we, therefore, systematically find longer drying times for the similar final moisture termination criterion due to the consideration of the overflowed tray length. However, the comparability of the drying times of this study with experimental studies is affected.

The base case parameter combination at 5 mm slice thickness provides a final CR of 16.5 %. Literature provides for both slice thicknesses of 3 mm and 6 mm CR values >40 % [21] or even >50 % [23]. The current model shows mean CR in the range of 37 % (3.5 mm) to 4 % (8 mm), thus significantly lower values. As discussed, the current model results in longer drying times due to the reduced heat- and mass transfer along the loaded overflown drying tray. The longer drying times - e.g. the time the carrot slices are exposed to elevated temperatures - lead to a longer time the β-carotene can thermally deteriorate. As a consequence, the final β-carotene contents are lower, and the CR is also lower compared to studies from the literature. In addition, the simplification of modeling β-carotene as a solely temperature-dependent decay reaction following a first-order reaction has limitations as, in reality, multiple factors are influencing the decay, such as pH value, moisture content, water activity, and oxygen availability. Sarpong et al. [46] found for slices of 2.5 mm thickness at 2 m/s in a range of 60 °C to 80 °C CR values ranging from 64 % to 42 % for 10 % relative humidity RH (60 °C: 12.5 g/kg; 70 °C: 19.8 g/kg, 80 °C: 30.7 g/kg). The current study also here finds significantly lower mean values of 35 % to 52 % for 2.5 mm slice thickness in the 50 °C to 80 °C temperature interval at a specific humidity of 17 g/kg. The differences can be partly explained by the reduced heat- and mass transfer, and partly by the simplifications of the decay reaction model. Consequently, the absolute CR values are limited in terms of comparability. However, the effects relative to the base case are still a valuable source of information due to the systematic nature of the errors introduced: which measure leads to which degree of CR change? Therefore, this study does not compare the CR values, but rather the relative change in the CR values compared to the base case.

However, it should be noted that also the variety, growing conditions, and the associated sorption behavior have an influence on the termination of the drying process: the sorption isotherms used for the model of this current study is *Daucus Carota* L. var. *Laguna*, based on data from Raut et al. [23]. Md Saleh et al. [21] also used the Laguna variety for their experiments and found that the water activity values were slightly higher than those indicated by the sorption isotherms used here (50 °C 0.35 vs. 0.29; 60 °C 0.36 vs. 0.28; 70 °C 0.35 vs. 0.28). These differences between studies of sorption isotherms is within a known wide range as also discussed by Md Saleh et al. [21] - other studies, such as by Kaya et al. [47] (variety not reported) and Eim et al. [48] on *Daucus Carota v. Nantes* showed comparatively low moisture contents of ~0.15 kg/kg_{dm} that correlate with the water activity of $a_w = 0.6$. Consequently, conservatively speaking, this study's absolute drying time results are limited to *Daucus Carota* L. var. *Laguna*, more precisely to the cultivation conditions described by Raut et al. [23].

Metal grids, as partly used in experimental dryers used for research, affect the hygrothermal behavior of carrot slices during drying due to thermal contact, impacting the overall drying time [4]. Therefore, their use and design can not be ruled out as a source of differences between the current findings and literature data. Subsequently, differences in the porosity of the tray can influence drying times. Md Saleh et al. [21] reported a drying time of 206 min for 3 mm slices at 0.6 m/s and 50 °C with a final MR of ~0.04. The current study shows a drying time of 263 min under similar conditions, a 57 min difference, partly due to tray porosity and the use of a metal tray in their studies.

The single-slice model, as validated by Schemminger et al. [4], may show deviations when applied to commercial tray dryers due to scaling effects, different operating conditions, and material variability. Factors like non-homogeneous airflow or varying tray loading procedures can impact results. The relevant energy consumption and associated costs may also differ when heat recovery systems are used. The inherent variability of biological materials inevitably causes discrepancies not only between the model and its application but also among different commercial applications.

5. Conclusions

In this study, Monte Carlo simulations were used to comprehensively show how adjustments to process, produce, and design parameters affect the population of carrot slices in the dryer. The metrics of drying time, throughput, and the retention of β-carotene (CR) relative to the base case were examined.

The findings revealed that increasing air velocity significantly reduces drying time and enhances throughput, although the benefits diminish at higher velocities. Higher airspeed also improves β-carotene retention due to reduced thermal exposure. Adjusting air humidity, while less effective for drying time and throughput, plays a significant role in β-carotene retention. Lower humidity enhances evaporative cooling, reducing slice temperature and preserving β-carotene, although the costs of dehumidification often outweigh the benefits.

Tray porosity has a modest impact on drying time and throughput but offers a cost-effective optimization measure. Wider-meshed trays with plastic mats provide reliable efficiency and energy consumption improvements. Slice thickness emerged as the most influential parameter on both drying time and β-carotene retention. Thinner slices significantly reduce drying time and improve nutrient retention, while thicker slices degrade β-carotene without substantial throughput benefits. Increasing air temperature is highly effective for reducing drying time, increasing throughput, and enhancing β-carotene retention. An optimal temperature of 80 °C achieves significant improvements.

In essence, this research bridges theoretical understanding and practical application, offering a roadmap for optimizing drying processes. The general statement of the results is transferable to other fruit and vegetable slice drying processes. Design-specific challenges related to heat losses to the environment, non-flow-through areas in the dryer, and varying airspeeds on different stacked trays and energy efficiency of electrical components were not addressed but should be considered for individual optimization cases.

Technical adjustments like frequency converters and component replacements should be implemented to optimize air velocity to enhance airflow and efficiency. Lower humidity should be considered for better β-carotene retention, despite higher costs. Utilizing wider-meshed trays can provide modest efficiency improvements. Thinner slices should be aimed for to improve drying time and nutrient retention, although customer requirements may impose restrictions here. Higher temperatures, such as 80 °C, should be used for significant improvements in drying time, throughput, and β-carotene retention.

Future research should use throughput as a metric and incorporate pre-treatments and auxiliary technologies like microwave-assisted drying into hybrid modeling approaches.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used deepL.com, grammarly.com, and Microsoft 365 Copilot in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Jörg Schemminger: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Sharvari Raut:** Writing – review & editing, Supervision, Conceptualization. **Barbara Sturm:** Writing – review & editing, Supervision, Conceptualization. **Thijs Defraeye:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, 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.

Acknowledgments

We would like to acknowledge INNOTECH Ingenieursgesellschaft mbH that provided expertise on industrial drying applications and critically reviewed the manuscript.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijft.2025.101221.

Data availability

Data will be made available on request.

References

[1] C. Bonazzi, E. Dumoulin, Quality changes in food materials as influenced by drying processes, Mod. Dry. Technol. 3 (2011) 1–20, https://doi.org/10.1002/9783527631667.
[2] D.I. Onwude, K. Iranshahi, D. Rubinetti, S. Schudel, J. Schemminger, A. Martynenko, T. Defraeye, How much do process parameters affect the residual quality attributes of dried fruits and vegetables for convective drying? Food Bioprod. Process. 131 (2022) 176–190, https://doi.org/10.1016/j.fbp.2021.11.005.
[3] B. Sturm, Systemic Optimisation and Design Approach For Thermal Food Processes - Increase of quality, process- and resource Efficiency in Dried Agricultural Products Manufacturing - Habilitationsschrift, Universität Kassel, 2018. https://karla.hds.hebis.de/Record/HEB434930008.
[4] J. Schemminger, S. Raut, B. Sturm, T. Defraeye, A hybrid digital shadow to assess biological variability in carrot slices during drying, Therm. Sci. Eng. Prog. (2024) 102507, https://doi.org/10.1016/j.tsep.2024.102507.
[5] A.M. Castro, E.Y. Mayorga, F.L. Moreno, Mathematical modelling of convective drying of fruits: a review, J. Food Eng. 223 (2018) 152–167, https://doi.org/10.1016/j.jfoodeng.2017.12.012.
[6] T. Defraeye, Advanced computational modelling for drying processes - a review, Appl. Energy 131 (2014) 323–344, https://doi.org/10.1016/j.apenergy.2014.06.027.
[7] P. Verboven, T. Defraeye, A.K. Datta, B. Nicolai, Digital twins of food process operations: the next step for food process models? Curr. Opin. Food Sci. 35 (2020) 79–87, https://doi.org/10.1016/j.cofs.2020.03.002.
[8] A. Cooman, E. Schrevens, A Monte Carlo approach for estimating the uncertainty of predictions with the tomato plant growth model, Tomgro, Biosyst. Eng. 94 (2006) 517–524, https://doi.org/10.1016/j.biosystemseng.2006.05.005.
[9] K. Cronin, S. Kearney, Monte Carlo modelling of a vegetable tray dryer, J. Food Eng. 35 (1998) 233–250, https://doi.org/10.1016/S0260-8774(98)00011-9.
[10] A.D. Demir, P. Baucour, K. Cronin, K. Abodayeh, Analysis of temperature variability during the thermal processing of hazelnuts, Innov. Food Sci. Emerg. Technol. 4 (2003) 69–84, https://doi.org/10.1016/S1466-8564(02)00084-X.
[11] A.S. Mujumdar, Handbook of Industrial drying (2006). https://doi.org/10.1201/9781420017618.
[12] FAO, Production Quantities of Carrots and Turnips By Country, 2020. https://www.fao.org/faostat/en/#data/QCL.
[13] W. Mühlbauer, J. Müller, Drying Atlas, Dry. Atlas (2020), https://doi.org/10.1016/C2018-0-02312-9.
[14] A. Heindl, Praxisbuch Horden- und Flächentrocknung (2020) 449–476. https://doi.org/10.1007/978-3-662-60433-5.
[15] VDI e. V., VDI-Wärmeatlas (2013). https://doi.org/10.1007/978-3-642-19981-3.
[16] F.J. Barba, O. Parniakov, S.A. Pereira, A. Wiktor, N. Grimi, N. Boussetta, J. A. Saraiva, J. Raso, O. Martin-Belloso, D. Witrowa-Rajchert, N. Lebovka, E. Vorobiev, Current applications and new opportunities for the use of pulsed electric fields in food science and industry, Food Res. Int. 77 (2015) 773–798, https://doi.org/10.1016/j.foodres.2015.09.015.
[17] M. Radojčin, I. Pavkov, D. Bursać Kovačević, P. Putnik, A. Wiktor, Z. Stamenković, K. Kešelj, A. Gere, Effect of selected drying methods and emerging drying intensification technologies on the quality of dried fruit: a review, Processes 9 (2021) 132, https://doi.org/10.3390/pr9010132.
[18] D.I. Onwude, N. Hashim, R.B. Janius, N.M. Nawi, K. Abdan, Modeling the thin-layer drying of fruits and vegetables: a review, Compr. Rev. Food Sci. Food Saf. 15 (2016) 599–618, https://doi.org/10.1111/1541-4337.12196.
[19] J. Wang, Y.S. Xi, Drying characteristics and drying quality of carrot using a two-stage microwave process, J. Food Eng. 68 (2005) 505–511, https://doi.org/10.1016/j.jfoodeng.2004.06.027.
[20] İ. Doymaz, Drying kinetics, rehydration and colour characteristics of convective hot-air drying of carrot slices, Heat Mass Transf. 53 (2017) 25–35, https://doi.org/10.1007/s00231-016-1791-8.
[21] R.M. Saleh, B. Kulig, O. Hensel, B. Sturm, Investigation of dynamic quality changes and optimization of drying parameters of carrots (Daucus carota var. laguna), J. Food Process. Eng. 43 (2020) e13314, https://doi.org/10.1111/jfpe.13314.
[22] Z.-W. Cui, S.-Y. Xu, D.-W. Sun, Microwave-vacuum drying kinetics of carrot slices, J. Food Eng. 65 (2004) 157–164, https://doi.org/10.1016/j.jfoodeng.2004.01.008.
[23] S. Raut, R.M. Saleh, P. Kirchhofer, B. Kulig, O. Hensel, B. Sturm, Investigating the effect of different drying strategies on the quality parameters of Daucus carota L. Using dynamic process control and measurement techniques, Food Bioprocess. Technol. 14 (2021) 1067–1088, https://doi.org/10.1007/s11947-021-02609-y.
[24] R.M. Saleh, B. Kulig, A. Arefi, O. Hensel, B. Sturm, Prediction of total carotenoids, color, and moisture content of carrot slices during hot air drying using non-invasive hyperspectral imaging technique, Food Process. Preserv. 46 (2022), https://doi.org/10.1111/jfpp.16460.
[25] J. Frias, E. Peñas, M. Ullate, C. Vidal-Valverde, Influence of drying by convective air dryer or power ultrasound on the vitamin C and β-carotene content of carrots, J. Agric. Food Chem. 58 (2010) 10539–10544, https://doi.org/10.1021/jf102797y.
[26] Z.-G. Chen, X.-Y. Guo, T. Wu, A novel dehydration technique for carrot slices implementing ultrasound and vacuum drying methods, Ultrason. Sonochem 30 (2016) 28–34, https://doi.org/10.1016/j.ultsonch.2015.11.026.
[27] T.M. Lin, T.D. Durance, C.H. Scaman, Characterization of vacuum microwave, air and freeze dried carrot slices, Food Res. Int. 31 (1998) 111–117, https://doi.org/10.1016/S0963-9969(98)00070-2.
[28] J. Kroehnke, J. Szadzińska, M. Stasiak, E. Radziejewska-Kubzdela, R. Biegańska-Marecik, G. Musielak, Ultrasound- and microwave-assisted convective drying of carrots - process kinetics and product's quality analysis, Ultrason. Sonochem. 48 (2018) 249–258, https://doi.org/10.1016/j.ultsonch.2018.05.040.
[29] M. Aghbashlo, M.H. Kianmehr, A. Arabhosseini, Performance analysis of drying of carrot slices in a semi-industrial continuous band dryer, J. Food Eng. 91 (2009) 99–108, https://doi.org/10.1016/j.jfoodeng.2008.08.020.
[30] D. Zhao, K. An, S. Ding, L. Liu, Z. Xu, Z. Wang, Two-stage intermittent microwave coupled with hot-air drying of carrot slices: drying kinetics and physical quality, Food Bioprocess. Technol. 7 (2014) 2308–2318, https://doi.org/10.1007/s11947-014-1274-1.
[31] H. Kocabiyik, D. Tezer, Drying of carrot slices using infrared radiation, Int. J. Food Sci. Technol. 44 (2009) 953–959, https://doi.org/10.1111/j.1365-2621.2008.01767.x.
[32] S.V. Jangam, C.L. Law, A.S. Mujumdar, Drying of food, vegetables and fruits Vol. 2, 2010, ISBN: 978-981-08-7985-3.
[33] S. Misha, S. Mat, M.H. Ruslan, K. Sopian, E. Salleh, Review on the application of a tray dryer system for agricultural products, World Appl. Sci. J. 22 (2013) 424–433, https://doi.org/10.5829/idosi.wasj.2013.22.03.343.
[34] J.A. Moses, T. Norton, K. Alagusundaram, B.K. Tiwari, Novel drying techniques for the food industry, Food Eng. Rev. 6 (2014) 43–55, https://doi.org/10.1007/s12393-014-9078-7.
[35] M.S. Rahman, Handbook of Food Preservation, 167, 2007, https://doi.org/10.1201/9781420017373.
[36] D.S.A. Delfiya, K. Prashob, S. Murali, P.V. Alfiya, M.P. Samuel, R. Pandiselvam, Drying kinetics of food materials in infrared radiation drying: a review, J. Food Process. Eng. 45 (2022) e13810, https://doi.org/10.1111/jfpe.13810.

[37] L.J. Goh, M.Y. Othman, S. Mat, H. Ruslan, K. Sopian, Review of heat pump systems for drying application, Renew. Sustain. Energy Rev. 15 (2011) 4788–4796, https://doi.org/10.1016/j.rser.2011.07.072.
[38] C. Kumar, M.A. Karim, Microwave-convective drying of food materials: a critical review, Crit. Rev. Food Sci. Nutr. 59 (2019) 379–394, https://doi.org/10.1080/10408398.2017.1373269.
[39] C. Catorze, A.P. Tavares, P. Cardão, A. Castro, M.E. Silva, D.W. Ferreira, S. Lopes, I. Brás, Study of a solar energy drying system—energy savings and effect in dried food quality, Energy Rep. 8 (2022) 392–398, https://doi.org/10.1016/j.egyr.2022.01.070.
[40] J. Muhammad, J. Risnto, G. Gimin, Drying fresh cassava chip using biomass energy with IoT monitoring system, Agric. Eng. Int. CIGR J. 24 (2022). ISSN: 16821130.
[41] H. Qu, M.H. Masud, M. Islam, M.I.H. Khan, A.A. Ananno, A. Karim, Sustainable food drying technologies based on renewable energy sources, Crit. Rev. Food Sci. Nutr. 62 (2022) 6872–6886, https://doi.org/10.1080/10408398.2021.1907529.
[42] M.I.H. Khan, S.S. Sablani, M.U.H. Joardder, M.A. Karim, Application of machine learning-based approach in food drying: opportunities and challenges, Dry. Technol. 40 (2022) 1051–1067, https://doi.org/10.1080/07373937.2020.1853152.
[43] A. Martynenko, N.N. Misra, Machine learning in drying, Dry. Technol. 38 (2020) 596–609, https://doi.org/10.1080/07373937.2019.1690502.
[44] S. Raut, J. Schemminger, G.J.E. von Gersdorff, J. Mellmann, B. Sturm, Moving towards digital twin based smart drying systems for agricultural products, in: 2022 ASABE Annual International Meeting, 2022, https://doi.org/10.13031/aim.202200465.
[45] M.H. Sonmete, H.O. Mengeş, C. Ertekin, M.M. Özcan, Mathematical modeling of thin layer drying of carrot slices by forced convection, Food Meas. 11 (2017) 629–638, https://doi.org/10.1007/s11694-016-9432-y.
[46] F. Sarpong, C. Zhou, J. Bai, L.P. Amenorfe, M.K. Golly, H. Ma, Modeling of drying and ameliorative effects of relative humidity (RH) against β-carotene degradation and color of carrot (Daucus carota var.) slices, Food Sci. Biotechnol. 28 (2019) 75–85, https://doi.org/10.1007/s10068-018-0457-3.
[47] A. Kaya, O. Aydın, C. Demirtaş, Experimental and theoretical analysis of drying carrots, Desalination. 237 (2009) 285–295, https://doi.org/10.1016/j.desal.2008.01.022.
[48] V.S. Eim, C. Rosselló, A. Femenia, S. Simal, Moisture sorption isotherms and thermodynamic properties of carrot, Int. J. Food Eng. 7 (2011), https://doi.org/10.2202/1556-3758.1804.