1 When to stop drying fruit: insights from hygrothermal modelling

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12

13 Abstract

14 Stopping the drying process prior to complete dehydration reduces energy consumption and processing time but can
15 also improve product quality. Using hygrothermal simulations, different stopping criteria are evaluated, which are
16 based on the final water activity and residual moisture content in the fruit. Their impact on drying time and moisture
17 redistribution kinetics inside fruit is quantified. One of the variants leads to a significant reduction in residence time
18 in the dryer (24%), compared to full dehydration. For this variant, drying is stopped when the average moisture
19 content in the sample reaches the value corresponding to an equilibrium water activity of 60% in the sample, as
20 determined from the sorption isotherm. At the same time, this variant does not induce problems with fruit spoilage,
21 as a sufficiently low water activity is reached after moisture redistribution during relaxation in the ambient
22 environment. In addition, the relation of the drying time to the drying air temperature was quantified for all stopping
23 criteria, as well as the impact of the humidity of the ambient environment in which the dried fruits are placed
24 afterwards. This study gives a better quantitative insight in when fruit drying should be stopped, given specific drying
25 conditions, without having to compromise food safety.

26 1. Introduction

27 Drying is one of the oldest and most important technologies for food preservation, including for fresh fruit [1].
28 Further optimization of such drying processes is essential to reduce the environmental impact of this energy-
29 intensive unit operation and to enhance product quality [2]. A key question here is when to stop the drying process.
30 Insufficient drying of fresh fruit leads to high water activity levels. These reduce shelf life and can cause spoilage,

31 which leads to food safety risks. Typically fruits should be dried so their equilibrium water activity is below 60-65%
32 [3].

33 To avoid problems, fruits are therefore often dried a bit too long. Overdrying however results in excessive energy use
34 due to the longer duration of the drying process, and the additional energy used to evaporate the remaining water.
35 The almost complete removal of moisture is however not required. The reason is that these fruits are afterwards
36 brought to an ambient environment for further processing, packaging and storage. Due to the lower temperatures
37 and often higher humidity than in the dryer, they will take up some moisture again. As such, the energy that was
38 originally used to evaporate this water by drying, i.e. the latent heat needed to induce a phase change from liquid
39 water to vapor, was spent in vain.

40 It is energetically more beneficial to stop the drying process earlier. It is feasible to do so while, at the same time, still
41 achieving a sufficiently low water activity in the fruit to ensure food safety. To this end, the residual moisture in the
42 fruit needs to redistribute or diffuse further out into the ambient environment during so-called equilibration, in
43 order for the equilibrium water activity to fall below its critical value ($\sim 60\%$). In such a way, all the water that is
44 present in the final dried product was originally contained in the product instead of coming partially from its
45 environment, so no energy has been wasted in removing it first by evaporation. Such equilibration after drying can
46 take place in the food processing plant or inside the package. Finding the optimal time to stop drying is imperative to
47 evolve to more energy-smart drying processes. Furthermore, excessive dehydration implies more shrinkage, which
48 will probably not be entirely recovered during partial rehydration into the ambient environment. Hence, fruit quality
49 aspects, such as structure, texture or mouthfeel, which determine palatability and consumer acceptance, can also be
50 improved by halting the drying process earlier.

51 Recent research on drying of fresh-cut fruit evaluated, amongst others: (1) the impact of different process
52 parameters, such as air speed, fruit size or environmental conditions [4–8]; (2) various process control strategies [9];
53 (3) the spatial heterogeneity of the moisture content within the sample during drying [10,11]; (4) energetically more
54 beneficial processes, including intermittent drying [12–14]. In most cases however, complete dehydration of the
55 samples was considered. Typically, the drying time was taken the same for all cases, even though some samples
56 dried out faster than others. The question on whether and when to stop the drying process earlier, which makes
57 more sense from an energy or even quality point of view, was not the main target. This stopping time is however
58 very case dependent. The impact of when to stop drying is not considered in most studies.

59 Determining an appropriate stopping time requires measurements of the water activity after equilibration. Water
60 activity, not moisture content, is the suitable parameter to evaluate if fruits are sufficiently dry to ensure food safety
61 and to guarantee sufficient shelf life. Moisture content, on the other hand, is often used as a criterion to assess if the
62 drying process is finalized, namely by measuring gravimetrically if a sample is fully dry. Water activity is related to the
63 moisture content via the sorption isotherm, so if the latter is known, water activities can be estimated from moisture
64 content measurements in principle. Nevertheless, measuring both water activity and moisture content

experimentally at different points in time during drying is tedious and rather labor-intensive, especially if various drying conditions need to be evaluated. Therefore, only the moisture content, and not the water activity in the fruit, is usually monitored gravimetrically in drying studies.

As an alternative, this study relies on numerical hygrothermal modelling of the drying process to explore what the impact is of stopping the process before complete dehydration. To this end, we monitor how the moisture distribution within the fruit evolves during and after drying, including the moisture redistribution kinetics during equilibration in the ambient environment. Different stopping criteria are evaluated, namely based on the water activity or the residual moisture content in the sample. We also explore the impact of the humidity level of the ambient environment in which the dried fruit is placed after drying. This study gives a better quantitative insight in when fruit drying should be stopped for specific drying conditions, in order to save energy and to obtain higher quality products.

2. Materials and methods

2.1 Continuum model for fruit tissue

A validated continuum model was developed previously [15] to calculate the heat and moisture transfer in fruit tissue during drying. Only its main characteristics are highlighted below and more details can be found elsewhere [15]. The main model assumptions are that evaporation is assumed to occur only at the tissue surface and that shrinking and swelling of the tissue are not modelled.

Conservation equations

The following conservation equations for moisture and energy are solved to the dependent variables temperature T [K] and water potential ψ [Pa], which are the driving potentials for heat and moisture transport in the fruit tissue:

$$\frac{\partial w_m}{\partial \psi} \frac{\partial \psi}{\partial t} + \nabla \cdot (-K_m \nabla \psi) = 0 \quad (1)$$

$$h_l \frac{\partial w_m}{\partial \psi} \frac{\partial \psi}{\partial t} + (c_{p,s} w_s + c_{p,l} w_m) \frac{\partial T}{\partial t} + \nabla \cdot (-h_l K_m \nabla \psi) + \nabla \cdot (-\lambda_{PM} \nabla T) = 0 \quad (2)$$

where w_s and w_m are the dry matter density (solid) and moisture content of the tissue [kg m^{-3}], respectively. K_m is the moisture permeability of the tissue [s], h_l is the enthalpy of liquid water [J kg^{-1}], λ_{PM} is the thermal conductivity of the tissue (porous medium) [$\text{W m}^{-1} \text{K}^{-1}$], $c_{p,s}$ and $c_{p,l}$ are the specific heat capacities of dry matter and liquid water [$\text{J kg}^{-1} \text{K}^{-1}$], respectively.

These material properties are given in Table 1. K_m and the sorption isotherm are taken from [16]. Although the permeability can change as a function of moisture content, it is challenging to determine this relation accurately. The variability in permeability induced by harvest year or harvest location can even be larger than the variation of the

permeability with moisture content. The numerical model (with a constant permeability) was validated [15] and matched the experimental data well. In the energy conservation equation, the impact of the first and third term on the left-hand side is actually very low in the present study due to the low drying rates. These terms are not accounted for usually [17]. The water potential is related to the water activity a_w by:

$$\psi = \rho_l R_v T \ln(a_w) \quad (3)$$

The water activity in turn is related to the moisture content w_m via the sorption isotherm (see Table 1), namely w_m vs. a_w . From the sorption isotherm, the moisture capacity $C_m = \frac{\partial w_m}{\partial \psi}$ can be determined.

Boundary conditions

The boundary conditions at the air-tissue interface (continuity of fluxes) are specified as:

$$\mathbf{n} \cdot (-K_m \nabla \psi) = g_m = h_{c,m} (p_{v,w} - p_{v,ref}) \quad (4)$$

$$\mathbf{n} \cdot (-h_l K_m \nabla \psi - \lambda_{PM} \nabla T) = g_T = (h_{c,T} (T_w - T_{ref}) - h_v g_m) \quad (5)$$

where g_m [$\text{kg m}^{-2} \text{s}^{-1}$] and g_T [$\text{J m}^{-2} \text{s}^{-1}$] are the mass and heat fluxes at the interface, $\mathbf{n}$ is the unit vector normal to the interface, $h_{c,m}$ is the convective mass transfer coefficient (CMTC [s m^{-1}]), $h_{c,T}$ is the convective heat transfer coefficient (CHTC [$\text{W m}^{-2} \text{K}^{-1}$]), $p_{v,w}$ and $p_{v,ref}$ are the vapor pressures at the interface and of the ambient air [Pa], T_w and T_{ref} are the temperatures at the interface and of the ambient air [K], h_v and h_l are the enthalpies of water vapor and liquid water [J kg^{-1}].

For mass transfer, the boundary condition states that the moisture loss from the tissue equals the convective vapor removal from the surface. For heat transfer, the boundary condition states that heat loss from the tissue, due to conduction and liquid water transport, equals the convective (sensible) heat exchange with the environment and the heat removal due to the water vapor loss, including evaporation. In the present study, long-wave radiation exchange of the tissue with the environment via the surface is not modelled.

117 **Table 1. Material properties, boundary conditions and initial conditions for the base case.**

Material properties	Symbol	Value
Moisture permeability fruit tissue	K_m	8×10^{-16} [s]
Thermal conductivity fruit tissue	λ_{PM}	0.418 [$\text{W m}^{-1}\text{K}^{-1}$]
Specific heat capacity of dry matter	$c_{p,s}$	1634 [$\text{J kg}^{-1}\text{K}^{-1}$]
Specific heat capacity of liquid water	$c_{p,l}$	4182 [$\text{J kg}^{-1}\text{K}^{-1}$]
Specific heat capacity water vapor	$c_{p,v}$	1880 [$\text{J kg}^{-1}\text{K}^{-1}$]
Dry matter content	w_s	130 [kg m^{-3}]
Sorption isotherm	$w_m(a_w)$	$w_s \left(\frac{0.15926}{\ln \left(\frac{1.0177}{a_w} \right)} \right)^{\frac{1}{0.97014}}$ [kg m^{-3}]
Density liquid water	ρ_l	1000 [kg m^{-3}]
Latent heat	L_v	2.5×10^6 [J kg^{-1}]
Specific gas constant for water vapor	R_v	461.52 [$\text{J kg}^{-1}\text{K}^{-1}$]
Boundary and initial conditions	Symbol	Value
Initial tissue temperature	T_{ini}	20 [$^{\circ}\text{C}$]
Initial tissue moisture content (dry base)	X_{ini}	6 [kg kg_{dm}^{-1}]
Initial tissue moisture content	$w_{m,ini}$	780 [kg m^{-3}]
Air temperature during drying	$T_{ref,d}$	20°C
Relative humidity during drying	$RH_{ref,d}$	30%
Convective heat transfer coefficient during drying	$h_{c,T}$	100 [$\text{W m}^{-2}\text{K}^{-1}$]
Convective mass transfer coefficient during drying	$h_{c,m}$	7.03×10^{-7} [s m^{-1}]

118

119 **Constitutive equations**

120 The enthalpies of water vapor and liquid water, h_v and h_l [J kg^{-1}], are:

121
$$h_l = c_{p,l} (T - T_{ref,0}) \quad (6)$$

122
$$h_v = c_{p,v} (T - T_{ref,0}) + L_v \quad (7)$$

123 where L_v is the heat of vaporization [J kg^{-1}], also called latent heat, which is the energy needed for the phase change
124 from liquid to vapor. $T_{ref,0}$ is a reference temperature, taken equal to 273.15 K (0°C).

125 .

The vapor pressures $p_{v,w}$ and $p_{v,ref}$ are determined based on the water activity at the interface ($a_{w,w}$) and the relative humidity of the drying or ambient air (RH_{ref}), together with the corresponding temperatures, via the saturated vapor pressure ($p_{v,sat}$ [Pa]):

$$p_{v,w} = a_{w,w} p_{v,sat}(T_w) \quad (8)$$

$$p_{v,ref} = RH_{ref} p_{v,sat}(T_{ref}) \quad (9)$$

$$p_{v,sat}(T) = e^{65.8094 - \frac{7066.27}{T} - 5.976 \ln T} \quad (10)$$

2.2 Configuration and computational model

The configuration used to evaluate convective drying of fresh-cut apple tissue is a cubic piece (length $L_c = 20$ mm) suspended in the surrounding air. This study departs from apple fruit, as it is a frequently applied material to study fruit drying with a significant economic relevance. A base case is simulated, namely full dehydration, as well as other variants, which evaluate partial dehydration for different stopping criteria and for different environmental conditions.

Base case

The computational model and the imposed boundary conditions are specified in Figure 1. A 3D model of the fruit is used, but only one eighth of the cube is modelled due to symmetry. The apple fruit is of the cultivar *Braeburn*. The relevant material properties and boundary/initial conditions used for modelling are specified in Table 1. The fruit is assumed to be initially (fresh-cut state) at a uniform moisture content $w_{m,ini}$ of 780 kg m^{-3} at a uniform temperature T_{ini} of 20°C . This moisture content leads to a dry base moisture content X_{ini} of 6 ($= w_{m,ini}/w_s [\text{kg kg}_{dm}^{-1}]$).

Figure 1. Computational model with boundary conditions.

The airflow around the cube is not modelled explicitly, but its impact on the drying process is accounted for by the use of convective transfer coefficients (CTCs). The same CTC value is applied on all sides of the cube. This is a simplified representation as a spatial CTC variation between the sides of the cube exists in reality for forced convection [11,18]. Within the scope of this study, including such a spatial variation is not of interest as it will not affect the main outcome of the study. Also note that the CTCs are taken constant in time, which implies, amongst others, that the air speed remains constant during drying, which is normally the case for forced convective drying. The ambient air during drying is kept at a constant temperature ($T_{ref,d}$) and relative humidity ($RH_{ref,d}$). The convective heat transfer coefficient is $100 \text{ W m}^{-2}\text{K}^{-1}$ for the base case, which is typical for forced convective drying. The CMTC is estimated from the CHTC using the heat and mass transfer analogy, similar as in [19], leading to a ratio CMTC/CHTC (analogy factor) of 7.03×10^{-9} .

An appropriate grid is built for the porous material, based on a grid sensitivity analysis. The grid consists of 64000 hexahedral finite elements, namely 40 divisions on each side ($1/8^{\text{th}}$) of the cube. A gradual refinement towards the air-tissue interface is applied to enhance numerical accuracy and stability as the largest gradients occur here, particularly at the start of the drying process.

Variants

Various cases of partial dehydration are simulated (Table 2). A first type evaluated three different stopping criteria for the drying process, namely:

- Var1_WAavg: Stopping when the (volume-)averaged water activity in the sample reaches 60%, as the latter is the critical equilibrium water activity below which no spoilage occurs ($a_{w,crit}$) for dried fruit [3].
- Var2_WAcore: Stopping when the water activity in the core of the sample reaches 60%.
- Var3_MCavg: Stopping when the (volume-)averaged moisture content in the sample reaches the critical moisture content ($w_{m,crit}$). The latter is defined as the moisture content that corresponds, via the fruit sorption isotherm (Figure 2), to an equilibrium water activity of 60% ($a_{w,crit}$). In principle, if the drying process is stopped at $w_{m,crit}$ and the sample is equilibrated in an ambient environment where the relative humidity equals $a_{w,crit}$ or lower, the average final water activity in the tissue will be below $a_{w,crit}$. This was verified by numerical simulations as well (results not reported). For the present study, $w_{m,crit}$ was 37.8 kg m^{-3} , leading to an X_{crit} of $0.29 \text{ kg kg}_{dm}^{-1}$.

Figure 2. Sorption isotherm for apple fruit (cv. Braeburn, from [16]). The red dots indicate the initial water activity (fresh tissue), and a water activity of 30% and 60%.

For this type of simulations, the times at which these stopping conditions are met, are extracted from the base case simulation (see Table 2). Afterwards, separate simulations are run for each variant, which involve partial dehydration until the stopping criterion. After stopping the drying process, each sample is placed in a low convection environment ($CHTC = 10 \text{ W m}^{-2}\text{K}^{-1}$, and $CMTC$ changes accordingly) at ambient conditions, in which the sample can equilibrate with the environment. The humidity of this environment is chosen to equal the critical equilibrium water activity ($a_{w,crit} = 60\%$) necessary to avoid spoilage. This change in environmental conditions is implemented as a step function. A smoothing function was applied to achieve a gradual transition from one environment to the other, with a transition time of 10 min. The sensitivity to smaller transition times (e.g. 1 min) was found to be very small.

A second type of simulations involves evaluating the base case for higher drying temperatures, in order to quantify how the stopping times are affected by temperature. To determine these stopping times, only the complete drying process needed to be simulated. A third type of simulations evaluates what happens if the samples are placed in an ambient environment with lower humidity ($<60\%$), after partial dehydration, and if this positively affects the drying time.

192 **Table 2. Drying conditions for different variants. If no specific value is given (indicated by a dash), the same one is**
193 **taken as the base case.**

	Drying process			Time drying is stopped	Storage process		
Name	CHTC [W m ⁻² K ⁻¹]	$RH_{ref,d}$ [%]	$T_{ref,d}$ [°C]	[hours]	CHTC [W m ⁻² K ⁻¹]	$RH_{ref,a}$ [%]	$T_{ref,a}$ [°C]
Base case	100	30	20	n.a.	n.a.	n.a.	n.a.
Stopping criterion							
Var1_WAavg	-	-	-	12.1	10	60	20
Var2_WAcore	-	-	-	39.4	10	60	20
Var3_MCavg	-	-	-	30.8	10	60	20
Drying temperature							
Base_Tref30C	-	-	30	n.a.	n.a.	n.a.	n.a.
Base_Tref40C	-	-	40	n.a.	n.a.	n.a.	n.a.
Base_Tref60C	-	-	60	n.a.	n.a.	n.a.	n.a.
Base_Tref80C	-	-	80	n.a.	n.a.	n.a.	n.a.
Ambient environment after drying							
Var1_WAavg_RHref45	-	-	-	12.1	-	45	-
Var2_WAcore_RHref45	-	-	-	39.4	-	45	-
Var3_MCavg_RHref45	-	-	-	30.8	-	45	-
Var1_WAavg_RHref15	-	-	-	12.1	-	15	-
Var2_WAcore_RHref15	-	-	-	39.4	-	15	-
Var3_MCavg_RHref15	-	-	-	30.8	-	15	-

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195 [2.3 Numerical simulations](#)

196 This hygrothermal continuum model was implemented in COMSOL Multiphysics (version 5.0), which is a finite-
197 element based solver. The partial differential equations interface (coefficient form) was used, in which the
198 aforementioned conservation equations were implemented. Transient simulations simulated a drying process of 100
199 hours, starting from the specified initial conditions. Such a long simulation time is needed as drying is performed at
200 low temperatures and since we want to monitor the fruit dehydration as well for a sufficiently long time after the

201 active drying process is stopped. All simulations applied adaptive time stepping, as determined from a temporal
202 sensitivity analysis. The tolerances for convergence and other solver settings were determined based on sensitivity
203 analysis as well. A fully coupled solver was used to solve to the dependent variables ψ and T . The simulations were
204 performed on a 12 core Intel Xeon processor (2 x 3.47 GHz) with 48GB RAM memory.

205 3. Results and discussion

206 3.1 Stopping criterion for drying process

207 The drying process for the base case and for the three stopping criteria (Table 2) are compared in Figure 3. The main
208 advantage of the simulations, compared to experiments, is that values at the surface of the fruit are available, such
209 as the mass flux and relative humidity. As they assist in interpreting the data and gaining insight in the drying
210 process, they are also depicted in Figure 3. The mass loss (change in dry matter moisture content, $X = w_m/w_s$) and
211 drying rate are shown versus time, as well as the surface-averaged temperature and relative humidity (or water
212 activity) at the air-tissue interface. Note that the drying rate equals the mass flux at the surface. The volume-
213 averaged fruit temperature was very similar to the surface temperature, which is why it is not depicted. The base
214 case is indicated with a bold black line. The dotted vertical lines indicate the stopping time for each variant.

Figure 3. Comparison of drying process simulations of the base case and three different stopping criteria: Dry matter moisture content, including the critical moisture content X_{crit} (a), drying rate (b), temperature at the surface of the fruit (c) and corresponding relative humidity (or water activity) at the surface of the fruit (d), as a function of time. The dotted vertical lines indicate the stopping time for each variant.

The three stopping criteria clearly induce a different drying behavior. As indicated in Figure 3a, the earliest stopping time occurs for Var1_WAavg, namely if the volume-averaged water activity in the sample equals $a_{w,crit}$ (60%). The reason for this is the highly nonlinear sorption isotherm (Figure 2): even if a large part of the sample is at very low water activity, its average moisture content is still quite high. The subsequent stopping time occurs for variant Var3_MCavg, so if the average moisture content in the sample reaches a critical value, namely the moisture content corresponding to a water activity of 60% ($a_{w,crit}$). This critical moisture content is extracted via the sorption isotherm at $a_{w,crit}$. For a linear sorption isotherm, Var1_WAavg and Var3_MCavg would lead to the same stopping time. The longest duration before stopping the drying process is found for Var2_WAcore. In this case, the drying process is

228 stopped if the water activity in the core of the sample equals 60% ($a_{w,crit}$). As the core holds the highest value of the
 229 water activity throughout the drying process, this obviously leads to the longest drying time.

230 For all stopping criteria, the sample takes up some moisture from the environment right after ending the convective
 231 drying process. This is indicated by an increase in moisture content (Figure 3a), a negative drying rate (Figure 3b) and
 232 an increase in temperature (Figure 3c) due to latent heat release from absorption. The reason for such uptake is that
 233 the tissue near the surface is at a very low water activity. When it is brought into contact with a higher relative
 234 humidity environment, moisture absorption is induced. Note that for higher drying temperatures ($T_{ref,d}$), a very
 235 similar behavior as in Figure 3 is found (results not shown), except for the surface temperature of course.

236 A safe moisture content to stop the drying process is $w_{m,crit}$ since, if the sample is equilibrated in a sufficiently low RH
 237 environment, the average final water activity in the tissue will be below $a_{w,crit}$. From Figure 3, we clearly see that if
 238 the drying process is stopped early (Var1_WAavg), namely when the volume-averaged water activity in the sample
 239 equals 60%, the drying time to reach a safe moisture content ($w_{m,crit}$) is about twice as large as the one for
 240 Var3_MCavg, namely when the average moisture content in the sample reaches the critical moisture content. From a
 241 food safety perspective, such extensive drying time could become problematic but this aspect should be addressed
 242 separately by experiments.

243 On the other hand, if the sample is dried to much (Var2_WAcore), so below $w_{m,crit}$, significant moisture uptake occurs
 244 after drying, namely up to $w_m = w_m(RH_{ref,a})$ which equals $w_{m,crit}$ in this case. As a part of the final moisture present in
 245 the fruit did not have to be removed by convective drying, such overdrying is energetically not efficient. From these
 246 results, the most logical stopping criterion is drying until $w = w_{m,crit}$, so Var3_MCavg (blue line in Figure 3). This
 247 stopping time should also pose no problems with food safety as equilibration within the sample to a safe water
 248 activity occurs rather fast. Stopping when the (volume-)averaged moisture content in the sample reaches the critical
 249 moisture content seems a good compromise between reducing drying time and ensuring food safety.

250

251 The dry base moisture content and the water activity inside the sample at different points in time are shown in
 252 Figure 4 and Figure 5 for the base case and the variants. For all cases, moisture redistribution inside the sample
 253 clearly occurs after the drying process is stopped. The temperature distribution is not shown as the gradients within
 254 the sample were very low due to the rather slow mass transfer process compared to the heat transfer kinetics.

Figure 4. Dry matter moisture content X (range 0 – 1 kg kg_{dm}^{-1}) in a center plane of the cube (1/4 of cube depicted due to symmetry) for the base case and the three variants at different points in time.

Figure 5. Water activity a_w (range 0 – 1) in a center plane of the cube (1/4 of cube depicted due to symmetry) for the base case and the three variants at different points in time.

262 3.2 Impact of drying temperature

263 The impact of the drying air temperature on the magnitude of the aforementioned stopping times is evaluated. To
264 this end, simulations similar to the base case, but at higher drying temperature ($T_{ref,d}$), are performed (Table 2). The
265 stopping time for each criterion is evaluated for each temperature and represented in Figure 6. The stopping time for
266 each variant is presented relative to that of the corresponding variant at 20°C (Figure 6a, $t_s/t_{s,20^\circ C}$), and relative to the
267 time until the sample is fully dry at each corresponding temperature (Figure 6b, $t_s/t_{s,dry}$). Fully dry is defined here as
268 the time when the moisture content does not change significantly anymore compared to the final moisture content,
269 i.e. with less than 0.1 kg m⁻³ difference.

270 From Figure 6a, each stopping criterion has a different dependency on the drying temperature, where in general the
271 process can be stopped earlier when a higher drying temperature is used. Var2_WAcore and Var3_MCAvg have a
272 very similar behavior, since they both occur close to the end of the drying process. From Figure 6b, the time that a
273 fruit has to spend in the dryer, compared to when it is fully dried, is much lower for Var3_MCAvg, namely when the
274 average moisture content in the sample reaches the critical moisture content. However, a particularly low drying
275 time is found for Var1_WAavg for each $T_{ref,d}$, namely the case when the (volume-)averaged water activity in the
276 sample reaches 60%. The drying time is roughly 25% and 70% lower for Var3_MCAvg and Var1_WAavg respectively.
277 Such a reduced residence time in the dryer still leads to a sufficiently dry product, but significantly increases
278 throughput and can reduce energy consumption. For Var2_WAcore on the other hand, i.e. when drying is stopped if
279 the water activity in the core of the sample equals 60%, the fruit is already quite dry.

280 The representation used in Figure 6a is useful to compare drying processes at different conditions in a quantitative
281 way, since a drying curve can be represented by a single characteristic value, namely the stopping time t_s . For
282 Var3_MCAvg, the stopping time equals the critical drying time (t_{crit}), as it is the time needed for the sample to reach
283 the critical moisture content ($w_{m,crit}$). This $w_{m,crit}$ can serve as a useful parameter to decide to stop a drying process.

Figure 6. Stopping time at different drying temperatures for three stopping criteria: (a) relative to stopping time at 20°C for each variant; (b) relative to the time when sample is fully dry at each corresponding drying temperature.

3.3 Impact of ambient environment after drying

The impact of the ambient environment in which the sample is placed after partial dehydration is evaluated in Figure 7 for three different stopping criteria. Two lower $RH_{ref,a}$ are considered, namely 45% and 15%. These environments represent for example a storage room, the ambient environment in the food processing plant, or the package. Note that if samples are placed in a closed container or package, the humidity of the environment will increase with time, and will thus not be constant. Similar to Figure 3, the dry matter moisture content ($X = w_m/w_s$) and drying rate are shown versus time, as well as the surface-averaged temperature and relative humidity (or water activity) at the air-tissue interface.

When placed in a 45% environment, the graphs look similar to Figure 3. Obviously however, placing the sample in such a drier environment after drying is beneficial for reaching a safe water activity earlier. When placed in a very dry environment ($RH_{ref,a} = 15\%$), the fruit even reaches a higher drying rate than the base case over the majority of the time ($RH_{ref,a} = 30\%$) and no noticeable moisture adsorption occurs when the drying process is stopped. In addition, the larger evaporation rate induces a clear temperature drop.

Figure 7. Comparison of drying process simulations of the base case and three different stopping criteria for two relative humidities of the ambient environment: Dry matter moisture content, including the critical moisture content X_{crit} (a), drying rate (b), temperature at the surface of the fruit (c) and corresponding relative humidity (or water activity) at the surface of the fruit (d), as a function of time. The dotted vertical lines indicate the stopping time for each variant.

3.4 Discussion

When to stop drying?

This study indicates that it is more advantageous to stop the drying process before complete dehydration, as unnecessary re-adsorption of water is avoided. This procedure should in principle not compromise food safety, as still a sufficiently low water activity can be obtained within the fruit after equilibration.

From the insights in the moisture redistribution, it seems that stopping the drying process when the (volume-)averaged moisture content in the sample reaches the critical moisture content ($w_{m,crit}$) (Var3_MCavg) is a good compromise. For sufficiently small samples and dry environments ($RH < 60\%$), the sample will be able to equilibrate rather fast to a safe water activity ($a_w \approx 60\%$) to avoid spoilage. Stopping when the (volume-)averaged water activity in the sample reaches 60% (Var1_WAavg), implies that the sample still contains a quite large amount of water and, if applied, it should be further looked at in terms of food safety.

A remark should be made regarding the applicability of $w_{m,crit}$ as a stopping criterion. This study considered small temperature differences between the sample, the drying air and the ambient environment in which the fruit is placed in after drying. As the water activity and sorption isotherm are dependent on temperature, $w_{m,crit}$ during drying can differ a bit from $w_{m,crit}$ at ambient temperature. Although this will not drastically impact the results, this effect should be explored further.

Model improvements

The simulations enabled to evaluate different stopping criteria, which is less straightforward in experiments. The reason is that this has to be done in an offline manner as the samples need to be physically removed from the dryer. Specialized equipment is required and, for water activity measurements, the sample needs to be equilibrated in the device. Modelling, on the other hand, requires knowledge of the sorption isotherm and moisture permeability of the tissue, which need to be measured experimentally.

The continuum model that is used to evaluate the drying process is known to many drying technologists and is rather straightforward to implement in commercial software (e.g. COMSOL Multiphysics). Model improvements can still be made to better represent the physical processes and further increase model realism.

One of them is including tissue shrinkage, induced by moisture loss, as already implemented by other authors [20–22]. As a result, the drying behavior will differ a bit, as shrinkage reduces the fruit volume. However, this would also require to determine new sorption isotherms and moisture permeability of different states of the shrunken tissue. This implies an extensive material characterization effort, which is rarely performed in drying engineering. In principle, adding shrinkage will not alter the conclusions of the present study, but will result in somewhat altered stopping times, as volume-averaged values are used.

Another model improvement is to implement a prediction of fruit quality evolution during drying. This can be done, for example, by implementing quality models, which predict degradation reactions based on temperature and water activity [23]. Finally, the material properties (moisture permeability, thermal properties) are taken constant. It would be useful to include the biological variability of these properties in the modelling, for example by using Monte Carlo simulations [24].

4. Conclusions

This study explored the impact of stopping the drying process, prior to complete dehydration, on the drying time and moisture redistribution kinetics inside the fruit during equilibration in the ambient environment. The three stopping criteria that were evaluated were based on the magnitude of the final water activity or the residual moisture content in the sample. These variants led to a decrease in residence time in the dryer of 70% (Var1_WAavg), 2% (Var2_WAcore) and 24% (Var3_MCavg), compared to full dehydration. Particularly variant Var3_MCavg was interesting as it reduced the residence time significantly. At the same time, this variant did not pose food safety issues, after the moisture was redistributed in the fruit during equilibration in the ambient environment. For this variant, drying is stopped when the average moisture content in the sample reaches the value corresponding to an equilibrium water activity of 60% in the sample, as determined from the sorption isotherm.

We also quantified how the humidity of the ambient environment in which the dried fruits are placed after drying affected the moisture redistribution kinetics. Furthermore the relation of the drying time to the drying air temperature was quantified for all stopping criteria.

This study gives a better quantitative insight in when fruit drying should be stopped, given specific drying conditions, as a way to reduce energy consumption (less rehydration) and processing time, and to improve product quality. The hygrothermal model allowed a detailed evaluation of the drying process and what happens within the fruit material during relaxation after stopping the drying process. Such modelling of the moisture redistribution kinetics could be of use for process optimization of intermittent drying, amongst others.

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