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# Mathematical modelling of convective drying of fruits: A review

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ABSTRACT

The convective drying of fruits is the most implemented drying technique to stabilize fruits and to increase their shelf life. The mathematical modelling of drying is a useful tool in process optimization and dryer design. The modelling involves the solution of complex partial differential equations of coupled heat, mass and momentum transfer, which can be solved by several numerical and analytical methods. The aim of this review is to present and analyse the main published researches on the modelling of the convective drying of fruits focused on theoretical models. The main parameters involved in the numerical modelling of fruit drying are presented, such as the main mathematical models in the conjugated or non-conjugated approach, the applications on different geometries and dimensions, the scale approach, the thermophysical and transport properties determination, the alternatives of numerical solutions, the main methods to determine convective transfer coefficients, and other modelling considerations such as the shrinkage inclusion and quality deterioration are presented and analysed in this review based on the studies reported in the literature in the past decade. Through their comparison and analysis, future perspectives and challenges in fruit drying modelling are discussed. The computational tools increase the accuracy in predicted values and the possibility to extrapolate the characteristics from a micro-scale level to a macro-scale level. The challenges for convective drying of fruit lead to overcoming the dependence on empirical models for drying parameters determination, the lack of shrinkage inclusion and 3D modelling by means of advanced procedures such as multi-scale and conjugated modelling. The definition of the application of the model is important. Simple models present an effective use in some cases of engineering applications. More complex models are closer to reality and useful to engineering and research purposes.

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## Nomenclature

| | |
|---|---|
| $a_w$ | water activity |
| $T_\infty$ | air temperature (°C) |
| $C_m$ | water capacity (kg $kg^{-1}Pa^{-1}$) |
| x, y, z | coordinates (m) |
| $C_\mu$ | empirical turbulence model constant |
| X | moisture content ((kg $kg^{-1}$, dry basis, db) |
| $C_p$ | specific heat (J $kg^{-1}$ $K^{-1}$) |
| $w^*$ | dimensionless moisture content |
| $C_\infty$ | water concentration in air (mol $m^{-3}$) |

*Greek symbols*

| | |
|---|---|
| $C_o$ | water concentration in fruit (mol $m^{-3}$) |
| $\alpha$ | thermal diffusivity ($m^2s^{-1}$) |
| $C_{w,c}$ | water content on wet base (kg $kg^{-1}$) |
| $\varepsilon$ | turbulent dissipation rate ($m^2$ $s^{-3}$) |
| $D_{eff}$ | effective moisture diffusivity ($m^2s^{-1}$) |
| $\phi$ | porosity |
| $D_c$ | water diffusion coefficient inside cells ($m^2s^{-1}$) |
| $\theta$ | dimensionless temperature |
| h | heat transfer coefficient (W $m^{-2}$ $K^{-1}$) |
| $\rho$ | density (Kg $m^{-3}$) |
| $h_{fg}$ | latent heat of evaporation (J $kg^{-1}$) |
| $\rho_s$ | density of solid product = dry mass/total volume (kg $m^{-3}$) |
| $h_l$ | enthalpy of liquid water (J $kg^{-1}$) |
| $\rho_{w,c}$ | wet base cell density (Kg $m^{-3}$) |
| $h_m$ | mass transfer coefficient (m $s^{-1}$) |
| $\sigma_\kappa$ | model parameter |
| I | net superficial incident radiation (W $m^{-2}$) |
| $\varsigma$ | ($\varkappa L_o^{-1}$)diffusion timescale(dimensionless) |
| J | Jacobian of the transformation ($m^{-3}$) |
| $\tau$ | time in the transformed domain |
| k | turbulent kinetic energy ($m^2$ $s^{-2}$) |
| $\omega$ | specific dissipation ($s^{-1}$) |
| $K_m$ | moisture permeability of the tissue (s) |
| $\varkappa$ | thickness (m) |
| $K_g$ | intrinsic permeability of gas ($m^2$) |
| $\eta$,$\mu$ | dynamic viscosity (N s $m^{-2}$) |
| $K_{r,g}$ | relative permeability of gas |
| $\mu_\tau$ | turbulent viscosity (Kg $m^{-1}$ $s^{-1}$) |
| $K_1$-$K_4$ | model coefficients |
| $\xi$, $\gamma$ | axes of the system of generalized coordinates (dimensionless) |
| *Le* | Lewis number |
| $\lambda$ | thermal conductivity (W $m^{-1}$ $K^{-1}$) |
| $\dot{m}$ | evaporation rate (kg $m^{-2}s^{-1}$) |
| $\psi$ | water potential (Pa) |
| $\dot{m}_{v,loss}$ | internal water vapor loss (kg $s^{-1}$) |

*Subscripts*

| | |
|---|---|
| $a_{11}$- $a_{22}$ | coefficients for the diffusion model in generalized coordinates |
| a | air |
| P | pressure (Pa) |
| c | cell |
| ($\dot{Q}$) | volumetric heat generation ($Wm^{-3}$) |
| g | gas |
| R | radius (m) |
| eq | equilibrium |
| RH | relative humidity of drying air (%) |
| pol | polyphenols |
| r, y | position in cylindrical coordinates (m, m) |
| PM | porous medium |
| u | shrinkage velocity ($ms^{-1}$) |
| sol | solid |
| *u* | velocity (m $s^{-1}$) |
| t | drying time (s) |
| T | absolute temperature (K) |
| $\bar{T}$ | scaled temperature (dimensionless) |

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## 1. Introduction

Fruits are biological materials and the source of many biological, flavour and aroma compounds of interest in health and industry. Fruits can be consumed fresh or processed, and drying is one of the most used methods to stabilize fruits and their compounds. Dried fruit has been used as snack and ingredient to formulate functional foods, pharmaceuticals and cosmetic products. Drying is a unit operation to remove water from a product and consequently to reduce its water activity (Omolola et al., 2015). There are many advantages of fruit drying, such as: the inhibition of the growth of microorganisms and deterioration reactions by the water activity reduction (Caccavale et al., 2016) as well as the reduction of transport and storage costs due to product weight and volume decrease (Fernandes et al., 2011; Kaleta et al., 2013; Márquez and de Michelis, 2011; Tzempelikos et al., 2015).

Convective drying is the process of removing water with air via simultaneous heat, mass and momentum transfer. The required heat is conducted to the food by a stream of hot air. The energy is transferred to the surface of the product by convection and then is transferred inside the product by diffusion or convection, depending on the product structure. This heat flux causes a product temperature increase and water evaporation (Bezerra et al., 2015; García-Alvarado et al., 2014). The moisture is transferred from the product surface to the air by convection as water vapor and from inside the product by diffusion, convection or capillarity (Ertekin and Firat, 2015; Fernando et al., 2011). The drying rate and the dried product properties depend on the external conditions of the process such as air temperature, humidity, velocity and the air flux direction. Additionally, the drying rate depends on internal conditions such as the product geometry, thickness, shape and structure. The complexity of the fruits structure and composition, the variety of transport phenomena and the biological variability make the drying of fruits a challenge. For these reasons, mathematical modelling and simulation is an appropriate tool to deal with the complexity of fruit drying. It also allows for obtaining the suitable operational conditions through optimization.

Mathematical modelling in fruit drying is the use of mathematical equations to predict the behaviour of the operation (Wang et al., 2007). There are several steps to approach the drying mathematical model. First, the transport phenomena equations are established. These equations are based on the general transport equation, which governs the way in which the heat and mass transfer evolve and behave. There are simplified cases for modelling and simulation; therefore, the general transport equation is expressed by means of partial differential equations system (PDEs) under different assumptions and constraints. Second, the model assumptions are established: dimensionality, transport phenomena coupling, material properties, and shrinkage, among others. Then, the initial and boundary conditions are determined based on the fruit-air interaction. Subsequently, the fruit parameters are set, which depend on the assumptions and the boundary parameters related to transfer coefficients. Finally, the PDEs are solved through numerical or analytical methods and model validation with experimental data.

Due to the complexity of the measurement of some variables during drying experiments, mathematical models can be used to simulate the distribution of temperature, moisture, and velocity, among other variables with high spatial and temporal resolution (Abera et al., 2016; Defraeye, 2014). In addition, mathematical models allow for the design and evaluation of dryer performance, control and optimization of the process, which is of paramount importance in maintaining food safety, sensory and nutritional quality.

Several parameters must be defined for the mathematical modelling of drying. The main parameters of modelling are presented in Fig. 1. These parameters should be established before starting a mathematical modelling during the model conceptualization. These parameters include the dimension, geometry, and thermophysical properties of the fruit, the transport phenomena and the scale approach. In addition, the transfer coefficients, the method to solve the PDEs system have to be determined. Finally, other approaches such as the inclusion of shrinkage, the modelling of the quality deterioration or the mechanical deformation can be considered. Diverse assumptions of these parameters are accounted for in this review. The distribution of the studies in the modelling of convective fruit drying according to the simulation parameters is presented in Fig. 2.

The importance of modelling is to not only provide process predictions, but also extract more details and gain new insights about the process of fruit drying. The state-of-the-art establishes the development of different mathematical models according to their complexity, sophistication and application. Therefore, there is no universally valid type to model drying behaviour, which performs well for all the fruits. It is worth comparing and analysing the different approaches on convective drying modelling.

The aim of the present review is to provide insight about the several alternatives on fruit convective drying modelling in the past 10 years. The fruit properties modelling, the scale approach, the alternatives to determine the convective transfer coefficients, the numerical and computational solutions of the phenomenon equations and other modelling considerations such as shrinkage and quality deterioration modelling such as colour, texture and bioactive compounds are presented and analysed in this review based on studies reported in the literature in the past decade. Through their comparison and analysis, the future perspectives and challenges in fruit drying modelling are discussed.

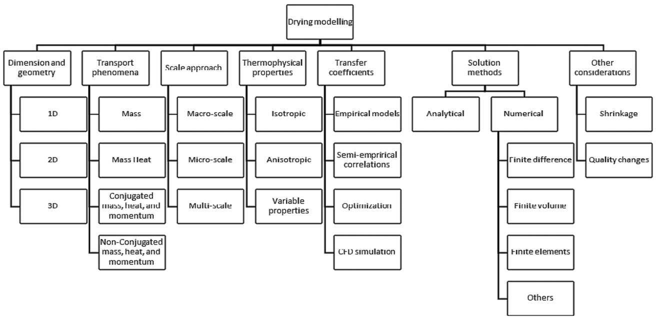

**Fig. 1.** Parameters of mathematical modelling of fruit drying.

## 2. Theoretical modelling

The mathematical models for fruit drying can be classified in two categories: those involving semi-theoretical equations, for example the models under the concept of thin layer and the theoretical models based on the fundamental physics of drying. The semi-theoretical models are still used and represent a good tool for modelling fruit drying kinetics. However, the use of the theoretical models is increasing thanks to the availability of the advanced numerical computation and to its relevance for the fruit drying understanding. The present review is focused on the theoretical modelling. For an analysis of the semi-theoretical models, the works of Erbay and Icier (2010), Ertekin and Firat (2015) and Putranto et al. (2011) can be reviewed.

At the same time, theoretical models can be developed at the macro and micro level and are found in the works of Luikov and Whitaker in the 1970s, who settled the foundation of posterior theoretical mathematical models for drying (Wang et al., 2007). Luikov's system has been used to model the moisture and temperature transport at the macro and micro level. Lamnatou et al. (2010, 2009), Wang et al. (2007) and Datta (2007) indicated that this model presents drawbacks related to lack of theoretical foundation leading to semi-empirical solution and the physical interpretation of the parameters is not clear. Despite this, the Luikov model is still used and represents a good approximation in the micro-scale approach. However, Whitaker's theory has been also used in both the macro and micro-scale models. This approach is based on conservation equations, and the physics of the model are better understood than Luikov's (Defraeye, 2014; Defraeye and Radu, 2017).

The theoretical models are used to study the heat, mass and momentum transfer in two subdomains (air-fruit). These transport phenomena form a system of non-linear (PDEs). The PDEs are equations based on the general transport equation, which can be derived into physical laws such as Fick's Second Law for mass transfer, Fourier's Law for heat transfer by conduction and Newton's law for momentum transfer. The PDEs can be coupled in the boundary conditions or coupled in the air and fruit thermophysical properties. The representative equations for heat, mass and momentum transfer at the macro and micro scale for fruit undergoing the convective drying process are presented in Table 1.

Eq. (1) describes at the macro scale the transient heat transfer within the fruit during drying according to Fourier's law of heat conduction. The diffusional parameter of heat transfer is the thermal diffusivity ($\alpha$) which can be expressed as a function of thermal conductivity, density and specific heat. The driving force of heat transfer is the temperature gradient. Eq. (6) represents the

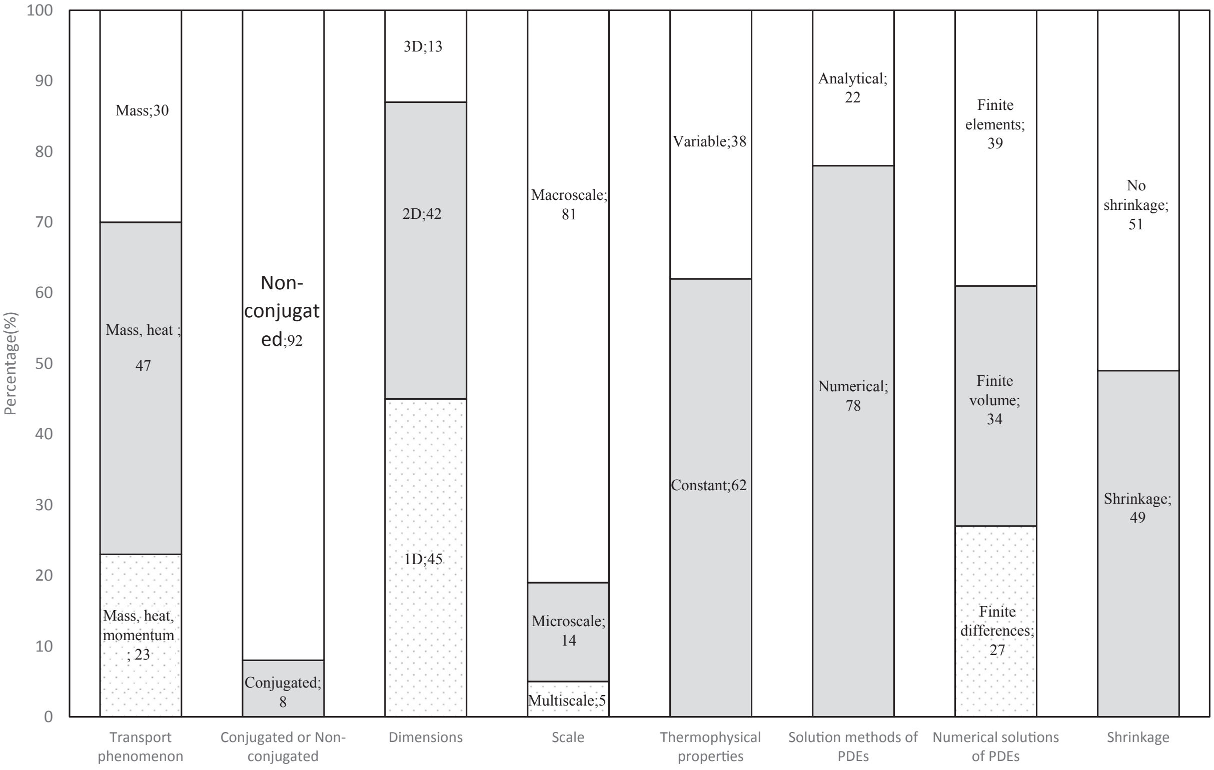

**Fig. 2.** Distribution of the studies in modelling of convective fruit drying according to the simulation parameters.

moisture transfer inside the fruit during drying as a function of time and position. $D_{eff}$ is the mass diffusional parameter in Fick's law. $D_{eff}$ represents the conductive term of all the moisture transfer mechanism inside the fruit such as molecular diffusion, capillary flow, Knudsen flow and hydrodynamic flow. All these are lumped in this term (Bon et al., 2007; Erbay and Icier, 2010). The driving force for water diffusion inside the fruit is the concentration gradient developed by the evaporation of water on the surface, due to the difference of the water vapor partial pressure between the surface and the air. Eqs. (1, 5) and (13) can be rewritten according to the model conceptualization and assumptions for the drying system. For example, Eqs. (2, 3, 6, 7), represent the heat and mass transfer in 2D and 3D and constant values of $\alpha$ and $D_{eff.}$

## 3. Conjugated and non-conjugated models

The theoretical models can be formulated with a conjugated or non-conjugated approach. The non-conjugated approach solves all the transport phenomena in the solid domain only, while the conjugated approach takes into account all the transport phenomena in two domains (air and fruit) and solves them simultaneously (Defraeye and Verboven, 2017a; Lamnatou et al., 2010; Lemus-Mondaca et al., 2017; Sabarez, 2015, 2012). For the non-conjugated models, the momentum transfer is used just to determine velocity profiles and to determine convective coefficients. The individual mass transfer consideration has been recognized for 30% of papers included in this review (Fig. 2). In this approach, the diffusion models have been extensively recognized in the fruit drying process to describe moisture transfer. These models consider the moisture transfer mainly in two dimensions, followed by one dimension. In addition, they have the assumption that the water transfer from the interior of the product to its surface occurs by liquid diffusion. The theoretical modelling of moisture transfer in fruit drying has been addressed mainly by Da Silva et al. (2014a, 2013b, 2012). These works consider that the moisture transport is the main mechanism in drying and it is suitable to describe drying kinetics. Moisture transport is affected by both internal and external conditions. The most common consideration is that external conditions govern the process in the constant drying period. Then, during the falling period, the internal conditions are predominant. However, the work of Giner (2009), established the influence of both the internal and external conditions at the constant drying period. Finally, the studies that consider only the mass transfer, suggest that the fruit drying is an isothermal process without temperature internal gradients. Thus, temperature transport is neglected. This assumption is commonly used for fruits with small size, arranged in thin layer, with low air temperatures or for long drying time.

The solution of moisture PDE is simplified when only the mass transfer is considered, leading to an analytical solution (Da Silva et al., 2013b; Schössler et al., 2012; Torki-Harchegani et al., 2015) but also numerical solution (Da Silva et al., 2014b, 2009, Janjai et al., 2010, 2008a, 2008b). Additionally, the purposes of these studies when considering only mass transfer are: (i.) The determination of moisture transport properties such as convective mass transfer coefficient, effective moisture diffusivity and thermophysical parameters by optimization (Da Silva et al., 2012) or by analytical models (Bezerra et al., 2015); (ii.) To include shrinkage (Aregawi et al., 2014b, 2013a, 2013b) and variable effective moisture diffusivity (Da Silva et al., 2014b, 2013b; Schössler et al., 2012); (iii.) The study of the effect of the external resistance to mass transfer (Bon et al., 2007) or pre-treatments such as ultrasound (Do Nascimento et al., 2015; Gamboa-Santos et al., 2014). The models mentioned above belong to the macro-scale approach (Eq. 10) in terms of water potential ($\psi$) and moisture capacity $C_m$. Moreover, with the micro-scale approach, the works of (Aregawi et al., 2014a;

**Table 1**
Representative models of transport phenomena during convective drying of fruits.

| No | Models | Description | Reference |
|---|---|---|---|
| | **Macroscale Models** | | |
| | **Heat transport equations** | | |
| 1 | $\frac{\partial T}{\partial t} = \nabla \cdot (\alpha \nabla T)$ | The general representation for energy PDE. Here, $\alpha$ is considered variable | (Golestani et al., 2013; Ruiz-López and García-Alvarado, 2007) |
| 2 | $\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)$ | The 2D representation for energy PDE. Here, $\alpha$ is considered constant. | (Esfahani et al., 2014, 2015; Janjai et al., 2010; Kaya et al., 2008, 2007b; Moraga et al., 2011; Oztop and Akpinar, 2008; D. a. Tzempelikos et al., 2015a; Vahidhosseini et al., 2016; Villa-Corrales et al., 2010) |
| 3 | $\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$ | The 3D representation for energy PDE. Here,$\alpha$ is considered constant. | (Chandra Mohan and Talukdar, 2010; Chandramohan, 2016; Esfahani et al., 2015; Lemus-Mondaca et al., 2013a) |
| 4 | $\frac{\partial \bar{T}(\varsigma,\tau)}{\partial \tau} = \mathrm{Le} \frac{\partial^2 T(\varsigma,\tau)}{\partial \varsigma^2}$ | The energy transport equation expressed in terms of non-dimension scaled variables | (Shahari et al., 2016) |
| | **Mass transport equations** | | |
| 5 | $\frac{\partial X}{\partial t} = \nabla \cdot (D_{eff} \nabla X)$ | The general representation for moisture PDE. Here, *Deff* is considered variable | (Golestani et al., 2013; Janjai et al., 2010; Ruiz-López and García-Alvarado, 2007) |
| 6 | $\frac{\partial X}{\partial t} = D_{eff} \left( \frac{\partial^2 X}{\partial x^2} + \frac{\partial^2 X}{\partial y^2} \right)$ | The 2D representation for moisture PDE. Here, *Deff* is considered constant. | (Esfahani et al., 2014, 2015; Janjai et al., 2010; Kaya et al., 2008, 2007b; Moraga et al., 2011; Oztop and Akpinar, 2008; D. a. Tzempelikos et al., 2015a; Vahidhosseini et al., 2016; Villa-Corrales et al., 2010) |
| 7 | $\frac{\partial X}{\partial t} = D_{eff} \left( \frac{\partial^2 X}{\partial x^2} + \frac{\partial^2 X}{\partial y^2} + \frac{\partial^2 X}{\partial z^2} \right)$ | The 3D representation for moisture PDE. Here, $D_{eff}$ is considered constant. | (Chandra Mohan and Talukdar, 2010; Chandramohan, 2016; Esfahani et al., 2015; Lemus-Mondaca et al., 2013a; Rodríguez et al., 2014) |
| 8 | $\frac{\partial}{\partial \tau} \left( \frac{X}{J} \right) = \frac{\partial}{\partial \xi} \left( a_{11} JD \frac{\partial X}{\partial \xi} + a_{12} JD \frac{\partial X}{\partial \gamma} \right) + \frac{\partial}{\partial \gamma} \left( a_{21} JD \frac{\partial X}{\partial \xi} + a_{22} JD \frac{\partial X}{\partial \gamma} \right)$ | The diffusion model for solids obtained by revolution of arbitrary shaped plane surfaces | (da Silva et al., 2014, 2010, 2009) |
| 9 | $\frac{\partial X}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r\mathrm{Deff} \frac{\partial X}{\partial r} \right) + \frac{\partial}{\partial y} \left( \mathrm{Deff} \frac{\partial X}{\partial y} \right)$ | The 2D moisture equation expressed in cylindrical coordinates with variable $D_{eff}$ | (Baini and Langrish, 2007; da Silva et al., 2013; Fernando et al., 2011; Guiné, 2008; Guiné and Barroca, 2013; Guiné et al., 2007; Torki-Harchegani et al., 2015) |
| 10 | $C_m \frac{\partial \psi}{\partial t} + \nabla.(-K_m \nabla \psi) = 0$ | The moisture transfer model where water moves in the tissue due to a gradient in water potential. Model used to coupled with mechanical deformation | (Aregawi et al., 2014b, 2013a, 2013b; Defraeye and Verboven, 2017a; Fanta et al., 2014) |
| 11 | $\frac{\partial X}{\partial t} + u \frac{\partial X}{\partial x} = D_{eff} \frac{\partial^2 X}{\partial x^2}$ | The moisture transfer model in 1D incliuding shrinkage as a convective velocity | (Golestani et al., 2013) |
| 12 | $(1 - \varphi) \rho_{sol} \frac{\partial X_{pol}}{\partial t} = \dot{m}pol$ | The mass balance in the solid, accounting for changes in polyphenols | (Alean et al., 2016) |
| | **Momentum equations** | | |
| 13 | $\rho \frac{\partial u}{\partial t} - \nabla \left( \eta + \rho \frac{C_\mu k^2}{\sigma_\kappa \varepsilon} \right) \cdot (\nabla u + (\nabla u)^T) + \rho u \cdot \nabla u + \nabla P = 0 \lim_{x \to \infty}$ | The equation for the momentum transport for the air in the drying tunnel is represented by the standard k-ε model | (Sabarez, 2012) |
| 14 | $\rho_a C_{pa} \left( \frac{\partial T_\infty}{\partial t} \right) + \nabla(-\lambda_a \nabla T_\infty) + \rho_a C_{pa} u \nabla T_\infty = 0$ | The energy balance in the drying air, considering convection and conduction | (Sabarez, 2012) |
| | **Microscale models** | | |
| | **Heat transfer equations** | | |
| 15 | $\frac{\partial \theta}{\partial \tau} = \frac{\partial}{\partial x} \left[ K_1 \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_1 \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial x} \left[ K_2 \frac{\partial w*}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_2 \frac{\partial w*}{\partial y} \right]$ | The 2D energy dimensionless equation for the porousmedia | (Lamnatou et al., 2010, 2009) |
| 16 | $h_l C_m \frac{\partial \psi}{\partial t} + C_{m,t} \frac{\partial T}{\partial t} + \nabla.(-h_l K_m \nabla \psi) + \nabla.(k_{PM} \nabla T) = 0$ | The continuum energy model for porous media | (Defraeye and Verboven, 2017a) |
| | **Mass transfer equations** | | |
| 17 | $\frac{\partial w*}{\partial \tau} = \frac{\partial}{\partial x} \left[ K_3 \frac{\partial w*}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_3 \frac{\partial w*}{\partial x} \right] + \frac{\partial}{\partial x} \left[ K_4 \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_4 \frac{\partial \theta}{\partial y} \right]$ | The 2D moisture dimensionless equation for the porous solid | (Lamnatou et al., 2010, 2009) |
| 18 | $\frac{\partial \rho_{w,c}}{\partial t} = \nabla \cdot \rho_c D_c \nabla c_{w,c}$ | The water transport model for the cell wall | (Aregawi et al., 2014a; Fanta et al., 2014) |
| | **Air equations for conjugated models** | | |
| 19 | $\mu_t = \rho C_\mu \frac{k}{\varepsilon}$ | The $k - \varepsilon$ turbulence model of eddy viscosity. Is based on the transport equations for the turbulent kinetic energy $k$ and its dissipation rate $\varepsilon$, | (Norton et al., 2013) |
| 20 | $\mu_t = \rho \frac{k}{\omega}$ | The $k - \omega$ turbulunce model of eddy viscosity. Is based on modelled transport equations for the turbulent kinetic energy $k$ and the specific dissipation rate $\omega$ | (Norton et al., 2013) |
| | **Equations for hybrid technologies** | | |
| 21 | $\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda r \frac{\partial T}{\partial r} \right) + \dot{Q} - \frac{m_{\dot{v},loss} h_{fg}}{V}$ | 1-D heat transfer model for Convective-microwave. It accounts for the internal water vapor loss ($m_{\dot{v},loss}$) and microwave volumetric heat generation ($\dot{Q}$). | (Bingol et al., 2008). |
| 22 | $\frac{\partial}{\partial t} (\rho_g \varphi S_g) - \nabla \left( \rho_g \frac{k_g k_{r.g}}{\mu_i} \nabla P \right) = R_{evap}$ | Equation that describes the evaporation rate for gas phase for intermittent microwave convective drying | (Kumar et al., 2016) |
| 23 | $Nu = \frac{h L}{k} = a Re^{0.5} \left( \frac{T_g}{T_s} \right)^2 \left( \frac{T_{FIR}}{T_G} \right)^4 (MR)^b$ | Equation for heat transfer for far-infrared drying. The parameter $\left( \frac{T_g}{T_s} \right)^2$ describes the convective transfer. $\left( \frac{T_{FIR}}{T_G} \right)^4$ is the radiation heat transfer rate. | (Jaturonglumlert and Kiatsiriroat, 2010) |

Fanta et al., 2014, 2013) used the one-variable model to predict moisture loss coupled with deformation, although the one-variable model is still used because of its simplicity for drying at relatively low temperature or without the effect of temperature. It should be avoided because the effect of temperature is important for moisture transport. A coupled model accounting for mass and heat transport is more suitable for fruit convective drying.

The simultaneous and coupled heat and mass transfer approach has been the most used by researches during the past ten years (47%), as shown in Fig. 2. In addition, both transport phenomena are mainly modelled unidimensionally (Baini and Langrish, 2007; Ben Mabrouk et al., 2012; Bingol et al., 2008; Defraeye, 2017, 2016; Golestani et al., 2013; Guiné, 2008; Guiné et al., 2007; Jaturonglumlert and Kiatsiriroat, 2010; Kumar et al., 2016; Oztop and Akpinar, 2008; Ratti and Crapiste, 2009; Shahari et al., 2016; Villa-Corrales et al., 2010). Nonetheless, Barati & Esfahani (2013) considered the uncoupled governing equations of temperature and moisture using an analytical solution. As discussed by Shahari et al. (2016), this practice is not correct in terms of model structure. This coupled approximation allows one to calculate the temperature and moisture fields inside the fruit undergoing drying, and they give insights of the operation. In this approach, moisture transport involves two dependent processes: the evaporation of liquid water at the fruit surface that needs heat from the drying air and the internal diffusion of liquid from the centre of the fruit to the surface. It is common to find in these models the assumptions: (i.) To treat drying as non-isothermal process; (ii.) Mass transfer inside the fruit is performed by diffusion and the heat transfer by conduction; (iii.) The evaporation occurs only at the surface and the moisture transport is not split up in vapor and liquid water transport, suggesting that moisture transport inside the fruit occurs in the liquid phase and not by water vapor (Defraeye and Radu, 2017; Esfahani et al., 2014); (iv.) Negligible radiation effects; and (v.) No heat generation inside the fruit.

The simple way to solve heat equation implies the lumped capacitance method for heat transfer within the food. Here, the temperature gradient within the food is negligible. Therefore, the heat equation is easier to solve by means of an analytical solution (Barati and Esfahani, 2011; Nuñez Vega et al., 2016). Other researchers used analytical solution solving both heat and moisture equations (Barati and Esfahani, 2013; Esfahani et al., 2015; Vahidhosseini et al., 2016). In addition, to reduce the number of parameters and minimize computer time on the problem, non-dimension numbers have been used in Eq. (4) (Shahari et al., 2016). However, numerical methods are the most used for the solution of PDEs. In addition, the coupled heat and mass transfer allows for optimization in terms of air velocity, temperature and moisture content, and also allows for the two-dimensional and three-dimensional analysis of heat and moisture transfer during drying.

A more advanced approach of coupled heat and mass transfer is to include the momentum equation for the air. This approach is considered by 24% of reviewed papers (Fig. 2). The application of these models is relatively recent (Chandra Mohan and Talukdar, 2010; Da Silva et al., 2014b; Defraeye and Verboven, 2017a; Esfahani et al., 2014; Golestani et al., 2013; Janjai et al., 2010; Kaya et al., 2008, 2007b; Khan and Straatman, 2016; Lamnatou et al., 2009, 2010; Lemus-Mondaca et al., 2017; Moraga et al., 2011; Sabarez, 2012; Tzempelikos et al., 2015), and CFD can be used to predict air velocities, as is explained in Section 7. Furthermore, these models account for the three transport phenomena in two dimensions mainly, followed by three dimensions.

The conjugated approach offers high accuracy and widespread applicability. However, the solution process is complex and requires a strong mathematical treatment of equations and computational tools. For this reason, just 5% belongs to the conjugated approach (Fig. 2). Several approximations have been used for momentum transport in the air. The most common models are the k-ε models, k-ω models and the Reynolds stress model (RSM). According to (Defraeye et al., 2013), the k-ε and k-ω models Eqs. (19, 20) are both eddy-viscosity models, which assume isotropic behaviour of turbulence, solving two additional turbulence transport equations, namely for turbulent kinetic energy and for turbulence dissipation. The RSM is a more advanced turbulence model solving all Reynolds stresses and turbulence dissipation. However, it increases computational costs, and the convergence stability is a drawback. An example of the boundary equation using the k-ε terms is presented in Eq. (13). More details and applications of these models can be found in (Defraeye et al., 2013; Norton et al., 2013). Eq. (14) represents convective and conductive contributions in the drying air for momentum transfer.

The non-conjugated approach is the most used for fruit drying modelling, and it is generally used to simulate the flow field temperature and velocity with the purpose to calculate the convective heat and mass coefficients (CTCs) at the air-fruit interface and then the calculations of heat and mass transfer inside the fruit. A big difference between the conjugated and non-conjugated models is that in the conjugated approach, the CTCs are not required because these models introduce mathematical conditions to enforce continuity of heat and mass transfer at the air-fruit interface. These coefficients are instead evaluated as part of the simulation process (Lamnatou et al., 2009). However, in the non-conjugated approach, the CTCs are needed as inputs to the model. According to (Lamnatou et al., 2010), when good and reliable estimation of CTCs is obtained, the use of the non-conjugated approach can be used. In addition, an advantage of this approach is to account for the spatial variations of transfer coefficients considering them variables along the surface, which led them to show the effect of front and rear faces of the fruit during drying (Chandra Mohan and Talukdar, 2010; Esfahani et al., 2015).

Modelling the individual mass transfer can be useful as a beginning step of mathematical modelling of drying. Modelling the coupled heat and mass transfer gives deeper comprehension of drying. Also, with this approach, a better sensitivity analysis can be performed through the simulations. On the other hand, the conjugated approach, gives more insights, particularly at the fruit-air interface. However, the PDEs solution of the mass, heat and momentum transport in the air and the solid, requires a deep drying knowledge to choose the suitable assumptions to represent the operation. Finally, an overview of some selected papers of theoretical modelling for convective drying of fruit is presented in Table 2.

## 4. Dimensions and geometry definition

During modelling conceptualization, it is essential to define the geometry and the dimension of the system, which implies the direction of heat and mass transfer in the defined geometry. Some researches choose known geometries, then an elemental control volume is defined, and the assumptions of the model occur by symmetry along the geometry. The assumptions in these parameters have implications in the formulations of PDEs and initial and boundary conditions. The above recognitions lead to the schematic configuration of the computational domain (also physical model) shown in the papers of convective drying modelling, which is a graphic representation where the model assumptions, operational conditions and initial and boundary conditions for the simulation are evaluated.

The literature review indicates that the main fruit geometry employed in theoretical modelling is the rectangular and cylindrical shape. When the geometry is cylindrical, it is common to assume as infinite cylinder. With this approximation, the longitudinal heat, moisture and momentum transfer can be neglected, which simplifies the solution of PDEs. However, spherical and ellipsoidal geometries are also used but in a minor way (Sabarez, 2012). A known geometry facilitates the structure of the grid used to the fruit shape when a numerical solution is considered. For example, orthogonal grids simplify the numerical solution to a few geometries. However, in arbitrary geometries, for example, the revolution solids, a solution is the use of generalized coordinates (Eq. 8). In diffusion models, this implies writing the transport equation with a non-orthogonal coordinates system. This transformation of transport equation is known as equation in the transformed domain (Da Silva et al., 2014b, 2010, 2009). According to the authors, this approach gives acceptable predicted values for any solid with revolution symmetry. In addition, for irregularly shaped fruits, Bezerra et al. (2015) used the shape factor expressed in dimensionless parameters named drying coefficient and lag factor that lead to the analytical solution of the moisture transfer equation. The lag factor is obtained by regressing the dimensionless values of moisture.

The most common dimensional adoption on modelling of fruit drying is the 1D and 2D approximation with 45 and 43% of the papers reviewed (Fig. 2.), respectively. However, 3D modelling is a more realistic approximation with accurate predictions, yet the prediction accuracy has a strong dependence on the model assumptions; 3D modelling is a future trend in convective drying modelling. However, these models demand a high computational power. For this reason, the consideration of simple dimensions and geometries is valid for engineering applications. Thus, the dimension must be selected according to the final application of the model.

## 5. The scale approach

The theoretical modelling for convective drying of fruit has been applied in different scales, micro-scale, macro-scale, and the multi-scale approach. The most common are the macroscopic models (Defraeye, 2014). 81% of the reviewed papers proposed macro-scale models, 14% micro-scale and just 5% develop the novel multi-scale approach as shown in Fig. 2.

The general assumptions of the macro-models are: (i.) The fruit is treated as a continuum and homogenous medium. It is an isotropic approach, which means that the properties of the fruit do not change when the tissue is subdivided, and they are lumped for modelling. (ii.) The mass transfer in the solid interior occurs by diffusion and the moisture evaporation occurs only at the air-food interface. This suggests that moisture transport occurs in the liquid phase and not by water vapor, so there is no phase distinction or phase change within the fruit (Aregawi et al., 2014b, 2013a, 2013b; Aversa et al., 2007; Baini and Langrish, 2007; Barati and Esfahani, 2013, 2011; Ben Mabrouk et al., 2012; Chandra Mohan and Talukdar, 2010; Da Silva et al., 2010, 2013b; Defraeye, 2016; Defraeye et al., 2013; Defraeye and Verboven, 2017a, 2017b; Do Nascimento et al., 2015; Esfahani et al., 2015, 2014; Fanta et al., 2014; García-Alvarado et al., 2014; Guiné et al., 2007; Janjai et al., 2008a, 2008b; Lemus-Mondaca et al., 2013; Oztop and Akpinar, 2008; Sabarez, 2012; Shahari et al., 2016; Vahidhosseini et al., 2016; Váquiro et al., 2009; Villa-Corrales et al., 2010). In addition, some macro-models consider porous media adding a porosity parameter. For example, Defraeye and Verboven (2017a) modelled a porous material by solving the macroscopic conservation equations, which can be derived by volume-averaging the microscopic conservation equations of each phase or by adopting a phenomenological approach on a macroscopic level Eq. (16).

However, the micro-scale models can include the transport phenomena at different composition of its lower (micro) scale components, for example pores, cell walls, cell membranes and cell vacuoles. This means that the heterogeneity of the material is explicitly recognized, and the cellular structure is represented explicitly by a geometrical model where its properties may change when subdivided (Datta, 2007; Lamnatou et al., 2010; Lemus-Mondaca et al., 2016). However, these models consider thermal and moisture equilibrium inside the tissue and combine the vapour and water transport into a single moisture transport equation, which make them an approach that is not capable of predicting local exchanges of energy and moisture between constituents inside a cell (Gulati and Datta, 2015). The work of (Fanta et al. (2014, 2013) developed a micro-scale water transport model coupled with deformation of the tissue microstructure. The water transport in the intercellular space, the cell wall network and cytoplasm were modelled using diffusion laws and irreversible thermodynamics. Eq. (18) is expressed in terms of water potential as driving force for water exchange between different compositions of tissue, and then a deformation of tissue model was established expressed in terms of turgor pressure. Both models were coupled through the relationship between turgor pressure and water potential. Here, the change in water potential of the cells produces loss of turgor pressure. In addition, a cell shrinkage algorithm was included to determine the fruit tissue geometry and perform simulations of dynamic deformation of individual cells (Fanta et al., 2014). One advantage of considering the microscale approach is to model the shrinkage outside the classical mechanistic approximation, particularly for the individual mass transfer modelling.

Separately, the work of Khan and Straatman (2016) develops a dynamic phase-coupled approach that accounts for heat and moisture transport for the fluid-porous interface as well as the vapour and water exchanges between the tissue constituents using a circuitous analogy for thermal and mass non-equilibrium in the porous region. The review article of (Khan et al., 2016) highlighted the consideration of variable porosity and shrinkage related with the migration of bound water. In addition, it is noted that there is an enormous lack of appropriate material properties and transport data for multiphase model development.

Several studies (Lamnatou et al., 2010, 2009) made use of a simplified version of Luikov's model that neglects internal pressure gradients. Luikov adopts a term in the equations that implies water evaporation inside the material. This term is written as a function of an arbitrary parameter, which has come to be known as Luikov's phase change criterion and is analogous to the thermogradient coefficient in the moisture balance equation. Luikov's phase change criterion appears in Eqs. (15) and (17) immersed in the coefficients $K_1$-$K_4$. However, this approach has received severe criticism.

For example, both approaches, micro and macro scale have been considered for apple drying by Ben Mabrouk et al. (2012); Esfahani et al. (2014) and Golestani et al.,(2013) and by Aregawi et al. (2014b, 2013b) and Khan and Straatman (2016) respectively. Both methodologies agree properly with experimental data. The macro-scale approach was useful to include variable thermophysical and transport properties, irregular geometries (González-Fésler et al., 2008), the shrinkage, and the conjugated and non-conjugated approach. On the other hand, in the microscale approach, the shrinkage is closer to the actual phenomenon and the conjugated and non-conjugated approach is used. Although variable properties are less accounted given the complexity of the model, this approach is a good step to consider an anisotropic medium.

Finally, the multi-scale approach is innovative in the fruit drying modelling (Abera et al., 2016). The works of (Aregawi et al. (2014a) and Fanta et al. (2014), used this type of approach to understand water loss and large deformations in fruit dehydration, combining

**Table 2**
Overview of some theoretical models for convective drying of fruit.

| Fruit | Objective | Operational conditions | Main Results |
|---|---|---|---|
| Quince (D. A. Tzempelikos et al., 2015) | To develop a 1D unsteady heat and moisture transport macro-scale model, considering shrinkage and variable thermophysical properties. | Air temperatures: 40,50,60 °C<br>Air velocity: 1.0–2.0 $ms^{-1}$<br>Geometry: slab<br>Thickness: 9.2–10.6 mm<br>Initial moisture content: 4.274 d.b.<br>Software: COMSOL | The CTCs are calculated from CFD simulations considering the SST $k - \omega$ turbulence model. A new correlation is derived for the heat convective transfer coefficient, as a function of Reynolds and Prandtl numbers. PDEs were solved by the volume finite method. |
| Prunes (Sabarez, 2012) | To describe the conjugated 2D heat, mass and momentum transfer for industrial drying. The macro-scale model accounts for shrinkage and variable properties for air and fruit. | Air temperatures: 70,80 °C<br>Air velocity: 1.5–7.0 $ms^{-1}$<br>Geometry: ellipsoidal<br>Initial moisture content: 69% w.b.<br>Software: COMSOL | $D_{eff}$ is expressed as a function dependant on moisture and temperature. The model assessed the effect of fruit size, initial fruit moisture content and the conditions of the drying air. PDEs were solved by the finite element method, and the model addressed a moving boundary mesh. |
| Apple (Aregawi, Defraeye, et al., 2014) | To study the effects of external flow on the tissue drying with a 2D coupled and a deformation model. | Air temperatures: 25.1 °C<br>Air velocity: 2.34 $ms^{-1}$<br>Geometry: rectangular<br>Thickness: 10 mm<br>Initial moisture content: 6.5 d.b.<br>Software: COMSOL | It is a macro-scale model valid for the slow drying process. The mechanical deformation is based on non-linear elasticity theory. The drying kinetics were dominated by the water transport in the tissue. The model was verified with Neutron imaging. |
| Apple (Defraeye, 2017) | To explore the impact of stopping drying before complete dehydration using a macro-scale model. | Air temperatures: 30,40,60,80 °C<br>Air velocity: not reported<br>Geometry: cubic<br>Length: 20 mm<br>Initial moisture content: 6.0 kg d.b. Software: COMSOL | The 1D macro-scale model suggests that drying can be stopped when the fruit reaches moisture content of 60% of the equilibrium water activity without implications on food safety. |
| Apple (F. A. Khan and Straatman, 2016) | To model and simulate the 3D heat and mass transfer in conjugate fluid-porous domains. | Air temperature: 60 °C<br>Air velocity: 0.64–2.75$ms^{-1}$<br>Geometry: rectangular<br>Dimensions: 20 × 20 × 5 mm<br>Initial moisture content: 7.45 d.b.<br>Software: not reported | Inside the porous material, both the liquid water and water vapour transport were accounted by non-equilibrium heat and moisture transfer approach. The moisture transfer at the air-porous was made using an electric circuit analogy at the pore-level scale. The model accurately simulates the drying operation. |
| Papaya (Lemus-Mondaca et al., 2017) | To describe the drying of a porous fruit into a dryer using a conjugate 3D unsteady heat/mass transfer model. | Air temperature: 60 °C<br>Air velocity: 3.0 $ms^{-1}$<br>Geometry: slab<br>Thickness: 10 mm<br>Initial moisture content: 10.2% w.b.<br>Software: original computer program in FORTRAN language | The $k–\varepsilon$ model is used to describe turbulent airflow. The thermophysical properties were measured and expressed as a function of temperature. The PDEs were solved by the finite volume method. The predicted values were satisfactory. |
| Quince (Vahidhosseini et al., 2016) | To predict the distribution of temperature and moisture content using the analytical approach of Green's function method. | Air temperature: 40,50,60 °C<br>Air velocity: 1.0–2.0 $ms^{-1}$<br>Geometry: slab<br>Thickness: 9.2–10.6 mm<br>Initial moisture content: 4.27 d.b.<br>Software: MATLAB | The 1D macro-scale model included the evaporation term and expressed in cylindrical coordinates. The thermophysical properties were variable. The predicted values showed acceptable accuracy. |
| Apple (Aregawi, Abera, et al., 2014) | To develop a 2D multiscale model to predict the water loss and deformation. | Air temperature: 25 °C<br>Air velocity: 0.01$ms^{-1}$<br>Geometry: cylindrical<br>Diameter:16.6 mm<br>Software: MATLAB and COMSOL | On the micro-scale, water transport and deformation of tissue were computed. Then, the apparent water diffusion and mechanical properties of tissues were calculated through a homogenization procedure. Finally, the properties were used in a macro-scale model. |
| Rectangular moist objects (Chandramohan, 2016) | To develop a 3D model for predictions of heat and mass transfer coefficients on the surface. | Air temperature: 60 °C<br>Air velocity: 2.0, 4.0, 6.0 $ms^{-1}$<br>Geometry: rectangular<br>Dimensions: 40 × 20 × 20 mm<br>Initial moisture content: 4.88 d.b.<br>Software: ANSYS | A new correlation for CTC determination were achieved. The variable and constant consideration of mass and heat transfer coefficients was accounted. Overestimated predicted values were determined by using constant CTCs. The use of variable spatial distribution of CTCs was compared favourably with experimental data. |

continuum type models defined at the macro-scale level with the level of detail of models including the micro-scale characteristics. First, the water transport in the constituents of the tissue was modelled as was mentioned before (Eq. 18). Second, the apparent water transport (apparent diffusivity and water capacity) and mechanical properties of fruit tissue were determined through numerical computation. Third, these properties were scaled up to a macro-scale model of water transport coupled with the Yeoh hyperelastic model and the PDEs were solved by the finite difference method. The numerical results were in good agreement with the experimental data. However, these works do not recognize the connectivity between cell wall and air. As discussed by Aregawi et al. (2014a), to achieve this approach, 3D modelling is necessary.

## 6. Thermophysical and transport properties determination

The thermophysical properties, such as density, conductivity and specific heat, represent fundamental parameters in the study of fruit drying. These parameters can be considered constant or variable in the mathematical models. Fig. 2 shows that 58% of the reviewed papers account for constant properties and 42% for variable properties. When they are variable, it is common to find in the literature, empirical equations as functions of moisture and temperature by means of experimental measurement of the fruit mass and volume change during drying or using specific methods to measure these properties (Askari et al., 2013; Bon et al., 2010; Da Silva et al., 2014a; Kaya et al., 2008). However, the mathematical approaches for variable thermal properties include the solution of a transient heat transfer problem either analytically or numerically using experimental temperature–time data (Celma et al., 2009; Erdoğdu, 2008). The use of optimization was proposed by (Da Silva et al., 2014a). In addition, the Choi-Okos equations are commonly used. Those models can predict thermal and physical properties as a function of the temperature and the fruit composition (Guiné et al., 2007; Moraga et al., 2011; Ramallo and Mascheroni, 2013; Sabarez, 2012). A theoretical model to simulate bulk density of dried materials was proposed by (Khalloufi et al. (2010, 2009). This model used the shrinkage and collapse functions to analyse the mechanisms by which bulk density varies during air-drying.

The transport properties in heat transfer lead to thermal diffusivity, which determines how fast heat diffuses through a material. Several approaches have been used. The main one calculates thermal diffusivity from the values of density, conductivity and specific heat (Bart-Plange et al., 2012; Shahari et al., 2016; Vahidhosseini et al., 2016). The thermal diffusivity can be obtained also by the analytical solution of the heat equation (Baïri et al., 2007) or by the optimization technique. For example, (Mariani et al. (2008) proposed a stochastic method called Differential Evolution that optimizes the parameters of two equations as functions of dimensionless temperature and moisture. In addition, ((Da Silva et al. 2014a) proposed an expression that relates thermal diffusivity with average moisture content. The parameters of this equation are determined by optimization.

The transport properties in mass transfer lead to effective moisture diffusivity ($D_{eff}$) According to published papers in convective drying of fruit, mass transfer properties are more studied than heat transfer properties. $D_{eff}$ encompasses all mechanisms of water transport and is well accepted in modelling. The use of experimental data to determinate the effective diffusivity by different approaches is common. The principal approach is the Arrhenius-type equation, using the experimental moisture loss curve in combination with an analytical, thin-layer solution of this drying curve, based on Fick's law and the Crank solution for different geometries but accounting only for axial or radial moisture diffusion (Kaya et al., 2007a; Schössler et al., 2012; Vahidhosseini et al., 2016; Vega-Gálvez et al., 2009; Zlatanović et al., 2013). From a phenomenological point of view but also with experimental data, the approach of (Fernando et al. (2011) described the variation of $D_{eff}$ with slice thickness and radius of fruit with cylindrical shape. The model used Eq. (10), and with a combination of moisture ratio equation, it was possible to determine the values of diffusion in axial and radial directions.

A modified Arrhenius type equation in terms of temperature and moisture was proposed by (Váquiro et al. (2009), where the effective diffusivity dependence on the moisture content was introduced by a term corresponding to the activation energy as an empirical function of moisture. Similarly, (Guiné et al. (2007), considered diffusivity related with sugar concentration. Furthermore, optimization techniques were used (Bon et al., 2007; Da Silva et al., 2012). Both developed a function that related the effective mass diffusivity with the local value of moisture content. The analytical approach of Dincer and Dost to determinate effective diffusivity by means of a dimensionless Fick's equation was used (Bezerra et al., 2015; Corzo et al., 2009, 2008; Torki-Harchegani et al., 2015). Here, dimensionless parameters named the drying coefficient and lag factor, which represents the drying process and are expressed in terms of Biot and Fourier numbers, are introduced.

The determination of $D_{eff}$ in the microscopic approach allows for knowing moisture transfer at the tissue level, and through macroscale modelling, water transport properties can be scaled up from microscopic to macroscopic models. In this context, the effective diffusivity can be obtained through a phenomenological approach of water diffusion through cell walls. Here, water transfer is due to a gradient of water potential that is a function of water capacity, which is determined with the sorption isotherm curve from experimental data (Fanta et al., 2013, 2012).

The empirical models used for $D_{eff}$ determination are product and process specific. Consequently, these models are non-applicable to other fruits or experimental conditions. In addition, when the $D_{eff}$ values are taken from the literature, this can lead to errors because although it is a value in the same fruit, $D_{eff}$ must be determined for the corresponding cultivar and drying conditions of the investigation (Defraeye and Verboven, 2017a). These empiric approaches give good fit of experimental data but they offer limited insight into the mechanism involved in the drying process. It is necessary to develop theoretical models for the prediction of thermophysical properties that can be applied to a variety of products and allows for a better understanding of the changes of these properties during drying.

## 7. Convective coefficients determination

The determination of the convective mass and heat transfer coefficients (CTCs) is necessary in non-conjugate drying models. The CTCs are set in the boundary conditions when it is assumed that heat is transferred from the air to the product by convection and the moisture is evaporated at the surface of fruit. These assumptions make the CTCs sensitive and linked to air properties such as moisture, temperature, turbulence, velocity and fruit properties such as geometry, thickness, composition, area of exposed surface, roughness and moisture properties (Defraeye and Verboven, 2017a; Erdoğdu, 2008). According to this, several studies have determined the influence of these parameters on CTCs and developed methods to include them in CTC determination. The correct estimation of CTCs is fundamental to predict drying rates accurately.

Several methods have been employed to determine the convective transfer coefficients. According to the literature, the known Chilton and Colburn analogy is the most used method for CTC determination. Here, the convective heat transfer coefficient is estimated from the Nusselt–Reynolds–Prandtl correlation. Then, the convective mass transfer was obtained from the Sherwood–Reynolds–Schmidt correlation for laminar or turbulent flow (Aversa et al., 2007; Defraeye, 2017, 2016; Defraeye and Verboven, 2017b; Golestani et al., 2013; Sabarez, 2012; Vahidhosseini et al., 2016). The work of (Defraeye and Verboven (2017a) highlighted the importance of the determination of heat transfer coefficient over mass transfer coefficient. Therefore, the use of the heat and mass transfer analogy is justified. However, the same author indicated that in some cases, the conditions where the analogy is valid are not accomplished and the application of this analogy does not allow to account for the spatial and temporal variability of CTCs along the process because at the boundary, each drying case has a variable behaviour. Other approximation is by optimization using the inverse method for diffusive models (Da Silva et al., 2014a, 2014b, 2013b, 2010; Mariani et al., 2008; Ramsaroop and Persad, 2012; Rodríguez et al., 2014). In addition, the Arrhenius-type equation has been used to relate the heat transfer coefficient and temperature (Da Silva et al., 2013b, 2012).

The mass transfer coefficient is mostly determined by empirical relations. For example, (Guiné et al. (2007) used an expression based on pressure and the specific mass of the air. In addition, well-established co-relations of Nusselt and Sherwood for laminar and turbulent flow over flat planes, spherical and cylindrical shapes were used (Aregawi et al., 2014b, 2013b; Barati and Esfahani, 2011; Bingol et al., 2008; Bon et al., 2007; Golestani et al., 2013; Khan and Straatman, 2016; Khan et al., 2016; Kumar et al., 2015). Other empirical methods for CTC determination include the use of moisture and temperature measurements described by means of the heat and mass balance equations. This approach has been implemented in the models of (Kaya et al., 2008, 2007b, Lemus-Mondaca et al., 2016, 2013a; Rahman and Kumar, 2007; Villa-Corrales et al., 2010). An analytical approach was introduced by (Torki-Harchegani et al. (2015) and (Guiné and Barroca (2013). Here, the mass transfer coefficient was determined using an expression based on the lag factor, Biot number and $D_{eff}$. However, this analytical approach ignores the effect of heat transfer and accounts for constant thermophysical properties of fruit, which does not represent the reality of drying.

The computer fluid dynamics (CFD) is an advanced computational technique. In convective drying problems, CFD allows the simulation of flow temperature and velocity through commercial software or in-house CFD source code. It is used to calculate CTCs, solving in the first place the temperature and velocity profiles of external flow through simultaneous momentum and energy equations (Norton et al., 2013). From these distributions of temperature and velocity, the local distributions of the convective heat transfer coefficients are determined. Then, the convective mass transfer coefficients are calculated through the analogy between the thermal and concentration boundary layers. The simultaneous heat and mass transfer equations inside the fruit are solved using these convective coefficients in the boundary conditions (Kaya et al., 2008; Tzempelikos et al., 2015).

Some insights with the use of CFD are obtained. For example, (Esfahani et al. (2014); (Chandra Mohan and Talukdar (2010) and Chandramohan (2016) used CFD to know the spatial CTCs variation between the sides of the fruit in 2D and 3D. It was concluded that the main effect of the increase of inlet velocity is on the rear face while the top and bottom faces have the least effect. Increments in the value of velocity lead to an increase in the CTCs, particularly at the upside and downside faces. In addition, the authors do not recommend the extrapolation of CTCs values because CTCs can be different due to the exposure of the fruit boundaries with the hot air depending on the geometry and the dimension of the system. Also, the use of advanced tools such as CFD should receive much more attention to predict temperature and velocities profiles of the air, for example, for dryers designing (Defraeye, 2014).

The boundary equations for non-conjugated models are presented in Table 3. Eq. (24) represents in a general form the convective heat transfer from air to the fruit in a specific frontier domain ($\Omega$) that depends on the computational domain; it involves fruit geometry, flow configuration and dimension of the model. $\eta$ represents the normal vector, and it is directly related to the direction of the phenomena transfer or model dimension (1D, 2D, 3D). In a similar way, Eq. (25) represents the moisture transfer from the fruit surface to the air by convection as a water vapor. Eq. (26), represents the heat transported by convection from the drying air to the fruit. Part of the heat is used to raise the fruit temperature by conduction, and part is used to evaporate water at the food surface, represented by $h_{fg}$.

According to the assumption of neglect or account for external resistance to the moisture transport, a different approach for boundary conditions can be used. When the external resistance to the moisture transport is neglected, the boundary condition of the first kind is used (Da Silva et al., 2013b). Here, the convection term is not accounted in the boundary equation. The prediction of drying kinetics is not well represented with this approximation, because in drying, some external resistance to the moisture transport can occur. However, there is a study where the first type of boundary predicted well moisture values (Fernando et al., 2011). This may be because the experimental conditions for each experimental set were different, which consequently affected the Biot numbers for mass transfer. Therefore, neglecting external resistance to the moisture transport can be used.

The boundary condition of the third kind, also called the Cauchy boundary condition, is defined by considering equal diffusive (internal) and convective (external) fluxes at the surface (Da Silva, 2014b). It is represented by Eq. (27). It refers to an infinite cylinder with radius R, but it also can be used for fruits of a rectangular shape (Villa Corrales et al., 2010). This formulation leads to an analytical solution. Eq. (28), represents the use of heat evaporation term in the boundary. Under this approach the heat and mass transfer are coupled. However, some studies neglected the effects of the evaporation (Chandra Mohan and Talukdar, 2010; Esfahani et al., 2015; Kaya et al., 2008; Vahidhosseini et al., 2016). This is valid when the amount of unbound moisture is less than bound moisture. Consequently, the constant drying rate period can be neglected. This consideration leads to the analytical solution of the model. Additionally, the boundary formulation can be expressed in terms of water activity on the solid surface ($a_w$) and the relative humidity of the drying air ($RH_\infty$) Eq. (29).

The radiation at the surface with the environment could be included. However, it is rarely suggested for convective fruit drying (Defraeye and Verboven, 2017a). The study of convective and infrared radiation (Ben Mabrouk et al., 2012) has taken into account a superficial incident radiation *I* on the energy balance equation Eq. (30).

## 8. Solution methods

The use of numerical and analytical methods becomes a fundamental tool to approximate the solution of the PDEs. The selection of an appropriate method of solution involves characteristics of the mathematical models, such as the classification of the differential equation, the domain geometry, and the initial conditions. The three main numerical methods that have been successfully applied to approximate the solution of PDEs are finite differences, finite volume and finite elements, also known as grid-based methods (Rathnayaka Mudiyanselage et al., 2017).

The finite differences use the decomposition of the differential terms of PDE in discrete representations through the domain discretization in a rectangular grid. Therefore, this method is usually applied in rectangular domains, which limits its use due to irregular geometry of fruits. Depending on the differential approximation, the algorithm is classified as an explicit (Guo and Zhao, 2003) or implicit recurrent system (Kulkarni and Rastogi, 2014), generating time evolution chains linked to initial conditions. In convective drying modelling for fruits, this method has been applied by 27% of reviewed papers (Fig. 2).

The finite volume method is used by 33% of reviewed papers. This approach also discretizes the domain, generating various polyhedral that are not necessarily regular grids. The volume of the generated polyhedra is controlled by numerical methods that are related to interpolation, differential and integral approximations, which consider not only the vertices, but also the inner points of the polyhedral (Moukalled et al., 2015). The use of polyhedron grids and integral approximations implies advantages over the finite difference method, since it can be applied to different domain geometries, facilitates the use in higher dimensions and allows for making approximations on nonlinear terms that represent conservation laws.

**Table 3**
Boundary equations for a non-conjugated approach.

| No | Transport phenomena | Boundary equation | Transfer mechanism | Reference |
|---|---|---|---|---|
| 24 | Heat | $\lambda \frac{\partial T}{\partial n}\|_{\partial\Omega} = h(T_\infty - T)$ | Convection | (Chandra Mohan and Talukdar, 2010; Chandramohan, 2016; Janjai et al., 2010; Kaya et al., 2008) |
| 25 | Mass | $D_{eff}\frac{\partial X}{\partial n}\|_{\partial\Omega} = h_m(X - X_\infty)$ | Diffusion | (D. a. Tzempelikos et al., 2015b) |
| 26 | Heat and mass coupled | $-n(-\lambda\nabla T) = h_{fg}h_m(C_\infty - C_o) + h(T_\infty - T_o)$ | Convection, conduction, diffusion | (Sabarez, 2012) |
| 27 | Mass | $-D_{eff}\frac{\partial X(r,y,t)}{\partial r}\|_{r=R} = h_m[X(r,y,t)]\|_{r=R} - X_{eq}$ | Convection | (da Silva et al., 2013; Villa-Corrales et al., 2010) |
| 28 | Heat | $\lambda_{sol}\frac{\partial T}{\partial n}\|_{\partial\Omega} = h(T - T_\infty) - h_{fg}\rho_s D_{eff}\frac{\partial T}{\partial n}\|_{\partial\Omega}$ | Conduction, convection, | (D. a. Tzempelikos et al., 2015a; Vahidhosseini et al., 2016) |
| 29 | Mass | $-D_{eff}\ \rho_s\frac{\partial X}{\partial x} = h_m(a_w - RH_\infty)$ | Diffusion | (Gamboa-Santos et al., 2014) |
| 30 | Heat | $I - h(T_o - T_\infty) = \dot{m}\lambda$ | Convection, radiation | (Ben Mabrouk et al., 2012) |

The finite elements method is the most applied by researchers (40%), as shown in Fig. 2. This method uses the same type decomposition of domain as finite volume, but the approximation is different. For algorithm generation, the model weak formulation is necessary. This implies working in spaces not necessarily polynomial. In addition, the use of auxiliary functions (test functions) is required to apply the Gauss theorem, which is commonly associated with mass, energy and momentum conservation laws (Gosz, 2006). This theorem implies combining boundary conditions at the initial formulation through line or surface integrals, i.e., the algorithm has a local character because it links the volume approximation with boundary conditions.

However, the analytical approach is mostly used to solve the uncoupled mass transfer equation, mainly in 1D. This corresponds to 22% of papers reviewed (Fig. 2.). Here, the separation of the variables method and the Fourier and Biot dimensionless variables are used to rewrite the governing equations (Vahidhosseini et al., 2016). The coupled PDEs solution by means of analytical tools are scarce in the literature. (Barati and Esfahani (2011) suggested a novel approach to solve coupled energy and mass equations in 1D by means of two dimensionless numbers that relate the amount of heat used for water evaporation and mass transport from the food surface to air.

Finally, a mathematical analysis of consistency (existence and uniqueness) and convergence (speed of approach to the solution) of numerical methods can help to select the appropriate approximation method for model solution (E. Mayorga et al., 2011). Both advances in computer science and those in mathematical analysis will develop new methodologies to solve complex models of PDEs. Comparative studies between different numerical approaches to solve the model would be of interest. Those studies are useful for developing better modelling tools based on the analysis of the stability and sensitivity of the numerical method.

## 9. Hybrid technologies

The hybrid drying systems include combined drying methods to improve drying outcomes. Commonly, the minimization of the drying time and energy as well as the improvement of the fruit quality are expected (Chua and Chou, 2014). The most common combined technologies with convective drying that report mathematical models are microwave and infrared.

Models for convective-microwave drying have been proposed by (Bingol et al., 2008); for grapes. The model was developed for uncoupled heat and mass transfer. The Eq. 21 (Table 1) represented the heat transfer. Thin-layer models were used for the mass transfer. A multiphase porous media model for intermittent microwave convective drying was proposed by (Joardder et al., 2017; Kumar et al., 2016) for apples. This model considered liquid water, gases and the solid matrix. The model did not consider the shrinkage. The heat and mass transfer were expressed by conservation equations. The Eq. 22, represents the mass balance equations for the gas phase. The mass and heat balance equations for the other phases are presented in this study. The same authors, developed a recent model which consider the shrinkage and pore evolution. The shrinkage was determined by a Neo-Hookean constitutive model that describes material deformation and Arbitrary-Lagrangian-Eulerian (ALE) approach to account structural deformation. Also, the model was compared with the model without shrinkage obtaining better fitting.

A model for far-infrared drying of longan puree was proposed by (Jaturonglumlert and Kiatsiriroat, 2010). The equation 23, represents the empirical relation based on the analogy of heat and mass transfer coefficients in terms of fruit constants and terms that describes the convective transfer due to evaporation from a wet surface. Also, a term that accounts the radiation heat transfer rate. This model demonstrated that the increase of far-infrared radiation heat flux results in shorter drying time. The application of hybrid models requires knowledge of different fruit properties such as thermophysical, dielectrics (for microwave modelling) and radiation (emissivity, absorptivity, reflectivity and transmissivity) properties. Hybrid models still being a challenge in fruits drying research.

## 10. Other considerations

### 10.1. Shrinkage

During the convective drying of fruit, the loss of water and heating lead to a collapse in the cellular structure causing changes in shape and a decrease in dimension. Therefore, the mathematical model is influenced by the shrinkage phenomenon. The simplest approach to model shrinkage is the use of empiric and semi-empiric linear and non-linear models by means of regression analysis of the shrinkage data (Ochoa et al., 2007; Omolola et al., 2015). Under this approach, the works of Koç et al. (2008) and Filho et al. (2015) modelled the bulk density, porosity, shrinkage and volumetric contraction, respectively. The results showed that the non-linear models explained the change in shrinkage better than the linear models.

Most of the shrinkage models are based on continuum mechanics, which recognizes the change in the reduced dimension (volume, area, thickness, diameter, radius, and length) during drying is equivalent to the amount of moisture removed. The resulting empirical equation can be included in the determination of $D_{eff}$ (Gamboa-Santos et al., 2014; Janjai et al., 2010, 2008a, 2008b; Schössler et al., 2012). Golestani et al. (2013) proposed the shrinkage effect being similar to convective flow and entered as convective velocity in the heat and mass transfer equations Eq. (11). This velocity is expressed in terms of the change in volume and moisture. Other methods are the shrinkage inclusions in the numerical solution of PDEs through an adaptation of the computation domain. Here, the domain is fixed in each computational time and updated continuously (Baini and Langrish, 2007; Da Silva et al., 2014a; Ramallo and Mascheroni, 2013). In addition, Shahari et al. (2016) developed a shrinkage equation transforming the space coordinate in the equation of heat and mass transport (Equation 4 and 12). This approach does not require the separated procedure of regression analysis of the shrinkage data. A slightly different approach was used (Ben Mabrouk et al., 2012; Guiné, 2008; Guiné et al., 2007; Tzempelikos et al., 2015; Vahidhosseini et al., 2016). The model included the variable $\rho_{sol}$. It relates the mass of dry solids to the total volume of moist material, which varies along drying, and the equation is the function of bulk density, obtaining good agreement with the experimental data. Sabarez (2012) included shrinkage through a moving mesh with respect to the initial geometry. The moving boundary displacement is propagated throughout the domain to obtain a mesh deformation using the numerical solution of PDEs through the Arbitrary Lagrange–Eulerian (ALE) method.

The mass transfer coupled with a mechanical model is another way to consider shrinkage. Under this concept, the principal approach for the mechanical model is through linear elastic models, but the problem of this approach is that it is only valid for small deformations. The fruit behaves like a nonlinear viscoelastic continuum, and the tissue is exposed to high hygrostresses that causes large deformations along the process (Aregawi et al., 2013a). This approach requires experimental data of viscoelastic parameters and water transport properties, which is not an easy task. However, it is suitable for large deformations that really occur in convective drying. Under this approach, Aregawi et al. (2014b, 2013b) used Eq. (10) to account for the stresses in the fruit tissue. Some studies compare the modelling with and without shrinkage as well as with constant and variable properties. For example, Golestani et al. (2013) used a model with constant Deff and without shrinkage and compared it with a model with variable Deff and shrinkage. The best results were obtained for variable properties and shrinkage consideration, showing the importance of this approach.

### 10.2. Fruit quality modelling

During convective drying of fruit, a change in quality parameters such as colour, vitamins, texture, bioactive compounds and sensory properties is observed. The drying process can damage bioactive compounds such as phenols and flavonoids that are responsible for bioactivities that benefit human health such as antioxidant capacity and antimicrobial. Moreover, the final quality of a dried fruit determines the acceptability to the consumer. Thus, the assessment is essential as well as the modelling of these parameters in drying to obtain the best operational conditions that preserve the desirable characteristics in the final product.

Most of the reviewed articles that recognize and model the effect of convective drying on the change in quality parameters are not coupled to the drying modelling. The empirical models are the most used in quality modelling and include the degradation kinetics approach (Van Boekel, 2008). The experimental data can be fitted by four modelling strategies: (i.) the zero or first-order kinetic model, which has been applied for texture, colour, vitamin C, bioactive compounds and antioxidant capacity modelling (Akdaş and Başlar, 2015; Chen and Opara, 2013; Demarchi et al., 2013; Karaaslan et al., 2014; Mohammadi et al., 2008; Quevedo et al., 2009; Santos and Silva, 2008); (ii.) The Arrhenius type equation; (Behroozi Khazaei et al., 2013; Karaaslan et al., 2014); (iii.) The Eyring–Polanyi model, based on the transition state theory, and the Ball model were applied (Cisse et al., 2009; Karaaslan et al., 2014); (iv.) Linear and non-linear regression have been used by Ponkham et al. (2012); Chen and Opara (2013) and Sturm et al. (2014); Guiné et al. (2015a); Udomkun et al. (2015) and Romero J and Yépez V (2015) for several quality parameters. From a theoretical point of view, these empirical models found in the literature are rarely coupled with PDEs.

Sabarez (2014) coupled transport phenomena and colour development through the reaction rate of a first kinetic equation as a function of moisture and temperature. For texture prediction, Thussu and Datta (2011) proposed a model to predict the effective Young's modulus combined with a multiphase porous-media model. In addition, Alean et al. (2016) developed a phenomenological model that simulates the behaviour of water desorption and the degradation of polyphenols in Cacao. This model accounts for the mass and energy transfer for the air and fruit domains. The change of polyphenols was introduced in the solid phase mass balance as a function of the first order kinetics Eq. (12).

Currently, the use of Artificial Neural Network (ANN) coupled with computer vision systems (CVS) allows for the simulation of colour change, browning index and chroma as a function of drying air temperature and moisture ratio. This tool have been used for modelling apple colour, total phenolic (Nadian et al., 2016, 2015) and antioxidant activity in bananas (Guiné et al., 2015b).

Finally, it is paramount to choose or develop suitable models for predicting quality properties related to heat and mass transfer as well as to include other quality indicators such as sensorial and nutritional characteristics. However, the fruit quality properties are too complicated to be described by means of phenomenological or theoretical models. Thus, the diffusivity models used for moisture transfer prediction also can be used to model the transfer of other components in fruits such as the volatile compounds. The outstanding development in computational methods is a tool to better understand the effect of the operational conditions of drying in the spatial and temporal changes of these properties, which represents a challenge in the drying modelling field.

### 10.3. Validation of the models

To determine the prediction accuracy of the models, the researchers use several statistical indicators that allow for the evaluation of the adequacy of the model to the experimental data. The chi-square ($X^2$) and determination coefficient ($R^2$) are reported quite often. Low chi-square values and high determination coefficient values are the selection criteria for the good fit of the models (Da Silva et al., 2013a, 2012). Moreover, the mean relative percentage deviation (%P) is used, and it establishes that a model is acceptable, or a good fit, when $P < 10\%$. (Sabarez, 2012). Others calculate the mean bias error (MBE), the root mean square error (RMSE) (Guiné, 2008; Janjai et al., 2008b) and the percentage of explained variance (%VAR). High values of this statistical is indicating the goodness of the model fit (Do Nascimento et al., 2015). For example, Golestani et al. (2013), reported a $R^2$ of 0.9373 and RMSE of 0.3796 for an apple drying model that accounts for variable Deff and Shrinkage. The diffusion model for bananas of Da Silva et al. (2013a) established a $R^2$ greater than 0.9990 and $X^2$ were less than $5.3 \times 10^{-3}$. Sabarez et al. (2012), founded that the %P for prunes drying model was in the range of 2.3–8.7%. The RMSE value of the model proposed by Janjai et al. (2010) was of 8.4% for litchi drying. The %VAR above of 99.3% was obtained by Do Nascimento et al. (2015) for fruit passion peel modelling.

A lack of suitable statistical criterion for modelling validation has been identified. Some studies reported the simple comparison of predicted and experimental data through the moisture and temperature curves. The accuracy and precision are important in model validation. Furthermore, the use of statistics that only gives information about the precision or the accuracy is not recommended. For example, the $R^2$ only describes the model precision. The $X^2$ only describes the model accuracy. Thus, the agreement of the model can be assessed through statistic parameters that accounts for both the accuracy and the precision. Finally, the Lin's concordance correlation coefficient is an option to evaluate simultaneously the accuracy and precision. More details can be found in (Lin et al., 2011; Tedeschi, 2006; Watson and Petrie, 2010). A drawback in the validation of the model is that a well-presented and well-planned experimental data set is not available in the literature, which leads to the validation step being a difficult task for researchers.

## 11. Final remarks

Modelling is a complex process that requires the definition of several parameters. Modelling is a powerful tool for the optimization of the drying process and the understanding of the phenomenology of the operation. New tools or approaches, such as the multiscale, the conjugated models, and micro-modelling, have increased the accuracy of the predicted data and can overcome some of the drawbacks in pore modelling and macro-modelling, including the volume fraction consideration in pore modelling, the hard task in CTC determination, the assumption that evaporation occurs not only at the surface, but also in tissue components, and the possibility to consider a two way relationship between heat and mass parameters with mechanical ones. However, the challenges for the modelling of the convective drying of fruits are the dependence of the experimentation to generate parameters of the model, the absence or difficulty to include the shrinkage, and that the results of the model are largely dependent on the product and the range of conditions under which it is tested. Very detailed models are more rigorous and provide more accuracy. However, a drawback is the computing time required to solve the drying problem. Finally, future trends in the mathematical modelling of convective drying of fruit involve new approaches such as multiscale modelling, the drying modelling in 3D geometries, the increased use of conjugated models, and the development of models for hybrid technologies. The shrinkage determination has to be improved to obtain reliable values of $D_{eff}$ and hence the accuracy of predicted results. These improvements are related to advanced mechanistic modelling instead of phenomenological principles and empirical models. The calculation of convective coefficients can be determined with new methodologies that include the variation in 3D and the time. Comparative studies between different approaches would be useful. It is essential to know the purpose and application of the model, which differ depending upon whether a model is used to gain scientific insight into drying or to implement engineering aims such as dryer design, software development, control, or optimization. This knowledge will determinate the best approach for modelling. Complex models are closer to reality but are more difficult to solve. In some cases, the simplest models fitted the results properly, which is why they are still valid.

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