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Application of meshfree methods to numerically simulate microscale deformations of different plant food materials during drying

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ABSTRACT

Plant food materials have a very high demand in the consumer market and therefore, improved food products and efficient processing techniques are concurrently being researched in food engineering. In this context, numerical modelling and simulation techniques have a very high potential to reveal fundamentals of the underlying mechanisms involved. However, numerical modelling of plant food materials during drying becomes quite challenging, mainly due to the complexity of the multiphase microstructure of the material, which undergoes excessive deformations during drying. In this regard, conventional grid-based modelling techniques have limited applicability due to their inflexible grid-based fundamental limitations. As a result, meshfree methods have recently been developed which offer a more adaptable approach to problem domains of this nature, due to their fundamental grid-free advantages. In this work, a recently developed meshfree based two-dimensional plant tissue model is used for a comparative study of microscale morphological changes of several food materials during drying. The model involves Smoothed Particle Hydrodynamics (SPH) and Discrete Element Method (DEM) to represent fluid and solid phases of the cellular structure. Simulation are conducted on apple, potato, carrot and grape tissues and the results are qualitatively and quantitatively compared and related with experimental findings obtained from the literature. The study revealed that cellular deformations are highly sensitive to cell dimensions, cell wall physical and mechanical properties, middle lamella properties and turgor pressure. In particular, the meshfree model is well capable of simulating critically dried tissues at lower moisture content and turgor pressure, which lead to cell wall wrinkling. The findings further highlighted the potential applicability of the meshfree approach to model large deformations of the plant tissue microstructure during drying, providing a distinct advantage over the state of the art grid-based approaches.

1. Introduction

In the global food market, plant based food materials hold a significant proportion, and numerous research are being conducted to improve new food products and efficient processing techniques. In this context, food drying is used to process about 20% of the world's perishable crops and is therefore can be considered as one of the key plant food processing techniques (Grabowski et al., 2003). Since plant food materials usually contain very high moisture, even up to 90% by weight (Jangam, 2011), are highly subjected to spoilage. Therefore, food drying can be used as a preservation technique since it principally reduces moisture from the plant material structure. With the objective of improving such food drying processes, different drying techniques have evolved (Martin et al., 2006). All these processing techniques cause the food material to undergo structural deformations and other changes of the physical or chemical properties. These alterations eventually result in microscale and macroscale changes of the food structure such as shrinkage, which is one of the most critical parameters in food processing. Shrinkage is mainly governed by the moisture content of the food material (Hills and Remigereau, 1997; Karunasena et al., 2014a; Lee et al., 1967; Lewicki and Drzewucka, 1998; Lewicki and Pawlak, 2003; Lozano et al., 1980; Mayor et al., 2005; Ramos et al., 2004), drying temperature (Bai et al., 2002; Funebo et al., 2000; Karunasena et al., 2014a; Rahman et al., 2005) and cell turgor pressure (Bartlett et al., 2012). Such structural deformations are present in both microscale

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Nomenclature

A	cell top surface area (m^2)
A_0	cell top surface area at fresh condition (m^2)
A/A_0	normalized cell area
A_c	total surface area of the cylindrical cell (m^2)
C	cell compactness
C_0	cell compactness at fresh condition
C/C_0	normalized cell compactness
D	cell Feret diameter (m)
D_{major}	cell major axis length (m)
D_{minor}	cell minor axis length (m)
D_0	cell Feret diameter at fresh condition (m)
D/D_0	normalized cell Feret diameter
E	Young's modulus of the cell wall material (MPa)
EL	cell elongation
EL_0	cell elongation at fresh condition
EL/EL_0	normalized cell elongation
$\boldsymbol{F}^e$	cell wall stiff forces (N)
$\boldsymbol{F}^d$	cell wall damping forces (N)
$\boldsymbol{F}^{rf}$	wall–fluid repulsion forces (N)
$\boldsymbol{F}^{rw}$	wall–wall repulsion forces (N)
$\boldsymbol{F}^a$	wall–fluid attraction forces (N)
$\boldsymbol{F}^b$	forces due to the bending stiffness of the wall (N)
$\boldsymbol{F}^p$	cell fluid pressure forces (N)
$\boldsymbol{F}^v$	cell fluid viscous forces (N)
G	shear modulus of the cell wall material (MPa)
K	cell fluid compression modulus (MPa)
L	width of a given discrete wall element (m)
L'	width of a given discrete wall element at fully turgid state (m)
L_0	Initial width of a given discrete wall element (m)
L_p	cell wall permeability ($m^2\ N^{-1}\ s$)
P	cell perimeter (m)
P_0	cell perimeter at fresh condition (m)
P/P_0	normalized cell perimeter
P_a	pressure of any fluid particle a (Pa)
P_T	initial cell turgor pressure (Pa)
R	cell roundness
R_0	cell roundness at fresh condition
R/R_0	normalized cell roundness
S	ratio between fluid inter-particle distance and smoothing length (r_{ab}/h)
T	cell wall thickness (m)
T_0	initial cell wall thickness (m)
TP	positive cell turgor pressure effects
W	smoothing kernel
WD	cell wall contraction effects
WC	cell wall drying effects
X	x – coordinate axis
X	dry basis moisture content ($kg_{water}/kg_{dry\ solid}$)
X_0	dry basis moisture content at fresh condition
X/X_0	dry basis normalized moisture content
Y	y – coordinate axis
Z	cell height (m)
Z	z – coordinate axis
Z_0	initial cell height (m)
Z_t	cell height at the previous time step (m)
$Z_{t+\Delta t}$	cell height at the current time step (m)
f_0^{rf}	strength of the LJ repulsion forces between fluid and wall particles ($N\ m^{-1}$)
f_0^{rw}	strength of the LJ repulsion forces between non-bonded wall particles ($N\ m^{-1}$)
f_0^a	strength of the LJ attraction forces between fluid and wall particles ($N\ m^{-1}$)
h	smoothing length (m)
h_0	initial smoothing length (m)
k_b	bending stiffness of cell wall material ($N\ m\ rad^{-1}$)
k_{wc}	force coefficient of cell wall contractions ($N\ m^{-1}$)
m_a	mass of any particle a (kg)
n_f	cell fluid particle number
n_w	cell wall particle number
r	cell radius (m)
r_{ab}	distance between any given particle a and b (m)
t	time (s)
$\boldsymbol{v}_{ab}$	velocity of any given particle a relative to any other particle b ($m\ s^{-1}$)
$\boldsymbol{x}_{ab}$	position vector of any given particle a relative to any other particle b (m)
Δt	time step (s)
x_0	initial fluid grid spacing (m)
$\Delta\theta$	change of external angle θ of any given wall element (rad)
$\Delta\boldsymbol{x}_{ab}$	change of gap difference of any two particles a and b compared to their initial gap (m)
Π	osmotic potential of the cell (Pa)
α	factor governing the relationship between z-directional extension ratio and λ_θ of any wall element
β	parameter that relate 2-D deformations to 3-D deformations of any wall element
γ	cell wall damping constant ($N\ m^{-1}\ s$)
ε_0	initial minimum allowed gap between outer most fluid particles and cell wall particles (m)
θ	external angle between any adjacent cell wall elements (rad)
λ_θ	extension ratio of any given cell wall element
μ_a	dynamic viscosity of any fluid particle a (Pa s)
ρ_a	density of any given fluid particle a ($kg\ m^{-3}$)
ρ_0	initial density of the cell fluid ($kg\ m^{-3}$)
ρ_a^*	2-D density of any given particle a ($\rho_a^* = Z\rho_a$) ($kg\ m^{-2}$)

and macroscale of the food structure, and they are well interrelated (Han et al., 2010; Hills and Remigereau, 1997; Lee et al., 1967; Lewicki and Drzewucka, 1998; Mayor et al., 2005; Ramos et al., 2004; Sabarez et al., 2012; Witrowa-Rajchert and Rząca, 2009). In order to understand the driving factors of these deformations, researchers have extensively focused on different empirical models (Mayor and Sereno, 2004) and theoretical models (Crapiste et al., 1988-a; Zhu and Melrose, 2003).

However, limited research has been conducted on numerical modelling of the structural deformations, both in the macroscale and microscale. The available numerical models are mostly based on grid-based modelling techniques such as Finite Element Method (FEM) and Finite Difference Method (FDM), which have limited capability to model multiphase non-continuum materials, under large deformation and phase change conditions (Liu and Liu, 2003). For instance, in the case of macroscale models, a gel material model based on FEM is reported which is capable of simulating dried plant leaves (Liu et al., 2010). The key limitation here is the hypothetical gel material assumption, which approximates the plant material to a continuum, which is fundamentally not realistic. Also, when modelling different plant materials, it becomes quite challenging to estimate the appropriate hypothetical gel material properties corresponding to different drying conditions. Also, in their work, they have not demonstrated any means of directly relating the moisture content reduction with the shrinkage, which is another critical shortcoming when it comes to industrial drying