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Shrinkage of Food Materials During Drying: Current Status and Challenges

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Abstract: The structural heterogeneities of fruits and vegetables intensify the complexity to comprehend the interrelated physicochemical changes that occur during drying. Shrinkage of food materials during drying is a common physical phenomenon which affects the textural quality and taste of the dried product. The shrinkage of food material depends on many factors including material characteristics, microstructure, mechanical properties, and process conditions. Understanding the effect of these influencing factors on deformation of fruits and vegetables during drying is crucial to obtain better-quality product. The majority of the previous studies regarding shrinkage are either experimental or empirical; however, such studies cannot provide a realistic understanding of the physical phenomena behind the material shrinkage. In contrast, theoretical modeling can provide better insights into the shrinkage that accompanies simultaneous heat and mass transfer during drying. However, limited studies have been conducted on the theoretical modeling of shrinkage of fruits and vegetables. Therefore, the main aim of this paper is to critically review the existing theoretical shrinkage models and present a framework for a theoretical model for the shrinkage mechanism. This paper also describes the effect of different drying conditions on material shrinkage. Discussions on how the diverse characteristics of fruits and vegetables affect shrinkage propagation is presented. Moreover, a comprehensive review of formulation techniques of shrinking models and their results are also presented. Finally, the challenges in developing a physics-based shrinkage model are discussed.

Keywords: Characterization, dehydration, fruits and vegetables, shrinkage, theoretical modeling

Introduction

Fruits and vegetables are heterogeneous in structure and are comprised of about 80% to 90% water which is contained in different cellular environments. This vast amount of water makes these materials highly perishable and therefore an appropriate food preservation technique is essential (Karim & Hawlader, 2005; Khan, Joardder, Kumar, & Karim, 2016b). Drying is one of the most effective food preserving methods that can be applied to these perishable food materials. The porous and hygroscopic nature of fruits and vegetables make it highly shrinkable while drying. Transport of water from cellular locations to the surrounding environment causes irregular volume changes of high-moisture foods during drying, and this volume reduction is usually defined as a material shrinkage (Khan & Karim, 2017a). The shrinkage of fruits and vegetables is sometimes referred as deformation of material, and it is an obvious physical phenomenon commonly observed during drying.

Shrinkage of dried products has many negative consequences, ranging from quality to consumer satisfaction (Mulet, Garcia-Reverter, Bon, & Berna, 2000; Ochoa, Kesseler, Pirone, Márquez, & Michelis, 2002; Mayor & Sereno, 2004; Udomkun & Nagle et al. 2016), and including some other adverse effects, such as surface cracking and reduction of rehydration capability (Jayaraman, Gupta, & Rao, 1990; Senadeera, Bhandari, Young, & Wijesinghe, 2005). Shrinkage has a great effect on mechanical and textural properties of fruits and vegetables. For example, Vincent (1989) found that the torsional stiffness (0.5 to 7 MPa) of the apple samples varied with the shrinkage. Moreover, shrinkage is an important factor that enormously affects the drying rate as well as drying kinetics. Food researchers have argued that shrinkage should not be neglected while predicting actual heat and mass transfer during drying (Aprajeeta, Gopirajah, & Anandharamakrishnan, 2015). A model with shrinkage fits better with experimental data during drying than a model without shrinkage (Aprajeeta et al., 2015; Pacheco-Aguirre et al., 2015). Thus numerous studies for investigating material shrinkage have been conducted. Most of the research has been based on extensive experimental analysis (Krokida, Oreopoulou, & Maroulis, 2000; Krokida, Zogzas, & Maroulis, 1997; Madamba, Driscoll, & Buckle, 1994; Yan, Gallagher, & Oliveira, 2008; Dissa & Desmorieux et al. 2010; Mercier & Villeneuve et al. 2011; Liu & Chen et al. 2012; Madiouli & Sghaier et al. 2012; Koua, Koffi, & Gbaha, 2017).

Experimental studies have very limited applicability because they are conducted under highly specific product and process conditions (Zogzas, Maroulis, & Marinos, 1994; Rahman &

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Perera, et al. 1996; Krokida & Maroulis, 1997; Krokida, Karathanos, & Maroulis, 1998; McLaughlin & Magee, 1998). Mathematical modeling can provide better insight into the causes of shrinkage with continuous heat and mass transfer during drying. As a consequence, many mathematical models have been developed for material shrinkage. They can be broadly categorized as empirical models, semi-empirical models, and theoretical models.

To uncover the physical phenomena of shrinkage, many empirical models have been formulated based on experimental data that are suitable for a specified product and processing conditions (Akiyama, Liu, & Hayakawa, 1997; Gabas, Menegalli, & Telis-Romero, 1999; Izumi & Hayakawa, 1995; Lang & Sokhansanj, 1993; McMinn & Magee, 1997a; Ratti, 1994; Rovedo, Suarez, & Viollaz, 1995; Rovedo, Suárez, & Viollaz, 1997; Tsukada, Sakai, & Hayakawa, 1991; Vázquez, Chenlo, Moreira, & Costoyas, 1999). In response to the limitations of empirical models, a slightly improved model has been formulated that can generate a theoretical understanding (Kilpatrick, Lowe, & Arsdel, 1955; Suzuki & Kubota et al. 1976; Lozano, Rotstein, & Urbicain, 1980, 1983; Perez & Calvelo, 1984; Rahman, Perera, Chen, Driscoll, & Potluri, 1996). Nevertheless, the oversimplified assumptions of these types of models prevent them from providing a realistic understanding of the fundamental causes of shrinkage during drying. In contrast, theoretical models are developed considering fundamental physics and therefore they can predict the physicochemical changes accurately during dehydration of fruits and vegetables.

The complex structure of fruits and vegetables makes it very difficult to formulate a mechanistic shrinkage model. To develop a physics-based model, 4 different models can be applied for predicting shrinkage during drying of fruits and vegetables: linear elastic, hyper-elastic, elastoplastic, and viscoelastic material models. These models depend on the characteristics of food materials, and thus material characterization is crucial to develop a shrinkage model. Moreover, an appropriate selection of these models for a specific food material is vital for developing a realistic shrinkage model. In the existing literature, theoretical models have been developed based on some simplified assumptions; for example, treating food materials as rubbery (Gulati & Datta, 2015) or elastic (Jomaa & Puiggali, 1991; Kowalski, 1996; Mrani, Fras, & Benet, 1995; Mrani & Bénet et al. 1997; Ponsart & Vasseur et al. 2003; Chemkhi, Zagrouba, & Bellagi, 2004; Niamnuy et al. 2008). These assumptions simplify the problem formulation, but they are not conducive to a realistic understanding. Therefore, more rigorous study are essential to formulate a physics-based shrinkage model for food drying. The main aims of this paper are to present a comprehensive review of existing theoretical shrinkage models, considering the effects of the diverse nature of fruits and vegetables on material shrinkage, examine how process conditions affect material shrinkage, uncover current research gaps, and identify the challenges in developing a realistic physics-based shrinkage model.

Characteristics of Food Materials

Food materials, particularly fruits and vegetables are heterogeneous in structure and diverse in nature and therefore characterization of food materials is difficult. Fruits and vegetables are mainly categorized as elastic, hyperelastic, elastoplastic, and viscoelastic which are discussed below.

Food material as an elastic and hyperelastic material

In many cases, fresh produce are considered to be elastic in nature, where the deformation of material is considered to be very small (Chemkhi et al., 2004; Kowalski, 1996; Mrani, Bénet, Fras, & Zrikem, 1997; Niamnuy, Devahastin, Soponronnarit, & Raghavan, 2008; Ponsart, Vasseur, Frias, Duquenoy, & Meot, 2003). This elastic property strongly affects the thermal stresses that are induced by the continuous penetration of heat energy. The induced stresses will disappear due to the elastic deformations (Kowalski & Rybicki, 2007). In practice, however, some residual stresses remain inside the material after drying which may have a substantial influence on further behavior of the material during rehydration (Lewicki, Rajchert, & Mariak, 1997). Furthermore, elastic behavior mainly depends on the nature of the stress-strain properties of materials. Based on these properties, elastic materials can be categorized as linear elastic, where Hooke's constitutive law can be used to model the material shrinkage, and nonlinear elastic (or hyperelastic), where Neo-Hookean constitutive law can be used to model the material shrinkage. Many models that consider fruits and vegetables as linear elastic have been developed for shrinkage during drying (Chemkhi et al., 2004; Jomaa & Puiggali, 1991; Kowalski, 1996; Mrani et al., 1995; Mrani et al., 1997; Niamnuy et al., 2008; Ponsart et al., 2003). According to Hooke's constitutive law, the stress and strain remain proportional up to a certain limit (about 10%) that is not defined for diverse fruits and vegetables. Therefore, consideration of fruits and vegetables as a linear elastic material may only be applied to certain type of products and not be an effective approach due to the large deformation that occurs during drying and generating strains over the Hookean range (Gulati & Datta, 2015). Instead, a nonlinear elastic model may better predict large deformations of fruits and vegetables during drying. Considering the benefits of nonlinear elastic properties, some researchers have used Neo-Hookean constitutive law for developing a realistic shrinkage model (Dhall & Datta, 2011; Gulati & Datta, 2015). They developed their model based on a poromechanics concept for a less porous material (potato); however, it may be difficult to apply their model to other highly porous material such as apple and eggplant tissues because the porosity of potato is much lower than that of apple and eggplant.

Food material as an elastoplastic material

Fruits and vegetables are sometimes defined as an elastoplastic material when it exhibits both elastic and plastic properties that is, a rubberlike plastic. It depends on the state of stress between the elastic limit and the breaking strength. It is assumed that food material shows the elastoplastic properties in a small strain region (Akiyama & Hayakawa, 2000; Curcio & Aversa, 2014; Izumi & Hayakawa, 1995; Tsukada et al., 1991; Yang, Sakai, & Watanabe, 2001), while others have argued that the deformation of fresh produce are significant (about 30% to 70%) (Gulati & Datta, 2015). Moreover, within a small strain region the potato behavior has been assumed as elastoplastic and nonisotropic (Yang et al., 2001), while others have postulated that this assumption is not always suitable for other types of vegetables (Llave et al., 2016). This is mainly because of the lack of material characterization. Predicting material shrinkage without a material characterization, it is obviously not a justified inception due to the diverge nature of fruits and vegetables. In this context, viscoelastic properties might be the better assumption for characterizing fresh produce, are discussed below.

Food material as a viscoelastic material

Viscoelasticity is the property of materials that exhibit both elastic and viscous characteristics when undergoing deformation. The stress–strain relationship of those types of materials depends on time. This type of material shows strain rate dependency during compression, creep, stress relaxation, and very often hysteresis. Most of the plant-based food materials exhibit those types of properties that lead to consideration of the high-moisture foods as viscoelastic (Mahiuddin, Khan, Pham, & Karim, 2018). During food drying, the mechanical behavior of viscoelastic food material significantly affects the process conditions as well as sensory properties (Lu, Ma, Wang, & Yu, 2015). Many experimental and theoretical studies have been conducted to reflect the influence of various drying parameters on viscoelastic materials and to accurately describe the stress-strain relationship of food materials (Lu et al., 2015). These studies have used basic constitutive Maxwell and Kelvin models to predict stress-strain relationship for food materials. Maxwell and Kelvin models have been selected as the best approach to predict the shrinkage of food materials because fruits and vegetables are composed of a mixture of solid and liquid which exhibits the characteristics of a spring and dashpot.

Mechanism of Shrinkage

Structural heterogeneity makes it complex to understand the physicochemical changes that occur in fruits and vegetables during thermal processing. During food drying, microstructural stress is induced by the moisture and temperature gradient within the product. This microstructural stress leads to material deformation. This deformation can be referred to as shrinkage of the material. In most food processing, there are 2 main causes of material shrinkage. Firstly, the food tissue is incapable of holding its structural arrangement when the space occupied by water is constantly emptied and air-filled (Khan, Wellard, Nagy, Joardder, & Karim, 2016b). Secondly, the exterior skin structure collapse leads to shrinkage (Panyawong & Devahastin, 2007). Besides these, the cell shape remains intact due to the turgor pressure within individual cells (Rahman, Joardder, Khan, Nghia, & Karim, 2016). Turgor pressure is a fluid force inside the cell of high-moisture foods that pushes against the cell wall to maintain the cell wall's rigidity. If the turgor pressure fails during drying, the cellular structure will collapse due to internal thermal stresses (Lin & Pitt, 1986; Prothon, Ahrne, & Sjoholm, 2003). The changes of the turgor pressure in potato tissue cause changes in the tissue compressive strength, the critical strain, and also the critical stress that leads to cell collapse (Joardder, Karim, Brown, & Kumar, 2015b). Therefore, shrinkage of material not only depends on moisture content but also depends on cell wall rigidity and turgor pressure of intracellular water, as well as cell wall properties that are discussed below.

Influencing Factors that Affect Material Shrinkage During Drying

Due to the diverse nature of fruits and vegetables, there are many factors that can affect the magnitude of material shrinkage during drying. Cellular structure, mechanical properties of food material, and drying conditions are the predominant factors that strongly affect the magnitude of shrinkage, and they are discussed below.

Effect of cellular water transport on material shrinkage

Fruits and vegetables are mostly composed of a solid matrix with a significant amount of liquid water in the cell at different level. The structural rigidity of cellular tissue prevents shrinkage when subjected to drying process (Prothon et al., 2003). The structural rigidity depends on cellular water distribution and its characteristics. Fruits and vegetables are hygroscopic in nature and contain 80% to 90% water (Khan, Kumar, Joardder, & Karim, 2017e). This vast amount of water is located in different cellular environments such as the intracellular environment, intercellular environment, and the cell wall environment. The proportion of water that present inside the cell (intracellular spaces) is referred to as intracellular water, and water that is present in intercellular spaces is referred to as intercellular water or capillary water (Khan et al., 2016b).

The cell wall is mostly composed of solid material, but a very small amount of water is present in microcapillaries. This water is referred to as cell wall water. Migration of free water has little effect on material shrinkage; however, transport of intracellular and cell wall water strongly affects the material shrinkage during food processing (Joardder, Brown, Kumar, & Karim, 2015a). During drying, transport of intracellular water causes cellular shrinkage, pore formation, and collapse of the cell. Finally, overall food tissue is deformed due to the migration of cell wall water (Joardder et al., 2015b).

Very recently, Khan, Wellard, Nagy, Joardder, and Karim, 2017b, 2018) argued that intracellular water migrates from the intracellular region to the intercellular environment through rupturing the cell membrane. They proposed that cell membranes collapse progressively at different stages of drying rather than collapsing at once, while others argued that cell membrane of food tissue collapsed at a time that ultimately deformed the whole tissue at a certain drying period (Halder, Datta, & Spanswick, 2011).

Migration of cellular water affects the cellular shrinkage but the magnitude of shrinkage is still not clearly understood. Furthermore, cell walls are basic construction elements that are responsible for the strength of the whole tissue (Haman & Konstankiewicz, 2000). The cell wall thickness of various types of fruits and vegetables depends on the characteristics of its solid material content (Khan, Joardder, Kumar, & Karim, 2016a). For example, cucumber tissue is more shrinkable than potato because potato cell walls are thicker and stronger (Joardder et al., 2015a).

Effect of drying conditions on material shrinkage

The most important drying parameters that influence the shrinkage of material are the drying temperature, drying air velocity, and the relative humidity of drying air. They are discussed below.

Drying air temperature. Drying temperature plays a significant role for increasing the drying rate that ultimately affects the material shrinkage. Drying below 50 °C, the cells remain intact (Halder et al., 2011); therefore, conversion of the intracellular water to free water remains unchanged with the drying progress. The intracellular water moves to intercellular space only through microcapillaries and therefore this migration is very slow, resulting in very low deformation. Halder et al. (2011) argued that the membrane of the cells collapse at once after reaching a specific temperature during processing; however, their argument may not be justified because cell collapse depends on internal thermal stress (Joardder et al., 2015a) that first develops near the surface and gradually penetrates to the center of the sample during convective drying (Khan & Karim, 2017a; Khan et al., 2017b). As a result, the cells may collapse progressively from the surface to center; therefore, an anisotropic shrinkage may be observed (Khan et al., 2016a; Prothon et al., 2003).

Furthermore, to investigate the effect of temperature on material shrinkage during drying, much observation has shown that temperature has a significant effect on material shrinkage during drying (Valle, Cuadros, & Aguilera, 1998). Most of the fruits and vegetables experience huge volume reduction when they are subjected to drying process at low temperature (20 °C). In contrast, when subjected to drying at high temperature (50 to 70 °C), food material undergoes limited shrinkage. Likewise, Wang and Brennan (1995) found that shrinkage of potato tissue at higher temperature (70 °C) is lower than shrinkage at low temperature (40 °C). This is may be due to the case-hardening effect that controls the transport of moisture, which ultimately controls material shrinkage. At low temperature, the moisture is transported in a flat pattern, therefore the stresses inside the food are minimal. Consequently, the material shrinkage is uniform and pronounced. On the other hand, at high temperature the surface of samples is dried very quickly, causing the surface to become stiff (case hardening), which does not allow the material to shrink significantly. Finally, the drying air temperature is the principal controlling factor for material shrinkage, and therefore a linear correlation between moisture content and air temperature is crucial (McMinn & Magee, 1997a, 1997b).

Drying air velocity and relative humidity. Air velocity is another significant factor that affects material shrinkage during drying. Ratti (1994) found substantial changes of shrinkage with varying air velocity. Shrinkage of fruits and vegetables are decreased during drying with increasing air velocity (Khraisheh, McMinn, & Magee, 2004; Ratti, 1994). This is may be due to the changes of mass transfer from internal to external at different stages of drying. During drying with externally controlled energy transfer, mass transfer occurs by both the internal diffusion and the external convection. At low air velocities surface resistance prevails and therefore the moisture profiles in the sample are relatively flat resulting in low internal stresses. Consequently, food material shrinks uniformly at low air velocities. Besides this, changes in shrinkage with air velocity are not equally significant for all types of fruits and vegetables; for example, the effect of velocity on material shrinkage is most pronounced in potato tissues, less pronounced in apples, and practically negligible in carrots (Ratti, 1994).

Sometimes the relative humidity of air may control the material shrinkage. At low relative humidity the Biot number (a dimensionless quantity used in heat transfer calculation) increases, ultimately limiting the material shrinkage (Ratti, 1994). Case hardening strongly affects the amount of material shrinkage evident at low relative air humidity.

Effect of mechanical properties of food material on shrinkage

Porosity is the main driving factor that can influence material shrinkage significantly. When the volume reduction of the food material is exactly equal to the volume of the removed water during drying, it is known as ideal shrinkage. If this occurs, no pore formation can be considered in the product. In reality, no food materials follow ideal shrinkage during drying: porosity increases in food materials. Thus the porosity can be calculated from the experimental shrinkage curve, an ideal shrinkage biased curve and an ideal shrinkage curve (Krokida & Maroulis, 1997). From the literature, it is found that porosity is inversely proportional to material shrinkage. Katekawa and Silva (2006) have proposed a relationship between shrinkage and porosity, including variables such as initial density of the wet product, true density of the liquid phase, and true density of the solid phase.

The existing constitutive models depend on the modulus of elasticity and Poisson's ratio. The value of these 2 mechanical properties significantly changes throughout the drying process that leads to change in the material deformation. Increasing the modulus of elasticity with decreasing moisture content strongly depends on temperature. During drying, material become rubbery with various degree of softness at higher temperatures during drying. Gulati and Datta (2015) argued that with an increase in elastic modulus, the shear modulus of the material increases leading to an increase in the principal tensile stress inside the material. In addition, Poisson's ratio is responsible for the rate of evaporation of liquid water in food material. A lower Poisson's ratio means a higher evaporation rate, which ultimately increases the volumetric changes (Gulati & Datta, 2015).

Effect of glass transition temperature on shrinkage

The structure of fruits and vegetables are very complex where amorphous form of water present inside the solid food matrix (Sappati, Nayak, & Walsum, 2017). The temperature at (or above) which the amorphous water in the fruits and vegetables changes from a rubbery to glassy state is called glass transition temperature (T_g) (Champion, Le, & Simatos, 2000). Glass transition temperature is also known as solid mobility temperature. The glass transition theory can explain the process of shrinkage during drying (Cnossen & Siebenmorgen, 2000; Karathanos, Kanellopoulos, & Belessiotis, 1996; Krokida et al., 1998; Rahman, 2001; Karathanos, 1993). In the rubbery state, the food material has a high mobility within the solid matrix. Conversely, in the glassy state, the food material has a low mobility due to high viscosity (in the range of 10^{12} to 10^{13} Pa s) (Joardder, Kumar, & Karim, 2017). The food material stays in the rubbery state when its temperature is more than the glass transition temperature. The shrinkage rate is also higher in the rubbery state as the molecular movement is much higher than that in the glassy state. The shrinkage in the rubbery state is directly proportional to the moisture loss. The glass transition temperature (T_g) varies with respect to the components types and the water content in the food. When drying progresses, the glass transition temperature increases with the reduction of moisture content. This phenomenon leads to lower shrinkage rate in the glassy state due to high viscosity of the food material (Sappati et al., 2017). Glassy state during drying usually provides the crispy texture of dried foods.

Theoretical Shrinkage Models

Fruits and vegetables are highly heterogeneous materials with solid and semisolid structures that contain a 3-dimensional solid network or matrix usually holding large quantities of aqueous solution. The solid matrix consists mainly of biopolymer elements. In more complex cases, fruits and vegetables are sometimes considered as composite material which is made of additional structural elements with biopolymers. (Aguilera, Bustos, & Molina, 1992). Moreover, there are many factors that affect the magnitude of shrinkage such as volume of removed water, mobility of the solid matrix, drying rate, and processing conditions. The diverse characteristics of high-moisture foods and process conditions make it complex to understand the physics behind the material shrinkage during drying. In this context, a theoretical shrinkage model could be the best option to predict the actual mechanism of deformation of fruits and vegetables during drying. There are some theoretical shrinkage models based on continuum mechanics which are discussed below, and also shown in Table 1.

Linear elastic model

The linear elastic model is the basic mechanistic model of shrinkage prediction. It is the most simplified model in food

Table 1–Continuum mechanics-based shrinkage models for food materials.

Type of model	Material	Geometry	Drying methods	Remarks	Reference
Elastic	Gel	Parallelepiped	Convective drying	(i) Volume shrinkage was calculated (ii) Shrinkage velocity was considered for isotropic shrinkage (iii) Linear relation between stress and elastic strain was assumed (iv) The model is unable to provide the exact displacement fields at the end of drying	Jomaa and Puiggali (1991)
	Agar gel	Sphere	Convective drying	(i) Volume change & shrinkage stress were investigated (ii) Material was considered as elastic and isotropic (iii) It was assumed that the medium remained biphasic during drying (iv) Poisson's coefficient was 0.5, measured by ultrasonic method	Mrani et al. (1995)
	Agar gel	Cylinder	Convective drying	(i) Overall deformation was investigated (ii) The medium was biphasic without the appearance of a gas phase (iii) Material was assumed as isotropic and linear elastic (iv) The process was considered as isothermal (v) Chemical reaction and phase change were not considered	Mrani et al. (1997)
	Spaghetti	Infinite cylinder	Convective drying	(i) Shrinkage and the induced strain and stress were investigated (ii) It was considered that there was no gas phase and no porosity present in the sample (iii) The viscous effects were assumed to be negligible	Ponsart et al. (2003)
	Potato	Parallelepiped	Convective drying	(i) Shrinkage and rheological behaviors were studied (ii) Moisture and temperature distribution were considered uniform (iii) Deformation was considered as unidirectional	Chemkhi et al. (2004)
	Shrimp	Average equivalent diameter of 1.63 $\pm$ 0.07cm	Convective drying	(i) Mechanical deformation was predicted (ii) Thermal expansion of shrimp was neglected (iii) Poisson's ratio of shrimp was assumed to be constant and equal to 0.33	Niamnuy et al. (2008)
Elastoplastic	Hydrated amylose starch granules	Cylinder	Convective drying	(i) Volume changes were observed (ii) Uniform moisture distribution was considered throughout the drying process (iii) Hydro-deformation was considered.	Tsukada et al. (1991)
	Amylose starch	Cylinder	Convective drying	(i) Hygro-stress crack formation & propagation were investigated (ii) Within a small strain region, food was assumed as elastoplastic (iii) Hygro-stress crack was assumed to be orthogonal to the orientation of the critical principal tensile stress	Izumi and Hayakawa (1995)
	Semolina hydrate	Hollow cylinder	Convective drying	(i) Stress cracks formation & propagation were studied (ii) The sample was assumed an infinitely long hollow cylinder	Akiyama and Hayakawa (2000)
	Potato	Cylinder	Air-drying	(i) Volume & shape changes were observed (ii) 2-dimensional shrinkage deformation was assumed (iii) Poisson ratio was assumed as constant and equal to 0.492	Yang et al. (2001)
	Potato	Cylinder	Convective drying	(i) Volume changes were observed. (ii) Poisson ratio was assumed as constant and equal to 0.492	Curcio and Aversa (2014)
Hyperelastic	Hamburger patty, Potato slab	Cylinder/slab	Single-sided cooking & convective drying	(i) Volume reduction was calculated (ii) Food materials was assumed as rubberlike materials for large (30%–70%) deformation (iii) Poisson ratio was assumed close to 0.5	Dhall and Datta (2011)
	Potato	Slab/cylinder	Convective drying	(i) A relationship among the change of volume, diameter and height were developed (ii) Poisson's ratio, in rubbery state is 0.49 and glassy state is 0.33 were taken	Gulati and Datta (2015)

(*Continued*)

Table 1–Continued.

Type of model	Material	Geometry	Drying methods	Remarks	Reference
	Potato	Cube	Microwave drying	(i) Volume & shape changes were observed (ii) Poisson's ratio of potato was assumed as 0.49	Gulati et al. (2016)
Viscoelastic	Grain kernels (soybean and corn)	Cylinder	Convective drying	(i) Volume changes were calculated (ii) Thermo-hydro viscoelastic stresses are a consequence of temperature and moisture gradients	Irudayaraj and Haghighi (1993a), Irudayaraj, Haghighi, and Stroshine (1993b)
	Amylose starch granules & sucrose	Brick shape	Convective drying	(i) Volume changes were investigated (ii) Uniform moisture distribution in the sample was considered (iii) Negligible thermal strains were assumed	Itaya et al. (1995)
	Potato	Square section	Convective drying	(i) Effect of shape of the sample on shrinkage was investigated (ii) The sample was assumed to be isotropic (iii) The mass diffusion coefficient was considered constant (iv) Poisson's ratio was assumed 0.5	Perré and May (2001)
	Potato	Cylinder	Convective drying	(i) Shrinkage of the food material was predicted (ii) Deformation is due to the change in moisture content	Sakai et al. (2002)
	French roll bread	Parallelepiped	Baking	(i) Studied mechanical behavior in the model of compressed chewing, and established the stress–strain model in the mode of compressed chewing (ii) The experiments were carried out at room temperature of 25°C	Lu et al. (2015)
	Eggplant	Cylinder	Roasting	(i) Volumetric changes (volume shrinkage) and directional shrinkage of material due to moisture removal were studied (ii) Eggplant was considered as a fictitious continuum rather than a hygroscopic porous medium (iii) Radiation heat transfer was considered during roasting although the effect of this heat transfer mode is negligible	Llave et al. (2016)

drying. The mechanical behavior of materials is modeled as a continuous mass rather than as discrete particles. The fundamental linearizing assumptions of linear elasticity are: infinitesimal strains or small deformations (or strains) and linear relationships between the components of stress and strain (Gulati & Datta, 2015; Kowalski, 1996). In addition, linear elasticity is valid only for stress states that cannot produce yielding. For linear elastic materials, Hooke's law is used as the constitutive law.

Kowalski (1996) presented a basic mathematical linear elastic model describing the shrinkage phenomenon of materials undergoing dehydration processes. The model was constructed based on the methods of continuum mechanics and the principles of thermodynamics of irreversible processes. In his model, Kowalski (1996) assumed that the material is deformed simultaneously due to the progressive change of heat and moisture as well as the induced stresses during drying. According to the model, the strain tensor ε_{ij} is expressed as:

$$\varepsilon_{ij} = \varepsilon_{ij}{}^{X} + \varepsilon_{ij}{}^{T} + \varepsilon_{ij}{}^{\sigma} \tag{1}$$

where $\varepsilon_{ij}{}^{X}$, $\varepsilon_{ij}{}^{T}$, $\varepsilon_{ij}{}^{\sigma}$ are the strains due to the change in moisture content, the temperature change and the drying induced stresses, respectively (Kowalski, 1996). The mechanical strain $\varepsilon_{ij}{}^{\sigma}$ can be elastic, plastic, elastoplastic, viscoplastic, or viscoelastic. For the sake of simplicity, Kowalski (1996) considered the fruits and vegetables as linear elastic and isotropic. Although the model is physically simplified, it gives satisfactory results for the deformations of geometrically arbitrary shaped dried bodies. The result of the linear elastic model mainly depends on the mechanical and thermal properties of fruits and vegetables (Jomaa et al. 1991, Mrani et al., 1995, Mrani et al., 1997, Ponsart et al., 2003, Chemkhi et al., 2004). These properties alter continuously with time and temperature due to the simultaneous heat and mass transfer during drying. Therefore, prediction of accurate results through this model is insignificant.

Niamnuy et al. (2008) modeled highly shrinkable and irregular-shaped biomaterial where they considered the stress–strain relation obeyed Hooke's constitutive equations of elastic behavior. They developed the model according to the following formulation.

The total displacement $\{dU\}$ at any point in the sample during the finite time increment is expressed by

$$\{dU\} = \begin{Bmatrix} dU_x \\ dU_y \\ dU_z \end{Bmatrix} \tag{2}$$

where $\{dU_x\}$, $\{dU_y\}$ and $\{dU_z\}$ are displacement in x, y, and z directions.

The local total strain $\{d\varepsilon\}$ is a function of the changes in mechanical strain $\{d\varepsilon^p\}$ and the changes in shrinkage strain $\{d\varepsilon^d\}$ as expressed by

$$\{d\varepsilon\} = \{d\varepsilon^p\} + \{d\varepsilon^d\} \tag{3}$$

Total strain $\{d\varepsilon\}$ is a function of the total displacement $\{dU\}$ as expressed by

$$\varepsilon_{ij} = \frac{1}{2}\left[\frac{\partial u_{ij}}{\partial x_j} + \frac{\partial u_{ji}}{\partial x_i}\right], \quad i,j = x,y,z \text{ or } \{d\varepsilon\} = [A]\{dU\} \tag{4}$$

where x_i, x_j are distance in x, y, and z directions; u is displacement; and $[A]$ is deformation strain matrix.

Total displacement $\{dU\}$ was estimated from the observed total change in nodal displacement $\{dn\}$ using a nodal shape function matrix $[\Lambda]$, which could be calculated using a polynomial approach and the expression can be written as,

$$\{dU\} = [\Lambda]\{dn\} \tag{5}$$

It can be written from Eqs. (4) and (5) that

$$\{d\varepsilon\} = [A]\,[\Lambda]\{dn\} = [B]\{dn\} \text{ Where, } [B] = [A]\,[\Lambda] \tag{6}$$

Change of stresses is the function of mechanical strain $\{d\varepsilon^p\}$, as by,

$$d\sigma_{ij} = \frac{E}{1+\nu}\left[d\varepsilon^p_{ij} + \frac{\nu}{1-2\nu}\left(d\varepsilon^p_{xx} + d\varepsilon^p_{yy} + d\varepsilon^p_{zz}\right)\delta_{ij}\right], \text{ where } i,j = x,y,z \tag{7}$$

where E is Young's modulus, ν is Poisson's ratio (ratio between longitudinal and lateral strains), σ is stress, ε is strain and δ_{ij} is the Kronecker delta. This is the constitutive equation for elastic materials.

A free shrinkage strain increment $\{d\varepsilon^d\}$ is related to the linear shrinkage coefficient due to moisture loss, as expressed by

$$\left\{d\varepsilon^d\right\} = \begin{pmatrix} d\varepsilon^d \\ d\varepsilon^d \\ d\varepsilon^d \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad d\varepsilon^d = S_V^{1/3} \tag{8}$$

where S_V is the volumetric shrinkage coefficient.

The Young's modulus E then can be correlated by equation (9) (Yang et al., 2001),

$$E = c_1 \exp(-c_2 M) \tag{9}$$

where c_1 and c_2 are the empirical constants and M is the moisture content, kg kg^{-1}, dry basis.

Many limitations of the linear elastic model make it infeasible to apply this model for accurate prediction of shrinkage during drying of various types of food products. Moreover, Hooke's law is not valid for biological materials (Llave et al., 2016) because of its limitation when applied to large deformation (as discussed in Section "Food material as an elastic and hyperelastic material").

Elastoplastic model

Elastoplasticity is the condition of showing both elastic and plastic properties, typically as a result of being stretched beyond the elastic limit. Due to the diverse nature of food materials, different food materials show various stress–strain patterns. The stress–strain relationship is expressed through the elastoplastic stress–strain matrix. Yang et al. (2001) have developed a 2-dimensional shrinkage model and showed that the shrinkage coefficients in axial and radial directions are significantly different during dehydration processes. They assumed potato behavior as elastoplastic and nonisotropic within a small strain region (Yang et al., 2001); however, some researchers have postulated that this assumption is not valid for other types of fruits and vegetables (Llave et al., 2016). Yang et al. (2001) developed the elastoplastic model considering the strain displacement is proportional to the shrinkage coefficient. They developed their model according to the formulation discussed below.

Total displacement $\{dU\}$ at any point during a specific time increment is written as

$$\{dU\} = \begin{Bmatrix} du \\ dv \end{Bmatrix} \tag{10}$$

where du and dv are displacements in r and z direction, respectively.

Local total strain $\{d\varepsilon\}$ is a sum of mechanical strain (deformation due to elastoplasticity) $\{d\varepsilon_s\}$ and shrinkage strain (deformation due to loss of moisture), $\{d\varepsilon_o\}$,

$$\{d\varepsilon\} = \{d\varepsilon_s\} + \{d\varepsilon_o\}. \tag{11}$$

Then the elastoplastic stress–strain matrix is needed to solve the elastoplastic model. The elastoplastic stress–strain matrix can be formulated as follows:

$$\begin{Bmatrix} d\sigma_r \\ d\sigma_z \\ d\sigma_\theta \\ d\tau_{rz} \end{Bmatrix} = \left\{ \begin{array}{l} \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1 & \frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & 1 & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 1 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)} \end{bmatrix} \cdot \begin{pmatrix} d\varepsilon_{sr} \\ d\varepsilon_{sz} \\ d\varepsilon_{s\theta} \\ d\gamma_{srz} \end{pmatrix} \\ -\frac{9\xi G_m^2}{\bar{\sigma}^2(3G_m+H')} \begin{bmatrix} \sigma_r'^2 & \sigma_r'\sigma_z' & \sigma_r'\sigma_\theta' & \sigma_r'\tau_{rz} \\ & \sigma_z'^2 & \sigma_z'\sigma_\theta' & \sigma_z'\tau_{rz} \\ & & \sigma_\theta'^2 & \sigma_\theta'\tau_{rz} \\ Sym.\ matrix & & & \tau_{rz}^2 \end{bmatrix} \cdot \begin{pmatrix} d\varepsilon_{sr} \\ d\varepsilon_{sz} \\ d\varepsilon_{s\theta} \\ d\gamma_{srz} \end{pmatrix} \end{array} \right\} \tag{12}$$

where σ is stress, $\bar{\sigma}$ is equivalent stress, σ' is deviatoric stress, ε is strain, τ is time, G_m is shear modulus, H' is strain-hardening rate, ξ is yield stress parameter, E is Young's Modulus and ν is Poisson's ratio.

The yield stress parameter, ξ allowed for the transition from elastic to elastoplastic deformation. In particular,

$$\xi = 0 \text{ when } \bar{\sigma} < \sigma_d \text{ for any } \bar{\sigma}_d\bar{\sigma}$$

$$\xi = 1 \text{ when } \bar{\sigma} > \sigma_d \text{ and } \bar{\sigma}_d\bar{\sigma} > 0$$

where σ_d is yield stress and $\bar{\sigma}_d$ is equivalent yield stress.

Shrinkage strain increment $\{d\varepsilon_o\}$ is related to the directional shrinkage coefficient due to moisture loss and can be expressed by,

$$\{d\varepsilon_o\} = \begin{Bmatrix} d\varepsilon_{ro} \\ d\varepsilon_{zo} \\ d\varepsilon_{\theta o} \\ 0 \end{Bmatrix} = \begin{Bmatrix} dS_r \\ dS_z \\ dS_\theta \\ 0 \end{Bmatrix} \tag{13}$$

where S_r, S_z, and S_θ are directional shrinkage coefficient in r, z, and θ direction for a cylindrical sample.

Yang et al. (2001), found that the deformation of material depends on the shape and size of the material. They argued that the axial shrinkage coefficients and the radial coefficients were significantly different during air-drying. In the same direction, the shrinkage coefficients at the center of the sample were different from those of the side region. Therefore, the assumptions of equal shrinkage in all dimensions and the models based on this concept may not be valid for the potato during drying.

Hyperelastic model

A hyperelastic material model is a type of constitutive model for ideally nonlinear elastic material. In this model, the stress–strain relationship derives from a strain energy density function, whose stress–strain relationship can be defined as nonlinearly elastic, isotropic, incompressible and generally independent of strain rate. Dhall and Datta (2011) developed a poromechanics based modeling framework to describe shrinkage in fruits and vegetables. They discussed 2 special cases of deformation such as small and large deformation of the solid matrix. In their analysis, they have considered the biological materials as rubber and polymer like materials which often exhibit nonlinear stress–strain behavior. This is due to the continuous moisture loss and change of mechanical properties during drying, which causes the food tissue to transform from a soft rubbery state to a hard glassy state (Ratti, 2001; Katekawa & Silva, 2006; Kurozawa, Hubinger, & Park, 2012).

According to Gulati and Datta (2015), $\boldsymbol{S}$ is the total deformation gradient tensor, $\boldsymbol{S_{el}}$ and $\boldsymbol{S_M}$ are the elastic and moisture effects of the material deformation gradient tensors for large deformation during drying, respectively. Mathematically it can be written,

$$\boldsymbol{S} = \boldsymbol{S_M} \boldsymbol{S_{el}} \tag{14}$$

where all the parameters are in vector form.

Linear momentum balance considering no body force for the solid in Lagrangian coordinates can be written as,

$$\nabla_X . \left(\boldsymbol{\lambda}\, \boldsymbol{S}_{el}^T\right) = 0 \tag{15}$$

where $\boldsymbol{\lambda}$ is the second Piola–Kirchhoff stress tensor. The relationship of Piola–Kirchhoff stress tensor and the Cauchy stress tensor can be written as,

$$\boldsymbol{\lambda} = J_{el}\, \boldsymbol{S}_{el}^{-1} \boldsymbol{\sigma}\, \boldsymbol{S}_{el}^{-T} \tag{16}$$

where J_{el} is the elastic Jacobian (the elastic volume ratio of the material that can be calculated by taking the determinant of the elastic deformation gradient tensor). The second Piola–Kirchhoff stress tensor is a material stress tensor. The second Piola–Kirchhoff stress tensor is defined as the work conjugate of the rate of Green tensor, $\boldsymbol{E_{el}} = (1/_2)(\mathbf{C} - \mathbf{I})$, where $\mathbf{I}$ is the identity tensor and $\mathbf{C}$ is the right Cauchy–Green tensor. Thus, the second Piola–Kirchhoff stress tensor is given by,

$$\boldsymbol{\lambda} = \frac{\partial U_s}{\partial \boldsymbol{E_{el}}} \tag{17}$$

Material deformation can be characterized by the elastic strain energy density, U_S. A Neo-Hookean constitutive model can be considered for large deformation occurred due to moisture loss, given by,

$$U_S = \frac{\mu}{2}(\bar{I}_1 - 3 - 2ln\, J_{el}) + \frac{\eta}{2}(lnJ_{el})^2 \tag{18}$$

where η is the Lamé constant and μ is the shear modulus of the material, both are related to the elastic modulus E and Poisson's ratio ν; J_{el} is the elastic Jacobian and $\bar{I}_1$ is the first invariant of right Cauchy–Green tensor.

The isochoric part of the elastic deformation gradient, $\bar{\boldsymbol{S}}_{el}$, is a function of the dilatation part, $J_{el}^{1/3}$, and the elastic deformation gradient, $\boldsymbol{S_{el}}$.

$$\bar{\boldsymbol{S}}_{el} = J_{el}^{-1/3}\, \boldsymbol{S_{el}} \tag{19}$$

The elastic Jacobean, $J_{el} = \det(\boldsymbol{S_{el}})$, is the ratio of the total Jacobean, $J\,(= V/V_0) = \det(\boldsymbol{S})$ and the Jacobean due to moisture loss, J_M. The volume change due to moisture loss, J_M, can be determined from the change in the volume fraction of the liquid water.

$$J_M = \frac{1 - \varepsilon_{w0}}{1 - \varepsilon_w} \tag{20}$$

where ε_{w0} is the initial volume fraction of liquid water and ε_w, is the volume fraction of liquid water at any instant.

Formation of pores during drying is usual in the high-moisture foods, which significantly affects the physical quality of the food sample (Joardder et al., 2017). Glass transition temperature, sample temperature, drying air temperature, moisture content and variable material properties like, solid density, initial density, particle density are prior responsible for pore formation (Joardder et al., 2017). In literature, many mathematical models show that shrinkage and porosity are related to each other (Gulati & Datta, 2015). Moreover, porosity can be measured from the experimental shrinkage curve and the ideal shrinkage biased curve (Madiouli et al., 2007). Migrated water during drying create void spaces which leads to develop pore space inside the sample and the deformation of the solid matrix compensates that void volume. As the material shrinks, its porosity changes continuously but the mass of the solid phases remain same. Therefore, the porosity at any instant can be found from the mass conservation of solid phase during drying.

$$\left.\begin{array}{l} \rho_{solid}\, V(1-\varphi) = \rho_{solid}\, V_0\, (1-\varphi_0) \\ \Rightarrow \varphi = 1 - \frac{1-\varphi_0}{V/V_0} = 1 - \frac{1-\varphi_0}{J} \end{array}\right\} \tag{21}$$

where φ is the porosity at any instant, φ_0 is the initial porosity and ρ_{solid} is the density of the solid.

Viscoelastic model

Viscoelasticity is the property of materials that exhibit both elastic and viscous characteristics when undergoing deformation. The viscosity of a viscoelastic substance is strain rate dependent. Purely elastic materials do not dissipate energy (as heat) when a load is applied, then removed. However, a viscoelastic substance loses energy when a load is applied then removed. Hysteresis can be observed in the stress–strain curve, with the area of the loop being equal to the energy lost during the loading cycle. Viscoelasticity is studied using dynamic mechanical analysis by applying a small oscillatory stress and measuring the resulting strain. Itaya, Kobayashi, and Hayakawa (1995) developed a 3-dimensional model of heat and mass transfer for a composite body undergoing a dehydration process where they first assumed the materials (hydrates of high amylose starch granules) as viscoelastic. Considering the same assumptions, Sakai, Yang, and Watanabe (2002) developed a viscoelastic model to describe deformation for food materials accompanying changes in moisture content. They showed that the assumption of potato is viscoelastic which is theoretically more accurate for nonuniform volume reduction than the assumption of elastoplastic material during drying. To develop a theoretical model for roasting of eggplant, Llave et al. (2016) assumed vegetables as viscoelastic material where the constitutive relationship of stress–strain deviates from Hooke's law. However, they used Burgers model for the constitutive relationship between stress and strain, whereas Sakai et al. (2002) used a Maxwell model. A Maxwell viscoelastic model cannot predict creep accurately for diverse biological materials (Mahiuddin, Khan, Duc Pham, & Karim, 2018). According to the literature, viscoelastic model can be developed through the following formulations.

The local total strain increment $\{d\varepsilon\}$ can be represented by the sum of the elastic strains increment $\{d\varepsilon_s\}$, the initial shrinkage strains increment $\{d\varepsilon_o\}$ and the viscositic strains increment $\{d\varepsilon_c\}$ by the following equation (Sakai et al., 2002):

$$\{d\varepsilon\} = \{d\varepsilon_s\} + \{d\varepsilon_o\} + \{d\varepsilon_c\} \tag{22}$$

The stress is expressed by the equation,

$$[d\sigma] = \begin{Bmatrix} d\sigma_r \\ d\sigma_z \\ d\sigma_\theta \\ d\tau_{rz} \end{Bmatrix} = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1 & \frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & 1 & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 1 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2(1-\nu)} \end{bmatrix} \begin{pmatrix} d\varepsilon_{Sr} \\ d\varepsilon_{Sz} \\ d\varepsilon_{S\theta} \\ d\gamma_{Srz} \end{pmatrix}$$
$$= [D]\{d\varepsilon_s\} \tag{23}$$

where E and ν are the Young's modulus (Pa) and Poisson's ratio, respectively.

The viscositic strain increment $\{d\varepsilon_c\}$ is expressed as follows (Sakai et al., 2002):

$$d\varepsilon_c = \begin{Bmatrix} d\varepsilon_{rV} \\ d\varepsilon_{zV} \\ d\varepsilon_{\theta V} \\ d\varepsilon_{rzV} \end{Bmatrix} = \frac{3}{2\bar{\sigma}} \begin{Bmatrix} \sigma'_r \\ \sigma'_z \\ \sigma'_\theta \\ \sigma'_{rz} \end{Bmatrix} d\bar{\varepsilon}_c = \frac{3}{2\bar{\sigma}} \begin{Bmatrix} \sigma'_r \\ \sigma'_z \\ \sigma'_\theta \\ \sigma'_{rz} \end{Bmatrix} \bar{\varepsilon}'_c \Delta t \tag{24}$$

where $d\bar{\varepsilon}_c$ and $d\bar{\varepsilon}'_c$ are the equivalent viscositic strain increment and the equivalent viscositic strain rate, respectively, Δt is the increment of t (time), and σ'_r, σ'_z, and σ'_θ in the matrix of Eq. (18) are deviatoric stresses. Instead, the initial shrinkage strain increment $\{d\varepsilon_o\}$, a strain caused by heating, can be written as

$$\{d\varepsilon_o\} = \begin{Bmatrix} d\varepsilon_{ro} \\ d\varepsilon_{zo} \\ d\varepsilon_{\theta o} \\ 0 \end{Bmatrix} = \begin{Bmatrix} dS_r \\ dS_z \\ dS_\theta \\ 0 \end{Bmatrix} \tag{25}$$

where S_r, S_z, S_θ are the free shrinkage coefficients in r, z, and θ directions for a cylindrical sample. The total strain $\{d\varepsilon\}$ is a function of the total displacements vector, $\{dU\}$, as expressed by

$$\{d\varepsilon\} = \begin{bmatrix} \frac{\partial}{\partial r} & 0 \\ 0 & \frac{\partial}{\partial z} \\ \frac{1}{r} & 0 \\ \frac{\partial}{\partial z} & \frac{\partial}{\partial r} \end{bmatrix} \begin{Bmatrix} du \\ dv \end{Bmatrix} = [A]\{dU\} \tag{26}$$

where $[A]$ is the strain nodal displacement matrix, and du and dv are displacements in r and z directions, respectively.

General Trends of Output Parameters of Shrinkage

Based on the extensive review of the literatures on shrinkage models and the authors' current research, the general trends of the different output parameters are identified and presented in the following sections.

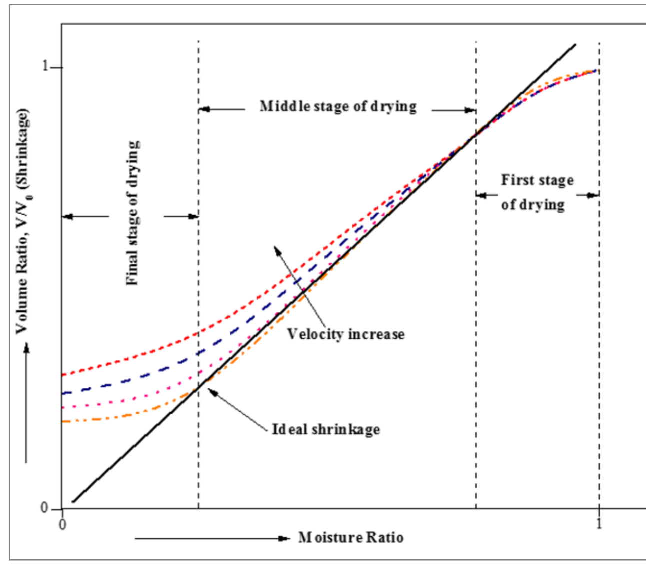

Figure 1–Effect of velocity on shrinkage of food materials during drying

Change of volume with drying air velocity

Figure 1 shows general trends of the effect of drying air velocity on material shrinkage of fruits and vegetables during drying. The rate of volume changes (V/V_0, where V is the volume at any time of drying, and V_0 is the initial volume of the sample) at the early stage of drying is not so significant. In the next stage (the middle stage) of drying, the rate of material shrinkage increases significantly, followed by the ideal shrinkage. However, the rate of volume reduction attenuates at the final stage of drying (Figure 1). This variation of volume reduction is governed by the rate of internal mass transfer as well as process conditions. At the early stages of drying, mostly free water is migrated from intercellular spaces to the environment through evaporation which has minor effect on material shrinkage (Joardder et al., 2015a; Khan, Kumar, & Karim, 2017d; Khan et al., 2017b). After the early stage of drying, intracellular water starts to migrate through rupturing the cell membrane (Khan et al., 2017b), and therefore a significant volume reduction follows (Joardder et al., 2015b). After the middle stage of drying, most of the intracellular water has been transferred to the intercellular spaces followed by transfer to environment through evaporation. After the middle stage of drying, a small amount of water remains in the micropores inside the intracellular spaces and the cell wall environment. This type of water is termed as strongly bound water which is strongly bonded with the internal micromolecular species and therefore difficult to transport during drying (Khan et al., 2016b; Khan, Wellard, Mahiuddin, & Karim, 2017c; Khan et al., 2017e). At the final stage of drying, this type of water is transported with a longer drying time that leads to attenuation of the rate of volume reduction. In addition, it can be seen from Figure 1 that the volume reduction decreases with increasing drying air velocity. This is mainly due to the case hardening that occurs while faster drying is imposed (as discussed in Section "Drying air velocity and relative humidity").

Change of volume with temperature

During drying, volume reduction may coincide with the ideal shrinkage for much of the drying process (that is, the middle stage) but not for the initial and final stages of drying, as shown in Figure 2, since shrinkage is referred to as ideal when volume change is equal to the amount of liquid water lost. The volume

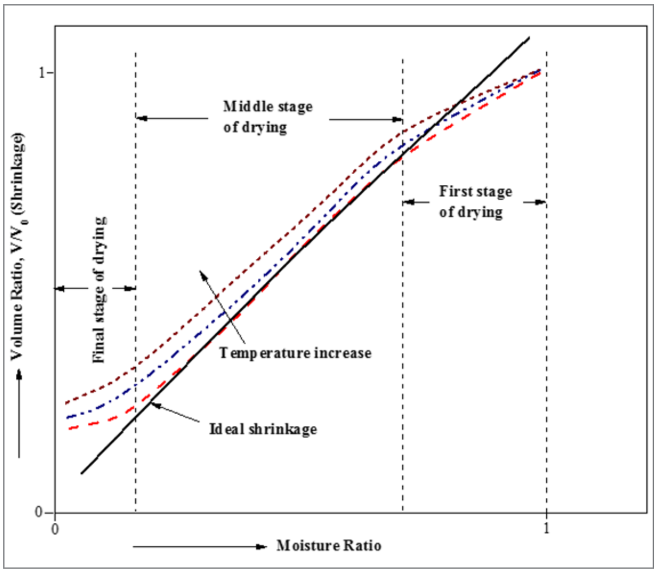

Figure 2–Effect of temperature on shrinkage of food materials during drying

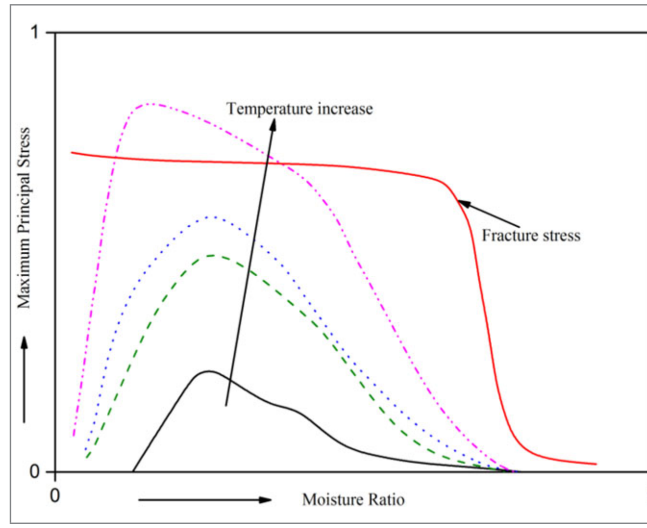

Figure 3–Change in stresses in food materials during drying

reduction at the early stage and final stage of drying is slower than the middle stage of drying. This is mainly due to the transport characteristics of different types of water (free water, loosely bound water, and strongly bound water) at different stages of drying (Khan et al., 2017b), as discussed in Section "Change of volume with drying air velocity". In addition, when drying at high temperature, the surface of the material dries out much faster than the core; therefore, crust formation occurs at the surface that leads to decrease the volume reduction. On the other hand, at low drying temperature, the moisture is transported in a flat pattern; therefore, the stresses inside the food are minimal. Consequently, there is a uniform, large material shrinkage (as discussed in Section "Drying air temperature"). Moreover, at high temperature when the drying rate is higher, the surface of the sample enters a glassy state while the core is still wet and in a rubbery state, leading to the coexistence of both rubbery and glassy states at higher than average moisture content. This rubbery–glassy phase transition is accompanied by large changes in the mechanical properties and transport properties (Gulati & Datta, 2015).

Changes in stresses during drying

The principal stress (that is, thermal stress) is induced while drying is in progress due to the moisture and temperature gradient. This stress increases at different stages of drying. It mainly depends on the penetration rate of heat energy during drying. Figure 3 shows the variation of maximum principal tensile stress with moisture ratio. It can be seen that the stress increases with the propagation of heat energy. The cell membrane of the material collapsed when this stress just crosses the fracture stress line (Figure 3). Gulati and Datta (2015), found that while drying at the highest rate, the principal tensile stress curve crosses the fracture stress line at a specific drying time (about 1.2 hr). Likewise, Wang and Brennan (1995), reported that potato samples cracked near the top surface about after 1 hr in the drying process. For intermediate drying rates, the maximum principal tensile stress value stays below the fracture stress curve, indicating that there is no material fracture. Moreover, it is also noted by Wang and Brennan (1995), that there was no visible crack on the material surface during drying, and the material shrank to a solid core. For the lowest drying rate, the maximum principal tensile stress stays well below the fracture strength of the material and there is no crack incipience (Gulati & Datta, 2015).

Challenges for Prediction of Material Shrinkage During Drying

Based on an extensive literature review, the following key factors contribute to the current challenges to developing an accurate physics-based shrinkage model for food drying.

Food material characterization

Due to the diverse nature of fruits and vegetables, it is very important to characterize the material as to whether it is elastic, plastic, viscoelastic, elastoplastic or something else. Existing research has been conducted based on some simplistic assumptions regarding the behavior of fruits and vegetables, including that it behaves like elastic (that is, a rubberlike material) (Dhall & Datta, 2011; Gulati & Datta, 2015; Gulati, Zhu, & Datta, 2016), elastoplastic (Akiyama & Hayakawa, 2000; Curcio & Aversa, 2014; Izumi & Hayakawa, 1995; Tsukada et al., 1991; Yang et al., 2001), and viscoelastic (Itaya et al., 1995; Llave et al., 2016; Lu et al., 2015; Perré & May, 2001; Sakai et al., 2002;). However, the heterogeneous structure of different fruits and vegetables makes its actual behavior complex, and therefore, without material characterization, categorization of the material behavior may not be justified. By interpreting the necessity of material characterization, much research has been done on the characterization of different porous materials, such as for polymers (Paola, Pirrotta, & Valenza, 2011). Nevertheless, there is no study that adequately addresses the categorization of the behavior of fruits and vegetables. To investigate some of the mechanical properties, a few researchers have conducted experimental analysis of stress relaxation behavior (Blahovec, 1996; Lewicki & Jakubczyk, 2004; Lu & Puri, 1992; Roopa & Bhattacharya, 2014). Although results of those studies are significant for calculating material properties, material characterization is still lacking. This is because of the complexity of stress–strain relaxation analysis of diverse food materials.

Modeling of shrinkage of food materials

Existing models are based on some simplistic assumptions to minimize the complexity of the model formulation and calculation. In most cases, it is considered that fruits and vegetables are deformed on a small scale and therefore they have used Hooke's law for up to 10% strain levels during drying. However, these assumptions may not true for different types of food materials because most of the fruits and vegetables undergo a large anisotropic deformation when they are subjected to simultaneous heat and mass transfer processes during drying (Dhall & Datta, 2011; Gulati & Datta, 2015). These types of simplistic assumptions have been used in the existing literature in order to reduce the complexity of the model formulation and solution. Therefore, for accurate prediction of material shrinkage a realistic generalized theoretical model is needed and that is the challenge for further research.

In addition, the classical viscoelastic material models that have been used in the existing literature have some limitations. For instance, to reproduce the actual material's viscoelastic behavior (with creep and relaxation phases) many parameters are needed which makes the model more complex. Moreover, the parameters are found by means of best fitting numerical procedures which can lead to meaningless parameters from a physical point of view (for example, negative coefficients of stiffness and viscosity in a spring and dashpot) (Paola et al., 2011). Besides this, most of the current literature has used the classical Maxwell model; however, this model cannot accurately predict the creep property of the viscoelastic fruits and vegetables.

Mechanical properties of food materials

Shrinkage of fruits and vegetables strongly depends on the mechanical properties. Most of the existing literature considered the modulus of elasticity of potato tissue as a function of moisture content; however, the modulus of elasticity also depends on the temperature and the material structure (Khan et al., 2016a). Moreover, the modulus of elasticity relationship that has been widely used in the current literature was based on data from experiments conducted at room temperature (Yang et al., 2001). Instead, for a realistic understanding, an accurate relationship of modulus of elasticity is needed based on data that has been generated while drying is in progress; and this is the ultimate challenge for future research. Furthermore, the correlation developed for potato may not be applicable for other food materials due to their diverse nature and properties; therefore further investigation of the modulus of elasticity for specific food materials is crucial.

In addition, the value of Poisson's ratio was assumed for most of the cases without proper justification although these values are strongly dependent on moisture content and temperature, and changes throughout the drying process. The use of an inappropriate Poisson's ratio may lead to erroneous prediction of deformation. Therefore, consideration of accurate Poisson's ratio for different fruits and vegetables is important for better prediction of material shrinkage during drying.

Shrinkage Measuring Techniques

Shrinkage of food sample during drying can be measured by the liquid displacement method and imaging technique. The liquid displacement method gives the homogeneous volume shrinkage whereas heterogeneous shrinkage (both area and volume change) can be measured by imaging technique. Imaging technique for measuring shrinkage is also known as nonintrusive technique. In literature several techniques were used for the shrinkage measurement which are summarized below.

Volume of the samples can be measured by the liquid displacement method (Gulati et al., 2016; Krokida et al., 1997; Zogzas, Maroulis, & Marinos Kouris, 1994). The experimental apparatus consists of a compartment, in which the sample is put, and of a measuring burette that is marked in volume scale in (ml) to measure the displaced volume of the liquid. The compartment of the apparatus can be closed hermetically by a lid. The apparatus is filled with a suitable portion of a liquid. Toluene, n-heptane, and mercury can be used as test liquid. The displaced volume of the test liquid is measured by turning the apparatus upside down without and with the sample immersed. The measuring accuracy depends on the accuracy of the burette, usually an accuracy of 0.05 mL is used.

Shrinkage measurement by using imaging technique involves image segmentation, noise reduction and then conversion to a binary image. In the segmentation process, the information of every pixel of the image is specified and noise is eliminated from the image, which is then followed by converting to a binary image for identifying the surface area. Raw images can be taken by X-ray micro-tomography (μCT), Laser Scanning, Scanning Electron Microscope (SEM), camcorder, digital video camera attached with stereo-microscope, computer vision, and colour line-scan digital camera. Raw images can be processed by different software to get the shrinkage data. ImageJ, MATLAB, CAD software, UTHSCSA Image Tool, Presitt algorithm, and Digital Image Correlation (DIC) algorithm are widely used for image processing techniques to measure shrinkage.

Gulati et al. (2016) measured shrinkage during microwave drying by placing a digital camcorder near the hole on the side face of the microwave and analyzing the images using ImageJ software to get the area shrinkage. Hansson, Couceiro, and Fjellner (2016) experimentally measured radial and tangential shrinkage of wood by tomography (CT) images and compared the results with those obtained by computer-aided design (CAD) software on the same images. Computer vision systems which include sample distributing unit, image capture unit and image processing unit were successfully designed and implemented for characterizing the drying shrinkage of tobacco lamina (Zhu, Wang, Xu, & Du, 2014). A stereo-correlation technique was used to determine the volume (both the radial and axial shrinkage) of a banana during convective drying where 2 cameras were used to determine the shrinkage parameters of each camera (Madiouli et al., 2011). Recently an image processing algorithm has been effectively used for measuring the relative area reduction during convective drying of sugar kelp (Sappati et al., 2017). They have developed a new image processing algorithm based on pixel thresholding in MATLAB.

Conclusion

Drying of fruits and vegetables are very complex process where heat and mass transfer occurs simultaneously along with volume reduction. Physical quality of dried food materials largely depends on the extent of deformation during drying. In contrast, rehydration capacity and rehydration rate of the dried fruits and vegetables are strongly related to the shrinkage. These attributes can be improved by controlling the extensive deformation of the dehydrated product during simultaneous heat and mass transfer.

This article presented the different aspects of shrinkage and the factors that affect the large deformation during drying. It has been manifested from the previous literature that the fruits and vegetables can be considered as elastic, hyperelastic, elastoplastic or viscoelastic while developing a shrinkage model. Then the formulation of current shrinkage models and their typical results have been discussed. Finally, the current challenges to develop theoretical shrinkage model have been identified and discussed. The critical review in this paper identified many limitations of the existing models and therefore a generalized shrinkage model that is applicable for diverse fruits and vegetables is essential. This review also discussed that varying drying parameters and changing mechanical properties are primarily responsible for large and anisotropic shrinkage that occurs during drying. The variation of drying air velocity and temperature does affect the material shrinkage. Therefore, the future research should be devoted toward developing a generalized theoretical shrinkage model considering the material characterization and real-time thermophysical properties of fruits and vegetables during drying. This paper will contribute to a better understanding of shrinkage phenomena and associated factors through the development of a physics-based shrinkage model.

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Author Contributions

Md Mahiuddin researched the previous articles published in the field of food drying and shrinkage, organized and drafted the manuscript. Md. Imran H. Khan, C. Kumar, M. M. Rahman, and M. A. Karim led the work and critically revised the manuscript.

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