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Review

Cellular water distribution, transport, and its investigation methods for plant-based food material

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ABSTRACT

Heterogeneous and hygroscopic characteristics of plant-based food material make it complex in structure, and therefore water distribution in its different cellular environments is very complex. There are three different cellular environments, namely the intercellular environment, the intracellular environment, and the cell wall environment inside the food structure. According to the bonding strength, intracellular water is defined as loosely bound water, cell wall water is categorized as strongly bound water, and intercellular water is known as free water (FW). During food drying, optimization of the heat and mass transfer process is crucial for the energy efficiency of the process and the quality of the product. For optimizing heat and mass transfer during food processing, understanding these three types of waters (strongly bound, loosely bound, and free water) in plant-based food material is essential. However, there are few studies that investigate cellular level water distribution and transport. As there is no direct method for determining the cellular level water distributions, various indirect methods have been applied to investigate the cellular level water distribution, and there is, as yet, no consensus on the appropriate method for measuring cellular level water in plant-based food material. Therefore, the main aim of this paper is to present a comprehensive review on the available methods to investigate the cellular level water, the characteristics of water at different cellular levels and its transport mechanism during drying. The effect of bound water transport on quality of food product is also discussed. This review article presents a comparative study of different methods that can be applied to investigate cellular water such as nuclear magnetic resonance (NMR), bioelectric impedance analysis (BIA), differential scanning calorimetry (DSC), and dilatometry. The article closes with a discussion of current challenges to investigating cellular water.

1. Introduction

Food materials, specifically plant-based foods, are complex in nature as they have heterogeneous, hygroscopic and porous properties that contain up to 80–90% water (Khan, Kumar, Joardder, & Karim, 2017). This vast amount of water is located in different cellular environments inside the food structure. According to biological analysis, the vacuole, cytoplasm, cell wall and extracellular space are the main cellular locations in food tissue that contain this water in differing proportions (Aguilera & Stanley, 1999). Food thermal processing (drying, frying, and cooking) researchers have found that the water in food tissue mainly exists in three different cellular environments, namely intercellular space, intracellular space, and the cell wall environment (Khan, Joardder, Kumar, & Karim, 2016). The intercellular spaces or environments are those where some unrestricted spaces have been made by the connection of two or more cells as shown in Fig. 1. These unrestricted spaces are mostly composed of air, a small portion of water, and other solutes (such as sugar). The small portion of water that is contained in this space is termed intercellular water or simply free water (FW). The vacuole and cytoplasm together are considered as intracellular spaces that act as a water reservoir in fruit tissue. Generally, the water that resides in this area is known as intracellular water. The water held in the microspace in a cell wall environment is sometimes referred as extracellular water (Van Der Weerd, Claessens, Efdé, & Van As, 2002) or cell wall water. The waters in different cellular environments have different bonding capacities. According to their bonding strength, some waters are referred as bound water (see Section 2). Understanding the proportions of water occupying different cellular environments in plant-based food tissue is crucial for optimizing energy consumption and obtaining better quality of dried foods during food drying (Khan, Wellard, et al., 2016). However, the proportions of different cellular waters, transport mechanisms, and the effect of bound water transport on food quality have not been widely reported in the available literature to date. To obtain a better understanding of how

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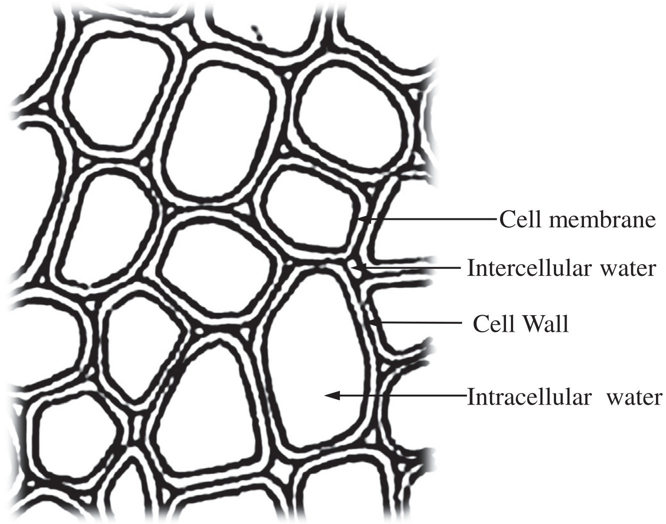

Fig. 1. Cellular water distribution in plant-based food tissue (Khan, Joardder, et al., 2016).

cellular water moves from one cellular environment to another cellular environment as well as their effect on food quality, extensive experimentation is needed.

There are several methods that can potentially be used for measuring the different types of water, including differential scanning calorimetry (DSC), differential thermal analysis (DTA), dilatometry, bioelectric impedance analysis (BIA), and nuclear magnetic resonance (NMR). Due to the specific limitations of the various methods, they may not be equally suitable for the application in plant-based food tissue for measuring cellular level water (Khan, Wellard, et al., 2016).

Therefore, the primary aim of this article is to present a comprehensive review of various methods for measuring cellular water and identify which method is best for plant-based food material. It is also the objective of the present work to a provide a comprehensive review of the characteristics of different types of cellular water and their transportation mechanisms, their effect on the food properties during food drying, and consideration of cellular water transport in existing drying models. This article is organized as follows. First, a clear explanation of the different types of cellular water and their classification with their characteristics is presented. Second, the transport mechanism of cellular water and its consideration of transport in existing food drying models are clearly explained. Third, a comprehensive review of different methods (NMR, DSC, BIA, DIL) that can be used for measuring cellular waters is presented. Then the current status of research on cellular water distribution in food tissue is discussed. The article closes with discussion of a major challenge to the measurement of cellular water distribution and transport.

1.1. *Classification of cellular water and its characteristics*

In cellular tissue, water is distributed in different cellular environments in different proportions according to their macromolecular bonding strength, and therefore they are categorized by terms and definitions that reflect their diverse characteristics, as discussed below.

Bound water is the water that is physically trapped within a restricted environment and therefore is hard to transport during food drying (Khan, Joardder, Kumar and Karim, 2016). Bound water can be defined as the proportion of water in various materials (such as animal and plant cells or soils) that are associated with the colloid phase with strong micromolecular binding strength (Caurie, 2011). In plant-based food material, water can be bound physically and chemically. The water that resides in intracellular environment, and cell wall environment is categorized as physically bound water (Joardder, Kumar, & Karim, 2017; Karel & Lund, 2003). A very small amount of water bonded with the chemical (nutrition) is categorized as chemically bound water. The chemically bound water should not be considered for transport due to its great impact on the taste and flavor of the dried food (Kuprianoff, 1958). Therefore, physically bound water is the main concern for transport during food processing.

Physically bound water can be divided into two different categories based on its micromolecular bonding strength: loosely bound water (LBW) and strongly bound water (SBW); intracellular water is LBW and cell wall water is SBW (Caurie, 2011; Khan, Wellard, et al., 2016). These two types of water (LBW and SBW) are sometimes referred to as the monolayer water and multilayer water respectively (Rockland, 1969), or as vicinal water and constitutional water (Yamsaengsung & Moreira, 2002).

Sometimes bound water can be defined based on its physical characteristics. The physical characteristics of bound water are different from FW. Free water is located in the pores and the capillaries and can easily be removed during drying. One of the major characteristics of FW is that it diffuses faster than bound water (Khan, Joardder, et al., 2016). Yamsaengsung and Moreira (2002) argue that the enthalpy of vaporization of SBW is much greater than that of pure water. This water forms a monolayer over the hydrophilic region of the solid material by either water–ion or water–dipole interaction. Moreover, in food material, LBW is associated with neighboring molecules mainly by water-water and water-solute hydrogen bonding (Yamsaengsung & Moreira, 2002). Based on the consideration of the water mobility, the LBW has the lower diffusivity than FW. Therefore, the variation in binding energy of bound water strongly affects the drying process, since it requires more energy than FW (Shafiur, 2007). Furthermore, it is reported that bound water (SBW) is not free to act as a solvent for salts and sugars (Vaclavik & Christian, 2008). It can be frozen only at very low temperatures (below the freezing point of normal water), it exhibits essentially no vapor pressure, and its density probably greater than that FW (Vaclavik & Christian, 2008). Based on these characteristics, Briggs (1932) argued that bound water is the proportion of water in a system associated with the colloid phase with such strength that it is no longer available to act as a solvent or to be separated from the colloid phase by freezing, because they are prevented from separating from the non-water constituents and other substances by high heats of adsorption. Thus, it can be argued that the physical characteristics of bound water are not similar to that of FW and therefore the transport properties (for instance, diffusivity) of bound water will differ from FW.

1.2. *Transport mechanism of cellular water during drying*

The mechanisms of heat and mass transfer in a food material depend on the physical structure and the chemical composition of that material. Hygroscopic food material contains three types of water: SBW, LBW, and FW as discussed above. SBW is tightly held in the cell wall environment and therefore cannot be transported during thermal processing. The latter two types of water are the main concern during thermal processing (Khan, Joardder, et al., 2016). The transport mechanism of FW and LBW may be different due to their diverse transport properties. FW can migrate from intercellular spaces to the surface by diffusion and convection where it can be removed by evaporation from the surface to the environment air (Srikiatden & Roberts, 2007). Studies of the transport mechanism of LBW are inadequate and unclear (Feng, Tang, Cavalieri, & Plumb, 2001). Turner, Puiggali, and Jomaa (1998) assumed that bound water transfer was caused by only diffusion while others postulated a capillary mechanism to characterize bound water flow (Peishi & Pei, 1989). Feng et al. (2001) hypothesized that a universal driving force that comes from the chemical potential gradient is responsible for migrating LBW. It has also been hypothesized that bound water is removed by progressive vaporization within the solid matrix, followed by diffusion and pressure-driven transport of water vapor through the solid (Datta, 2007).