Trends in Food Science & Technology 78 (2018) 11–24

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Review

Water transport in starchy foods: Experimental and mathematical aspects

Oguz Kaan Ozturk, Pawan Singh Takhar*,[1]

Food Science and Human Nutrition Department, University of Illinois at Urbana-Champaign, IL, 61801, USA

ARTICLE INFO

Keywords:
Moisture sorption
Swelling
Gelatinization
Glass transition
Modeling
Non-Fickian

ABSTRACT

Background: The availability and movement of water inside the food materials play essential roles for food stability by affecting their physical and chemical properties, and microbiological activity. Understanding the moisture sorption behavior is a necessary step to control food properties. Food processing unit operations like drying and cooking influence the behavior of starch since such systems trigger swelling or shrinkage as a result of moisture sorption or desorption mechanisms. Also, these processes alter many aspects of starch-containing foods such as acceptability, nutritional value, quality, and shelf-life.

Scope and approach: Therefore, understanding the water transport in starchy foods and the changes occurring in functional properties of starch has a great importance to describe and model their sorption and drying behavior. First, the primary mechanisms occurring during water transport such as moisture sorption, swelling, gelatinization, and glass transition are discussed using experimental results presented in the literature. Additionally, the hybrid mixture theory (HMT) and its potential for predicting transport mechanisms in starchy foods is discussed.

Key findings and conclusions: In addition to experimental considerations, the mathematical modeling provides complementary information to predict the heat and fluid transfer. The hybrid mixture theory based multiscale models are able to describe the physico-chemical changes and general transport mechanisms occurring within a porous food matrix. This theory can also be used to predict the quality changes in food products during processing.

1. Introduction

Starch is an important component of human diet and health since it is one of the primary energy sources in foods. Slow digestion of starch has many health benefits such as control over blood glucose level and increased prebiotic effects (Wang, Li, Copeland, Niu, & Wang, 2015). It is also completely biodegradable in water and soil (Frost, Kaminski, Kirwan, Lascaris, & Shanks, 2009). Besides food industry, it is also used in many other industries such as paper, cosmetics, and textiles due to its high adsorption capacity and adhesiveness (Tamaki, Konishi, & Tako, 2011). It can also be used as a thickening agent or a stabilizer after its functional properties are enhanced with physical, chemical, and enzymatic modifications (Tamaki et al., 2011; Zavareze & Dias, 2011).

Starch is the most abundant carbohydrate-based polymer in nature. It is widely available from numerous sources such as wheat, barley, corn, rice, and potatoes (Frost et al., 2009). It is a semi-crystalline biopolymer and comprised of two structural isomers, amylose and amylopectin, which differ from each other regarding length and distribution (Tang & Copeland, 2007). Amylose constitutes the linear part with a few branches consisting of α-(1 → 4)-linkages between D-glucose units while amylopectin forms highly branched parts consisting of both α-(1 → 4) and α-(1 → 6) linkages (Vandeputte, Vermeylen, Geeroms, & Delcour, 2003). Amylose is a hydrophobic molecule due to its helical structure with hydrogen atoms inside and hydroxyl groups outside. It can form complexes with free fatty acids due to its hydrophobic nature, and these amylose-lipid complexes can change functional properties of starch such as gelatinization temperature, textural and viscoelastic properties, and consequently water transport within the structure. On the other hand, amylopectin has a tree-like structure, which includes both crystalline regions with double helical structures and amorphous areas with branching points (Zavareze & Dias, 2011).

The structure of starch has been investigated by several researchers. Goesaert et al. (2005) compiled these studies and described this complex structure at different levels (Fig. 1). Fig. 1a shows that the starch granules consist of alternating amorphous and semi-crystalline rings with varying radial thicknesses. Some findings demonstrated that these structures organize and form spherical shapes called blocklets (Fig. 1b). Amorphous rings include amylose and less ordered amylopectin. On the other hand, semi-crystalline rings contain alternating amorphous, and crystalline lamellae, which have amylopectin branching regions and

---

* Corresponding author.
E-mail address: ptakhar@illinois.edu (P.S. Takhar).
[1] Author has previously published as Pawan P. Singh.

https://doi.org/10.1016/j.tifs.2018.05.015
Received 1 November 2017; Received in revised form 8 May 2018; Accepted 19 May 2018

Nomenclature

a_w	water activity
B	constant in Vogel-Tamma-Fulcher equation
B_c	relaxation parameter
C	concentration of material (mol cm^{-3})
C_1	constant in Williams-Landel-Ferry equation
C_2	constant in Williams-Landel-Ferry equation
C_3	constant in molecular relaxation time calculation
c_s	mass fraction of material
c_w	mass fraction of water
D	diffusion coefficient (cm^2 s^{-1})
D_G	the effective diffusion coefficient in the glassy state (cm^2 s^{-1})
D_R	the effective diffusion coefficient in the rubbery state (cm^2 s^{-1})
E_a	apparent activation energy (kJ/mol)
G_e	the equilibrium stress (mPa)
G_i	the stress coefficient of the ith element of the Maxwell model
$G(t)$	the stress relaxation function
G_∞^*	the factor of proportionality
J	the rate of flow per unit area of the diffusing molecules (mol cm^{-2} s^{-1})
k	constant in Gordon-Taylor equation
MC	moisture content (% dry basis)
q_{st}	the net isosteric heat of sorption (kJ/mol)
R	the universal gas constant (kJ/(mol K))
t	diffusion time (s)
T	temperature (K)
T_g	glass transition temperature (K)
T_{g_s}	glass transition temperature of the material (K)
T_{g_w}	glass transition temperature of water (K)
T_0	the theoretical Kauzmann temperature (T_k) (K)
x_f	the fraction of fluid taken by the solid matrix

Greek symbols

ε^f	volume fraction of the fluid
τ	molecular relaxation time (s)
τ_0	constant in molecular relaxation time calculation
τ_{mol}	the characteristic time of mobility or relaxation time (s)
η	viscosity (mPa s)
η_0	initial viscosity (mPa s)
η_{Tg}	viscosity at T_g(mPa s)
λ_i	the relaxation time of the Maxwell element

Special symbols

$D\varepsilon^f/Dt$	the material time derivative with respect to the solid phase particles (s^{-1})
∇	the gradient operator in spatial dimensions

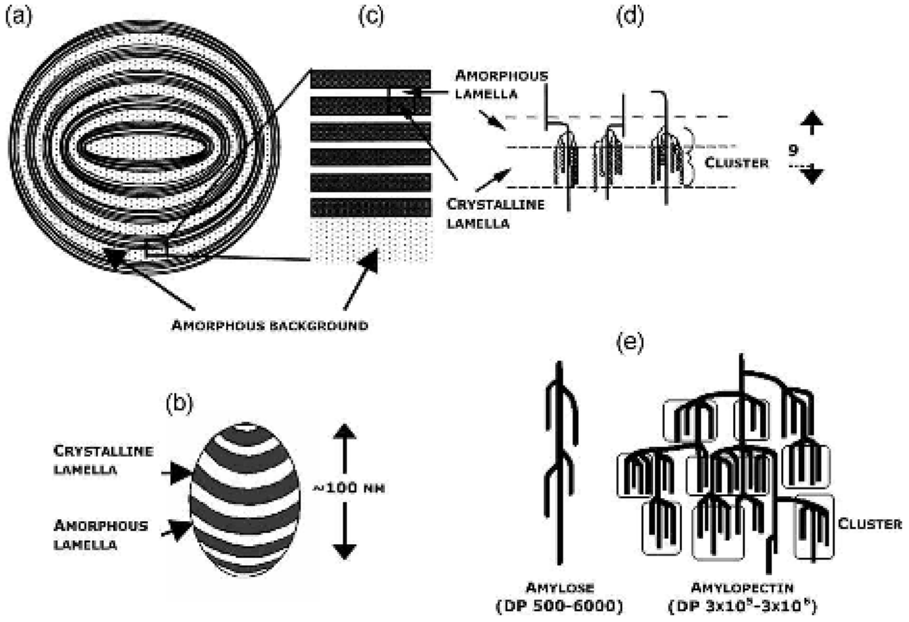

Fig. 1. Schematic representation of structural levels of a starch granule (a) granule with alternating amorphous and semi-crystalline shells, (b) blocklet structure, (c) overall view of the semi-crystalline layer, (d) the cluster structure of amylopectin within the semi-crystalline layer, (e) the structure of amylose and amylopectin (Reprinted from Goesaert et al. (2005) with permission from Elsevier).

amylopectin double helices, respectively (Fig. 1c and d). Also, the highly branched structure of large amylopectin and mainly linear structure of amylose molecules are shown in Fig. 1e.

Water transport in granular structure of starch plays a significant and unique role by affecting functional properties of starch during processes. The behavior of starch due to processes such as cooking and drying is of great interest to food scientists since it alters various aspects of starch-containing foods such as acceptability, nutritional value, quality, and shelf-life. Therefore, understanding the relationship between starch and water molecules, the changes occurring in its functional properties, and the effects of time and temperature on its structural properties is critical to describe and model the sorption and drying behavior of starchy foods. However, the effect of glass transition and the underlying mechanisms during adsorption/desorption on water transport and swelling are complex. Accordingly, the objective of this study is to review the primary mechanisms occurring during water transport in starchy foods. Therefore, moisture sorption, swelling, gelatinization, and glass transition characteristics of starchy foods will be discussed in the following sections. In addition to the experimental research, the mathematical modeling approach based on multiscale transport theory will be briefly presented, which can be utilized for describing transport mechanisms during processes such as cooking, drying, and sorption of starchy foods.