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Review

Review on the control of ice nucleation by ultrasound waves, electric and magnetic fields

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A B S T R A C T

Freezing is the most popular and widely used food preservation method of the modern times. The freezing process of food matrices is related to their high water content and its metamorphoses into ice on cooling. The final quality of the frozen product is highly depended on the ice crystal morphology because it can cause irreversible damage on the microstructure of the food matrix. Supercooling and ice nucleation temperature need to be controlled both in suppressing and inducing the solidification to improve technological processes such as freeze drying, freeze concentration, cryopreservation, ice formation and cold-energy storage both in food industry and domestic preservation. However, the mechanism of freezing is not yet well known and it is affected by several factors.

Several emerging technologies have been recently proposed for ice nucleation control during freezing. This review article is focused on the alternative freezing methods such as ultrasound waves, magnetic, electric, and electromagnetic field assisted freezing. In addition, the properties, mechanism of action and possible applications of electrofreezing are extensively discussed.

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1. Introduction

Water is the major but Janus-faced component of almost all the fresh food materials. The two faces of water lie in the facts that although water is an essential constituent for the freshness characteristics of foods, it is also actively involved in all the deteriorative mechanisms which influence their texture, appearance, quality, as well as in the acceleration of their microbial, chemical, and biochemical degradation. Water in food matrices exists in two states, namely as "non-bound" and "bound." First, the term "non-bound" is related to the freely available solvent water, condensed within the capillary structure or in the cells of a food that behaves physically and chemically as pure water. Second, water fraction is "bound" to polar groups or ionic sites on molecules such as starches, pectins, and proteins, thus becoming less active (Belton, 1997; Choi and Kerr, 2003; Fellows, 2009; Fessas and Schiraldi, 2001, 2005). During freezing, water is converted into ice crystals and the water activity of the food system decreases due to the reduction of the available liquid water. The reduced water activity helps to preserve foods for longer periods of time, and freezing temperatures reduce the rate of chemical reactions as well as the activity of microorganisms and enzymes, thereby extending the storage life of frozen foods. Although freezing causes minimal deterioration of original color, flavor, texture or nutritional values in comparison with thermal processing, food materials are prone to bei subjected to irreversible tissue damage due to the solute-concentration damage, dehydration damage and mechanical damage from ice crystals (Reid, 1993). The quality of frozen food is considered inversely related to the extent of freezing-induced cellular dehydration, the size of the ice crystals and their location inside the foods (Delgado and Sun, 2001; Li and Sun, 2002b). It is well-known that rapid freezing like cryogenic freezing results in the formation of smaller and more numerous ice crystals, which is preferable for minimizing the damage to the cellular structure. However, the major disadvantages of this freezing method are: the high total cooling costs, the environmental impacts and the susceptibility of some products to crack or even shattering when exposed directly to extreme low temperature (Kim and Hung, 1994; Smith, 2011). Therefore, the selection of methods that maximize the quality of frozen food while lowering the costs and the power consumption, are of major importance for the frozen food industry. The last decades, several studies and many promising technologies have been introduced providing the potentials for better quality attributes of frozen food matrices while lowering the energy demands. The novel freezing methods can be categorized in three different classes with respect to their approach. i) Improvement of the heat transfer rate during freezing like hydro- fluidization or impingement freezing, ii) change the properties of food material like ice nucleation protein and antifreeze protein and iii) assisted freezing methods which can alter the nucleation, crystal growth and nucleation rate of food materials during freezing like high pressure freezing, microwave assisted freezing, radiofrequency assisted freezing, magnetic freezing and electrofreezing (James et al., 2015).

Among all the assisted freezing methods, we will focus on the effects of ultrasound, magnetic fields, electric fields and electromagnetic wave. The aim of this paper is to explore the effects of ultrasound waves, magnetic, electric and electromagnetic field assisted freezing and to discuss their potential applications in frozen food technology. The outputs of recent studies as well as the mechanism of action, the thermodynamics and the influence on crystallization of electrofreezing will be comprehensively discussed.

2. Freezing

In principle freezing process consists of three stages namely, pre-cooling or chilling stage, in which the material is cooled from its initial temperature to the freezing point temperature; phase change period which represents the crystalisation of most of the water; and sub cooling or tempering stage in which the product reaches the finally established temperature (Kiani and Sun, 2011; Xanthakis et al., 2014a). The crystalisation comprises nucleation and crystal growth. Nucleation refers to the process by which an adequate amount of molecules associate in three dimensions to form a thermodynamically stable aggregate, the so called critical nucleus, which provides surfaces suitable for crystal growth. The growth stage, which immediately follows the nucleation, is governed by the diffusion of particles to the surface of the critical nuclei and their ordered assembling onto the growing crystal (Russo Krauss et al., 2013). Two distinct processes are identified in the nucleation of crystals, namely, primary and secondary or contact nucleation. Primary nucleation involves the formation of crystal in a solution containing no existing crystals. Primary nucleation can take place in two categories; Homogenous and heterogeneous. Homogeneous nucleation occurs when the nuclei is formed spontaneously from the random density fluctuation within the supercooled liquid but heterogeneous nucleation takes place due to the presence of solid impurities that form stable surfaces for nuclei formation (Gülseren, 2008; Sahagian and Goff, 1996). The distinction between heterogeneous and homogenous nucleation can be made using DSC techniques by evaluating the differential heat flow signals (Gülseren, 2008; Özilgen and Reid, 1993).

Secondary nucleation involves the production of new crystals in a solution containing pre-existing crystals, and it can occur either by the crystals acting as templates for new crystals nuclei to be formed or by the crystals fragmenting to produce more nucleation sites (Adriana and Da-Wen, 2011). It is believed that the nucleation is the most important step during crystallization, since it can affect both crystal size and distribution of ice crystals (Saclier et al., 2010b). But the nucleation temperature (T_n), which is the temperature at which crystallization starts, is quite variable and is affected by several factors such as foreign particles, the surface area, process conditions, sample volume, composition of the matrix and contact area between sample and container. The aforementioned and other factors are responsible for the random and stochastic nature of ice nucleation (Anuj, 2012; Kiani et al., 2012a; Petersen et al., 2006). On the other hand, the ability to control supercooling (temperature difference between the freezing point of a matrix and the nucleation temperature) and ice nucleation is essential to produce a homogeneous and uniform frozen batch (Anuj, 2012; Passot et al., 2009), to increase food quality (Orlowska et al., 2009) and to the

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