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Non-thermal hybrid drying of fruits and vegetables: A review of current technologies

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ABSTRACT

Fruits and vegetables are very perishable commodities that have enormous industrial and commercial importance. To preserve its quality attributes, increase shelf life, and reduce transport weight, fruit and vegetable can be processed by drying. Over the years, conventional drying techniques have been widely applied, both industrially and commercially for the processing and preservation of fruits and vegetables. However, most of the conventional techniques are time and energy consuming, and affect important quality attributes of final products. Recently, there has been increased interest in the use of non-thermal drying methods in combination with other conventional drying techniques for preserving fruits and vegetables. These methods have been reported to enhance the quality attributes of dried products, reduce drying time and energy demand, and increase the overall drying efficiency. In this regard, the development of a cost effective non-thermal hybrid drying systems, such as combined ultrasound (US) and hot-air drying, ultraviolet (UV) and hot-air drying, and pulse electric field (PEF) and hot-air drying have recently been researched on. These drying techniques have become potential substitute for conventional industrial and commercial dryers, owing to their advantage of producing quality dried fruit and vegetable products, with reduced drying time and energy consumption. This study therefore attempts to highlight recent developments of the commonly used non-thermal combined convective hot-air drying (CHAD) techniques for fruits and vegetables, with emphasis on drying time, drying rate, quality attributes of products, and modelling approach. This study further highlights the primary constraints for industrial application of this technology as the inadequate medium of transmission for power ultrasound, cost of design and installation, and the limited study on (UV) and PEF assisted CHAD. The necessity for conducting more detailed studies on non-thermal assisted convective hot-air drying of fruits and vegetables was emphasized.

1. Introduction

Drying is perhaps the oldest and widely used method of postharvest food preservation. It involves the removal of moisture from a product due to couple heat and mass transfer (Erbay & Icier, 2010; Onwude, Hashim, Janius, Nawi, & Abdan, 2016b). Drying improves postharvest handling and packaging, increases the ease of product transportation, and improves other processing operations such as milling, and mixing (Mujumdar & Law, 2010). As an important unit in postharvest operation, especially for food and agricultural processing industries, it remains an area of incessant interest for food research.

The most commonly used conventional methods for drying fruits and vegetables include vacuum drying (Akbudak & Akbudak, 2013), solar drying (Fadhel, Abdo, Yousif, Zaharim, & Sopian, 2011), sun drying (Akpinar, 2006), freeze drying (Vergeldt et al., 2014), fluidized bed drying (Arumuganathan, Manikantan, Rai, Anandakumar, & Khare, 2009), tray drying (Kadam, Goyal, & Gupta, 2011), and hot-air drying (Onwude, Hashim, Janius, Nawi, & Abdan, 2016a; Ratti, 2001). With the exception of freeze drying, these drying methods largely depend on the application of heat to the product either through convection, conduction, or radiation. These heating modes have been reported to influence the drying process, efficiency, and quality of dried materials (Perera & Rahman, 1997; Zhang et al., 2017).

Different novel techniques that involve the application of some of these heating modes or a combination thereof have recently been developed, specifically for drying of fruits and vegetables (Aktaş, Şevik, & Aktekeli, 2016; Bonafonte, Iglesias, & Bueno, 2002; Chong, Figiel, Law, & Wojdyło, 2013; Mongpraneet, Abe, & Tsurusaki, 2002).

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However, the choice of the most appropriate drying technique depends on various factors such as the product type, drying conditions, drying efficiency, and cost of drying operation. Other critical selection parameters include energy consumption, and quality of the final product.

Convective hot-air drying (CHAD) is widely used in the industry for preserving and processing fruits and vegetables, owing to the advantages of convective hot-air drying (CHAD) over other conventional drying methods. CHAD provides uniform distribution of hot-air and temperature over the product, compared to other traditional methods, it reduces energy consumption and drying time and provides better dried products when utilising optimum conditions (da Silva, Rodrigues, e Silva, de Castro, & Gomes, 2015). In addition, hot-air dryers are easy to construct, simple in operation, and are very familiar to operators both industrially and commercially (Ratti, 2001). However, due to drying process conditions: temperature, air velocity, and relative humidity, important product properties, such as texture, colour, total carotenoid content, phenolic composition, total phenolic content, antioxidant capacity and other bioactive compounds could be affected (Degirmencioglu, Gürbüz, Herken, & Yildiz, 2016; Jangam, 2011; Onwude, Hashim, Janius, Nawi, & Abdan, 2017; Silva, Oliveira, & Branda, 2015). Although some studies have attempted to address the challenges associated with CHAD including drying products using low temperature, low relative humidity, and optimized drying parameters in order to improve the quality of dried products (Ratti, 2001; Sturm, Hofacker, & Hensel, 2012), practically, the quality attribute of final product is still affected. More so, these approaches still require high amount of energy and drying time, and the associated total cost becomes unacceptable. In order to improve overall efficiency, reduce operating cost and enhance the quality of dried products, innovative methods which involve the combination of non-thermal techniques and CHAD (either as pre-treatment or simultaneously) have recently gained increasing interest in the advancement of drying technology.

Application of non-thermal (NT) technologies which include ultrasound, pulsed electric fields, and ultraviolet radiation may cause a change in the temperature inside a product, but does not generate heat within the product. During non-thermal processing, the quality of the food product is preserved due to the temperature difference inside the product which is lower than the temperatures during thermal processing (Raso & Barbosa-Cánovas, 2003). Additionally, non-thermal processing does not often rely on limiting heat transfer coefficients and temperature boundary conditions. Other advantages of non-thermal techniques include enhanced quality attributes, reduced drying time and increased processing efficiency (Cullen, Tiwari, & Valdramidis, 2012).

The combination of NT and CHAD, otherwise known as non-thermal hybrid drying provides the synergistic effect during the heat and mass transfer process within a product. This effect leads to a better quality and stable dried product, increased energy saving, reduced drying time, and increased drying efficiency (Andrés, Fito, Heredia, & Rosa, 2007; Beck, Sabarez, Gaukel, & Knoerzer, 2014; Moses, Norton, Alagusundaram, & Tiwari, 2014). Recently, several research involving combined non-thermal CHAD, also known as hurdle technology (Cullen et al., 2012) have been carried out; in particular, the application of ultrasound (US) assisted CHAD for fruits and vegetables over the past decade. Still, there are less industrial and commercial application of this technology due to inadequate information, poor understanding of operation mode, energy requirements and overall energy efficiencies, efficient transmission of acoustic energy (in the case of US) and the practical difficulties in adapting the technology at an industrial scale. Moreover, there are less information on the quality of dried products and modelling approach using these techniques. This knowledge gap is a serious setback for the advancement of emerging drying technology, and the production of quality dried fruits and vegetables. In view of this, the objective of this review is to highlight recent advances of non-thermal assisted convective hot-air drying of fruits and vegetables, with emphasis on drying time, drying rate, combination mode, quality attributes and modelling approach.

2. Non-thermal hybrid drying

Non-thermal processes, as the name suggest, are processes that do not involve the generation of heat, but can cause a change in temperature inside a product. In other words, these processes do not depend on the temperature of source. According to Cullen et al. (2012), non-thermal techniques involves technologies that are effective at room or less intense temperatures. They also stated that some of these technologies could result in the rise in temperature during processing.

The application of non-thermal technology has gained momentum in recent years due to its numerous advantages over traditional thermal technology, which include short processing time, increased process efficiency, environmentally friendly, and better product quality amongst others (Cullen et al., 2012; Morris, Brody, & Wicker, 2007; Ortega-Rivas & Salmerón-Ochoa, 2014; Vicente & Castro, 2007; Witrowa-Rajchert, Wiktor, Sledz, & Nowacka, 2014). This technology can be used to develop hybrid drying systems.

Hybrid drying involves the combination of two or more different processing unit operation or drying system either as a single unit or multistage arrangement (Atuonwu, Van Straten, Van Deventer, & Van Boxtel, 2013). The combination of NT and CHAD can improve and control the lethal influence of CHAD, minimize the severity of each technology due to the synergetic effect, enhance the final quality of dried product, and higher overall drying efficiency as compared with utilising just CHAD. Several researches regarding to combined NT and CHAD have focused on combined ultrasound (US) and CHAD, combined pulse electric field (PEF) and CHAD, and most recently, combined ultraviolet (UV) and CHAD. The examples covered in this paper include combined US and CHAD, combined pulse electric field (PEF) and CHAD, and combined ultraviolet (UV) and CHAD.

3. Combined ultrasound and hot-air drying

Ultrasound (US) is a type of sound energy transmitted by waves in the form of pressure at frequencies of 20 kHz and above (Demirdöven & Baysal, 2008; Witrowa-Rajchert et al., 2014). US can be categorized into high frequency (low energy, low intensity) at frequencies > 100 kHz (MHz range), and low frequency (high energy, high intensity) at frequencies range of 20–100 kHz (Jambrak, Mason, Lelas, Herceg, & Herceg, 2008; Witrowa-Rajchert et al., 2014). High frequency-low intensity ultrasound technology is often applied as an analytical method for non-destructive quality and process inspection, and control, such as to determine various food properties, to check the quality of food product, to measure severity of spoilage, to measure flow rate, and so on (Dolatowski, Stadnik, & Stasiak, 2007; Jambrak, Lelas, Mason, Kresic, & Badanjak, 2009; Knorr, Zenker, Heinz, & Lee, 2004; Zheng & Sun, 2006). Low frequency-high energy also referred to as "power ultrasound," produces variety of effects that results in cavitation (swift development and implosion of gas bubbles), which can regulate enzymes (activate or inactivate), and enhance the rate of heat and mass transfer for different postharvest applications on agricultural crops, like drying, freezing and osmotic dehydration (Dolatowski et al., 2007; Gallego-Juárez et al., 2007; Kek, Chin, & Yusof, 2013; Ortuno, Perez-Munuera, Puig, Riera, & Garcia-Perez, 2010; Ozuna, Cárcel, Walde, & Garcia-Perez, 2014; Riera-Franco De Sarabia, Gallego-Juárez, Rodríguez-Corral, Acosta-Aparicio, & Andrés-Gallegos, 2002; Santacatalina, Contreras, Simal, Cárcel, & Garcia-Perez, 2016).

3.1. Mechanism of operation

As an emerging NT technology, US drying is very promising and can be easily applied together with other conventional drying technology such as CHAD. Unlike the thermal drying technologies (Onwude, Hashim, & Chen, 2016), US basic drying principle is based on mechanical mechanism and less on heating mechanism, which leads to a