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Review

Radio frequency heating for postharvest control of pests in agricultural products: A review

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ABSTRACT

Radio frequency (RF) treatment is one of the most promising physical disinfestation methods in agricultural products due to rapid heating, deep penetration depth, and leaving no chemical residues. This paper focuses on reviewing uses of RF energy for disinfestation of agricultural products. It provides a brief introduction on the basic principle of RF heating technology, analyzes the differential heating of pests in host products at RF range, and discusses the factors influencing the RF heating uniformity and the possible methods to improve heating uniformity by computer simulations. This paper presents a comprehensive review of recent progresses in developing RF treatment protocols for disinfesting fresh fruits and dry products, and recommendations for future research to effectively achieve the required RF heating uniformity and bridge the gap between laboratory research and industrial applications.

Contents

1. Introduction

One of the main issues during production, storage, and marketing of agricultural products is the damage and loss due to infestation by pests. Losses caused by pests in agricultural

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products include reduced nutrition, low germination rate, and weight reduction (Yuya et al., 2009). Furthermore, the pests produce sticky substances and feces, which promote the microbial growth and reduce market price of agricultural products. It is estimated that annual losses of cereal grains due to pests is about 9% in developed countries and approximately 20% or more in developing countries (Azab et al., 2013; Huang et al., 2015b). Therefore, developing an effective and efficient disinfestation method can largely reduce pest damages to agricultural products during storage (Tang et al., 2007).

Regulatory agencies worldwide have established phytosanitary and quarantine protocols intended to prevent the movement of exotic pests through marketing channels and re-infestations during the storage. Currently, the agricultural product industry relies heavily on methyl bromide (MeBr) and phosphine fumigations for postharvest insect control (Carpenter et al., 2000). After used for commodity fumigation (Yokoyama et al., 1990), MeBr gas eventually enters the atmosphere during aeration, which results in depleting the ozone layer. Its use has been scheduled to be phased out in developed countries by 2005 and developing countries by 2015 according to the Montreal Protocol (UNEP, 1992). Phosphine fumigation is problematic because the gas corrodes copper, gold and silver, and can seriously damage electrical equipment. Fumigation with phosphine requires longer exposures than that with MeBr, making phosphine unsuitable for applications where a quick treatment is needed. Phosphine fumigation also results in increased resistance in pest populations (Fields, 1992). Regulatory actions against both MeBr and hydrogen phosphine may make these fumigants difficult to obtain or even unavailable to the industry. Therefore, thermal treatments are proposed to be non-chemical alternative to control insect pests in postharvest agricultural products (Feng et al., 2004; Tang et al., 2007).

Except for applying easily, leaving no chemical residues, and offering some fungicidal activity (Armstrong, 1994), conventional thermal disinfestation treatments often cause deleterious effects to product quality due to long heating times at the target temperature (Armstrong, 1994; Wang et al., 2001b). Recently, radio frequency (RF) energy has been widely studied to overcome the slow heating rate of the conventional heating due to its volumetric and fast heating (Tang et al., 2000). RF heating has been successfully used in many industries, such as plastic welding, curing of glue in plywood processing, textile drying, and finish drying of bakery products (Orfeuil, 1987). Many recent studies on the use of RF energy have been conducted to control insects in postharvest agricultural products (Nelson and Payne, 1982; Nelson, 1996; Tang et al., 2000; Marra et al., 2009). With long wavelengths and large penetration depths, RF treatments have also been used for disinfestations in large scale industrial applications (Wang et al., 2007a,b; Jiao et al., 2012). For successful commercial implementations, the RF treatments should provide adequate insect mortality to meet quarantine or phytosanitary requirements, cannot adversely affect product quality, and be economically feasible to use in industrial operations.

Heating non-uniformity is a major problem in RF treatments, which would result in either insect survival or product damage (Birla et al., 2004; Wang et al., 2005b, 2008). Hot air or water as surface heating, sample moving, and mixing are commonly used to improve the RF heating uniformity (Hansen et al., 2006a,b; Wang et al., 2006, 2014; Tiwari et al., 2008; Gao et al., 2010; Sisquella et al., 2013). With the computer simulation, RF heating uniformity has also been improved by placing the samples in the middle of the two plate electrodes and using a similar dielectric material around the samples (Jiao et al., 2014).

Based on the dielectric properties difference, the differential heating between the target insects and host products has been observed both theoretically and experimentally, resulting in the insects reaching a lethal temperature while the product is heated to lower temperatures that do not cause quality loss (Wang et al., 2001a, 2010; Birla et al., 2005; Tiwari et al., 2008; Gao et al., 2010; Jiao et al., 2012; Hou et al., 2014). By exploring differential heating, the time and the product temperature needed for effective RF treatments could be significantly reduced, thereby reducing adverse effects on product quality and enabling a greater throughput of product in a processing plant (Nelson, 1996; Shresth and Baik, 2013; Wang et al., 2013). This is important to systematically analyze possible selective RF heating of the insects in agricultural products.

The purposes of this review are (1) to introduce the basic principle of RF heating, (2) to analyze the differential heating in pests and host products in RF range, (3) to discuss the potential methods to improve RF heating uniformity by computer simulations, (4) to review the literature on RF treatments for control of pests in agricultural products, and (5) to propose recommendations for the future research to enhance practical applications of RF heating to postharvest control of pests in agricultural products.

2. Properties of RF heating

2.1. Principle of RF heating

RF heating is one of thermal treatments using electromagnetic energy to heat the pest to its lethal temperature with holding an adequate time. When any material with polarized molecules and charged ions is subjected to an electromagnetic field that rapidly changes direction, heating occurs as polarized molecules and charged ions interact with the alternating electromagnetic field, resulting in frictional losses as they rotate and move (Barber, 1983). The higher the frequency of the alternating field, the greater the energy imparted to the material, until the frequency is so high that rotating molecules cannot keep up with the external field due to lattice limitations (Zhao et al., 2000). In RF heating, the applied frequencies are between 10 and 300 MHz, and specifically allocated to be 13.56, 27.12, and 40.68 MHz by the US Federal Communications Commission (FCC) to avoid disturbing with the communication system.

Many factors influence the RF heating of agricultural products. However, the major factors are dielectric properties of agricultural products and distribution of electromagnetic fields, which determine the thermal energy in agricultural products converted from electromagnetic energy. RF energy generates heat volumetrically and rapidly within agricultural products by the combined effects of polarization mechanisms of dipole rotation and ionic conduction, which are discussed in the following section (Piyasena et al., 2003).

2.1.1. Dielectric properties

Most of agricultural products act as an electric capacitor to store electrical energy, and also as a resistor to transform electric energy to thermal energy, thereby heating the products. These abilities are defined by dielectric properties (ε) normally described by the following equation (Risman, 1991):

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1}$$

where $j = \sqrt{-1}$. ε' is the relative dielectric constant, and describes the ability of a material to store energy in response to an applied electric field (for a vacuum $\varepsilon' = 1$). ε'' is known as the relative electric loss factor, and describes the ability of a material to dissipate energy in response to an applied electric field, which typically results in heat generation.

Dielectric properties of agricultural products depend on the frequency of electromagnetic field, temperature, moisture content, density, and composition of agricultural products (Ryynänen,