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Kinetic modeling and characterization of a diffusion-based time-temperature indicator (TTI) for monitoring microbial quality of non-pasteurized angelica juice

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ABSTRACT

Time-temperature-indicator, or integrator (TTI), can be used for visual display of food product safety information for consumers. A prototype isopropyl palmitate (IPP) diffusion-based TTI system was characterized and evaluated for monitoring microbial quality of non-pasteurized angelica (NPA) juice based on temperature abuse. Diffusion of IPP in the TTI system was measured at various iso-thermal and dynamic temperatures and a mathematical model based on relationships between diffusion and time-temperature was established. Predicted results from the established model were in good agreement with experimental results. Total aerobe counts in NPA juice reached a critical level of 6 log CFU/mL from an initial load of 3.7 log CFU/mL after 36.6 h and 12.5 h of storage at 15 °C and 25 °C, respectively. IPP diffusion distances were 9.7 mm and 7.2 mm at 15 °C and 25 °C, respectively. IPP diffusion of 7.0 mm in the TTI system was considered to be a threshold point for bacterial quality of NPA juice. However, the proposed TTI was only verified for indicating temperature abuse above 13.5 °C. The TTI system characterized in this study showed potential for monitoring the microbial quality of perishable food products during distribution and storage.

1. Introduction

Temperature and time, widely recognized as major factors influencing the rate of microbial activity in foods, often deviate from specifications during manufacturing, distribution, handling, and storage (Giannakourou, Koutsoumanis, Nychas, & Taoukis, 2005; McMeekin et al., 2008). Therefore, it is important to monitor changes in temperature and time parameters from production to final consumption to ensure microbial safety and quality of food products (Taoukis & Labuza, 2003). Characteristics of a modern quality and safety assurance system should be based on capability to monitor, record, and control critical parameters to prevent contamination throughout the product life cycle (Lu, Zheng, Lv, & Tang, 2013; Wanihsuksombat, Hongtrakul, & Suppakul, 2010).

A TTI is an intelligent packaging system, usually in the form of a small intelligent tag or label attached to a food product. A TTI indicates the cumulative time-temperature history of a food product using an irreversible chemical change in the TTI device that is detected as a visible response in the form of mechanical deformation, color development, or color movement. A TTI is a simple, cost-effective, and consumer friendly device for monitoring, recording, and translating quality information for consumers (Pavelková, 2013; Taoukis & Labuza, 2003; Vaikousi, Biliaderis, & Koutsoumanis, 2008; Zabala, Castán, & Martínez, 2015). The overall effect of the temperature history of a food product on food quality, safety, and shelf-life can be observed using a TTI (Ellouze & Augustin, 2010). Different commercial TTI types have been developed based on enzymatic, polymer, and biological reactions (Ellouze & Augustin, 2010; Kim, Kim, & Lee, 2012; Lu et al., 2013; Wu et al., 2015).

A prerequisite for effective application of a TTI based control

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system is kinetic study and modeling of food quality loss indices and of the response of the TTI (Tsironi, Stamatiou, Giannoglou, Velliou, & Taoukis, 2011; Wanihsuksombat et al., 2010). The temperature-dependent performance of a TTI system has been investigated previously using the Arrhenius equation (Ellouze & Augustin, 2010). Fick's law of diffusion can also be applied to establish a kinetic model with regards to the TTI diffusion rate (Galagan, Hsu, & Su, 2010).

Angelica keiskei is a well known herbal plant in Asian countries. Green juice extracted from fresh leaves of this plant is used as a functional food drink that is known for nutritional and health benefits (Akihisa et al., 2003; Kim et al., 2014; Zhang, Yamashita, Yasuda, Yamamoto, & Ashida, 2015). Fresh angelica juice reaches consumers without pasteurization mostly through a home delivery service and is recommended for consumption within 48–72 h with storage at 5 °C (Pulmuone, 2015). However, temperature deviations occur from specified values during product transport, handling, and storage, particularly when consumers store the product at home during summer. Such temperature variations put this product at risk of microbial contamination. Previous studies reported that unpasteurized vegetable juices can support growth of microorganisms (Song et al., 2006; Zhou, Wang, Hu, Wu, & Liao, 2009). On the other hand, there are concerns about nutritional and sensory quality deterioration in vegetable juices after thermal pasteurization (Song et al., 2007).

The aim of this study was to establish a model for prediction of the response of a diffusion-based TTI system and to evaluate applicability of the TTI system as an indicator of threshold microbial growth in NPA juice or similar types of perishable food products due to temperature abuse during storage and distribution. A mathematical kinetic model was established based on measurement of the time-temperature dependent diffusion distance of a TTI at different temperatures. Predicted diffusion distances were then compared with measured values to validate the kinetic model. Finally, the relationship between TTI response and microbial growth in NPA juice was investigated under both isothermal and dynamic temperature conditions.

2. Materials and methods

2.1. Materials

Non-pasteurized angelica (NPA) juice (pH = 6.12) was obtained directly from Pulmuone Health & Living (Jeungpyeong, Republic of Korea). Isopropyl palmitate (IPP) (model: Hipure 13T) was provided by OhSung Chemical Ind. Co., Incheon, Republic of Korea. Prototype TTIs based on diffusion of IPP were provided by Inditech Korea Co., Hwaseong, Republic of Korea. The IPP type of TTI has a multi-layered structure (maximum diffusion distance: 41 mm; width: 5.0 mm; thickness: 0.2 mm) comprised of a red bottom layer and an upper microporous film (3M, St. Paul, MN, USA) (Fig. 1). The microporous film is originally opaque white (non-transparent). As IPP diffuses and fills micropores in the film, light passes through oil-containing pores and the IPP containing film becomes transparent, revealing the color of the bottom layer. The diffusion of IPP from the injection site can be clearly observed as IPP melts and diffuses from the injection site as a function of time and temperature (Park, 2010).

2.2. Experimental design and storage conditions

TTI prototypes were stored at isothermal temperatures of 15, 20, 25, 30, and 35 °C for 48 h to establish a kinetic response model. The temperature was recorded using a data logger (QuadTemp 2000, MadgeTech, Inc., Contoocook, NH, USA). Validation of the kinetic model was accomplished using TTI storage at three isothermal temperatures of 13, 23, and 33 °C. NPA juice samples taken directly from the manufacturing plant were used to enumerate initial microbial counts. Other juice samples were stored isothermally at 5 , 15 , and 25 °C (278, 288, and 298 K), respectively, with the TTI to investigate correlations between microbial growth in NPA juice and TTI response. Temperature fluctuations between 5 °C (refrigeration temperature) and 25 °C (room temperature) were used for simulation of dynamic storage conditions. NPA juice storage at 5 °C for 6 h, followed by storage at 25 °C for 6 h, was repeated 4 times. Temperature was recorded using a temperature logger (TL20, 3M, St. Paul, MN, USA) that remained with juice samples during the dynamic storage period.

2.3. Characterization of the isopropyl palmitate (IPP) diffusion-based TTI

2.3.1. Differential scanning calorimetry (DSC)

A DSC 8000 differential scanning calorimeter (Perkin Elmer, Waltham, MA, USA) was used for the measurement of the melting point of IPP. Samples of IPP and an empty stainless steel pan as a reference were heated from −10 °C to 60 °C at a rate of 5 °C/min. Nitrogen was used as a purge gas at a flow rate of 50 mL/min. Samples were then allowed to cool to −10 °C, followed by reheating to 60 °C at the same rate. The calorimeter was calibrated using indium and zinc as standard reference materials.

2.3.2. Measurement of the isopropyl palmitate (IPP) diffusion distance in the TTI

IPP (200 μL) was injected into a TTI well made with a cotton pad (10 × 4 × 2 mm) and the hourly diffusion distance was measured using images recorded with a digital single-lens reflex camera (EOS500D, Cannon, Tokyo, Japan). The camera and the TTI were set

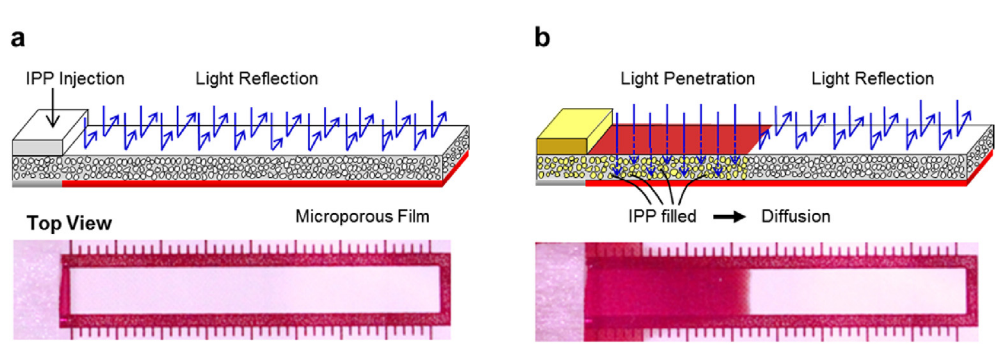

Fig. 1. Schematic diagram and photos showing isopropyl palmitate (IPP) diffusion through microporous film in a TTI system (a) before and (b) after injection of IPP.