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Effect of electric field on calcium content of fresh-cut apples by inductive methodology

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ABSTRACT

An experimental impregnation system based on the inductive methodology was established and used to investigate the effect of electric fields on the calcium content of fresh-cut apples. An induced electric field was generated when the Ca^{2+} solution acted as the secondary coil of the transformer system under the action of an alternating magnetic flux. The calcium content in fresh-cut apples was found to increase with the enhancement of the excitation voltage. Additionally, samples immersed in a $CaCl_2$ solution exhibited a calcium content higher than those suspended in the calcium lactate solution. The latter presented a higher load power factor, the impedance in the $CaCl_2$ solution being lower. Frequency at 20–60 kHz had a negative impact on the calcium content of fresh-cut apples due to the weakening of the electropermeabilization effect. This method utilized the conversion of electric energy into magnetic energy, and the electric field induced needing no insertion of powered electrodes into the solution under treatment. This might provide a reference for rapid impregnation of agricultural materials.

1. Introduction

In recent years, research interest in functional foods has been specifically directed to enrich foods with trace minerals and valuable substances, especially convenience, fresh-cut calcium-fortified apples and inorganic substances, being essential components of bones, teeth, tissues, and the nervous system (Moraga et al., 2009). Thus, there is an increasing demand for fresh edible mineral-fortified foods.

Among the methods capable of producing mineral-fortified vegetables and fruits, vacuum impregnation has been mainly investigated owing to its enhanced mass transport efficiency (Hironaka et al., 2011). Other reports showed that the diffusion coefficient of free ions in porous tissues increased by applying an electric field, generated by inserting powered electrodes into the solutions (Kusnadi and Sastry, 2012; Parniakov et al., 2014).

Under the action of alternating magnetic flux, Pryor (2013) indicated seawater conductivity can be detected by using the induced voltage and current through simulation analysis. Solid matters rapidly accumulate in salted juice owing to enhancement of ionic conduction under the action of the induced electric field (Jin et al., 2015). Hence, the migration of charged ions influenced by the induced electric field would improve the mass transfer efficiency in porous materials, thus resulting in calcium fortification.

However, there is no report on the application of the inductive methodology to impregnation, likely due to the lack of purpose-made reactors. Therefore, the main aim of this work was to explore a novel impregnation method, based on the electric transformer structure. An excitation voltage with different frequencies was applied to a primary coil to induce mutual voltage into a secondary coil filled with a Ca^{2+} solution, thus allowing calcium impregnation on fresh-cut apples. The results will provide information for the processing of fruits and vegetables through the use of magneto–electric mutual conversion, thus avoiding the insertion of a pair of stainless steel electrodes in the sample.

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2. Materials and methods

2.1. Experimental system

The experimental impregnation system is shown in Fig. 1a. It included the following items: 1) Power source; 2) Glass chamber (Fig. 1b); 3) Glass coil where the electrolyte solution circulates, thus acting as the coil conductor (Fig. 1b); 4) Primary coil; 5) Ferrite core (two blocks of U-types ferrite) (Fig. 1c); 6) Water cooling bath; 7) Sand filter (100 mesh); 8) Solution inlet; 9) Sample inlet.

A power source (WJE-5 kW, Beijing Perfect Electronic Science &Technology Co., Ltd. China) allowed a primary voltage U_{Pi} (0–300 V) with different frequencies (20–60 kHz) to be applied to the primary coil consisting of N_P (=160) turns. The resulting alternating magnetic flux in the ferrite core yielded an induced voltage (E_S) in the secondary coil, this consisting of N_S (=16) turns. The Ca^{2+} solution acted as the conductor connected to a glass chamber. The induced electric field in the Ca^{2+} solution was used to assist material impregnation.

Instrumentally, transformers can deliver electrical energy from circuit to circuit without changing the frequency according to *Faraday's Law of Induction* (Bleil, 1972). At the same time, transformers are also able to increase or reduce voltage. As shown in Fig 2, the equivalent circuit of the system corresponds to an electric transformer. Specifically, U_P and E_P are the excitation voltage and induced voltage on the primary coil; U_S and E_S are the terminal voltage and induced voltage on the secondary coil; N_P and N_S are the numbers of turns in the primary coil and secondary coil; I_P and I_S are the currents in the primary and secondary coils, respectively.

The electrolyte solution filling the glass chamber presented by an overall impedance. (Z_{load}), this representing the load of the secondary coil (Fig. 2), the $U_S = Z_{load} I_S$. By assuming an ideal electric transformer and constant-phase cycles in the primary and secondary coils(i.e., zero winding resistance, no leakage flux, infinite permeability, zero core loss), the following relationship can be written (Kulkarni and Khaparde, 2013):

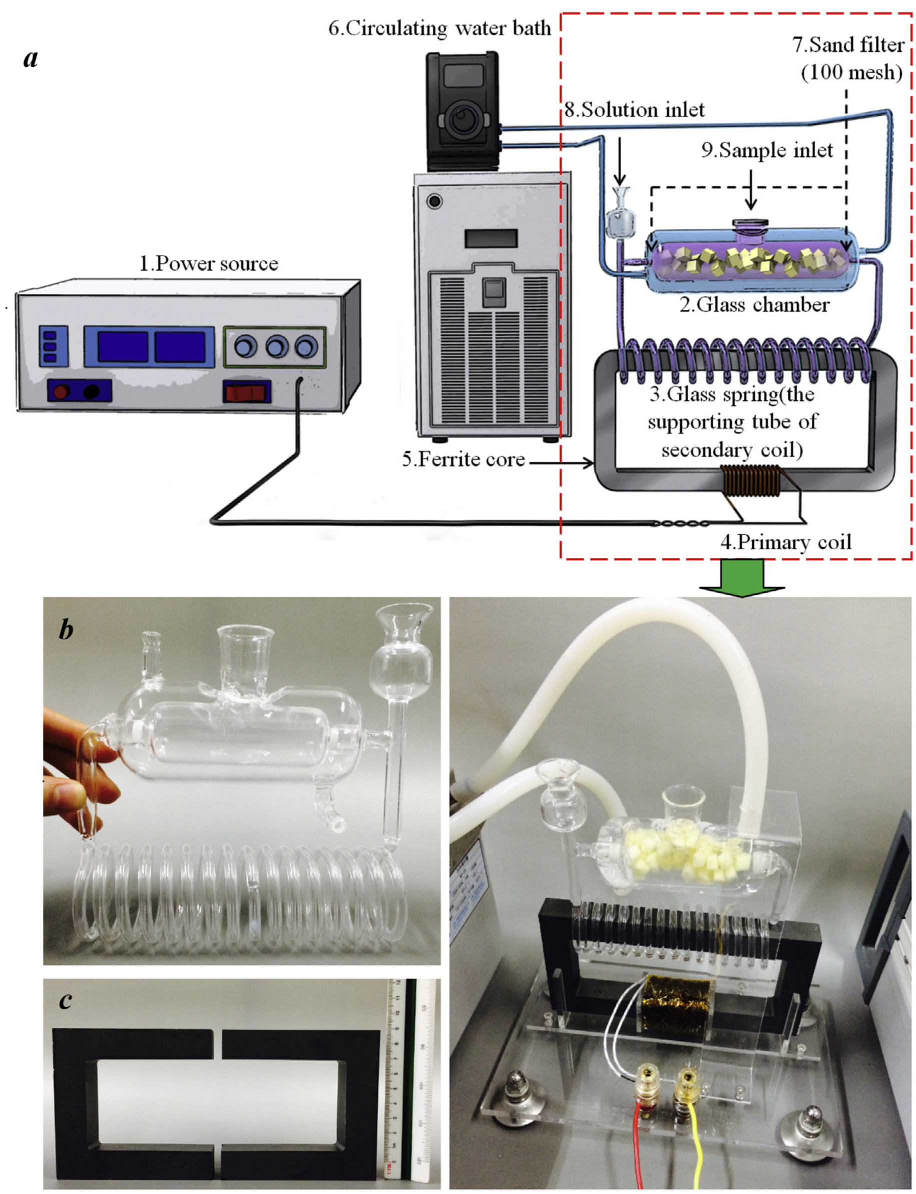

Fig. 1. Schematic diagram of the impregnation system. ***a***. Layout of instrumental chain; ***b***. Glass reactor ; ***c***. Ferrite core.