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Effect of rotating magnetic field and flowing Ca^{2+} solution on calcium uptake rate of fresh-cut apple

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ABSTRACT

The combination of a rotating perpendicular magnetic field and a flowing Ca^{2+} solution accelerated the calcium uptake of fresh-cut apple cubes and shortened the time needed for calcium equilibration between the Ca^{2+} solution and samples. The influence of operational parameters (Reynolds number of the flowing Ca^{2+} solution, magnetic flux density of the magnetic field, rotating frequency of the magnetic field, and temperature) on the calcium uptake rate were investigated. Negative exponential models were used to sufficiently describe the calcium uptake rate of samples. Magnetic flux density and temperature positively affected the calcium uptake rate. Higher Reynolds number and rotating frequency both accelerated the calcium diffusion, but excessively high levels (turbulent flowing at Re = 4134 or rotating frequency at 10 Hz) decreased the calcium content. Neither the flowing Ca^{2+} solution alone, nor the magnetic field alone, accelerated the calcium diffusion. This study provides an alternative methodology for the mineral fortification of fresh-cut fruits under the joint action of a rotating magnetic field and a flowing electrolyte solution.

1. Introduction

Calcium, an abundant essential mineral for life, plays an important role in physiological activities such as maintaining the normal muscle contraction, prevention of osteoporosis, and rickets (Ebashi & Endo, 1968; Ross, Taylor, Yaktine, & Del Valle, 2011). However, calcium deficiency is nearly a worldwide problem, due to either a lower intake than the recommended amount or incomplete absorption (Looker, 2006; Weaver, 2013). The mineral-fortification of foods has been considered as the most effective and safest approach for the supplement of calcium so far (Hurrell, 1997).

Fresh-cut fruits and vegetables have been popular in developed countries, and are also increasingly consumed in some developing countries for their convenience, attractive appearance, and nutritional value (Barrett, Beaulieu, & Shewfelt, 2010).

Vacuum impregnation has been widely used as a technique to obtain these mineral-fortified vegetables and fruits products rapidly (Fito et al., 2001; Zhao & Xie, 2004). Calcium enrichment of fresh apple can be realized using vacuum impregnation, with a diluted high-fructose corn syrup containing calcium gluconate and calcium lactate, which improves the firmness of apple samples (Xie & Zhao, 2003). According to Moraga, Moraga, Fito, and Martínez-Navarrete (2009), the shelf-life of grapefruit is be extended by impregnation with a calcium lactate solution, since the dehydration decreased the cellular respiration rate. Park, Kodihalli, and Zhao (2005) report that both the color and firmness of fresh-cut apple are excellently retained during 3-week of cold storage after fortification with 10 g L^{-1} calcium caseinate. Gras, Vidal, Betoret, Chiralt, and Fito (2003) find that calcium can significantly modify the mechanical behavior of eggplant and carrot with vacuum impregnation treatment, although no notable change is observed in oyster mushrooms. In order to obtain high-quality Ca-fortified fruits and vegetables, carbohydrates such as sucrose (Gras et al., 2003; Perez-Cabrera, Chafer, Chiralt, & Gonzalez-Martinez, 2011), fructose corn syrup (Lin, Leonard, Lederer, Traber, & Zhao, 2006), and honey (Park et al., 2005) can be added into the impregnating solutions.

A porosity range of 2%–30% is reported for most plant tissues (Derossi, De Pilli, & Severini, 2012). This porous structure allows ions and some small molecules to easily diffuse from the impregnating solution into plant materials. As an electrolyte solution flows

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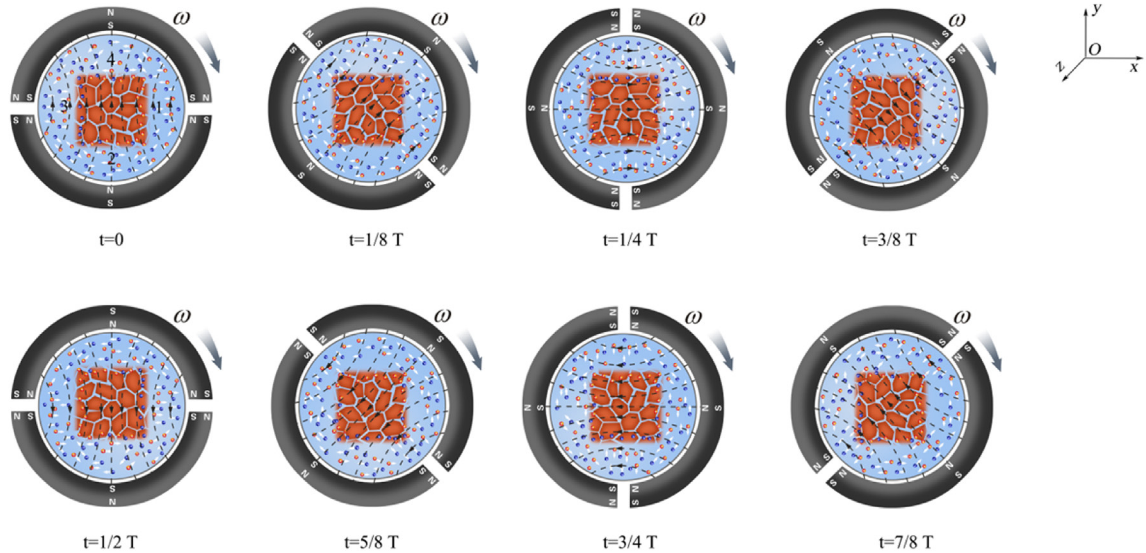

Fig. 1. The direction of Lorentz force on ions in one rotating period of the perpendicular magnetic field.

through a perpendicular magnetic field, the charged ions will experience Lorentz force, F_L, quantitatively expressed as $F_L = qvB$, where q is net ion charge, v is the ion velocity, and B is the magnetic flux density (Wright & Van Der Beken, 1972). In other words, under the action of a perpendicular magnetic field, orientation movement of free ions will occur, which could enhance mass transfer efficiency (Oshitani, Uehara, & Higashitani, 1999). As reported, induced voltage could be detected by a special detector as NaCl solution moved through a perpendicular magnetic field (Wright & Van Der Beken, 1972), indicating the existence of separation and orientation migration of cations and anions. That chemical reactions (e.g. electrolysis and electrolytic deposition) kinetic parameters were significantly influenced by the magnetic field were also observed. It was demonstrated that the effects of magnetic field on ionic conduction is related to ion variety, fluid flowing state (described by Reynolds number), magnetic flux density of magnetic field, and rotating frequency of magnetic field (Devos et al., 2000; Monzon & Coey, 2014).

Few data on the calcium fortification of fruits and vegetables with the combination of magnetic field and flowing minerals solution have been reported, which promises to be an important area of study. Therefore, the objective of this study was to propose an alternative method that combined a perpendicular magnetic field with a flowing Ca^{2+} solution to accomplish the calcium fortification of fresh-cut apple cubes. The effects of operating parameters (Reynolds number of the flowing Ca^{2+} solution, magnetic flux density of the magnetic field, rotating frequency of the magnetic field, and temperature) on calcium content of fresh-cut apples were investigated, and calcium uptake of fresh-cut apples was also analyzed by the negative exponential equation to verify the effectiveness of this method.

2. Materials and methods

2.1. Experimental principle and instruments

In one period, T, of the rotating magnetic field, the Lorentz force of moving ions and the movement direction of ions are summarized in Fig. 1 and Table 1. Hypothesizing that the electrolyte solution flows in z-direction and the magnets rotate in a clockwise direction; charged ions will experience the Lorentz force with varying directions, which can be predicted using Fleming's left hand rule. For example, when t = 0, cations are subject to the Lorentz force in −x-direction and then forced to gather towards side 1 of the sample. On the contrary, anions are subject to the Lorentz force in x-direction and forced to gather towards side 3 (Fig. 1 t = 0). As a whole, both the cations and anions can diffuse and accumulate on each side of samples as the Ca^{2+} solution flows through the rotating magnetic field. When a static magnetic field is applied on the flowing electrolyte solution, cations and anions will be forced to accumulate only on fixed sides of samples rather than on each side consecutively.

Table 1
The direction of Lorentz force of free ions in one rotating period.

Time	Cations		Anions	
	The direction of Lorentz force	Ionic gathering sides of sample	The direction of Lorentz force	Ionic gathering sides of sample
t = 0	−x	1	x	3
t = 1/8 T	(−x, y)	1,2	(x, −y)	3,4
t = 1/4 T	y	1,2	−y	3,4
t = 3/8 T	(x, y)	2,3	(−x, −y)	1,4
t = 1/2 T	x	3	−x	1
t = 5/8 T	(x, −y)	3,4	(−x, y)	1,2
t = 3/4 T	−y	3,4	y	1,2
t = 7/8 T	(−x, −y)	1,4	(x, y)	2,3

T, period of the rotating magnetic field.