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Rotary magnetic field combined with pipe fluid technique for efficient extraction of pumpkin polysaccharides

Yamei Jin [a,b], Na Yang [a,b,*], Qunyi Tong [b], Zhengyu Jin [a,b], Xueming Xu [a,b,*]

[a] State Key Laboratory of Food Science and Technology, Jiangnan University, Wuxi 214122, China
[b] School of Food Science and Technology, Jiangnan University, Wuxi 214122, China

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A B S T R A C T

Pumpkin polysaccharides are considered as functional materials with bioactivities. However, the conventional aqueous extraction method for pumpkin polysaccharides is limited by long time consumption, low efficiency and potential damage to their bioactivities. To improve the efficiency of pumpkin polysaccharides extraction, we designed a new experimental system combining a rotary magnetic field and flowing conductive solution. Polysaccharide extractions by 1) acidic sample solution with agitation, 2) flowing acidic sample solution, 3) static magnetic field combined with flowing acidic sample solution, and 4) rotary magnetic field combined with flowing acidic sample solution were conducted at pH level of 2–4, temperature of 30–50 °C, and treatment time of 0–180 min. The extraction by use of rotary magnetic field combined with flowing acidic sample solution resulted in the highest polysaccharide yield. Then, the effects of rotational frequency, Reynolds number, pH, and temperature on extraction yield were investigated. The yield increased at first and then decreased with an increase in rotational frequency. The high polysaccharide yield was achieved at large Reynolds number, high temperature, and low pH. From the ultraviolet, Fourier transform-infrared spectrum and chromatographic analysis, the extracts proved to be polysaccharides with an average molecular weight of 1.435×10^5 Da. The extracted pumpkin polysaccharides exhibited a dose-dependent radical-scavenging capacity within 0.1 to 5 mg/mL in the order of hydroxyl radical > DPPH radical > superoxide radical.

Industrial relevance: Rare report on the application of the combined magnetic field and pipe-fluid technique in extraction functional components from food materials. In this study, a novel experimental apparatus combining rotary magnetic field and spiral-pipe flow was designed to accelerate the extraction of pumpkin polysaccharides. In comparison with 1) agitation, 2) flowing acidic sample solution, and 3) static magnetic field combined with flowing acidic sample solution, the method combining rotating magnetic field and flowing acidic sample solution 4) significantly increased the polysaccharide yield. The increments were 40.18%, 32.14%, and 23.32%, respectively, after 180-min extraction. The pumpkin polysaccharides extracted by this novel method possessed a molecular weight of 1.435×10^5 Da and showed desirable antioxidant activities in vitro. Therefore, the combined magnetic field and pipe-fluid technique it is a potential method for efficient extraction of valuable compounds from food materials.

1. Introduction

Polysaccharides are widely employed as valuable compounds in pharmaceutical products and functional foods owing to their bioactivities, such as antioxidation, hypoglycemic activities, and anti-inflammation (Charalampopoulos, Wang, Pandiella, & Webb, 2002; Cheung, 2008; Voragen, 1998; Zhang, Li, Xiong, Jiang, & Lai, 2013). Their physiological, functional and economic benefits stimulate collective research about efficient extraction methods of polysaccharides (Vilkhu, Mawson, Simons, & Bates, 2008; Yin, You, & Jiang, 2011; Zhao et al., 2011). Various extraction methods by heat reflux, enzyme, ultrasound assistance, moderate electric filed assistance and microwave assistance have been reported (Ge et al., 2014; Jiang, 2014; Tao & Xu, 2008). However, high-temperature (>80 °C) long-time processing of plant materials by the conventional heating method or heat reflux method would cause the loss of thermosensitive substances or undesirable degradation of polysaccharides (Li, Ding, & Ding, 2007). Moreover, the application of ultrasound, pulsed electric field or enzyme method on polysaccharide extraction requires expensive equipment and reagents (Parniakov, Barba, Grimi, Lebovka, & Vorobiev, 2014; Zhao et al., 2011).

The flow of charge-carrying solutes passing through a perpendicular magnetic field would generate a Lorentz force and an induced voltage (Hubbard & Wolynes, 1981). Both the forces acted on charged ions and the flow of electrolyte solution in a small pipe could accelerate

* Corresponding authors at: State Key Laboratory of Food Science and Technology, Jiangnan University, Wuxi 214122, China.
E-mail addresses: yangna@jiangnan.edu.cn (N. Yang), xmxu@jiangnan.edu.cn (X. Xu).

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the mass transport of ions. There are many investigations having been conducted about how a magnetic field boosts mass transport of particles and chemical reactions in pipe fluids (Hessel, Kralisch, Kockmann, Noël, & Wang, 2013; Hossain, Ansari, & Kim, 2009). Visual experiment was carried out to explore the effects of pipe geometry on the chromogenic reaction of phenolphthalein and KOH solution, and as a result, the reactive dose of phenolphthalein in serpentine pipe was 16-fold larger than that in a straight pipe (Liu et al., 2000). In the electronic exchange of 10-methylphenothiazine and 2,2,6,6-tetramethylpiperidin-1-oxyl in a homogeneous flowing solution, the production of free ions was considerably enhanced by the application of a 2 Tesla magnet field (Kenis et al., 2000).

It is the joint effect of Lorentz force, the hydrodynamic effect, induced voltage and currents that contributes to the enhancement on the mass transport of charged particles and chemical reaction (Fukuyama, Rahman, Kamata, & Ryu, 2009; Hessel et al., 2013; Hossain et al., 2009) This comprehensive effect depends on various operating parameters, such as ionic concentration, fluid velocity, type, strength, and density and rotational frequency of the magnetic field (Aaboubi et al., 1990; Busch, Busch, Parker, Darling, & McAtee, 1986; Kronenberg, 1985; Oshitani, Uehara, & Higashitani, 1999). Meton and Gerard (1976) measured the electrodynamic potential in diluted solutions of 25 acids and salts, and found it was correlated to the ion variety and concentration. Besides, pulsed and rotary magnetic fields (RMF) were more effective in enhancing mass transport than static magnetic field (SMF) (Busch et al., 1986; Hinds, Coey, & Lyons, 2001).

In the food processing industry, a magnetic field was administered in regard to the sterilization of liquid food items, like fruit juice, milk and beer. The physiology and cell structure of microorganisms would be also changed by the application of a magnetic field (Barbosa-Cánovas, Gongora-Nieto, & Swanson, 1998; Ma, Pan, Gao, & Luo, 2008). Recently, we conducted studies on enhancing the diffusion of solute into the garlic with the designed device composed of a magnetic field and cycle pipe for brining fluid. As a result, the optimal processing parameters proved to be a magnetic flux density of 0.13 T, rotational frequency of 5 Hz, and Reynolds number of 1127 (Jin et al., 2015).

Pumpkin, a species of *Cucurbitaceae*, is rich in polysaccharides, vitamins, minerals and dietary fibers that are often processed as various foods and functional additives, such as baking desserts, sauce, jam and puree in many countries (Akwaowo, Ndon, & Etuk, 2000; Dhiman, Sharma, & Attri, 2009; Fu, Hi, & Li, 2006). The polysaccharides in pumpkin are usually obtained through hot water extraction (Qi et al., 2005). Besides, complex enzyme extraction (Matora et al., 1995; Shkodina, Zeltser, Selivanov, & Ignatov, 1998), acid or alkalis extraction (Jun, Lee, Song, & Kim, 2006; Sun, Yin, & Chen, 2010), and ultrasound-assisted extraction (Maran, Mekala, & Manikandan, 2013) were also used to obtain these valuable compounds.

In order to extend the application of the magnetic field and pipe-fluid technique in the food field, we established a new experimental system combining RMF and mixed HCl-sample fluid to extract polysaccharides from pumpkin. The effect of flowing conditions (characterized by Reynolds number, *Re*), pH of the solution, rotational frequency of RMF, and temperature on polysaccharide yield were studied. Then, the physical characterization and antioxidant properties of polysaccharides obtained at the above optimal extraction parameters were analyzed. Our results will provide useful information for developing an alternative technique for the efficient extraction of pumpkin polysaccharides with a combination effect of alternating magnetic field and pipe fluid.

2. Materials and methods

2.1. Samples preparation

Fresh pumpkins (*Cucurbita moschata*) with similar size and maturity (°Brix = 9.6–10.2) were purchased from a local supermarket in Wuxi, China. After the seeds were removed, the remaining parts were washed with running tap water, sliced and dried in a forced air circulation oven at 40 °C for 6 h. The dehydrated samples were crushed and sifted through a 40-mesh sieve to attain fine powder with 9%–10% moisture (dry basis).

2.2. Instrumental chain

The extraction system shown in Fig. 1 composed of a glass chamber (GC), magnetic field area (MFA), a servomotor (SV), circular pipeline (CP), a peristaltic pump (PP), and a circular water bath (CWB). Eight blocks of 80-mm-long semicircle neodymium magnets (D_{in} = 70 mm and D_{ex} = 90 mm) were aligned to generate the perpendicular magnetic field of 0.13 T, which could rotate at different frequencies by a servomotor (LCADA103002L-LB8220, Siemens Ltd., China). The peristaltic pump (Baoding Lead Fluid Technology Co., Ltd., China) forced the acidic sample solution to circularly heliciform-flow in the glass chamber through the glass spiral (Fig. 2). The spiral number of the glass spring was 60 with the spiral length of 7.16 m and the internal diameter of 4 mm.

In this system, the moving charged solutes were enabled to cut magnetic field lines since the electroconductive solution traversed the magnetic field area. The charged solutes would be affected by the Lorentz force and get separated, forming an induced voltage and enhancing the ionic conduction in the mixture. The Lorentz force F_L can be quantified as follows (Blank & Goodman, 2001):

$$F_L = qvB \tag{1}$$

where q is the ion charge, v is the ionic velocity, and B is the magnetic flux density. Under the joint effect of Lorentz force, induced voltage and hydrodynamic force, therefore, the relative migration and transport of charged ions contribute to the effective contact of the targeted substances.

2.3. Polysaccharide extraction conditions

Hydrochloric acid solutions of pH 2, 3 and 4 were prepared by adding 0.1 M HCl into distilled water. Then 30 g of pumpkin powder, mixed with 300 g of HCl solution, was used as the acidic aqueous suspension. Under the drive of the peristaltic pump, the suspension was injected into the circular pipeline and then recurrently flowed through

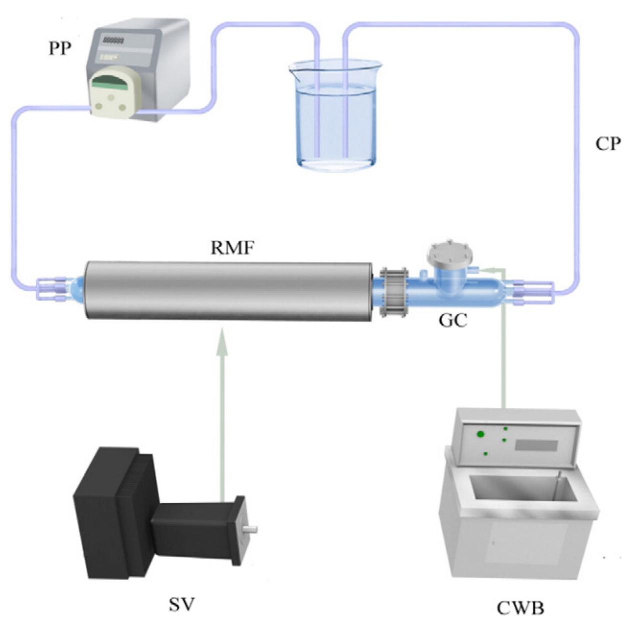

Fig. 1. The schematic of the extraction system.