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Enhancement of Salt Uptake with the Application of Rotary Magnetic Field in Brining Cucumber

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Abstract

An experimental system by use of magnetic and hydrodynamic force was established to accelerate mass transport and thus to shorten the salting equilibrium time in salting of fresh-cut cucumbers. The cucumbers were brined with flowing 3% NaCl solution under rotary magnetic field at 22 ºC. During brining period, salt contents of the cucumbers at varying Reynolds number of flowing brine, rotary frequency, and magnetic flux density of magnetic field were separately investigated and the salt uptake kinetics was also analyzed. Results showed that flowing brine disturbed the salt diffusion into cucumber tissues without the application of magnetic field. Consequently, the salt uptake rate decreased compared to the conventional brining. No significant difference in salt content of cucumbers was observed between the conventional brining and static-magnetic-field-assisted brining. The salt uptake rate was improved by the combination of rotary magnetic field and flowing brine. The increment of salt uptake rate during this combined treatment got larger with the increase of magnetic flux density. Salt uptake rate of cucumber increased with the increase of rotational frequency of the magnetic field and Reynolds number of the flowing brine, up to a critical value. A 170% increment in salt uptake rate constant could be achieved at magnetic flux density 0.13 T, rotational frequency 5 Hz and Reynolds number 1127. Thus, an intergrated technique based upon rotary magnetic field and flowing brine is provided for brining of porous agricultural products.

Keywords: salt uptake rate, fresh-cut cucumber, rotary magnetic field, flowing brine

1. Introduction

Salted foods are widely popular owing to their special flavors, long storage life and convenience. Traditional salting methods are mainly dry salting and brining (Bellagha, Sahli, Farhat, Kechaou, & Glenza, 2007). In order to shorten the salting period and accelerate the ion diffusion into food materials, researchers have developed many methods such as agitation-assisted salting (Bona, Carneiro, Borsato, Silva, Fidelis, & Monken, 2007; Mayor, Moreira, Chenlo, & Sereno, 2006), ultrasound-assisted salting (Ozuna, Cárcel, Walde, & Garcia-Perez, 2014; Turhan, Saricaoglu, & Oz, 2013; Benedito, Carcel, Gonzalez, & Mulet, 2002; Cárcel, Benedito, Bon, & Mulet, 2007), electric-field-assisted salting (Kusnadi & Sastry, 2012; Oboturova, Evdokimov, Nagdalian, Kulikov, & Gusevskaya, 2015; Arroyo, Lascorz, O'Dowd, Noci, Arimi, & Lyng, 2015) and vacuum impregnation salting (Pavia, Trujillo, Guamis, & Ferragut, 2000; Barat et al., 2006; Valdez-Fragoso, Martínez-Monteagudo, Salais-Fierro, Welti-Chanes, & Mújica-Paz, 2007; Quintero-Chávez, Quintero-Ramos, Jiménez-Castro, Barnard, Márquez-Meléndez, Zazueta-Morales, & Balandrán-Quintana, 2012; Rastogi, Raghavarao, Niranjan, & Knorr, 2002).

Agitation treatment: The salting time for Prato cheese to obtain 2% salt content at Biot Number below 100 under agitation-assisted treatment was half that without agitation (Bona et al., 2007). *Ultrasound treatment*: The investigation of ultrasound-assisted brining on pork loins at frequency 20 kHz showed that ultrasound treatment contributed to the salt diffusion of meat (Siró, Vén, Balla, Jónás, Zeke, & Friedrich, 2009). The effective diffusivities of NaCl and water increased by 25%-45% and 41%-153%, respectively, when pork was brined with ultrasonic wave at frequency 40 kHz and density 37.5 $W \cdot dm^{-3}$ in comparison with the samples without ultrasonic treatment (Ozuna et al., 2014). *Electric filed treatment*: Kusnadi and Sastry (2012) analyzed the effective salt diffusion coefficients in different vegetables (celery, mushroom and water chestnut) at an electric field intensity of 0, 658, 1316 and 1842 $V \cdot m^{-1}$. The diffusion coefficients increased after the electric field was applied in the brining and this increment is positively correlated to the electric field intensity. Moreover, the NaCl uptake of potato slices or trips was improved after the treatment by a pulsed electric field, and this improvement was also in proportion to density of pulsed electric field (Janositz, Noack, & Knorr, 2011). *Vacuum impregnation treatment*: In the research of Valdez-Fragoso et al. (2007), the optimal vacuum impregnation condition for pickling whole jalapeño peppers: 12% NaCl, brine-to-pepper mass ratio of 4.6 and a vacuum pulse (666 mbar, 5 min)-atmospheric pressure (22 d) treatment was determined by the response surface methodology. On this condition, the ratio of NaCl gain to moisture loss was maximized. Besides, the osmotic dehydration of sliced tomato was reported to significantly expedite under the vacuum impregnation at 56.25 mbar with osmotic solution containing 7.5% NaCl and 32.5% sucrose compared to the conventional dehydration treatment (Corrêa, Viana, de Mendonça, & Justus, 2016).

The NaCl solution (used as brine in the current study) belongs to strong electrolyte solution that contains massive charged ions such as Na^+ and Cl^-. Charged particles in a flowing fluid will be subjected to the magnetic force, F_L, when this fluid passes through a non-parallel magnetic field, then altering the movement orientation (Lindley, 1964). The mass transport of flowing Na^+ and Cl^- is supposed to be influenced by the magnetic field. However, there are rare reports about brining vegetables under the joint influence of rotary magnetic fields and flowing brine. Therefore, the primary goal of the study was to establish a novel apparatus combining the magnetic field and flowing brine in order to accelerate the salt uptake rate of cucumber cubes during the brining process. A glass chamber was placed inside a perpendicular magnetic field generated by four pairs of tile-type NdFeB magnets, to contain the cucumber samples. These magnets could be driven by a servo motor with different rotary frequencies. A 3% NaCl solution was used as the brine and forced by a peristaltic pump to flow circularly in the established system.

The objective of this research was to explore the influences of rotary perpendicular magnetic field and flowing brine on the salt uptake of the cucumber cubes.

2. Method

2.1 Instrument

As shown in Figure 1, while the sodium chloride solution flowed through a perpendicular magnetic field, Na^+ and Cl^- were subject to the equal and opposite magnetic force, $F_L = qvB$ (Blank & Soo, 2001). Affected by the magnetic force, these ions were forced to gather towards the surface of cucumber cubes and permeate into the food matrix.The brine system consisted of glass chamber (A), perpendicular magnetic field (B), servo motor (C), circular pipeline (D), peristaltic pump (E) and circulating water bath (F), which is presented in Figure 2. The perpendicular magnetic field was generated by fixing eight semicircle neodymium magnets (D_{in} = 70 mm, D_{ex} = 90 mm, L = 80 mm) in opposite poles towards each other. The inner magnetic flux densities of 0.09 T and 0.13 T were obtained with different NdFeB magnets of N38 type and N50 type assembled.

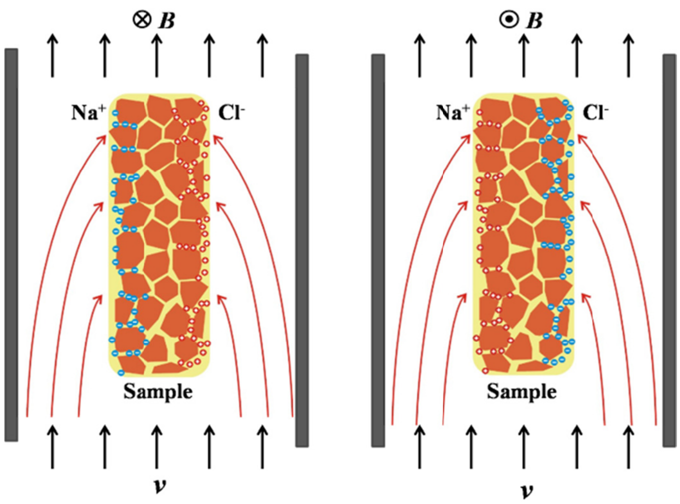


Figure 1. Action of magnetic force on moving charged ions under the perpendicular magnetic field

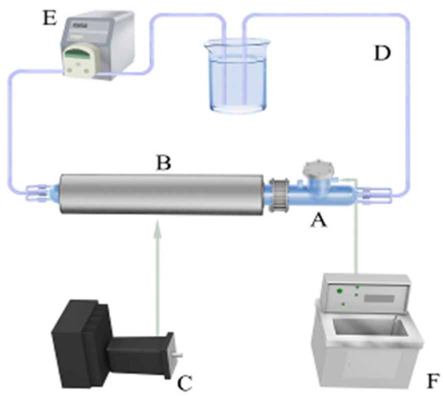


Figure 2. Schematic diagram of brining system

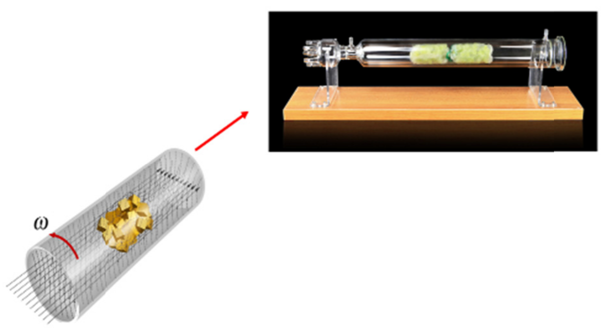


Figure 3. Placement of sample

2.2 Sample Preparation and Treatments

Fresh cucumbers in similar size and maturity were bought from a local supermarket. The cucumbers were rinsed, peeled and diced into 15-mm cubes. Approximately 120 g of samples were kept in a nylon mash bag. Two bags of sample were put into the glass chamber that was surrounded by the perpendicular magnetic field per time, as presented in Figure 3. The NaCl solution (3 g·100 g^{-1}) was used as the brine and the mass ratio of samples to NaCl solution were 1:25. The peristaltic pump was initiated to remove the air inside the chamber, fill the circular pipeline with the brine and drive the solution to circularly flow at different volume flow rates of 355.19, 711.02, 1234.03, and 2606.86 uL·min^{-1}. The brining process variables were Reynolds number (563, 1127, 1956, and 4132, which were calculated according to Equation (1), the magnetic flux density (0.09 and 0.13 T) and the rotational frequency (1, 5, and 10 Hz). The fresh-cut cucumbers were immersed in NaCl solutions without flowing and not subjected to the perpendicular magnetic field were used as the control samples.

The status of flowing brine were described in Table 1, in which *Re*-value was calculated from the following formula.

$$Re=\rho\bar{v}D/\eta \tag{1}$$

Where *Re* is the Reynolds number, ρ is the density of the fluid (kg·m^{-3}), $\bar{v}$ is the mean velocity of the fluid (m·s^{-1}), *D* is the inner diameter of pipeline (m), and η is the dynamic viscosity of the fluid (mpa·s) (Stein & Sabbah 1974). $\bar{v}$ was transformed by the volume flux of the brine, ρ was the obtained as mass per unit volume at 20 ºC and η was measured with a Brookfield viscometer (DV-E, Brookfield Engineering Labs Inc., Stoughton, USA) at 20 ºC.

Table 1. Conditions of flowing brine

Volume flow rate (uL·min^{-1})	Mean velocity $\bar{v}$ (m·s^{-1})	Density ρ (kg·m^{-3})	Inner diameter *D* of pipeline (m)	Dynamic viscosity μ (mpa·s)	Reynolds number, *Re*
355.19	0.0128	1041.27	0.046	1.091	563
711.02	0.0256	1041.27	0.046	1.091	1127
1234.03	0.0445	1041.27	0.046	1.091	1956
2606.86	0.0940	1041.27	0.046	1.091	4132

2.3 Salt Content Determination and Mathematical Modeling

Salt content in the cucumber cubes was determined by the titration with 0.1 M $AgNO_3$ solution (Passos et al., 2005) at the brining period of 0, 0.5, 1, 1.5, 2, 2.5, 3, 4, 6, 8, and 12 hours. The salinity changes were modeled using negative exponential functions (Equation (2), Quintero-Chávez et al., 2012). Then the salt uptake rates were obtained and analyzed.

$$Y(t) = a + b[1-\exp(-kt)] \tag{2}$$

Where *Y*(*t*) is the salt content (g·100 g^{-1}) in cucumber cubes estimated at the brining time, *t*; *a* is the initial salt content (g·100 g^{-1}) in the samples at initial time; *b* is the brining potential salt content (g·100 g^{-1}); *k* is the rate constant (h^{-1}) of the potential brining.

2.4 Data Analysis

Differences between the means of salt content at brining treatments were tested by ANOVA at a significant level of 5%. SPSS software (version 19.0; SPSS, Chicago, IL) was used to determine the standard deviation. Parameters in the salt uptake models were solved by using SAS software (version 9.3; SAS Institute, Cary, NC).

3. Results and Discussion

3.1 Effects of Magnetic Field or Turbulent-Flowing Brine

The salt content in cucumber cubes subjected to traditional brining, static magnetic field-static brining, static magnetic field-turbulent flowing brining and rotary magnetic field-turbulent flowing brining are illustrated in Figure 4. The model parameters of these negative exponential models for salt content changes in cucumber samples are summarized in Table 2. Great determination coefficients, R^2, (≥ 0.9188) and low mean square error, MSE (≤ 0.0114), were observed, indicating acceptable quality of these models in the description of the salt diffusion process. The higher *k*-value meant a shorter salt equilibrium time. As shown in Figure 4, the increase of salt content in the cucumber tissues was rapid in the early brining period while gradually slowing until the equilibrium between the solution and the sample dominated by osmotic pressure was reached. This coincided with the trend of salt content changes in pickled celery and pepper (Quintero-Chávez et al., 2012). No significant difference ($P > 0.05$) was observed in salt content in the samples subjected to traditional brining and static magnetic field-static brining process. This indicated that the static magnetic field alone (B = 0.13 T) did not accelerate salt diffusion into the cucumber tissue. Meanwhile, static magnetic field-turbulent flowing brine (B =

0.13 T, *Re* = 4132) and rotary magnetic field-turbulent flowing brine (B = 0.13 T, f = 5 Hz, *Re* = 4132) treatments caused decrease in the salt content of the samples in contrast with traditional brining treatment, which was revealed by comparing the rate constant that $k_{\text{static magnetic field-turbulent flowing brining}} < k_{\text{rotary magnetic field-turbulent flowing brining}} < k_{\text{traditional brining}}$. The decreasing trend of k-value was due to the turbulent flowing of the brine causing interference with mass diffusion towards the surface of the porous vegetable tissues (Bona et al., 2007).

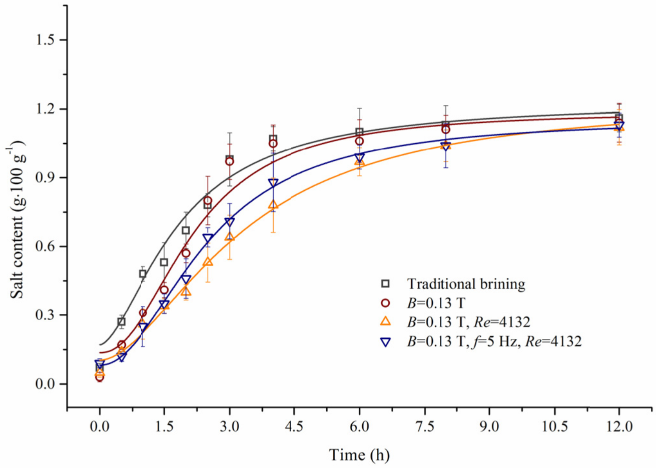


Figure 4. Salt content change in the cucumber under traditional brining, static magnetic field-static brining, static magnetic field-turbulent flowing brining, and rotary magnetic field-turbulent flowing brining treaments

Table 2. Parameters of the negative exponential models for salt uptake in cucumbers under traditional brining, static magnetic field-static brining, static magnetic-turbulent flowing brining and rotary magnetic-turbulent flowing brining treatments

Brining treatments	a (g·100 g^{-1})	b (g·100 g^{-1})	k (h^{-1})	R^2	MSE (g·100 g^{-1})
Traditional brining	0.0465	1.2052	0.4481	0.9821	0.0031
Static magnetic field-static brining	0.0793	1.1907	0.3944	0.9598	0.0077
Static magnetic field-turbulent flowing brining	0.0105	1.1683	0.2323	0.9188	0.0114
Rotary magnetic field-turbulent flowing brining	0.0050	1.1854	0.2808	0.9808	0.0034

Note. R^2 is determination coefficient; MSE is mean square error.

3.2 Treatments of Flowing Brine without Magnetic Field

The changes of salt content in the cucumbers subjected to treatment with laminar-flowing brine alone are depicted in Figure 5. The salt uptake model parameters are revealed in Table 3. Compared to traditional brining, the flowing of brine caused the rate constant to reduce significantly (P < 0.01), regardless of laminar flowing (*Re* < 2300) or turbulent flowing (*Re* > 4000). In current research, the greater decrease of salt content in the samples was further observed during the same period when the *Re*-value of brine was greater. The rate constants, at different brining conditions, were 0.4481 (traditional brining), 0.3372 (laminar-flowing brining, *Re* = 563), 0.2292 (laminar-flowing brining, *Re* = 1127), and 0.2161 h^{-1} (turbulent-flowing brining, *Re* = 4132), respectively. This result coincides with the conclusion of Capaccioni et al. (2011) that states that the agitation at 50 rmp decreases the salt concentration in the marinated filets in contrast to the non-agitated marination treatment.

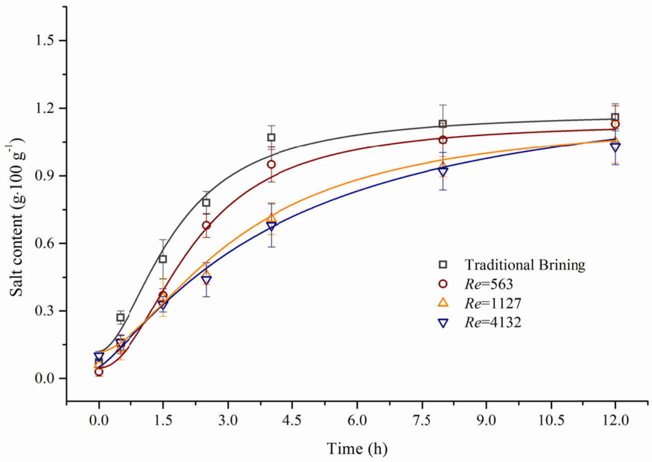


Figure 5. Salt content changes of the cucumber cubes under the treatment of flowing brine alone

Table 3. Parameters of the negative exponential models for salt uptake of cucumbers under flowing brine treatments without magnetic field

Brining treatments	a (g·100 g^{-1})	b (g·100 g^{-1})	k (h^{-1})	R^2	MSE (g·100 g^{-1})
Traditional brining	0.0465	1.2052	0.4481	0.9821	0.0031
Laminar flowing brining, Re = 563	0.0221	1.1627	0.3372	0.9951	0.0038
Laminar flowing brining, Re = 1127	0.0490	1.0670	0.2292	0.9903	0.0021
Turbulent flowing brining, Re = 4132	0.0708	1.0804	0.2161	0.9955	0.0010

Note. R^2 is determination coefficient; MSE is mean square error.

3.3 Treatments of Static Magnetic Field Combined with Laminar Flowing Brine

Figure 6 and Table 4 presented the changes of salt content and the parameters of salt uptake models in the cucumber cubes subjected to static perpendicular magnetic field combined with laminar flowing brine treatment. Except for the brining at B = 0.13 T and Re = 1956 condition, which processed a lower k-value of 0.4328 h^{-1} compared to 0.4481 h^{-1} for traditional brining, all other static magnetic field-laminar flowing brining treatment methods could boost the salt diffusion into the cucumber tissues. When the magnetic flux density was at the same level, k-value would increase by moderately increasing the velocity of the flowing brine. For example, as the Re-value rose from 563 to 1127 at B = 0.13 T, k-value increased by 16.77%. However, Re-value near or greater than 2000 had a negative effect on salt diffusion into the tissues. The k-value under operating condition of B = 0.13 T and Re = 1956, decreased by 25.88% than that of the condition at B = 0.13 T and Re = 563.

High salt uptake rate constant could be achieved at high magnetic flux density. For instance, with a Re-value of 563, the increment of magnetic flux density from 0.09 to 0.13 T caused the k-value to increase from 0.5345 h^{-1} to 0.5839 h^{-1}. As shown in Figure 6 and Table 4, the highest salt rate constant in the samples during processing (k = 0.6818 h^{-1}) was obtained at the static magnetic field-laminar flowing brining condition of B = 0.13 T and Re = 1127. In the report by Bund et al. (2003), an 11% increment was observed on the limiting current density when the flux density of the applied magnetic field was changed from 0.5 T to 1.0 T, indicating an accelerated electrochemical reaction.

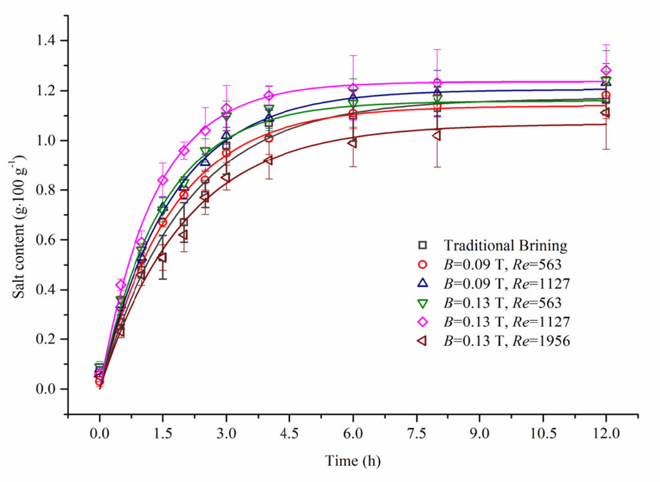


Figure 6. Salt content changes of the cucumber cubes under the treatment of static magnetic field-laminar flowing brine

Table 4. Parameters of the negative exponential models for salt uptake of cucumbers under static magnetic field-laminar flowing brining treatments

Brining treatments		*a* (g·100 g^{-1})	*b* (g·100 g^{-1})	*k* (h^{-1})	R^2	MSE (g·100 g^{-1})
Traditional brining		0.0465	1.2052	0.4481	0.9821	0.0031
Static magnetic-laminar flowing brining	B = 0.09 T, Re = 563	0.0490	1.1111	0.5345	0.9979	0.0004
	B = 0.09 T, Re = 1127	0.0735	1.2182	0.5350	0.9982	0.0003
	B = 0.13 T, Re = 563	0.0737	1.1847	0.5839	0.9913	0.0015
	B = 0.13 T, Re = 1127	0.0551	1.2213	0.6818	0.9956	0.0008
	B = 0.13 T, Re = 1956	0.0426	1.0389	0.4328	0.9922	0.0011

Note. R^2 is determination coefficient; MSE is mean square error.

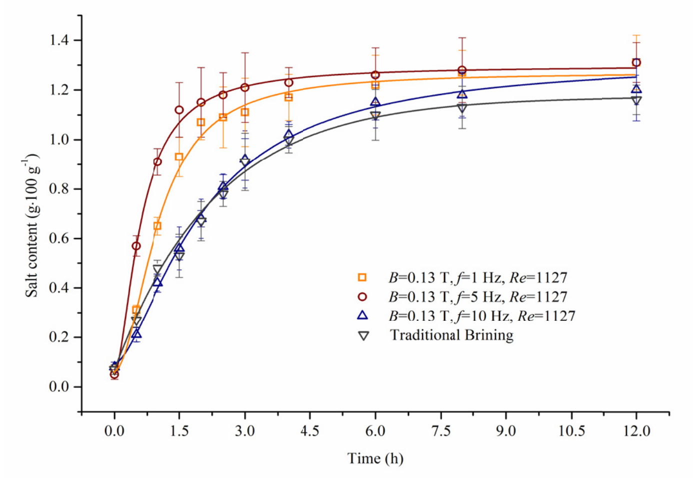
In the present experimental system, as the brine flowed through the perpendicular magnetic field, the movements of Na^+ and Cl^- were affected by the magnetic force, F_L. Then, the massive directional movement of free ions appeared. Finally, ions were propelled to accumulate on the surface and diffused into the cucumber tissues. According to the Equation (3) (Blank & Soo, 2001),

$$F_L = qvB \tag{3}$$

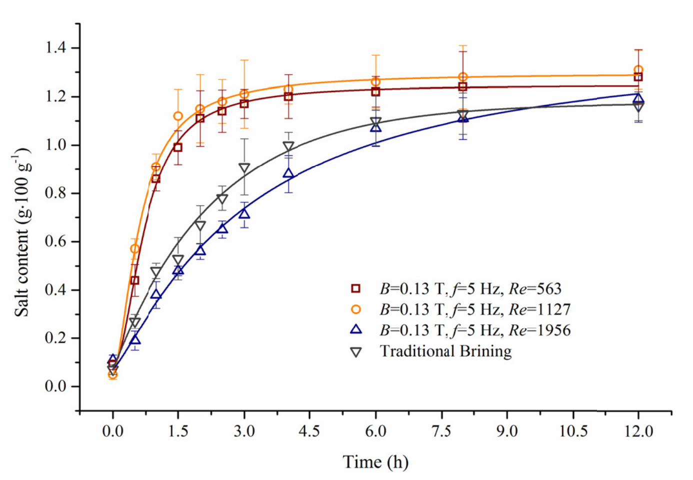
the magnetic force F_L is positively correlated with the net charge, q, of the ion, the velocity, v, of ions in the perpendicular magnetic field and the magnetic flux density, B. A higher magnetic flux density will cause the ions to experience a stronger magnetic force and then greatly accelerate the mass transfer. However, excessively large *Re*-value for flowing brine decreased the salt rate constant owing to the hydrodynamic interference (Capaccioni, Casales, & Yeannes, 2011). Therefore, high magnetic flux density and relatively steady flow of the brine were assumed to be more effective for enhancing salt diffusion.

3.4 Treatments with Rotary Magnetic Field Combined with Laminar Flowing Brine

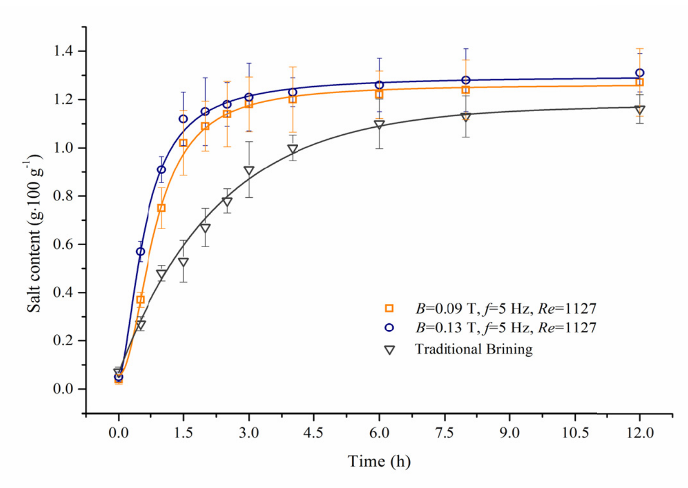
The cucumber samples were salted by the rotary magnetic field combined with laminar-flowing brine. The effects of operation parameters, rotational frequency, f (Figure 7a), Reynolds number, Re (Figure 7b), and magnetic flux density, B, (Figure 7c) on salt content in the samples are demonstrated in Figure 7.



(a) effect of rotational frequency, *f*



(b) influence of Reynolds number, *Re*



(c) influence of magnetic flux density, *B*

Figure 7. Salt content changes of the cucumber cubes under the treatment of rotary magnetic field-laminar flowing brine

Table 5. Parameters of the negative exponential models for salt uptake of cucumbers under rotary static magnetic field-laminar flowing brining treatments

Rotary magnetic-laminar flowing brining treatments	*a* (g/100 g)	*b* (g/100 g)	*k* (h^{-1})	R^2	MSE (g/100g)
Traditional brining	0.0465	1.2052	0.4481	0.9821	0.0031
B=0.13 T, f=5 Hz, Re=1127	0.0428	1.3166	1.2079	0.9947	0.0010
B=0.13 T, f=5 Hz, Re=563	0.0643	1.2073	0.9510	0.9917	0.0016
B=0.09 T, f=5 Hz, Re=1127	0.0051	1.2847	0.8723	0.9902	0.0020
B=0.13 T, f=10 Hz, Re=1127	0.0531	1.2339	0.3395	0.9949	0.0010
B=0.13 T, f=5 Hz, Re=1956	0.0807	1.1697	0.2741	0.9950	0.0008

Note. R^2 is determination coefficient; MSE is mean square error.

As shown in Figure 7a, when B-value was fixed to be 0.13 T and Re-value was fixed to be 1127, significant increase ($P < 0.05$) in salt content at the brining early period ($t < 2.5$ h) was observed with the rotational frequency increasing from 1 to 5 Hz. The varying magnetic flux density generated by the rotary perpendicular magnetic field induced electromotive forces in the brine. Then, the inductive voltage also expedited the ionic conduction (Rossow, 1958; Roth, 2011). However, the increase of frequency from 5 Hz to 10 Hz caused significantly ($P < 0.01$) decrease in the salt gain rate in comparison to that of treatments at 1 and 5 Hz. The k-value at 1, 5 and 10 Hz were 0.7506, 1.2079 and 0.3395 h^{-1}, respectively (Table 5). Similarly, in Kulshrestha and Sastry's research (2003), the diffusion coefficients of beet dye during brining at the frequency of 0, 10, 50, 250, and 5000 Hz, all increased initially and then decreased at the action of moderate electric field. The most rapid diffusion was obtained at the frequency of 10 Hz and at the electric field intensity of 23.9 $V \cdot cm^{-1}$.

Figure 7b reveals the effect of Re-value of the laminar flowing on the salt content in salted cucumber. A threshold Re value ought to exist. Below this threshold, a higher velocity of NaCl solution caused the increase of salting rate constant. The highest k-value (1.2079 h^{-1}) was achieved at operating condition of B-value equaled 0.13 T, f-value equaled 5 Hz, and Re-value equaled 1127 (Table 5). This result agrees with the previous findings where a salt diffusion into garlic samples was initially increased and then decreased by the high brine mobility (Jin et al., 2015).

A significant increase in salt content of cucumber cubes ($P < 0.05$) was noticeable at the first 1.5-hour of brining time as the magnetic flux density rose from 0.09 to 0.13 T at the rotational frequency of 5 Hz and Re value of 1127 (Figure 7c). Meanwhile, the k-value was increased from 0.8723 h^{-1} to 1.2079 h^{-1}, which was 170% higher than that of traditional brining (Table 5).

Both the contribution of large magnetic flux density and Reynolds number to enhancing salt diffusion were resulted from the strong action of magnetic force on the moving ions, which could be explained by formula $F_L = qvB$ (Blank & Soo, 2001).

4. Conclusion

A novel brining method that combines perpendicular magnetic field with flowing brine was proposed to accelerate the salting process of cucumbers. Negative exponential models were sufficiently used to analyze the salt absorption of cucumbers. The results showed that the combination of the perpendicular magnetic field with flowing brine could increase the salt uptake rate by 170% when compared with the traditional brining method. This promotion attributed to the action of Lorentz force on moving free ions. Without the assistance of perpendicular magnetic field, the salt diffusion into the samples was disturbed by the flowing brine. Meanwhile, brining treatment under perpendicular magnetic field alone showed no significant difference in salt content of cucumber cubes either when compared to the traditional brining method. Furthermore, rotary magnetic field was more effective than static magnetic field in promoting salt diffusion. For the rotary magnetic-laminar flowing brining treatments, salt uptake rate increased with the magnetic flux density and there existed threshold rotational frequency and Reynolds number for accelerating salt diffusion. This research lays the foundation for porous food processing, such as salting and mineral fortification based on the joint action of rotary magnetic fields and flowing electrolyte solutions.

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