Effect of processing parameters on fouling resistances during microfiltration of red plum and watermelon juices: a comparative study

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Abstract This study evaluated the total (R_t), reversible (R_{rev}), irreversible (R_{irr}), and cake (R_c) resistances during microfiltration of watermelon juice (as a juice with colloid particles) and red plum juice (as a juice without colloid particles). Results showed that the total resistance decreased by about 45% when the feed velocity was increased during clarification of red plum juice due to change in cake resistance. Also, increasing the feed temperature from 20 to 30°C decreased the total fouling resistance by about 9% due to decreases in the irreversible and reversible fouling resistances. Also, mixed cellulose ester (MCE) membrane (which is hydrophilic) had a lower cake resistance compared to polyvinylidene fluoride (PVDF) membrane (which is hydrophobic). Examination of the microfiltration of watermelon juice showed that R_t decreased by about 54% when the feed temperature was increased from 20 to 50°C, partially due to the reduction of reversible fouling resistance by 78%. Also, increasing transmembrane pressures from 0.5 to 2.5 bars greatly increased total fouling resistance. The feed velocity had a different effect on fouling resistances during microfiltration of watermelon juice compared to red plum juice: in contrast with red plum juice, increasing the feed velocity for watermelon juice increased cake resistance.

Keywords Fouling resistance · Juice · Membrane · Microfiltration · Red plum · Watermelon

Introduction

Microfiltration (MF) is a pressure-driven process that can be used to clarify juices (Girard and Fukumoto 2009). However, the use of this process in industrial juice processing is hampered by the fouling phenomenon exhibited with total resistance (R_t). Total resistance includes several individual resistances: cake resistance (R_c), reversible fouling resistance (R_{rev}), irreversible fouling resistance (R_{irr}), and membrane resistance (R_m). Cake resistance is produced by large particles that cannot enter into the membrane pores and are thus deposited on the membrane surface. Reversible fouling resistance relates to particles that have entered the membrane and are causing clogging that can be removed by membrane cleaning and includes cake resistance; in contrast, irreversible fouling cannot. The final component is the natural resistance of the membrane itself (Mirsaeedghazi et al. 2010a).

All these resistances can alter with changes in process parameters. Li et al. (2007) analyzed the fouling resistances during microfiltration of raw soy sauce using a ceramic membrane. They concluded that total fouling resistance increased with increase in the nominal pore size due to increasing the concentration polarization resistance which happens when convective flow of compounds to membrane surface is greater than back-diffusive flow to bulk solution. They showed that ZrO₂ membrane had a higher total fouling resistance mainly due to higher concentration polarization resistance compared to α -Al₂O₃ membrane. The concentration polarization resistance increased with increase in the transmembrane pressure; lower transmembrane pressures

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raised cake and internal plugging resistances. Li et al. (2007) also showed that increasing the cross-flow velocity can decrease concentration polarization resistance; however, cake resistance reduced only after initially increasing with increased velocity. Vladisavljević et al. (2003) evaluated the fouling resistance during ultrafiltration of depectinized apple juice using ceramic membranes. They showed that increasing the feed flow rate can decrease both total and fouling resistances, and that transmembrane pressure had a direct effect on the fouling resistance. Zeng et al. (2010) evaluated the effect of process parameters on fouling resistances during microfiltration of orange juice. They concluded that transmembrane pressure had a high effect on reversible polarized layer resistance (due to reversible solid deposited on membrane surface); however, increasing the cross-flow velocity decreased various polarized layer resistances. They also found that various resistances decreased with increases in temperature. Jinsong et al. (2008) compared membrane fouling under constant and variable loading influent in submerged membrane bioreactors and concluded that in the early stages of process the membrane fouling in variable loading was worse than another one; however in the steady state conditions it was mitigated. Mirsaedghazi et al. (2009) evaluated different resistances during membrane processing of pomegranate juice using polyethersulfone membrane with molecular weight cut off of 5 kDa. They showed that membrane, cake, reversible fouling and irreversible fouling resistances were 15.1%, 36.1%, 44.1% and 4.7% of the total resistance, respectively. Jun et al. (2007) compared fouling between the membrane processing of aerobic granular sludge and activated sludge systems. They concluded that aerobic granular sludge caused pore blocking fouling; however activated sludge caused cake formation.

The fouling resistances during microfiltration of different juices that have dissimilar textures may behave differently in different processing conditions. Despite its importance for the food industry, there is no study of this issue in the literature. In the current study, the total fouling resistance and its

component items were evaluated during membrane processing of watermelon and red plum juices, which have different physical natures. Watermelon juice has a fibrous texture that includes colloid particles (mean particle size is about 8 μm); however, red plum juice has neither fibrous texture nor colloid particles. This study examined the effects of processing parameters on all resistances for each juice.

Material and methods

Juice preparation

Watermelon (*vt.* All sweet) and red plum (*vt.* Vampire) were procured from a local market (Karaj, Iran). The juices were manually extracted from washed and peeled fruits. Large particles such as fruit peel were removed using a number 9 mesh (2 mm).

Membrane unit

Experiments were performed in a batch mode using a laboratory-scale plant (Fig. 1). The feed temperature was adjusted by circulating water in a two-layered tank. A rotary van pump (PROCON, Series 2, Milano, Italy) was used to introduce the feed above the membrane surface in a cross-flow mode. A transmitter (WIKA, type ECO-1, Klingenberg, Germany) coupled with an inverter (LS, model sv015ic5-1f, Korea) was used to maintain the feed pressure at the desired levels. The permeate was collected in a product tank. The retentate was recycled to the feed tank. Pressures in the feed and retentate sides were measured using two separate pressure meters (WIKA, model 213.53.063, Klingenberg, Germany). Hydrophilic PVDF flat membranes with pore sizes of 0.22 μm and a total effective filtration area of 0.0209 m^2 and contact angle of about 141° were used in this study (Milipore, USA).

Fig. 1 Membrane unit used in current study

Analysis of resistances

The membrane resistance was calculated with the following equation:

$$R_m = \frac{\Delta P}{\mu_w J_w}, \quad (1)$$

where R_m is membrane resistance, ΔP is transmembrane pressure (N m^{-2}), μ_w is water viscosity (N s m^{-2}), and J_w is the permeate flux of the membrane before the experiment ($\text{kg/m}^2\text{s}$).

The fouling resistance can be calculated as:

$$R_F = \frac{\Delta P}{\mu_p J_p} - R_m, \quad (2)$$

where μ_p (N s m^{-2}), and J_p ($\text{kg/m}^2\text{s}$) are watermelon permeate viscosity and its flux, respectively.

Fouling resistance is the sum of cake (R_c), reversible fouling (R_{frev}), and irreversible fouling (R_{firr}) resistances. Reversible and irreversible fouling resistances were calculated as:

$$R_{firr} = \frac{1}{\mu_w L_{p1}} - R_m, \quad (3)$$

$$R_{frev} = \frac{1}{\mu_w L_{p2}} - R_m - R_{firr}, \quad (4)$$

where L_{p1} and L_{p2} were hydraulic permeability (transmembrane pressure divided by water flux) after washing with water, alkaline, and acid detergents and after washing with water, respectively. Cake resistance was calculated using following equation (Cassano et al. 2007):

$$R_c = R_t - R_m - R_{frev} - R_{firr} \quad (5)$$

where R_t is total resistance.

Results and discussion

Fouling resistances during treatment of red plum juice

Evaluation of the effect of feed velocity on the total fouling resistance during clarification of red plum juice showed that the total resistance decreased by about 45% with increased feed velocity. Studying the different resistances showed that reversible fouling made no contribution, and irreversible fouling very little, to the reduction in total fouling resistance. Cake resistance contributed the greatest to the reduction in total fouling resistance, falling by about 60% due to sweep the cake deposited on membrane surface by tangential forces (Fig. 2).

Fig. 2 Effect of velocity, temperature and membrane type on different resistances during membrane processing of red plum*. * All data were mean of three replications ($n=3$)

Studying the effect of feed temperature on the total fouling resistance showed that increasing the feed temperature from 20 to 30°C can decrease the total fouling resistance by about 9%. The contribution of each type of resistance in this reduction was separately evaluated. Results showed that increasing the feed temperature had no effect on the cake resistance; however, it slightly decreased irreversible and reversible fouling resistances due to higher molecular diffusivity and its mobility, which

caused lower particle sedimentation on the membrane pores' walls (Fig. 2). This phenomenon is not important in the cake formation.

Red plum juice was clarified with mixed cellulose ester (MCE) membrane (which has a hydrophilic characteristic) and polyvinylidene fluoride (PVDF) membrane (which has a hydrophobic characteristic) to evaluate the effect of membrane hydrophobicity on fouling resistances. Hydrophobic characteristic of PVDF membrane prevents fluid movement into the membrane pores and compresses particles on membrane surface as a cake layer. So, cake resistance in PVDF membrane was 46% more than in MCE membrane. However, other resistances including reversible and irreversible foulings, showed no significant changes (Fig. 2).

Fouling resistances during treatment of watermelon juice

Evaluation of the effect of feed temperature on the total fouling resistance during membrane processing of watermelon juice showed that total resistance decreased by about 54% when the feed temperature increased from 20 to 50°C. The greatest part of this reduction was due to a decrease of 78% in reversible fouling resistance and 17% in cake resistance; however, feed temperature had no effect on irreversible fouling resistance (Fig. 3) due to the effect of high temperature on particle mobility which effects on reversible and cake resistances. A comparison between red plum and watermelon juices showed that each 10°C increase in feed temperature decreased total fouling resistance by about 9.5% in the treatment of red plum juice; however, it decreased total fouling resistance by about 18% in treatment watermelon juice. Evaluation of individual resistances showed that reduction of cake resistance for watermelon juice was higher than for red plum juice (5% to 0.6%, respectively) probably due to more effect of high temperature on large particles which is responsible for cake formation in watermelon juice. Also, notwithstanding the fact that irreversible fouling did not change with increased feed temperature during the treatment of watermelon juice, it decreased in the treatment of red plum juice by about 21% with each 10°C increase in temperature, due to the difference between the nature of turbid particles in juices.

The watermelon juice was treated using two different transmembrane pressures (0.5 and 2.5 bar) to evaluate the effect of transmembrane pressure on the resistances. Results showed that increasing the transmembrane pressure could greatly increase total fouling resistance. Evaluation of individual resistances showed that cake, irreversible fouling, and reversible fouling resistances contributed at all pressures to the increase in total resistance, increasing by 85%, 73%, and 98%, respectively (Fig. 3). Higher

Fig. 3 Effect of feed temperature, transmembrane pressure and volumetric flow rate on fouling resistances during treatment of watermelon juice with membrane processing. * All data were mean of three replications ($n=3$)

resistances were due to the nature of microfiltration, which is pressure-driven; as found in the authors' previous work, particles flow toward the membrane surface along with bulk stream increases when transmembrane pressure is increased (Mirsaeedghazi et al. 2010b).

The watermelon juice was subjected to different volumetric flow rates at 20°C and 0.5 bar to study the effect of feed velocity on the fouling resistances (the geometric characteristics of the membrane module were constant). Evaluation of the effect of feed velocity on the fouling resistances had different results for watermelon juice compared to red plum juice microfiltration. Increase in velocity could increase the total fouling resistance due to increased cake resistance which was in contrast with the result of microfiltration of red plum juice (Fig. 3). The experiment was repeated at 50°C and 0.5 bar at the two previous volumetric flow rates. The results were the same: both reversible and irreversible fouling resistances were decreased; however, the cake resistance was increased by 72% when the volumetric flow rate was increased from 10 to 20 ml/s. This is caused by the two different effects of velocity on filtration described by Li et al. (2007):

- Increasing the velocity can decrease the cake layer due to its tangential force.
- Selective deposition associated with increased velocity due to creation of finer long-chain macromolecules and colloid particles; this has a negative effect on filtration.

More colloid particles and long-chain macromolecules in watermelon juice compared to red plum juice suggested that selective deposition has more effect than tangential force on resistance for watermelon juice. However, the different nature of red plum juice suggests that tangential force is the dominant mechanism governing changes in resistance in this case.

Conclusion

Evaluation of the effect of feed velocity on fouling resistances during the clarification of red plum juice showed that increasing the velocity could not change reversible fouling; however, it could greatly decrease cake resistance and, to a lesser degree, decrease irreversible fouling resistance. Increasing the feed temperature could partly decrease reversible and irreversible fouling resistances; however, it had no effect on cake resistance. Also, the

hydrophobicity of the membrane could only increase cake resistance due to particle back-passing.

Evaluation of fouling resistances during membrane processing of watermelon juice showed that increasing the feed temperature considerably reduced reversible fouling resistance, and, to a lesser degree, cake resistance. All resistances, including cake, reversible, and irreversible resistances, increased by more than 70% when the transmembrane pressure was increased. In contrast with red plum juice, increasing the velocity in membrane processing of watermelon juice increased the cake resistance.

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