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Cold sterilization and process modeling of tender coconut water by hollow fibers

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ABSTRACT

Tender coconut water is one of the popular sport drinks. In this paper, cold sterilization of tender coconut water was undertaken using hollow fiber ultrafiltration. Experiments were conducted at different transmembrane pressures in the range of 21–193 kPa and cross flow rate 5–15 l/h to optimize the operating conditions. A simple resistance-in-series model was used to quantify the flux decline behavior. A mathematical criterion between the operating conditions was derived for limiting flux. This is of immense importance for process modeling, scaling up and control of operating conditions of such systems. Various parameters of the feed and permeate, namely, total soluble solids, pH, clarity, concentration of sodium, potassium, polyphenol, protein and total solids were monitored. A subsequent storage study was undertaken and it was observed that the filtered juice was successfully stored for 18 weeks. This study was adequately backed up by conducting a taste analysis.

1. Introduction

Fruit juices are rich in minerals, proteins, anti-oxidants and have potential for rejuvenating the body and therefore, have a huge demand in today's world (Sagu et al., 2014). Coconut water is a natural beverage with high nutritional value and is considered as energy drink to joggers and athletes. Thus, to reduce the transportation volume and cost associated with the whole fruit and to improve the shelf life of tender coconut water, its processing is necessary. Tender coconut water is rich in essential minerals, like, potassium, sodium and natural nutrients, like, polyphenol (Yong et al., 2009). It is a good sports drink and has therapeutic values (Saat et al., 2002). It is available plenty in coastal areas and hence, it has a high demand in the areas interior to the country where coconut is not available. It is a good export item as well. The fresh coconut water has a shelf life of about 24 h (Reddy et al., 2005) and that can be enhanced by ultra-high temperature, pasteurization, refrigeration, freezing and microwave heating (Matsui et al., 2007).

Due to presence of sugar and a number of plant enzymes (Jackson et al., 2004), the tender coconut water has a strong tendency to undergo biochemical changes and spoilage, once the nuts are harvested from the tree. Efforts are made to arrest these changes by packing the nuts in plastic films and storing them at refrigeration temperature (Maciel et al., 1992). The above method is expensive in terms of energy and transportation cost and has lower shelf life of 2–3 weeks. The coconut water is processed by high temperature short time pasteurization in Thailand, Indonesia and Philippines (Magda, 1992). Polyphenol oxidase and peroxidise are the major plant enzymes causing the spoilage and loss of nutritional qualities of tender coconut water. Campos et al. (1996) studied the inactivation of these enzymes by heat treatment at 90 °C for 100 s with additives like ascorbic acid and potassium meta-bisulphite. Addition of these external chemicals deteriorates the taste and quality parameters of the treated juice significantly. Thermal processing is usually carried out between 60°C and 100 °C and it eliminates not only bacteria but also the entire delicate flavour profile is almost hampered. This severely limits the marketability of the product. Matsui et al. (2008) studied inactivation kinetics of these enzymes by microwave heating in tender coconut water. The process was carried at 90 °C, degrading the sensory properties of the juice. Membrane based processes offer attractive alternative in this regard.

Literature on membrane filtration of tender coconut water is scant. Magalhaes et al. (2005), reported filtration by 0.1 μm microfiltration (MF) and three cut off (20, 50 and 100 kDa) ultrafiltration (UF) membranes. Significant reduction in turbidity, microorganism and 24%–40% reduction in protein was obtained. The filtration was associated with severe (87%–93%) flux decline.

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However, a systematic storage study was not attempted with an appropriate selection of membrane. Reddy et al. (2007) used a two stage filtration process by whatman filter paper followed by 0.2 μm MF membrane. The final permeate was stored for one month only and its acceptability was reduced due to significant loss in sugar and other nutritional parameters. They also reported the development of significant fouling resistance over the membrane surface (Reddy et al., 2005). However, this study was purely in laboratory scale and had marginal significance in scaling up. Jayanti et al. (2010), reported clarification of tender coconut water using commercial UF, 50 kDa molecular weight cut off (MWCO), flat sheet membrane in a stirred cell. The specific flux was in the range of 16–20 l/m^2.h.bar. In this work, it was shown that polarization layer resistance, irreversible fouling resistance and membrane hydraulic resistance, all three are competitive and significant. However, sensory analysis and acceptability of the processed juice were not determined. Also, experiments were conducted in a stirred filtration cell and thus cannot be scaled up to an industrial level. In all the above works, experimental flux decline data are of little importance for process scaling up and they lack in detailed study of shelf life of the filtered juice.

In the present work, "cold sterilization" of tender coconut water was performed using highly scalable hollow fiber platform. A resistance-in-series model was formulated and used for analysing decline of permeate flux with operating conditions as well as identifying the limiting transmembrane pressure drop. All the quality parameters of the filtered juice were monitored after aseptic packaging. Since, thermal sterilization was not used, sensory properties of the product remained intact. Ultrafiltered juice was rich in polyphenol and potassium. The storage study was undertaken for eighteen weeks. Since, there are no additives or preservatives added externally and as the filtration is performed in a scalable system, the developed technology has immense potential for direct industrial scale application.

2. Theory

Flux decline during ultrafiltration of fruit juice is due to development of a fouling layer of rejected solutes on membrane surface (Mondal and De, 2010; Roy and De, 2014). Thus, the resistances encountered by the solvent during its permeation are membrane hydraulic resistance (R_M) and fouling resistance (R_F). For nascent membrane, R_M^0 is the membrane hydraulic resistance. After first run, the membrane resistance is determined from pure water run asR_M^1, where$R_M^1 = R_M^0 + R_{irr}^1$. R_{irr}^1 is the irreversible membrane resistance after washing at the end of first experiment. Therefore, the membrane resistance corresponding to the Nth experiment is directly measured as,

$$R_M^N = R_M^{N-1} + R_{irr}^N = \frac{\Delta P}{\mu_w \nu_w^0} \tag{1}$$

where, ΔP is the transmembrane pressure drop (TMP), μ_w is the viscosity of the water ($\mu_w = 0.9 \times 10^{-3}$ Pa s at 30 °C, measured using U-Tube viscometer) and ν_w^0 is the pure water flux at the end of Nth experiment (flux is the volume of filtrate per unit time, per unit area of the membrane) through the membrane. Thus, the irreversible membrane resistance is included in the estimation of membrane resistance corresponding to Nth experiment. The fouling layer resistance at any point of time can be determined from the experimental flux decline. It can be represented as,

$$R_F^N = \frac{\Delta P}{\mu(\nu_w(t))} - R_M^N \tag{2}$$

where, μ is the viscosity of the permeating solution ($\mu = 10^{-3}$ Pa s at 30 °C, measured using U-Tube viscometer) and $\nu_w(t)$ is the permeate flux through the membrane.

For a cross flow system, the growth of fouling resistance attains a steady state due to forced convection of retentate stream and the phenomenon is adequately described by a first order growth law (De et al., 1997),

$$\frac{dR_F^N}{dt} \alpha \left(R_F^{SN} - R_F^N\right) \tag{3}$$

where, R_F^{SN} is the steady state fouling resistance. The above expression can be integrated with an initial condition, at $t = 0, R_F^N = 0$.

$$R_F^N = R_F^{SN}[1 - \exp(-kt)] \tag{4}$$

where, k is the proportionality constant in Eq. (4). It may be noted that 'k' represents the rate of growth of the fouling layer. Therefore, a plot of $\ln\left[(R_F^{SN})/(R_F^{SN} - R_F^N)\right]$ with't' yields a straight line through origin with a slope 'k'.

3. Experimental

3.1. Materials

Tender coconut was purchased from local market in Indian Institute of Technology, Kharagpur, West Bengal, India. Polyacrylonitrile (PAN) co-polymer (copolymer of acrylonitrile, methyl acrylate, methacrylic acid in the ratio 96:3:1) of average molecular weight 150 kDa was purchased from M/s, Technorbital, Kanpur, India. N, N-dimethyl formamide (DMF), sodium hydroxide (NaOH) and polyethylene glycol (Molecular weight 200, 100, 35, 20, 10, 6, 4 and 0.4 kDa) were procured from M/s, Merck (India) Ltd. Storage bottles of glass were obtained from Borosil Glass Works Ltd. (India) and polypropylene bottles were purchased from Tarsons Products Pvt. Ltd. (India).

3.2. Membrane preparation

85 wt% of DMF was heated at 60 °C and 15 wt% PAN copolymer was added. The copolymer of PAN was used to achieve high flux membrane (Thakur and De, 2012). The solution was stirred using a REMI stirrer (supplied by M/s, Anupam Enterprise, Kharagpur, India) at 50 rpm for 6 h till a homogenous solution was formed. The solution was then cooled to room temperature. The polymer solution was transferred to the polymer tank in the spinning unit. Hollow fibers were extruded using the gas pressure in a nitrogen cylinder with bore fluid distilled water. The fibers were allowed to fall in the gelation bath containing tap water at room temperature completing the phase inversion process. The detailed spinning conditions are presented in Table 1. It has been well established in the literature that hydrolysis of PAN membrane reduces the MWCO of the membrane (Parashuram et al., 2013; Abedi et al., 2015). The effect of hydrolyzation time on the MWCO of the membrane is presented in Fig. S1 in the supplementary section. It can be clearly asserted that a MWCO of the 44 kDa can be achieved by subjecting the membrane to prolong contact with NaOH. Hence, the hollow fibers were then dipped in 1 (N) NaOH solution for 36 h and dried in