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Cost-effective disposal of milk whey II: recovery and purification of lactose and pure water from the diafiltration permeate stream

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ABSTRACT

The fractionation of the permeate stream resulting from a typical protein recovery section of a microfiltered cheese whey has been studied and a new membrane based process has been proposed to obtain: a) a concentrated solution of lactose; b) a concentrated solution of high bio available minerals; c) a net stream of pure water. To find the optimal connection between different sections of the process and optimal operating parameters for each section, the physico-chemical and thermodynamic properties of the solutions were studied and simulated in wide ranges of temperature and concentration.

Keywords: Whey; Solubility of lactose; Milk minerals solutions; Water recovery; Membrane filtration; Water activity

1. Introduction

An interesting historical survey concerning the fate of milk whey was reported by Smithers [1]. Nowadays, disposal and management of whey resulting from the production of cheese and casein attracts considerable attention by researchers for many reasons: a) the amount of whey produced annually all around the world is estimated at about 200 GL; b) a variety of high added value whey based products have been developed and are produced industrially [2]. However, there is much space for further process and product development and optimization; c) if whey is disposed of in rivers as a waste it has serious adverse environmental effects and huge amount of very useful compounds like lactose and high nutritional and functional values proteins are destroyed. One of the main reasons for this situation concerns with the size of the dairies and with the need for further developing economically feasible process for low potentialities; this problem was already discussed some years ago [3]. Actually, when environmental regulations started to be stringent, the most considered options were fermentation to single cell proteins for animal feeding [4], and evaporation to reduce and to stabilize the liquid waste into raw powder. Nevertheless, despite high potentiality (about 500 kL/d), it was difficult to achieve cost-effective disposal. Now, improved membrane separation technologies along with the grow of the number and of the value of the new whey based products having a wide range of applications [2,5], allow the development of optimized and cost-effective processes, along with the reduction of unsustainable transportation costs.

For better process and products development, nanofiltration (NF) and forward osmosis (FO), in addition to traditional microfiltration (MF), ultrafiltration (UF) and reverse osmosis (RO), are considered [7].The purpose of this study is to describe with some interesting and not yet discussed details, the procedure and the technologies required for producing: a significantly desalted concentrated solution of lactose, a concentrated solution of bio available minerals, almost free of lactose and, a net stream of pure water.

In fact, it is worth to emphasize that lactose has a number of modern applications including the use as raw

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material for the production of sustainable food packaging [1,5,6], while the salts have been considered for preparing dietary supplements, fortified food and drinks, sport and isotonic beverages, bakery and enriched dairy products [8].

2. Properties of the solutions

Microfiltered cheese whey (MFCW) is an aqueous solution with about 93.5% of water and 6.5% of total dissolved solids (TDS); of this 9.3% are whey proteins, 10.2% minerals and 80.5% is mainly lactose and a variety of other organic compounds like vitamins, NPN (non protein nitrogen compounds), trace elements and others [9].

In these conditions, deviations from the ideal behavior can be considered small but, when fractionated into concentrated streams, non-ideal behavior becomes high and must be quantified, since it significantly affects the choice of the best path for processing the whey and the identification of optimal sets of operating parameters for each section in order to achieve economic feasibility.

Three properties are of particular interest: a) the solubility of lactose; b) the volumetric properties of the solutions and, c) the water activity in wide ranges of temperature and concentration.

Fig. 1 shows the solubility of lactose as function of the temperature, for comparison with the solubility of sucrose. As can be seen, at room temperature the difference is very high, but at 90°C the difference is about half. Consequently, at 90°C it is possible to concentrate dilute aqueous solution of lactose up to 50%, which is about more than three times the solubility at room temperature. Eq. (1), obtained by fitting the experimental data [10,12,13] can be used to calculate with good accuracy (multiple determination coefficient, $R^2 = 0.996$; Average and Maximum Relative Deviation, $ARD = 2.5\%$ and $EMAX = 7\%$, respectively) the solubility of lactose, ,as weight percent in the whole range of temperature in °C.

$$\sigma = 10.619158 + 0.149694 \cdot T + 0.0062068 \cdot T^2 - 2.4744 \cdot 10^{-5} \cdot T^3 \qquad (1)$$

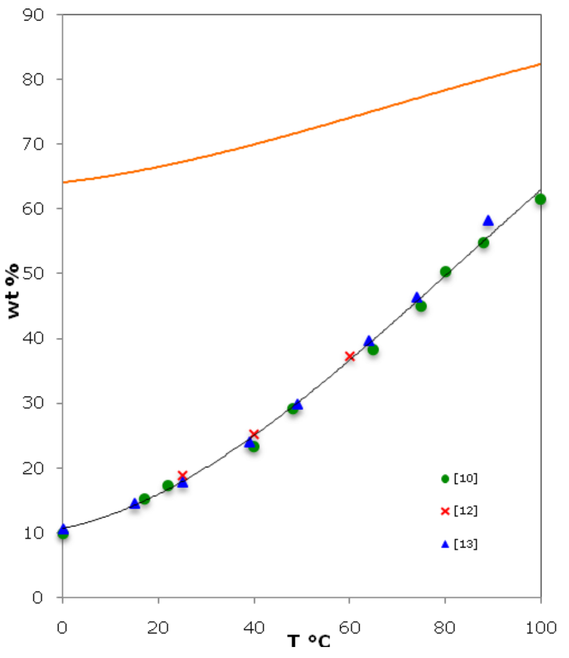

Fig. 1. Solubility of aqueous solutions of lactose (—) and of sucrose (—).

Fig. 2 shows the behavior of the molar volume of aqueous solutions of lactose, as function of temperature and concentration. This property has been calculated using density experimental data from the literature [11,14,15], accurately interpolated by Eq. (2) ($ARD = 6\%$; $R^2 = 0.999$), in the whole range of temperature and concentration of interest for this study. Actually, we believe that considering the volumetric properties of aqueous solution of lactose instead of the solution of the deproteinized whey is a good approximation, considering that the ratio between lactose and TDS is close to 1. In any case this assumption is conservative for the purpose of the present study. As can be seen, the dependence of the molar volume of the solutions with the molar fraction of the lactose is pretty much linear and, consequently, the partial molar volume of the water in the solutions can be well approximate by that of pure water.

$$\rho = \rho_w \omega_w + \left[\begin{array}{l} \left(-1.0377946 \cdot 10^{-6}\,\omega_L - 0.00068243\right) \\ T + \left(0.1572619\,\omega_L + 1.394888\right) \end{array}\right] \omega_L \qquad (2)$$

where: ω_w and ω_L are the mass fractions of water and lactose, respectively.

Fig. 3 shows the behavior of the activity of the water as function of temperature and concentration. Under the values of T and P considered in this work, the activity of the water is practically equal to the ratio of the vapor pressure of the solution to that of pure water at the same temperature [16]. The lines reported in Fig. 4 were obtained by fitting literature experimental data [13,18,19], using the NRTL equation [17] to calculate the activity coefficients of the solvent. The values of the NRTL dimensionless adjustable parameters, α, δ_{12} and δ_{21}, are 0.3, –2258.4024 and –46.7201, respectively; while the values of ARD, $EMAX$ and R^2 are 0.29%, 1.06% and 0.992, respectively.

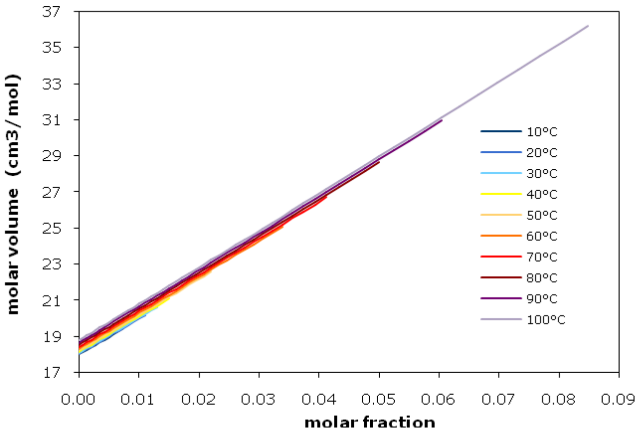

Fig. 2. Molar volume of aqueous solutions of lactose.

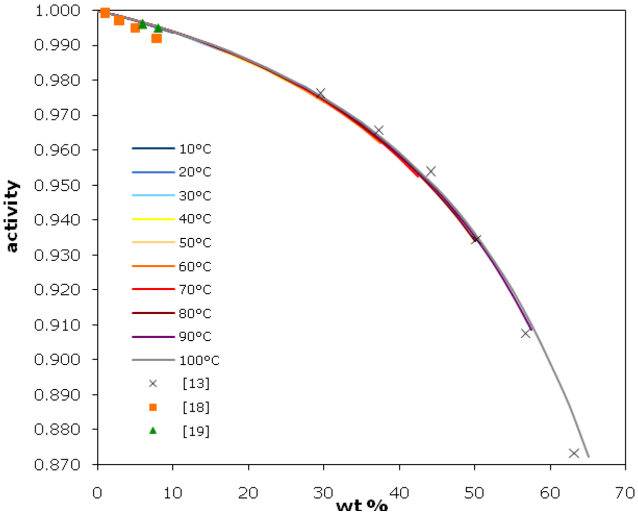

Fig. 3. Water activity of aqueous lactose solutions.

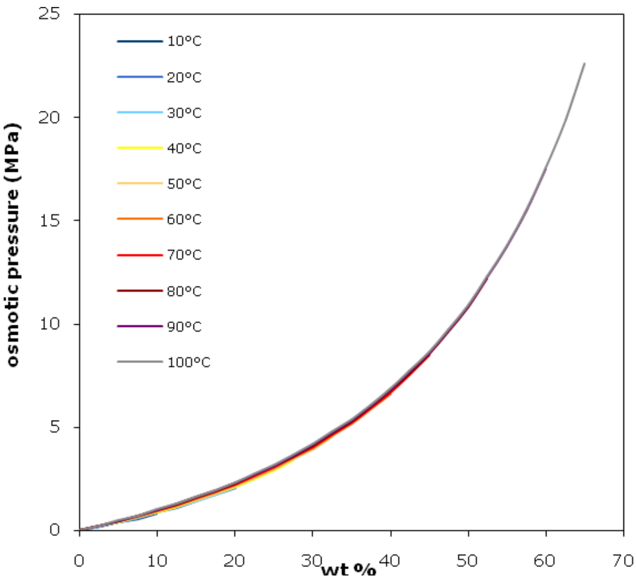

Fig. 4. Osmotic pressure of aqueous lactose solutions.

Fig. 4 shows the behavior of the osmotic pressure, π, of aqueous solutions of lactose as function of temperature and concentration. π was calculated by the non-simplified van't Hoff equation [19]:

$$\pi = \frac{-\ln\left(a_w\right)RT}{\overline{v}_w} \tag{3}$$

where π (MPa); a_w is the activity of water; $\overline{v}_w$ is the partial molar volume of water (cm^3/mol); R is the gas constant (8.31439); T (K).

As can be seen, π is a very weak function of the temperature but a strong function of the concentration; in addition the lines on Fig. 5 are practically super imposable to those representing the osmotic pressure of the aqueous solutions of sucrose and other simpler sugars [20]. Consequently, RO cannot be used to concentrate aqueous solutions of sugars above 25% by weight as found experimentally at pilot plant scale, using commercial spiral wound RO membranes modules, for concentrating grape musts [21]. This results in a big limitation for the net amount of water that can be produced, in higher costs of transportation of the aqueous solutions of lactose and in higher energy requirements for its crystallization.

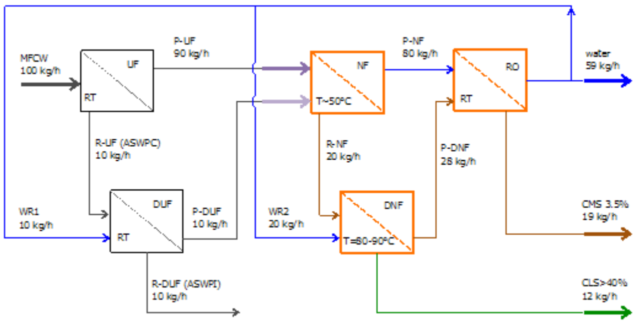

Fig. 5. Simplified diagram of the proposed process.

3. Process development

Fig. 5 shows the schematic diagram of the process proposed for the fractionation of MFCW with special emphasis on the processing of the permeate stream leaving the ultrafiltration section (P-UF) and the permeate stream leaving the dia-ultrafiltration section (P-DUF). These to streams are practically protein free while they retain almost all the lactose, the mineral salts and the minor compounds continuously fed with the MFCW stream.

To achieve the purpose stated in the introduction, lactose and mineral salts must be separated from water and further separated between each other into two small and concentrated streams. According to the results found in the previous paragraphs and to the most recent advances in membrane separation technology, it appears very useful to introduce in the P-UF treatment process, between the UF and the RO, a NF section which, working at temperature between 50 and 80–90°C, allows one to obtain a concentrated solution of lactose, significantly desalted. In this way the RO is used to obtain a big stream of desalted and sterile water in addition to a concentrated stream of bio available minerals.

4. Conclusions

An advanced process has been developed in order to achieve an optimal fractionation of the permeate stream coming from a typical membrane based section of production of whey protein isolate (WPI). This result was obtained considering with accuracy the solubility, the volumetric properties and the activity of aqueous solutions of lactose and salts in a wide range of concentrations, from very dilute up to almost saturated solutions.

This process allows the fractionation of the feed into two small valuable streams: an almost desalted concentrated solutions of lactose, and a concentrated stream of bio available minerals, almost free of lactose. These solutions have a variety of new and interesting applications in several sectors including the food and pharmaceutical industry, the formulations for infants and elderly, and the production of materials for environmental and tissue engineering applications.

In addition, about 60% of the water fed as MFCW is recovered in sterile and very pure form. Expected improvements in nanofiltration and reverse osmosis technologies can further enhance the quality and the added value of these products for a better achievement of the cost-effective whey disposal.

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