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The Effect of Temperature and Transmembrane Pressure on the Camel Milk Ultrafiltration Performance: An Optimization Study

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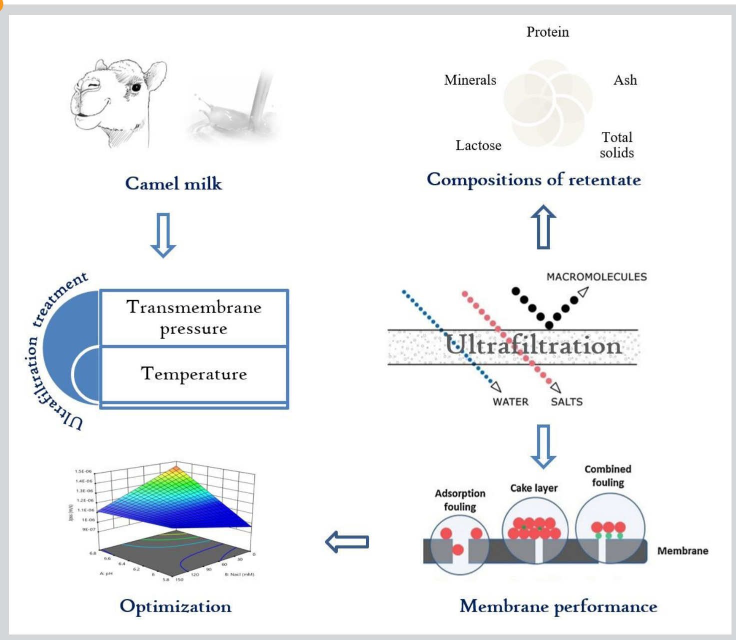
Highlights

- By controlling the transmembrane pressure and temperature, the camel milk ultrafiltration performance can be enhanced.
- The overall trend in the camel milk ultrafiltration process is similar to that of cow milk.
- The optimum camel milk ultrafiltration conditions were determined.

Graphical abstract



Abstract

In this study, the effects of transmembrane pressure (TMP, 80-160 kPa) and temperature (T, 20-40 °C) were investigated on the ultrafiltration (UF) performance of camel milk, including pseudo-steady state permeate flux (J_{PSS}), intrinsic membrane resistance (R_m), reversible fouling resistance (R_{rf}), irreversible fouling resistance (R_{if}), solutes rejection (protein (R_P), lactose (R_L), ash (R_A) and total solids (R_{TS})) and minerals rejection (aluminum (R_{Al}), iron (R_{Fe}), zinc (R_{Zn}), manganese (R_{Mn}), calcium (R_{Ca}), phosphorus (R_{Ph}), sodium (R_{Na}), magnesium (R_{Mg}), and potassium (R_K)). According to the obtained results, increasing TMP led to a significant increase in J_{PSS}, R_{rf}, and R_A while increasing T caused a significant increase in J_{PSS}, R_{rf}, R_L, R_A, and the rejection of all minerals. Although the total fouling resistance (R_f) increased by increasing TMP and T, the share of R_{rf} was higher in high TMP and T compared to R_{if}. The results also showed that none of the linear, quadratic, and interaction effects of TMP and T on the R_m, R_{TS}, and R_P of the samples were significant. In general, camel milk solute rejections, i.e., R_{TS}, R_P, R_L, R_A, R_{Al}, R_{Fe}, R_{Zn}, R_{Mn}, R_{Ca}, R_{Ph}, R_{Na}, R_{Mg}, and R_K were, on average, 51.03, 97.51, 4.73, 34.07, 99.05, 95.70, 90.64, 99.99, 46.09, 32.74, 20.44, 19.44, and 7.78%, respectively. Finally, the optimum UF performance conditions in this research with the lowest R_{rf}, R_{if}, R_L, and R_A while the highest J_{PSS} and R_P were 135 kPa TMP and 35 °C T.

1. Introduction

Increasing population and reducing per capita food production in the world has necessitated the development of marginal resources such as arid and semi-arid pastures and their optimization through introducing the appropriate livestock production systems, like camels. Camels are among the livestock that can be considered an important source of milk production. The growing trend of research and attention to camel milk and its products in recent years indicates its special social and economic position [1].

Ultrafiltration (UF) is among the most widely used membrane operations in the dairy industry, especially for fractionation and concentration of milk components. Using this process, several products can be produced, including milk concentrate used for cheese production, low-lactose dairy products, milk protein concentrate, and serum proteins for dietary supplements [2]. The

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efficiency and cost of a membrane process depend on the permeate flux (the phase passing through the membrane), the rate of fouling, and the rejection percentage of soluble components [3]. Therefore, using concentrated milk made by UF in the production of various dairy products relies on the efficiency of the membrane process and the changes in milk components during this process [4]. The most important limitation of the practical application of ultrafiltration process for complex fluids is the reduction in membrane efficiency because of the concentration polarization and fouling phenomena. In the first few minutes of the process, the concentration polarization significantly reduces permeate flux, expands fouling and changes the rejection pattern of solutes. In addition, fouling lowers the service lifetime of the membrane and raises the cost of cleaning-in-place process [5].

On the one hand, the physicochemical properties of camel milk differ with those of cow milk, especially in terms of type and amount of protein. In camel milk, for example, the ratio of whey protein to casein is greater than that of cow milk, and the distribution of casein micelles is wider and the amount of big micelles is more than that of cow milk [6]. Because of significant differences exist between physicochemical properties of camel and cow milk, it is likely that the membrane processing conditions and the physicochemical properties of their products will be different completely. Although many studies have been conducted on the efficacy of the UF processing of cow milk [4,7-10], there is no information about the efficacy of camel milk UF process and there is little information about the rejection percentage of solutes Mehaia [11] evaluated changes in camel milk protein, fat, lactose, total solids, and ash concentrations throughout the UF process and showed that 100% protein and fat, about 13% non-protein nitrogen and 1% lactose of camel milk were discarded by the membrane throughout the concentration process. Several researchers have also concentrated camel milk by an UF process and produced some products such as camel milk cheese and milk protein isolate [11,12], but have not studied the UF performance with respect to permeate flux, membrane fouling, and solutes rejection. Literature review shows that the UF performance is affected by the membrane characteristics (molecular weight cut-off, composition, and the like), hydrodynamic conditions (transmembrane pressure (TMP) and temperature (T), crossflow velocity, etc.) and the physicochemical properties of feed (pH, ionic strength, etc.), so the flux and fouling should be controlled using these factors. The present research mainly aims to optimize the impacts of TMP and T on the dynamic behavior of steady-state permeate flux, intrinsic membrane resistance, reversible fouling resistance, irreversible fouling resistance, solutes rejection including protein, lactose, ash, total solids and minerals (aluminum (Al), iron (Fe), zinc (Zn), manganese (Mn), calcium (Ca), phosphorus (Ph), sodium (Na), magnesium (Mg), and potassium (K)) during camel milk UF process.

2. Materials and methods

2.1. Membrane system and operation

A schematic diagram of the pilot-scale ultrafiltration unit utilized in this study is illustrated in Figure 1. A UF membrane (Model 3838 HFK-131, Koch membrane systems, Inc., the USA) was also applied, which was made of polysulfone amid with the molecular weight cut-off of 20 kDa. The UF system was equipped with a feed tank, a centrifugal pump, a flowmeter, a spiral UF module, a tube heat exchanger, two pressure gauges, two flow valves, a digital thermometer, and a digital balance connectable to the PC and the printer. After leaving the membrane, the permeate was poured into a container (on an electronic scale) and the dynamic changes of the flux were recorded at 30-second intervals. To prevent T changes during UF operation, a digital sensor was used to control the temperature of the retentate flux and was attuned to the desired level by passing through the heat exchanger. Camel milk was procured from a local marketplace in Mashhad and for camel skim milk production, its fat was separated by a pilot plant milk fat separator in the Food Research Complex, Ferdowsi University of Mashhad. For each run, the milk UF was performed in four steps in order to determine hydraulic resistances. The above-mentioned steps included the filtration of distilled water inside the clean membrane, the filtration of camel skim milk inside the clean membrane, the filtration of distilled water inside the clogged membrane, and the washing cycle according to the instructions of the manufacturer of the membrane system. Washing cycle according to the manufacturer of the membrane system (washing cycle ended when the flux difference at the beginning and end of an ultrafiltration operation did not exceed 3-5%, and other than that, the fouling was not eliminated and it was necessary to repeat the washing cycle).

2.2. Hydraulic resistances

Hydraulic (intrinsic) resistance of the membrane is describable using the Darcy's law as follows [13]:

$$R_m = \frac{\Delta P_T}{\mu_w J_w} \tag{1}$$

where ΔP_T is transmembrane pressure (Pa), μ_w is water viscosity (Pa.s) and R_m is the intrinsic resistance of the membrane (m^{-1}). ΔP_T in a crossflow ultrafiltration process is estimated by the equation below:

$$\Delta P_T = \frac{P_i + P_o}{2} - P_p \tag{2}$$

in this equation, P_i and P_o are the pressure of the solution entering and exiting the membrane, respectively, and P_P is the permeate pressure.

The total hydraulic resistance (R_T) to permeate flow assuming negligible osmotic pressure in the ultrafiltration process is expressed through the resistance-in-series model (or the boundary layer-surface adsorption model) as below [14]:

$$R_T = \frac{\Delta P_T}{\mu_p J_p} \tag{3}$$

where J_p is permeate flux (m/s) and μ_p is permeate viscosity (Pa.s). The total hydraulic resistance is the sum of the intrinsic resistance of the membrane (R_m) and the total fouling resistance (R_F), i.e.

$$R_T = R_m + R_F \tag{4}$$

$$R_F = \frac{\Delta P_T}{\mu_p J_p} - R_m \tag{5}$$

According to the resistance-in-series model, total fouling resistance (R_F) consists of two hydrodynamic resistances including concentration polarization (or reversible fouling, R_{rf}) and surface absorption (or irreversible fouling, R_{if}). Fouling resistances are obtained from the following equations:

$$R_{if} = \frac{\Delta P_T}{\mu_{wf} J_{wf}} - R_m \tag{6}$$

$$R_{rf} = R_F - R_{if} \tag{7}$$

In this equation, μ_{wf} and J_{wf} are viscosity and flux of distilled water permeated from the fouled membrane, respectively. With the completion of individual runs, the UF unit was first subjected to flushing by distilled water at situations similar to individual runs and irreversible fouling resistance (R_{if}) was calculated by measuring the water flux (J_{wf}).

2.3. Analytical methods

The weight percentages of protein, fat, lactose, ash, total solids, and minerals of UF permeate samples were measured by ISO 8968-1:2014, ISO 1211: 2010, ISO 26462/IDF 214:2010, ISO 5544:2008, ISO 6731:2010, and ISO 21424:2018 at two replications, respectively. The chemical compositions of camel skim milk (pH = 6.2) were included fat (0.6%), protein (3.22%), lactose (3.56%), ash (0.90%), total solids (8.25%), K (1361 mg/l), Ca (1176 mg/l), Ph (656 mg/l), Na (645 mg/l), Mg (77 mg/l), Al (6.5 mg/l), Zn (4.55 mg/l), Fe (0.35 mg/l), and Mn (0.04 mg/l), on average. Dynamic viscosity (Pa.s) and density (kg/m^3) were measured by an Ostwald U-tube capillary viscometer and a 25 ml pycnometer with three replications for the samples of distilled water, milk UF permeates, and the third stage distilled water at the T of the corresponding operations. The pH of milk, permeate, retentate, distilled water, and washing solution samples were computed at 25 °C by a pH meter (Jenway 3010 Ltd, Dunmow, Essex, UK). The percentage of the observed rejection of solutes (i.e., protein, lactose, ash, total solids, and minerals) during the UF operation was also calculated by Eq. (8) as follows:

$$R_{obs} = 1 - \frac{Cp}{Cb} \times 100 \tag{8}$$

where C_p and C_b are the concentrations of the solute in the permeate and retentate streams, respectively.

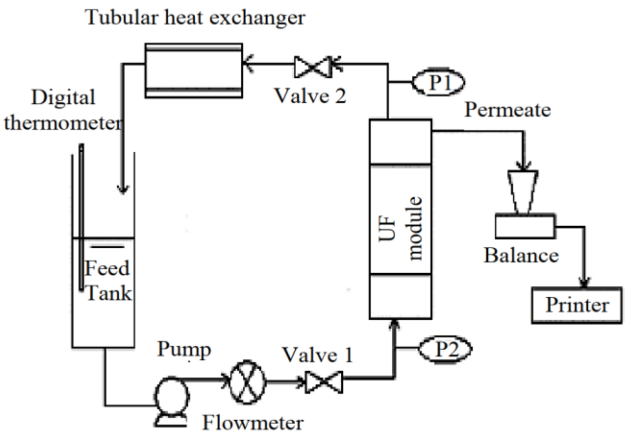

Fig. 1. Schematic diagram of ultrafiltration pilot plant system used in this study.

2.4. Experimental design and statistical analysis

In this study, the process treatments were performed in the form of a central composite design (CCD) (5 replications at the central point) for two independent variables at three levels, so that the total number of 13 treatments was obtained [15], as shown in Table 1. The data were modeled using the statistical software of Design Expert (version 11) using response surface methodology and each of the response variables (J_{PSS}, R_m, R_{rf}, R_{if}, R_P, R_L, R_A, R_{TS}, Rl, RA, RAl, RFe, RZn, RMn, RCa, RPh, RNa, RMg and RK) in the form of regression model were presented as a function of independent variables as follows:

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \beta_{ii} x_i^{\,2} + \sum_{i=1}^{2} \sum_{j=i+1}^{3} \beta_{ij} x_i x_j \qquad (9)$$

where Y is the function variable, x_i is the encoded levels of the independent variables (TMP, kPa and T, ºC), x_i^2 is quadratic effect, and x_ix_j is the coefficient of interaction. Using one-way analysis of variance (ANOVA), the significance of linear, quadratic and interactive effects of regression model coefficients for each variable was investigated at the probability levels of 0.05, 0.01, and 0.001.

3. Results and discussion

3.1. Model establishment

Table 2 presents the empirical models developed for prediction of the dependent variables using the response surface method for significant variables. The coefficient of determination (R^2) and the lack of fit test were used to check the accuracy of the models. Based on data in Table 2, the calculated R^2 values for all measured properties were in excess of 0.8 and the lack of the fit factor was not significant at a 95% confidence level. Therefore, the high coefficient of determination and the non-significance of the lack of fit for all solutions confirmed the accuracy of the model for fitting the data [15]. Surface response curves were drawn to better understand the effects of independent variables (TMP & T) on the measured properties (J_{PSS}, R_{rf}, R_{if}, R_L, & R_A).

3.2. Steady-state permeate flux

Figure 2 displays the permeate flux-time of camel milk UF for treatments No. 1, 4, and 9 (Table 1).
As shown in Figure 2, the flux at every level of the TMP and T reduced by increasing time, and the flux decline rate after about 10 minutes of the process for all curves is nearly constant and approaches a steady-state flux. This behavior was observed in all other tested treatments (data are not provided). This flux is called a pseudo-steady-state flux (J_{PSS}), which is the flux at the termination of every operation and shows relatively a stable or steady-state flux. According to test results, the J_{PSS} of the samples varied between 7.86×10^{-7} and 7.86×10^{-6} m/s. The polynomial quadratic model determined for J_{PSS} (Y_1, Table 2) showed that the linear effects of the TMP and T, along with the interaction between TMP and T at a 99% level on the J_{PSS} of the samples were significant ($P<0.05$).

The effects of TMP and T on the J_{PSS} of the samples according to the coefficients of model y1 is depicted in Figure 3.

Accordingly, J_{PSS} of the samples increases by rising TMP and T so that the sample s1 (TMP of 80 kPa and T of 20 ºC) has the lowest J_{PSS} (7.86×10^{-7} m/s) and the sample s6 (TMP of 160 kPa and T of 40 ºC) had the highest J_{PSS} of the samples (7.86×10^{-6} m/s). Regarding the effect of TMP, it can be stated that ultrafiltration is a pressure driven process. Therefore, as the TMP increases at constant temperature, the driving force of the ultrafiltration operation increases, and permeate flux is expected to increase at the same time. Many researchers have shown that as the TMP increases, permeate flow flux increases [16, 17]. Similarly, Grandison, Youravong and Lewis [4] observed that an increase in TMP in the range of 50-350 kPa increases the initial flux and flux decline rate. Likewise, as illustrated in Figure 3, rising the T at constant TMP increases the J_{PSS} of the samples, which is more intense (the higher slope of the curve) in high TMPs, indicating the greater effect of T on the high TMP and the synergistic effect of T and TMP on the J_{PSS} of the samples. This could be because of a drop in permeate viscosity and an rise in the solubility coefficient of the membrane and the greater mobility of the polymer chains of the membrane at higher Ts [10]. Moreover, increasing the T can increase the radius of membrane pores [9]. Some researchers reported that increasing the T of the process increases the permeate flux [16, 18]. Razavi, Mousavi and Mortazavi [19] also found that increasing the process T, J_{PSS} increases by a mean of 0.81% for each degree Celsius increase.

Table 1
Actual level of ultrafiltration processes variable in central composite design.

Sample codes	TMP (kPa)	T (°C)
S1	80	20
S2	80	40
S3	160	20
S4	160	40
S5	120	20
S6	120	40
S7	80	30
S8	160	30
S9	120	30
S10 (repeat)	120	30
S11 (repeat)	120	30
S12 (repeat)	120	30
S13 (repeat)	120	30

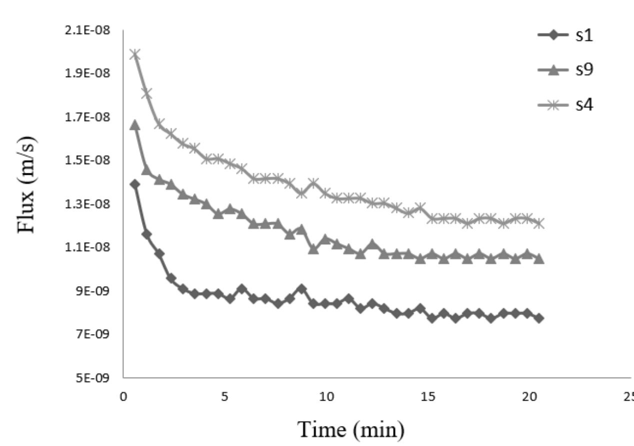

Fig. 2. Permeate flux of camel milk ultrafiltration shown for treatments No. 1, 4 and 9.

Table 2
Predicted models for the responses of ultrafiltration processes of camel milk samples.

Dependent variable	Equation	F Value	p-value Probe > F	R^2	CV	Lack of fit
J_{PSS}	$Y1=7.62\times10^{-7}-1.26\times10^{-9}$ A-1.45×10^{-8}B$+2.55\times10^{-10}$ AB	30.50	0.0005	0.93	4.5	*n.s.*
R_{rf}	$Y2=9.93\times10^{13}-1.09\times10^{12}$ A-4.96×10^{12} B$+5.98\times10^{10}$ AB	26.05	0.0002	0.90	29	*n.s.*
R_{if}	$Y3=-1.60\times10^{13}+9.06\times10^{11}$ A$+4.53\times10^{12}$ B-4.56×10^{10} AB	8.5	0.006	0.80	9.4	*n.s.*
R_L	Y4=6.20 + 0.13A + 0.19B - 0.004AB	6.95	0.0028	0.74	15	*n.s.*
R_A	$Y5=105.83+0.96A-8.92B-0.022AB-0.001A^2+0.181B^2$	0.18	0.0001	0.99	0.01	*n.s.*

3.3. Hydrodynamic resistances

3.3.1. Intrinsic membrane resistance (R_m)

The intrinsic membrane resistance of the tested samples varied between 1.07×10^{13} and 1.36×10^{13} m^{-1}. Additionally, the results showed that none of the linear, quadratic, and interactive impacts of TMP and T on the intrinsic resistance of the sample membrane were significant (P>0.05). Razavi, Mousavi and Mortazavi [19] also reported that in the process of the UF of cow milk, the R_m of the samples did not greatly change by variations in TMP and T.

3.3.2. Reversible fouling resistance (R_{rf}) and Irreversible fouling resistance (R_{if})

Fouling is among the critical factors limiting the application of membrane processes in various industries. The important factors in causing fouling include concentration polarization, the interaction between membranes and particles, particle accumulation, their reaction with each other and finally sediment formation on the membrane surface [8]. Tong, Barbano and Rudan [20] reported that the sediment on the membrane surface has two parts including a loose and soft layer that is easily removed by washing water (concentration polarization resistance or reversible fouling, R_{rf}) and a hard layer which is strongly adhered to the surface of the membrane, and a special detergent or cleaning method is required for its removal (gel layer resistance or irreversible fouling, R_{if}). The concentration polarization layer formed on the surface of the membrane increases the resistance of the membrane. The concentration polarization phenomenon not only causes fouling the membrane but also reduces the permeability of the membrane by increasing the osmotic pressure. In addition, the layer formed by the accumulation of particles on the surface of the membrane or within the membrane pores creates a gel layer on the surface of the membrane, which causes severe resistance to fluid passage. The R_{rf} and R_{if} values of the tested samples varied between 5.66×10^{11}-1.06×10^{13} and 4.83×10^{13}-8.54×10^{13} m^{-1}, respectively. The determined quadratic polynomial model for R_{rf} (Y_2, Table 2) demonstrated that the linear and interactive effects of TMP and T at a 99% level on the reversible fouling resistance of the samples were significant (P<0.05). Based on the determined quadratic polynomial for R_{if} (Y_3, Table 2), only the linear effect of TMP at a 95% level on irreversible fouling resistance was significant while the T represented no significant effect in this regard (P>0.05).

Figures 4 and 5 illustrate the effects of TMP and T on the R_{rf} and R_{if} of the samples, respectively, according to the coefficients of Y_2 and Y_3 models. As depicted in Figure 4, the R_{rf} of samples increases by increasing TMP and T. The intensity of this increase is more pronounced at high TMP and T so that sample S1 (80 kPa and 20 °C) had the lowest R_{rf} (5.66×10^{11} m^{-1}) whereas sample S6 (160 kPa and 40 °C) had the highest R_{rf} among the samples (1.06 $\times10^{14}$ m^{-1}). Further, according to Figure 5, the R_{if} of the samples increases by an increase in TMP from 80 to 120 kPa in the T range of 20-30 °C while the R_{if} of the samples significantly reduces by increasing TMP from 120 to 160 kPa at higher Ts (30-40 °C) although, as mentioned earlier, the T had no significant effect on the R_{if} of the samples. The TMP pushes soluble particles toward the membrane surface and makes them pass through it. However, the concentration of the solutes at the inlet of the membrane increases as the particles selectively pass through the membrane. If the concentration of the material in the concentration layer increases, this layer may have a high viscosity and finally form a gel. As the TMP increases, more particles accumulate at the membrane surface, leading to a rise of membrane fouling through concentration polarization [21]. Concentration polarization occurs in all membrane processes whose driving force is TMP. Consistent with the results of this research, Razavi, Alghooneh and Behrouzian [9] in a study on cow milk ultrafiltration reported that with increasing TMP at a constant concentration, the resistance of the polarization layer increased.

On the one hand, at lower Ts, the energy values of molecule activation are smaller. Thus, the absorption of solutes occurs due to weak bonds such as hydrogen bonding on the membrane surface, and chemical reactions do not interfere with the formation of concentration polarization or gel layers. Furthermore, the movement of fluids with high viscosity (due to low T) from inside the membrane is more difficult. At higher Ts, the feed viscosity reduces and the energy of fluid molecules is higher, therefore, it is possible to form stronger bonds of molecules with each other and the membrane in the adjacent layer of the membrane surface [22], causing a decline in the resistance of the polarization layer. Another reason for the reduction in reversible resistance by increasing T can be the improvement of the back-diffusion rate of solutes while the reduction in the thickness of the concentration polarization layer. Gautam [23] also found that increasing the UF process T can accelerate the membrane sediment due to protein denaturation. Moreover, St-Gelais, Haché and Gros-Louis [24] concluded that increasing the T leads to an increase in the solubility of mineral salts including Ca. Therefore, the removal of soluble Ca to permeate leads to further removal of Ca chloride phosphate in casein micelles, resulting in changes in the size of the milk casein case and probably affecting fouling. Luo, Ramchandran and Vasiljevic [7] also examined the scanning electron microscopy images of membranes from UF operations at Ts of 10 and 50 °C and showed that the membrane surface at 50 °C had a more adhesive white layer compared to the resulting membrane of the UF operation at 10 °C. He also analyzed the compounds attached to the membrane, most of which were included protein and Ca compounds. Nourbakhsh and co-workers [25] stated that the increase in the impact factor of protein emission by increasing the T leads to more penetration into the pores of the UF membrane and more sediments in the walls of the pores.

To investigate the share of each of the R_{rf} and R_{if} on the total fouling resistance (R_f), the effect of T and TMP on the R_{rf}/R_f ratio of the samples were investigated and the results demonstrated that T and TMP at a 99% level were significant on this ratio. The effects of TMP and T on the ratio of R_{rf} to R_f of the samples are also shown in Figure 6.

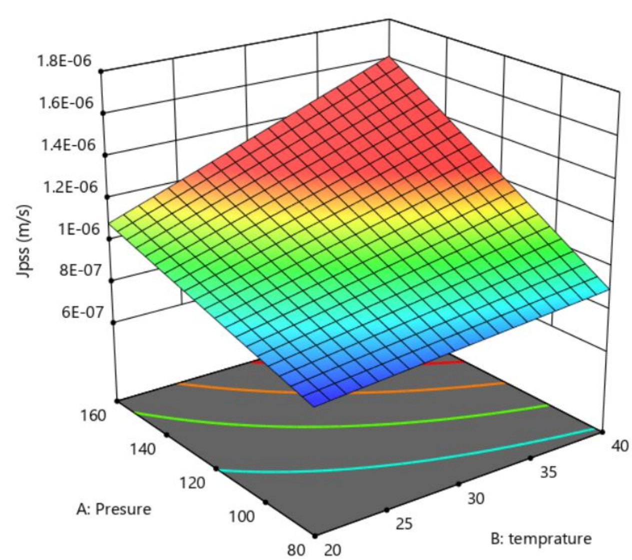

Fig. 3. Effects of transmembrane pressure and temperature on the J_{PSS} of camel milk ultrafiltration.

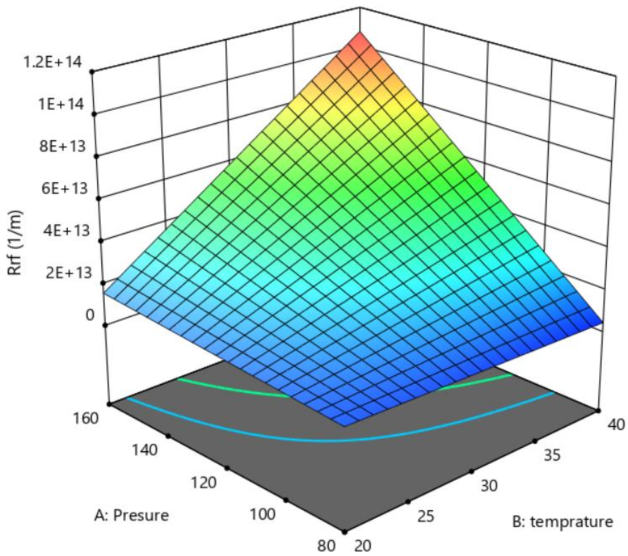

Fig. 4. Effects of transmembrane pressure and temperature on the R_{rf} of camel milk ultrafiltration.

As illustrated in Figure 6, the R_{rf} /R_f ratio R_{rf} /R_f of the samples increases by increasing TMP and T so that the shares of R_{rf} and R_{if} to R_f are equal for 120 kPa and 30 °C while the share of R_{rf} is greater than R_{if} to R_f for the TMP above 120 kPa and the T above 30 °C. Conversely, the share of R_{if} is greater than that of R_{rf} to R_f for the TMP below 120 kPa and T below 30 °C. Therefore, although the R_f increased by increasing TMP and T, the share of R_{rf} was higher than R_{if} at high TMP and T. In other words, the rate of convective transport to the membrane surface was equal to the back diffusion rate of the material to the fluid mass for the TMP of 120 kPa and T of 30 °C. Contrarily, the convective transport rate was higher than the rate of penetration at higher TMP and T, thus the phenomenon of absorption and compression of the gel layer occurred more frequently. Moreover, the rate at which particles are separated from the membrane surface is greater than the absorption rate at higher TMP and T, leading to a reduction in irreversible fouling. Grandison and co-workers [4] showed that R_{rf} is greater at higher pressures (200 kPa) compared to low pressures (50 kPa). Additionally, although the results indicate that the total fouling increases by increasing TMP and T, it should be noted that according to experimental data, the ratio of the flux decline due to increasing fouling in this case to the increasing flux as a result of increasing TMP and T is low, and in general, the permeate flux has increased by increasing these two variables despite the increase in the total fouling by increasing T and TMP.

3.4. Solutes rejection

3.4.1. Total solids rejection (R_{TS}) and protein rejection (R_P)

The rejection of total solids and the protein of the tested samples varied in the range of 45.4-51.03% and 94.09-97.51%, respectively, implying that more than 45% of the total solids and 94% of the protein of camel milk were kept by the membrane in each TMP and T. Mehaia [11] evaluated changes in the protein, fat, lactose, total solids, and ash of camel milk during the concentration process by UF and demonstrated that 100% protein and fat nitrogen and about 13% non-protein nitrogen, along with 1% lactose of camel milk were excreted by the UF membrane throughout the concentration process. The findings also revealed the lack of significance of the linear, quadratic, and interactive effects of TMP and T on the total solids and protein rejections ($P>0.05$). In this study, the completion of the UF process was considered to be the same in terms of the total solids (11%) of the retentate, and the time of the process was not evaluated, but in general, it was observed that treatments with a higher TMP reached the intended retentate total solids in less time. Kautake, Nabetani and Matsuno [16] reported that T did not affect significantly the rejections of the fat and protein of cow milk in the UF process.

3.4.2. Lactose rejection (R_L) and total ash rejection (R_A)

The rejections of lactose and the total ash of the tested samples varied between 4.99 and 14.73%, as well as 17.48 and 34.07%, respectively. Razavi, Mousavi and Mortazavi [19] found that on average, approximately 15 and 45% of the lactose and ash passed through the membrane pores in the UF process of cow milk, respectively. The quadratic polynomial model (Y_4, Table 2) showed that only the linear effect of T at a 99% level on the R_L was significant while the TMP had no effect on the R_L of the samples. Based on the quadratic polynomial model (Y_5, Table 2), the linear effects of T and TMP and the interactive effect of T-TMP at a 99% level on R_A were significant.

Figures 7 and 8 display the effects of TMP and T on the R_L and R_A of the samples, respectively, according to the coefficients of models Y_4 and Y_5. As shown in Figure 7, the R_L reduced by increasing T. An increase in the TMP also led to a reduction at low T while an increase in the R_L rate of the samples at a higher T. According to Figure 8, increasing T from 20 to 30 °C decreased the R_A rate of the samples whereas further increasing the T (30-35 °C) did not have that much effect on the R_A rate of the samples. In addition, the effect of TMP on R_A indicated a non-linear trend so that TMP at high T led to an increase whereas it led to a reduction in the R_A of the samples at low T. Razavi and coworkers [19] also observed that increasing the TMP partially increased the R_L and R_A. Based on their results, the rejection rate of each milk compound represented a slight change despite the significant increase in the permeate flux with pressure. It was proven that the layer consisting of casein micelles acts as a dynamic membrane whose pore size equals the size of the membrane pore [26]. Therefore, the rate of the migration of compounds due to the convective transport of the permeate flux to the membrane surface increases by increasing pressure, and therefore, the adsorption and sediment of solutes to the membrane surface increases, decreasing the effective size of the pores. Limsawat and Pruksasri [27] also reported that increasing the TMP in the UF process resulted in a lower R_L of low-fat ultra-high temperature milk. It seems that the reduction in the R_L and R_A of camel milk with increasing T is due to an increase in their penetration rate by increasing T. Considering the reduction in irreversible fouling by an increase in T, the increase in irreversible fouling with T does not rely on the percentage of milk solute rejection but rather the possibility of stronger bonds between the molecules in the interface layer as well as the molecules with the membrane and thus the more intense surface absorption. Pompei, Resmini and Peri [28] concluded that the inhibition rate of solutes was higher at 5 °C compared to 50 °C. Likewise, Eckner and Zottola [22] found that lower T improved the inhibition of milk compounds (lactose and ash) by the UF membrane.

3.5. Minerals rejection

The rejections of Al, Fe, Zn, Mn, Ca, Ph, Na, Mg, and K ions of camel milk UF samples varied in the range of 97.54-99.05, 75.65-95.70, 66.12-90.64, 41.06-99.99, 32.31-46.09, 24.39-32.74, 10.49-20.44, 12.39-19.44, and 2.65-7.78%, respectively. Therefore, Al, Fe, Zn, and Mn had the highest percentage of rejection while Na, Mg, and K represented the lowest percentage of rejection. The results also revealed that the linear effect of T at a 95% level on the rejection of all the aforementioned minerals was significant so that a rise of T resulted in increases in their rejection percentages. The TMP at a 95% level only affected the rejections of Al, Zn, Mn, and Na. The changes in TMP altered the rejection of minerals differently so that increasing the TMP led to an increase in Zn rejection while a reduction in Mn and Na rejections at all Ts. Furthermore, increasing the TMP at low and high T led to a reduction and an increase in the Al rejection, respectively. Some minerals such as Na, Mg, and K are soluble in milk, thus they pass through the membrane during the UF process and most of them enter the permeate stream. Moreover, minerals such as Ca, Mg, and Ph are present as partially bonded to milk components, especially milk proteins, and partially free in the solution. In the UF operation, the part binding to the protein is rejected and condensed by the membrane, and the freely present part in the solution passes through the membrane [29]. According to [30], increasing the T leads to a reduction in the solubility of minerals such as Ca and Ph thus the percentage rejection of minerals by the membrane increases by increasing T while reducing their solubility. Mehaia [11] also found that the rejections of Zn, Fe, Cu, Ca, Ph, Mg, K, and Na ions in the camel milk UF process were 99, 99, 98, 98, 91, 86, 37, and 32%, respectively, indicating that Zn and Fe were the most abundant minerals while K and Na had the lowest rejections. Peri, Pompei and Rossi [31] obtained similar results in the process of the UF of cow milk and stated that the RZn, RFe, RCu, RCa, RPh, RMg, RK and RNa for the UF of cow milk were 99, 99, 99, 98, 91, 86, 37, and 32%, respectively.

Syrios, Faka, Grandison and Lewis [32] showed that increasing the temperature of low-fat cow milk ultrafiltration led to a reduction in the Ca ion in the permeate stream. Finally, Chandrapala, Augustin, McKinnon and Udabage [33], On-Nom, Grandison and Lewis [34], and Lewis [35] also reported similar results in this respect.

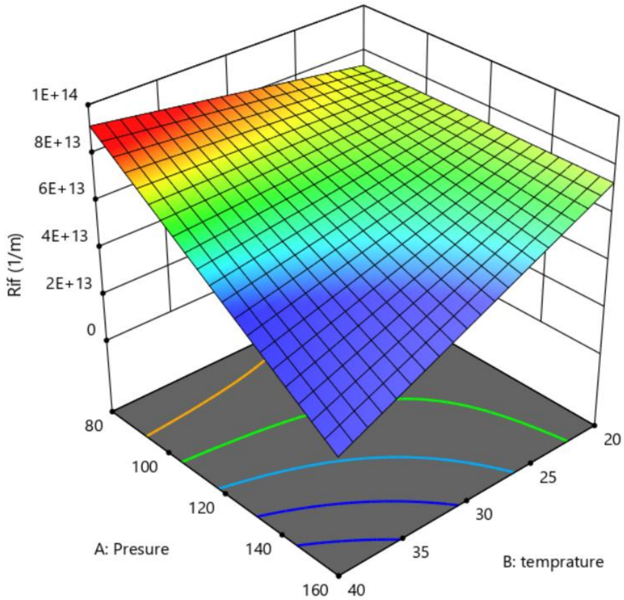

Fig. 5. Effects of transmembrane pressure and temperature on the R_{if} of camel milk ultrafiltration.

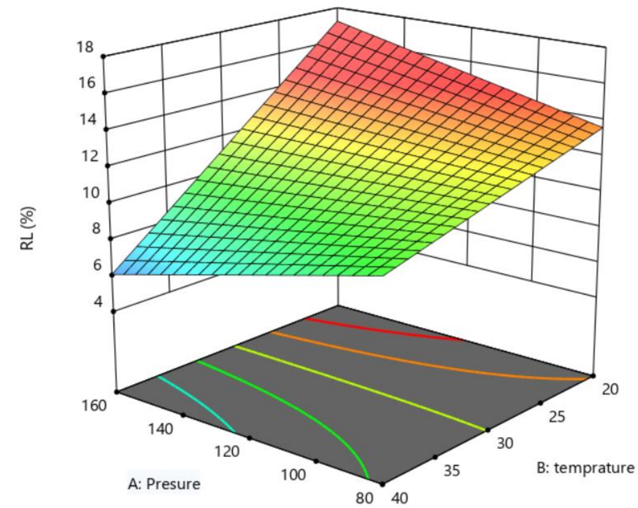

Fig. 7. Effects of transmembrane pressure and temperature on the R_L of camel milk ultrafiltration.

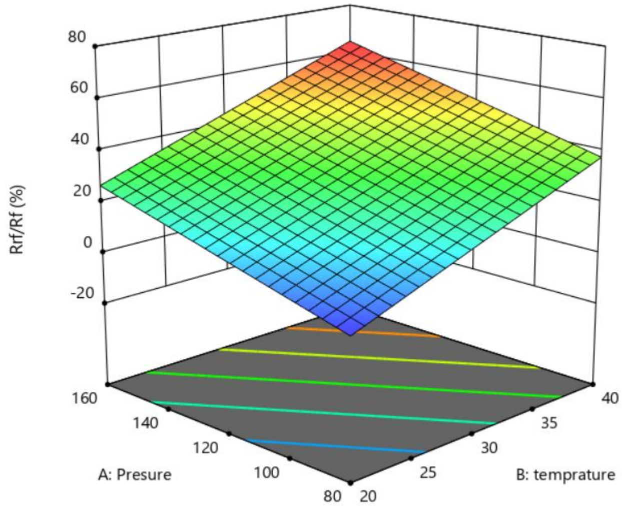

Fig. 6. Effects of transmembrane pressure and temperature on the ratio of R_{rf} to R_f of camel milk ultrafiltration.

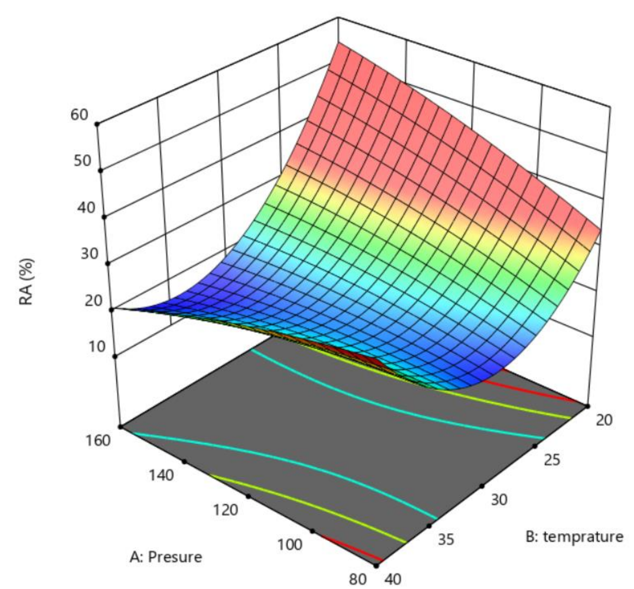

Fig. 8. Effects of transmembrane pressure and temperature on the R_A of camel milk ultrafiltration.

4. Numerical optimization

The exact conditions of the TMP and T on J_{PSS}, R_{rf}, R_{if}, R_L and R_P were also expressed by the numerical optimization option in Design-Expert software, named a desirability function. This technique utilizes an objective function, D(X), reflecting the desired ranges for every response (d_i). The desired ranges are between zero and one (minimum to most desired, in respective order). The simultaneous objective function is a geometric mean of the whole transformed responses as follows [15]:

$$D = (d_1 \times d_2 \times \ldots \times d_n)^{\frac{1}{n}} = \left(\prod_{1-2}^{n} d_i\right)^{\frac{1}{n}}$$

In the above equation, n is the number of responses in the research. In this study, minimum the R_{rf}, R_{if}, R_L and R_A and maximum JPSS and R_P were considered. According to the mentioned traits, the optimum TMP and T conditions were determined as 135 kPa and 35 ^oC, respectively. In such a process, J_{PSS}, R_{rf}, R_{if}, RP, R_L, and R_A are 1.29 $\times 10^{-6}$ m/s, 6.14 $\times 10^{13}$ m^{-1}, 4.83 $\times 10^{13}$ m^{-1}, 32%, 9.3%, and 20%, respectively.

5. Conclusion

Considering the importance of the products of the camel milk UF process and the lack of information about the dynamic behavior of permeate flux, hydrodynamic resistances, and the rejection percentage of camel milk solutes, the effects of T and TMP and their interaction on the traits were examined and these conditions were optimized using the response surface method. The results demonstrated that an increase in the TMP led to significant increases in J_{PSS}, R_{rf}, and R_A while increasing the T caused a significant increase in JPSS, R_{rf}, R_L, R_A, and the rejection of all minerals. The optimum UF conditions in this study with the lowest R_{rf}, R_{if}, R_L, and R_A and the highest JPSS and R_P were determined as 137 kPa TMP and 32 $^{\circ}$C T. The comparison of the results of the present research with those of similar studies on cow milk revealed that although the physicochemical properties of camel milk is greatly different from cow milk, the overall trend in the dynamic behavior of the permeate flux, fouling resistances, and the solutes rejections in the UF process is to the same as that of cow milk. Therefore, processing camel milk by UF process will supply a good market for producers provided that the process is efficient and cost-effective.

Nomenclature

Symbol	Meaning
Al	Aluminum
A	Ash
Ca	Calcium
C_b	concentrations of the solute in the retentate streams
C_p	concentrations of the solute in the permeate streams
CV	Coefficient of variation
Rm	Intrinsic membrane resistance
Fe	Iron
Rif	Irreversible fouling resistance
L	Lactose
Mg	Magnesium
Mn	Manganese
Ph	Phosphorus
P_p	Permeate pressure
K	Potassium
P	Protein
JPSS	Pseudo-steady state permeate flux
R_{rf}	Reversible fouling resistance
Na	Sodium
T	Temperature
TS	Total solids
TMP	Transmembrane pressure
UF	Ultrafiltration
μ	Viscosity
Zn	Zinc

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