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ANALYSIS OF A NEW DIAFILTRATION METHOD OF CLEANING BUTTERMILK FROM LACTOSE WITH MINERAL COMPOSITION PRESERVED

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Abstract. Removing lactose from buttermilk and other dairy products is a topical problem, as there is a significant increase in morbidity rates due to lactose intolerance. In many cases, milk and dairy products containing lactose can not be completely excluded from the diet. These products have a number of valuable components. There are several ways to remove lactose from milk or other dairy products. They are based on separation methods of processing and on the use of enzymes. Among the separation methods, membrane treatment, including diafiltration, is of particular importance. A technique of engineering calculation of cleaning an ultrafiltration buttermilk concentrate is suggested. As a solvent that reduces the concentration of lactose, a nanofiltrate permeate of buttermilk ultrafiltration is used. This method allows preserving the chemical composition of the concentrate with lactose effectively removed. Basing on the experimental data of membrane productivity and their selectivity for lactose, the main characteristics of diafiltration are calculated for various practical applications. For practical purposes, it is advisable to use a buttermilk permeate nanofiltrate using highly selective lactose membranes. Selectivity for salts should be minimal. When comparing the different diafiltration variants, the most suitable is a periodic method, with continuous dilution, and a continuous method with a crossflow and reverse flow of the nanofiltrate. The smallest amount of a nanofiltrate is observed in the case of a continuous countercurrent. The time for diafiltration treatment depends on the membrane's specific parameters, process operating parameters, and the selected lactose purification variant. The most cost-effective is the continuous variant with a countercurrent nanofiltrate. However, it can not be recommended because of the considerable duration of the process. The suggested technique for calculating diafiltration allows quick evaluation of possible options of purifying the product from lactose, and concludes which one is optimal.

Key words: buttermilk, lactose, diafiltration, nanofiltration, buttermilk concentrate, nanofiltration membranes, ultrafiltration membranes

АНАЛІЗ НОВОГО ДІАФІЛЬТРАЦІЙНОГО СПОСОБУ ОЧИСТКИ МАСЛЯНКИ ВІД ЛАКТОЗИ ІЗ ЗБЕРЕЖЕННЯМ МІНЕРАЛЬНОГО СКЛАДУ

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Анотація. Запропоновано методику інженерного розрахунку очищення ультрафільтраційного концентрату маслянки. Як розчинник використаний нанофільтраційний пермеат ультрафільтрації маслянки. Спосіб ефективно видаляє лактозу. На основі експериментальних даних продуктивності мембран і їх селективності по лактозі розраховані основні характеристики діафільтрації при різних варіантах практичного застосування. При порівнянні різних варіантів діафільтрації найбільш прийнятні періодичний спосіб з безперервним розведенням і безперервний спосіб з перехресним і протилежним потоком нанофільтраційного пермеату. Найменше співвідношення об'ємів розчинника і концентрата при діафільтрації досягається у разі безперервного протитока. Час діафільтраційної обробки залежить від питомих показників мембрани, робочих параметрів процесу і обраного варіанту очищення від лактози. Найбільш економічним є безперервний варіант. Запропонована методика розрахунку діафільтрації оцінює можливі варіанти очищення від лактози.

Ключові слова: маслянка, лактоза, діафільтрація, нанофільтрація, концентрат маслянки, нанофільтраційні мембрани, ультрафільтраційні мембрани

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Introduction. Formulation of the problem

Removing lactose from buttermilk and other dairy products is a topical problem, as there is a significant increase in morbidity rates due to lactose intolerance. In many cases, milk and dairy products containing

lactose can not be completely excluded from the diet. These products have a number of valuable components [1].

There are several ways to remove lactose from milk or other dairy products. They are based on separation methods of processing and on the use of enzymes. Among the separation methods, membrane treatment, including diafiltration, is of particular importance [2,3]. The most common industrial membrane processes include reverse osmosis, ultra, micro, and nanofiltration.

Nanofiltration is a baromembrane separation process in which the membrane retains particles and dissolved macromolecules larger than 2–10 nm. *Ultrafiltration* is a baromembrane separation process in which the membrane retains particles and dissolved macromolecules larger than 100 nm [4,5].

Membrane processes are characterized by the use of the triple-flow scheme of flows arrangement, where the raw material flow (the initial mixture) is divided into two streams (Fig. 1): the one that has passed through the membrane (permeate, filtrate), and the other that has not (retentate, concentrate).

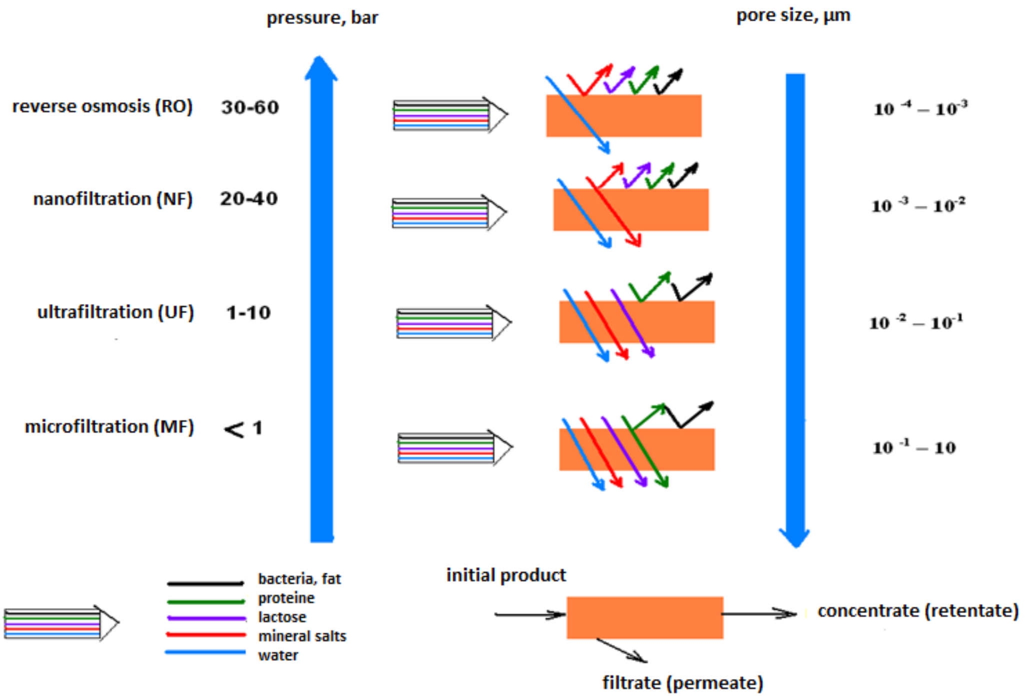


Fig. 1. The principle of membrane filtration

The choice of a lactose removal method depends on many factors. The main requirements are to the composition of the product and the total cost of the process. Membrane treatment has an obvious advantage over others, as reagents are not added to the product. Purification goes on at a low temperature, thus contributing to the preservation of biologically valuable components.

Membrane methods of removing lactose include diafiltration as the main process. *Diafiltration* is a kind of the baromembrane process of separating dissolved high-molecular and low-molecular components, the concentrate being diluted with a solvent. As a solvent, water is used. The concentration of compounds in the product decreases. Further ultrafiltration of the diluted solution leads to separation of high and low-molecular substances. Mineral substances with a solvent pass through the membrane. This method of treatment is applied to clean protein concentrates from lactose and minerals.

Buttermilk is a valuable food product. This is the basic element for many dairy products. The mineral composition of buttermilk is extremely important in the production of, for example, lactose-free ice cream. Therefore, the key task of filtration is to preserve the mineral composition. If water is applied as a solvent, then salts are removed together with lactose from the buttermilk by means of diafiltration. This disadvantage is eliminated when using the nanofiltration permeate of buttermilk ultrafiltration as a solvent of lactose. Nanofiltration permeate has a mineral composition identical to that of buttermilk.

The nanofiltration permeate is used in diafiltration in different ways. Buttermilk is diluted and concentrated according to the schemes shown below.

The choice of the optimal variant from the possible ones requires certain calculations. The calculation method should help in assessing the technological and economic efficiency of filtration. The results of the calculations can be used for comparison with other methods of lactose removal.

Analysis of recent research and publications

Calculations of dairy products diafiltration process are considered in a number of papers [6–13]. In all cases, the solvent used in the products is water.

The works [7, 10] present a theoretical approach to calculation based on modeling and optimization of "ideal" diafiltration. This process does not take into account the specific features of high and low-molecular substances. Not all of them behave in the same way in membrane separation. The above works assume that the selectivity of high-molecular substances R=1, and low-molecular substances R=0. In practice, depending on the type of membrane, R for lactose takes different values. In our case, for example, R=0.05. In these and other [8] studies, only one variant of diafiltration is considered – the one with continuous dilution, when the product volume remains constant. There can be several diafiltration options. This is shown in the main section of the paper.

In work [9], modeling of a diafiltration with variable product volume is presented. Food multi-component liquids and their composition are not taken into account.

The Wolfram Alfa computerized program is applied to calculate ultra and diafiltrations in operation [8]. The program significantly reduces the calculation time, but deals with a constant product volume, without taking into account its chemical composition.

The vast majority of studies of dairy products diafiltration in the literature of the former USSR and Russia are by V. Kruglik. Their results are summarized in [12,13]. These works use a rather complex mathematical technique. In the calculations, it is clean water, not a solution, that is taken as a solvent. The objects of the study are protein concentrates and their hydrolysates.

Thus, the problem of choosing a diafiltration buttermilk variant that would preserve the mineral composition is highlighted in literature but partially. There are no works where a nanofiltrate is taken as a solvent. Besides, a comparative calculation of diafiltration options requires experimental data on the chemical composition of products of ultra and nanofiltration of buttermilk. It is also necessary to determine the specific performance of the selected type of membranes and their selectivity. These data in sources [6–13] are ambiguous.

Therefore, a method which would use experimental data for calculating the diafiltration process with a nanofiltration permeate, is needed. The calculation results should be reliable and fully reflect the effect of diafiltration purification.

Purpose and objectives of the study. The aim of the study is developing a method for calculating the diafiltration process of lactose removal from the buttermilk when a nanofiltration permeate is used. The methodology should provide a comparative analysis and selection of the optimal variant of the process.

To achieve this goal, the tasks were set as follows:

1. To develop a calculation methodology for evaluating the effectiveness of different buttermilk diafiltration variants while maintaining the mineral composition.
2. To obtain experimental data necessary for calculating: the chemical composition of products of buttermilk's ultra and diafiltration, and of the ultrafiltration permeate's nanofiltration; specific performance and selectivity of membranes.
3. To justify and choose the best variant of the process according to results of calculations.

Research materials and methods

The theoretical studies were carried out by analyzing the possible variants of diafiltration, with the use of schemes and mathematical calculations of the main characteristics of the process. A number of formulas were developed to calculate the time of the process, the ratio of the volumes of the solvent used for cleaning and the buttermilk concentrate taken for cleaning (V_{nf} – diafiltration volume), and the degree of buttermilk purification.

In the experimental studies, the buttermilk concentrate obtained by buttermilk ultrafiltration was used as an object. The buttermilk used as raw material was churned at Municipal Milk Plant #1 (Odessa). The chemical composition of the buttermilk concentrate is given in Table 1.

Hollow-fiber membranes as part of module AR-1 (Mytishchi, Russia) were used for ultrafiltration (Fig. 2).

The laboratory unit for buttermilk ultrafiltration is given in Fig. 3

Membranes OPMN-P ("Vladipor", Russia) (Fig. 4) were used for nanofiltration of the buttermilk's ultrafiltration permeate, at operating parameters of p = 1.6 MPa, t = 50 °C that were obtained on laboratory unit FT-01 (Fig. 5).

The diafiltration treatment of the buttermilk concentrate was carried out in a periodic mode. There were no studies of how the membranes' performance depended on the operating parameters. Different diafiltration variants can be compared for their effectiveness at any specific performance value. The specific performance value was determined by means of a measuring cylinder and a stopwatch, with operating parameters p = 1.5 atm and t = 45°C.

Conventional methods [14] were applied to determine the chemical composition of products of buttermilk membrane treatment.

Results of the research and their discussion

Theoretical studies. Possible variants of diafiltration cleaning of buttermilk from lactose are given below.

Variant 1. A periodic process with a single dilution of the concentrate.

In this case, the buttermilk concentrate is immediately diluted with the necessary amount of nanofiltration permeate that does not contain lactose and is obtained by nanofiltration of the ultrafiltration permeate of buttermilk. The amount of the nanofiltration permeate is determined by the required final lactose concentration in the product. After the dilution, ultrafiltration is carried out till the concentrate is of its initial volume.

To simplify our reasoning, let us take into account that lactose and mineral substances are in the aqueous phase of the buttermilk. Fat and protein do not participate in the diafiltration process. In this case, we take a dilution factor (*Kp*) for the buttermilk's aqueous phase as the value

$$K_p = \frac{V_o + V_{nf}}{V_o}, \quad (1)$$

where V_o, V_{nf} are, respectively, the initial volume of the aqueous phase of the buttermilk, and the ratio between the volume of the solvent used for cleaning and the buttermilk concentrate taken for cleaning (diafiltration volume), L.

The final lactose concentration after the diafiltration will be as many times lower than the initial one, as the buttermilk water phase is diluted, considering the membrane selectivity

$$C_к^l = \frac{C_o^l}{K_p}(1 + R^l), \quad (2)$$

where $C_o^l, C_к^l$ are, respectively, the initial and the final lactose concentration in the buttermilk aqueous phase,%.

The membrane selectivity by lactose

$$R^l = \frac{C_{кon}^l - C_f^l}{C_{кon}^l}, \quad (3)$$

where $C_{кon}^l, C_f^l$ are, respectively, the lactose concentration in the buttermilk aqueous phase in the ultrafiltration concentrate and in the filtrate,%.

In this and further calculations, we assume that the diafiltrated solution density is taken 1 kg/l.

To achieve the desired final lactose concentration $C_к^l$, the required ratio of the volume of the solvent used for cleaning and the buttermilk concentrate taken for cleaning is easily calculated from the expression (1), taking into account (2):

$$V_{nf} = V_o(Rh - 1) \quad (4)$$

If it is necessary to consider the entire buttermilk volume taken for diafiltration, then we introduce a correction for high-molecular compounds

$$V_{nf} = V_o(1 + C^{HMS} \times 0.01)(K_p - 1), \quad (5)$$

where C^{HMS} is the concentration of high-molecular substances (protein and fat) in the buttermilk, not involved in the diafiltration process,%.

The initial volume of the buttermilk concentrate taken for processing we denote

$$V_{on} = V_o(1 + 0.01 \times C^{HMS}) \quad (6)$$

If the specific performance of membrane G is known, l/m^2•h (the performance depends on the characteristics of this membrane, process parameters, buttermilk chemical composition, etc.), then it is possible to determine the time during which the required final lactose concentration will be achieved in the unit with the membrane area F.

$$\tau = \frac{V_f}{G \times F}, \quad (7)$$

where V_f is the ratio between the volume of the solvent used for cleaning and the buttermilk concentrate taken for cleaning (diafiltration volume), L.

F is the membrane area in the unit, m^2.

Fig. 2. The hollow-fiber membrane within module AR-1 (Mytishchi, Russia)

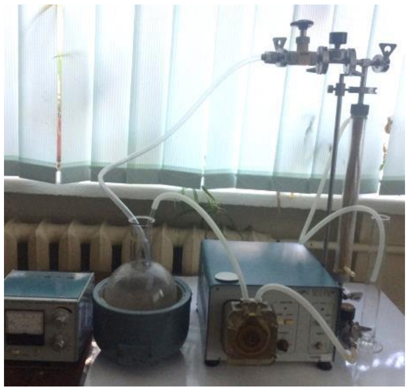


Fig. 3. Laboratory unit UPL-0,6

Fig. 4. Membrane OPMN-P ("Vladipor", Russia)

Fig. 5. Laboratory unit FT-01

Variant 2. Periodic process with multiple dilution of the buttermilk concentrate.

In this case, the initial buttermilk amount undergoes cyclic "dilution-filtration" treatment for several times. Thus, during the entire processing time, the buttermilk will pass N similar treatment cycles.

The dilution factor of the buttermilk aqueous phase in one cycle will be

$$K_p{}^1 = \frac{V_o + V_{nf}^1}{V_o}, \quad (8)$$

where V_{nf}^1 is the ratio of the volume of the solvent used for cleaning and the buttermilk concentrate taken for cleaning (diafiltration volume), for one dilution cycle, L.

For N dilution cycles, the solvent volume taken for cleaning (diafiltration volume) will be used up to,

$$V_{nf}^N = N \times V_{nf}^1 . \quad (9)$$

The dilution factor of the buttermilk aqueous phase for N cycles is equal to

$$K_p{}^N = (K_p{}^1)^N \quad (10)$$

Finally, the lactose concentration in the buttermilk aqueous phase after N cycles of filtration will be

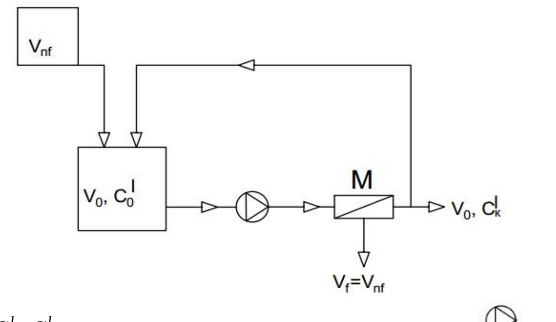
$$C_{\text{к}}^l = \frac{C_o^l}{(K_p{}^{1})^N} \times (1 + R^l), \quad (11)$$

where $K_p{}^1$ is the dilution factor of the aqueous phase for 1 cycle.

The initial buttermilk volume is associated with the aqueous phase volume and with the concentration of protein and fat by expression (6).

Variant 3. A periodic process with a continuous dilution of the buttermilk concentrate (Fig. 6).

In this variant, to the initial buttermilk volume, nanofiltration permeate is continuously added so that its consumption is equal to that of ultrafiltrate. The volume of the buttermilk concentrate, therefore, remains unchanged.



$C_o^l, C_{\text{к}}^l$ – the initial and the final lactose concentrations, ⊳ – pump, M – membrane module, V_o – initial volume of the aqueous phase of the concentrate, V_f – volume of the permeate (filtrate) V_{nf} – volume of the solvent taken for cleaning (diafiltration volume).

Fig. 6. Scheme of the periodic diafiltration process with continuous dilution

Let us assume that the whole filtration process in this variant will be presented as a multicycle, with a discreteness time equal to 1 s.

Therefore, the total number of processing cycles per time τ will be

$$N = 3600 \times \tau , \quad (12)$$

where τ is the total time of continuous diafiltration, h.

The dilution factor of the initial aqueous phase in this case will be

$$K_p{}^1 = \frac{V_o + V_{nf}^1}{V_o}, \quad (13)$$

where V_{nf}^1 is the ratio of the volume of the solvent used for cleaning and the buttermilk concentrate taken for cleaning (diafiltration volume), l/s.

The dilution factor over time τ will be

$$K_p{}^\tau = (K_p{}^1)^N = (K_p{}^1)^{3600\tau} \quad (14)$$

By analogy with the previous variant, the final lactose concentration in the aqueous phase of the buttermilk concentrate after time τ will be equal to

$$C_{\text{к}}^{l\tau} = \frac{C_o^l}{K_p{}^\tau} \times (1 + R^l) \quad (15)$$

or

$$C_{\text{к}}^{l\tau} = \frac{C_o^l}{(K_p{}^1)^{3600\tau}} \times (1 + R^l) . \quad (16)$$

Taking the logarithm of the expression (16), we will get

$$\lg C_{\text{к}}^{l\tau} = \lg C_o^l - \lg(K_p{}^1)^{3600\tau} + \lg(1+R), \quad (17)$$

$$\lg C_{\text{к}}^{l\tau} = \lg C_o^l - \tau \times 3600 \lg K_p{}^1 + \lg(1+R) \quad (18)$$

From (18) it is possible to find the total time of diafiltration at constant volume of the buttermilk concentrate, which is required for decreasing the concentration of lactose from C_o^l to $C_{\text{к}}^{l\tau}$:

$$\tau = \frac{\lg \frac{C_o^l}{C_{\text{к}}^\tau} + \lg(1+R)}{3600 \times \lg K_p{}^1} \quad (19)$$

Then the total ratio between the volume of the solvent used for cleaning and the buttermilk concentrate taken for cleaning, will be

$$V_{nf}^\tau = V_{nf}^1 \times \tau \quad (20)$$

The volume of the buttermilk concentrate to be purified from lactose is determined by the expression (6), with the expression (13) taking into account.

The value V_{nf}^1 is numerically equal to the membrane's specific performance per second multiplied by the total area of the membranes in unit F:

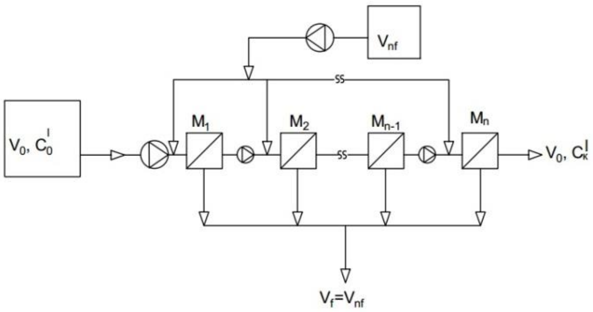
$$V_{nf}^1 = G \times F \quad (21)$$

Variant 4. A continuous process with the cross-flow of nanofiltration permeate (Fig. 7).

In this case, the membrane unit should be divided into *n* membrane modules (devices). Nanofiltration permeate is supplied to each module.

The diafiltration process is a set of *n* units of periodic action with the continuous dilution (see the previous option). All formulas from the previous section will be valid for each module.

The concentrate will be *n* times (cycles) cleaned from lactose. So, in all modules taken together, it will be a periodic process with cyclic treatment (processing).



$C_o^l, C_к^l$ – the initial and the final lactose concentrations,

– pump, M – membrane module, Vo – initial volume of the aqueous phase of the concentrate, V_f – volume of the permeate (filtrate), V_{nf} – volume of the solvent (diafiltration volume).

Fig. 7. Diagram of a continuous diafiltration process with the nanofiltration permeate cross-flow

Let us denote the expression (16) denominator as

$$Z = (K_p{}^1)^{3600 \times \tau}. \tag{22}$$

Then, the final lactose concentration will be

$$C_к^l = \frac{C_o^l}{Z^n} \times (1 + R^l), \tag{23}$$

where *n* is the number of modules in the membrane unit.

The total diafiltration time can be determined from the expression (19), and the ratio between the volume of the solvent used for cleaning and the buttermilk concentrate taken for cleaning can be determined from the expression (20).

Variant 5. Continuous process with the nanofiltration permeate counterflow (Fig.8)

In this case, *n* modules represent the unit, but the ultrafiltrate from each subsequent module is fed to the previous one. The last module is fed with the lactose-free nanofiltration permeate. The buttermilk concentrate comes into this module diluted in *n* times and is immediately concentrated to the initial volume of V_{on}.

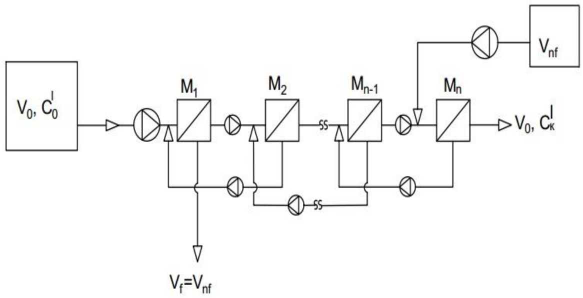
In one membrane module, the process can be represented as a single dilution at periodic diafiltration. The filtrate of the *n*-th module enters the *n*-1 module to dilute the concentrate by *n* times. The lactose concentration in this filtrate is *n* times less than its value in the *n*-1 module. Hence, the process in the *n*-1 module can also be represented as a periodic diafiltration with a single dilution.

Thus, the whole process in the unit can be represented by a set of periodic processes with a single dilution in each module and periodic dilution with cyclic (multiple) dilution in all modules.

For each module, the dilution factor will be

$$K_p{}^1 = \frac{V_o + V_{nf}}{V_o}, \tag{24}$$

where V_{nf} is the ratio between the volume of the solvent used for cleaning and the buttermilk concentrate taken for cleaning (diafiltration volume), which is used *n* times.



$C_o^l, C_к^l$ – the initial and the final lactose concentrations,

– pump, M – membrane module, V_o – initial volume of the aqueous phase of the concentrate, V_f – volume of permeate (filtrate) V_{nf} – volume of the solvent (diafiltration volume).

Fig. 8. Diagram of continuous diafiltration process with the nanofiltration permeate counterflow

Expressions from Variant 1 are valid for each module. Ultimately, after processing in the whole unit, we will receive

$$C_к^l = \frac{C_o^l}{(K_p{}^1)^n} \times (1 + R^l). \tag{25}$$

The process time is defined as the total time for each module, i. e.

$$\tau = \tau_i \times n. \tag{26}$$

In each module, the processing time τ_i is determined by the expression

$$\tau_i = \frac{V_{nf}}{G \times F_i}, \tag{27}$$

where G is the specific performance of membranes, l/m^2 · h. F_i - is the area of membranes of the *i*- module, m.

Accordingly, the area of membranes throughout the unit will be

$$F = \sum_{i=1}^{n} F_i. \tag{28}$$

We will require experimental data on the specific performance of membranes, characteristics of the chemical composition of the buttermilk nanofiltration permeate, ultrafiltrate and ultraconcentrate to compare different diafiltration options and choose the best. These data are used in calculations and may vary depending on the type of membranes applied. However, the course of calculations remains in accordance with this technique.

Experimental study. The chemical composition of products of nanofiltration of the buttermilk ultrafiltration permeate with the help of membranes OPMN-P is presented in Table 1.

Table 1 – Chemical composition of products of nanofiltration of the buttermilk ultrafiltration permeate (FK = 5)

Composition	Initial ultra-filtration permeate	Permeate	Concen-trate
Mass fraction of protein,%	0.11	–	–
Mass fraction of lactose,%	4.50	traces	22.3
Mass fraction of mineral salts,%	0.70	0.70	0.73

The chemical composition of the buttermilk concentrate obtained on hollow-fiber membranes VPU-15000 within the AR-1 module at the concentration factor 3: the mass fraction of protein – 9.6%, the mass fraction of fat – 1.2%, the mass fraction of lactose – 4.5%, the mass fraction of mineral salts – 0.7%.

The selectivity of membranes by lactose is R = 0.05 (formula 3).

The average hollow-fiber membranes performance at a diafiltration (p = 1.5 atm and t = 45°C) amounted to G = 8 $l/m^2 \cdot h$.

The following basic data were taken for further analysis:

– the initial lactose concentration in the buttermilk concentrate – 4.5%,

– the area of membranes in the unit F = 10 m^2,

– initial volume of the aqueous phase of the buttermilk concentrate – V_o = 100 liters.

The working diafiltration parameters are the same in all cases.

The following have been determined in the course of calculations for different diafiltration options:

– the final lactose concentration – $C^l_к$,%

– the duration of the process – τ, h

– the volume of the solvent (diafiltration volume) – V_{nf}, L

– degree of purification – $\frac{C^l_o}{C^l_к}$, times.

The periodic diafiltration process with the single dilution was not considered in calculations. This process is unprofitable due to the large amount of filtrate, the removal of which requires a lot of time.

The summary data of the results are given in Table. 2.

Tables 2. Calculated data for selection of the optimal diafiltration mode

Option number	Process	The volume of solvent (volume diafiltration), l	Process time, h	Final lactose concentration,%	Purification effect $\frac{C^l_o}{C^l_к}$
2	Periodic with cyclic dilution: a) n=2, N=4 b) n=4, N=2	 400 600	 5 7.5	 0.15 0.30	 30 15
3	Periodic with continuous dilution	384	4.8	0.15	30
4	Continuous with cross-flow	384	4.8	0.15	30
5	Continuous with the filtrate return (counterflow)	100	12.5	0.66	7

The membrane unit was split into 10 modules for variants 4 and 5. The membrane area of each module was 1 m^2. For the same diafiltration conditions, three options give the same effects of the buttermilk concentrate cleaning. The volume of the solvent (diafiltration volume) is the same as for periodic #3 and continuous # 4 options. The duration of the process is the same.

The nanofiltration permeate consumption is a factor determining the process efficiency. The most advantageous is the continuous option 5 with a nanofiltration permeate counterflow. In this case, the same volume of the solvent (diafiltration volume) is applied 10 times. The time of the cleaning process by this method compared to other options is the most significant. This does not allow recommending the last option for the buttermilk treatment due to the high risk of microbiological contamination of products. This option advantage is the minimum loss of protein fractions, which we did not consider in this case. As to other options, losses will be inevitable due to selectivity. In the latter case, a return of the protein fraction to the concentrate is observed.

The proposed method of calculation allows, with a small error rate, giving a forecast for choosing the option of the buttermilk diafiltration not only in relation to the membrane process, but also in comparison with other methods of lactose removal, for example, enzymatic one. Membrane methods of purification do not use foreign substances and affect but at minimum the native properties of valuable buttermilk components. This increases the biological value of buttermilk-based products. Further studies are needed in all cases of membrane purification to optimize the performance of membranes, which depends on many factors and is not the subject matter in this paper.

Testing of studies' results.

The results of the studies are obtained in the lab environment of ONAFT in the Department of Ecology and Environmental Protection Technologies. Experiments fully confirmed the calculated data. The proposed method of calculations can be used for the manufacturing environment of the dairy industry. Experimental data of the work are the basis of the being developed lactose-free ice cream technology.

Conclusions

1. Simple mathematical expressions were obtained as a result of theoretical studies, which allow estimating the main indicators of efficiency of the buttermilk concentrate diafiltration. These indicators include the process time, the volume of the solvent (diafiltration volume) and the degree of purification from lactose.

2. Laboratory experiments have shown that the average performance of membranes at diafiltration using nanofiltration permeates was 8 $l/m^2 \cdot h$. The chemical composition of the buttermilk concentrate before and after the diafiltration, and the chemical composition of nanofiltration buttermilk permeate prove that the selectivity of membranes VPU 15.000 by lactose was 5%. The mineral composition of the nanofiltration permeate at the level of 0.7% was in line with the mineral composition of the buttermilk concentrate and did not affect this indicator during the process.

3. The experimental data were used for calculations of different diafiltration options. Key performance indicators of various diafiltration options – time, solvent consumption, the degree of purification – were calculated.

4. The results of calculations confirmed the fact that the most effective diafiltration processes are the two: the periodic one with continuous dilution, and the continuous one with cross-flow of nanofiltration permeate. For them, the process time was 4.8 hours, and the volume of the solvent (diafiltration volume) – 384 liters per initial 10 liters of buttermilk concentrate; the final lactose concentration after purification was 0.15%. The most cost-effective as for the consumption of nanofiltration permeate is a continuous variant with a nanofiltration permeate counterflow. However, it cannot be recommended due to the considerable duration of the process of 12.5 hours.

Thus, the proposed methodology for calculating the diafiltration process allows, within the short time, evaluating the possible options for product purification from lactose, as well as giving an opinion about the optimality.

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