1
Cross-Flow Membrane Applications in the Food Industry

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1.1
Introduction

Over the last two decades, the worldwide market for membrane technology in the food industry increased to a market volume of about € 800–850 million and is now the second biggest industrial market for membranes after water and wastewater treatment including desalination. The key membrane technologies in the food industry are the pressure-driven membrane processes microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). The market share of UF systems and membranes accounts for the largest share of the membrane market with 35%, followed by MF systems and membranes with a share of 33%, and NF/RO systems and membranes with a share of 30%. Other membrane processes such as membrane contactors (MC), electrodialysis (ED) and pervaporation (PV) have only a small market share. The major applications in this market are in the dairy industry (milk, whey, brine, etc.) followed by other beverage industries (beer, fruit juices, and wine, etc.). The success of membrane technology in the food and beverage market is directly linked to some of the key advantages of membrane processes over conventional separation technologies. Among these advantages are:

- gentle product treatment due to moderate temperature changes during processing;
- high selectivity based on unique separation mechanisms, for example sieving, solution-diffusion or ion-exchange mechanism;
- compact and modular design for ease of installation and extension;
- low energy consumption compared to condensers and evaporators.

The key disadvantage of membrane filtration is the fouling of the membrane causing a reduction in flux and thus a loss in process productivity over time. The effect of fouling can be minimized by regular cleaning intervals. In the food industry it is common to have at least one cleaning cycle per 24-h shift. Other actions to reduce fouling are directly related to plant design and operation. During the plant design, the selection of a low-fouling membrane, for example hydrophilic membranes to reduce fouling by bacteria, and membrane modules with appropriate channel heights,

Membrane Technology, Volume 3: Membranes for Food Applications.
Edited by Klaus-Viktor Peinemann, Suzana Pereira Nunes, and Lidietta Giorno

ISBN: 978-3-527-31482-9

for example modules with open channel design to avoid blockage by particles, can reduce the risk of fouling and contamination significantly. Operating the plant below the critical flux – the flux below which a decline of flux over time does not occur, and above which fouling is observed – can extend the time between cleaning intervals significantly but is commonly related to low-pressure/low-flux operation, which translates into low capacities. Alternatively, operating the process in turbulent flow regime can reduce the effect of fouling, but the generation of turbulence is linked to an increase in pressure drop and therefore higher energy costs. Other limitations to the application of membrane processes might be related to the feed characteristics, for example increase of viscosity with concentration, or to separation mechanisms used in the membrane process, for example osmotic pressure increases with concentration.

In the following, successful applications of membrane processes in the food industry will be introduced. The first part of this chapter will focus on the dairy industry, the largest and most developed membrane market in the food industry, followed by the fermented food products – beer, wine and vinegar – fruit juices and other established membrane applications. The final section of this chapter will give an outlook of potential membrane applications in the food industry focusing especially on the emerging membrane technologies: membrane contactors, pervaporation and electrodialysis.

1.2 Dairy Industry

1.2.1 Dairy Industry Overview

The dairy industry has used membrane processing since its introduction in the food industry in the late 1960s to clarify, concentrate and fractionate a variety of dairy products. Applying membrane technology to whey processing allowed the production of refined proteins and commercial usage and thus transformed a waste by-product from cheese production into a valuable product. In addition to whey processing, membrane technology is also used for fluid milk processing with clear advantages. Further, specific milk components can be obtained without causing a phase change to the fluid milk by the addition of heat as in evaporation, or an enzyme, as done in most cheese-making techniques. The filtered milk can then be directly used in the manufacture of such dairy products as cheese, ice cream and yoghurt. By applying membranes with different pore sizes and molecular weight cut-offs (MWCOs), the milk can be modified by separating, clarifying, or fractionating a selected component in milk from other components. The pressure-driven membrane processes MF, UF, NF and RO are the most common membrane processes in the dairy industry and based on their applicability range it is possible to separate virtually every major component of milk as shown in Figure 1.1, thus enabling the manufacturing of products with unique properties and functionalities.

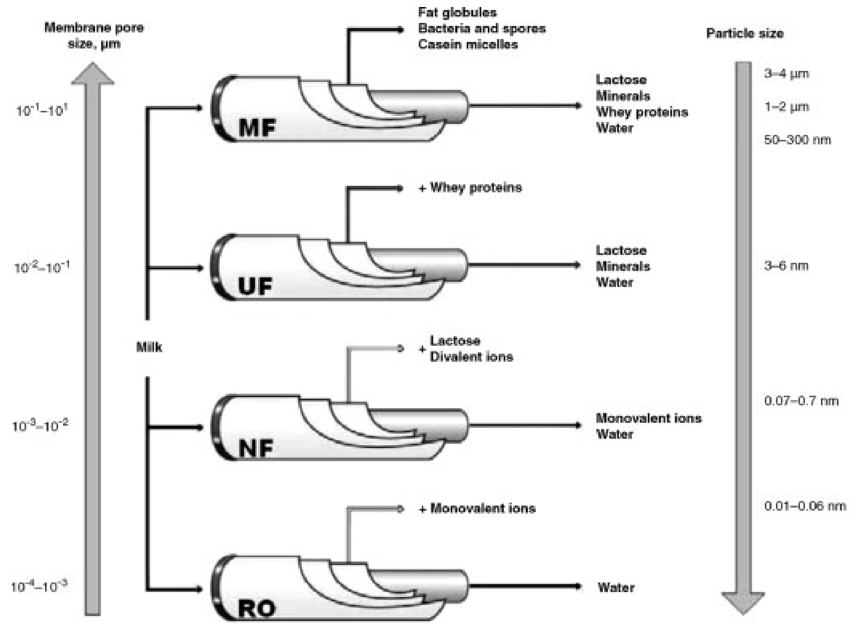

Figure 1.1 Milk processing with membrane technology.

1.2.2
Key Membrane Applications

In the following, the key applications of cross-flow membrane technology in the dairy industry are discussed.

1.2.2.1 Removal of Bacteria and Spores from Milk, Whey and Cheese Brine

The removal of bacteria and spores from milk to extend its shelf-life by MF is an alternative way to ultrapasteurization. In this approach, the organoleptic and chemical properties of the milk are unaltered. The first commercial system of this so-called Bactocatch was developed by Alfa Laval [1–3] and marketed by Tetra Pak under the name Tetra Alcross® Bactocatch. In this process, the raw milk is separated into skim milk and cream, see Figure 1.2. The resulting skim milk is microfiltered using ceramic membranes with a pore size of 1.4 µm at constant transmembrane pressure (TMP). Thus, the retentate contains nearly all the bacteria and spores, while the bacterial concentration in the permeate is less than 0.5% of the original value in milk. The retentate is then mixed with a standardized quantity of cream. Subsequently, this mix is subjected to a conventional high heat treatment at 130 °C for 4 s and reintroduced into the permeate, and the mixture is then pasteurized. Since less than 10% of the milk is heat treated at the high temperature, the sensory quality of the milk is significantly improved.

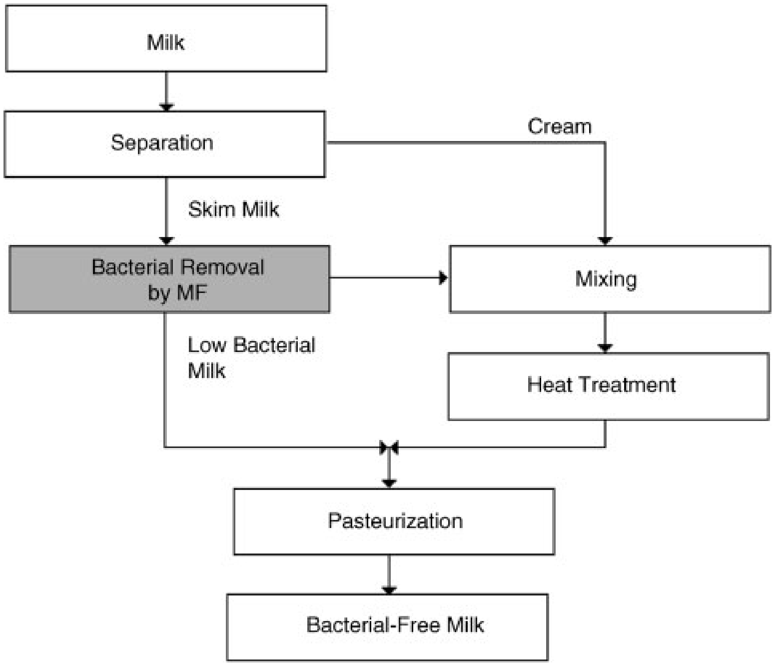

Figure 1.2 Bacterial removal from milk by MF.

MF for the removal of bacteria and spores can be further applied in the production of other dairy products. In the production of cheese, the use of low bacterial milk improves also the keeping quality of cheese due to the removal of spores, thus eliminating the need of additives (e.g., nitrate). While in the production of whey protein concentrates (WPC) and isolates (WPI), this MF concept is used to remove bacteria and spores giving a high quality product (see Figure 1.4). Hence, by applying MF the heat treatment of the WPC/WPI is kept to a minimum, which preserves the functional properties of the whey proteins.

Finally, in the manufacture of cheese the concentrated curd is submerged in a salt solution to improve the cheese preservation and to develop the flavor and other cheese properties. This process is called brining. Efficient sanitation of cheese brine has become a major concern to the dairy industry in recent years. This results from the possibility of post-contamination of cheeses in the brine, especially by pathogenic bacteria. The application of MF for sanitation of cheese brine, using ceramic or spiral-wound membranes, results in a superior cheese quality compared to the traditional processes of heat treatment and kieselguhr filtration. MF has the advantages of being simple to perform, of maintaining the chemical balance of the brine and of eliminating filter aids. In the brine treatment by MF it is normally necessary to make a prefiltration of the brine solution, which is easily done by dead-end filter bag or cartridge with a pore size of 100 μm [4].

1.2.2.2 Milk Protein Standardization, Concentration and Fractionation

The protein content of milk is subjected to natural variations during the year. Standardization of milk by UF offers the possibility of increasing or decreasing the protein content in milk without the need of adding milk powders, casein and whey protein concentrates. Skim milk and 1% milk with increased protein content have an improved appearance (whiter milk) and higher viscosity [5]. The sensory quality of increased protein milk is therefore more similar to that of higher fat milks resulting in an improved consumer appeal. Another application of UF is the standardization of protein and total solids in milk for use in fermented dairy products, such as cream cheeses, yoghurt and cottage cheeses. The resulting dairy products have superior quality and sensory characteristics compared to those produced from milk concentrated by conventional methods [6]. With the quality obtained by membrane filtration, attributes such as consistency, post-processing and extent of syneresis are easier to control. However, the use of membrane-processed milk often requires an adjustment in starter culture selection and fermentation conditions due to the compositional changes in the UF milk.

Concentration of milk, which conventionally is done by evaporation techniques, can also be achieved by RO. The concentrated milk has its greatest potential in ice-cream manufacturing, since all the solids are retained in the concentrate and 70% of the water is removed. MF and/or UF are used in the production of milk protein concentrates (MPC), which are products containing 50–58% of protein. These products are used as food additives and it is therefore extremely important to maintain the functionality of the proteins. By using UF membranes in combination with MF and/or diafiltration (DF) with the corrected adjustments of pH, temperature and filtration conditions, it is possible to produce the desirable MPC for a specific food application.

The most promising MF application in the dairy industry is the fractionation of milk protein. The separation of micellar casein from the whey proteins can be achieved by ceramic membranes with a pore size of 0.2 μm at a constant TMP. The resulting retentate has a high concentration of native calcium phosphocaseinate that can be used for cheese making. Native casein has an excellent rennet-coagulation ability that will make calcium phosphocaseinate an exceptional enrichment for cheese-milk. The permeate can be further processed by UF to produce high-quality WPC. These protein concentrates can be further separated into lactoferrin, β-lactoglobulin and α-lactalbumin via ion-exchange chromatography. Both β-lactoglobulin and α-lactalbumin have great potential markets. β-lactoglobulin can be used as a gelling agent and α-lactalbumin, which is very rich in tryptophan, can be used in the production of peptides with physiological properties. Another application can be the production of infant milk. The fractionation of milk proteins using membrane technology enables the recovery of value-added protein ingredients. Further, the casein and whey proteins are separated without the need of heat or enzymes. The potential applications of membrane separation in milk processing are shown in Figure 1.3.

1.2.2.3 Whey Protein Concentration and Fractionation

Whey is a by-product from the cheese industry. It has low content of solids and high biological oxygen demand (BOD), which creates a major disposal problem for the

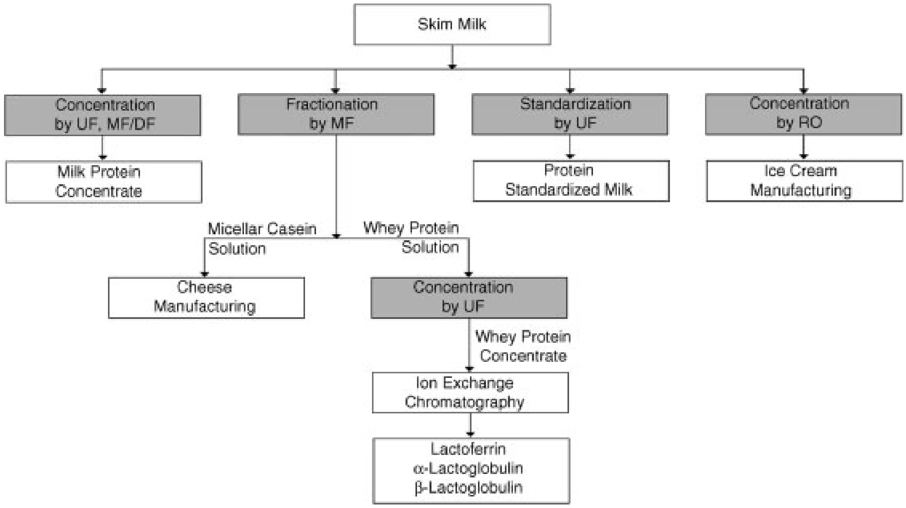

Figure 1.3 Applications of membrane technology in milk processing.

dairy industry. In the past, all whey was disposed of as sewage, sprayed on fields or used for animal feed. By applying membrane technology whey can be concentrated to produce WPC and WPI, as well as fractionated and purified to obtain purified α-lactalbumin and β-lactoglobulin. Hence, a once wasted product can be converted into high value-added products and at the same time one of the key pollution problems of the dairy industry can be solved. Consequently, the use of UF and RO to concentrate whey was one of the first applications of membranes in the dairy industry. Due to the complexity and diversity of whey, it is necessary to use different membrane processes to produce a specific product (see Figure 1.4). The production of WPC with 35–85% protein in the total solids can be achieved by a combination of UF and DF. MF can be used as a pretreatment to remove both bacteria and fat and allows the production of WPI with 90% protein in the total solids. Whey proteins have not only a high nutritional value but also functional properties. They can be used as gelling, emulsifying and foaming agents. Therefore, whey concentrates have far-reaching applications not only in dairy foods, but also in confectionary, nutritional foods, beverages and even processed meats.

The presence of fat in whey leads to decreased functional properties and shorter storage time. Several processes involving membranes have been developed to remove the residual fat from whey [7–11]. The most common process, developed by Maubois *et al.* [9] and Fauquant *et al.* [8], exploits the ability of the phospholipids to aggregate by calcium binding under moderate heat treatment for 8 min at 50 °C. This process is called thermocalcic precipitation. Defatted whey is then obtained by MF with a pore size of 0.14 μm to separate the resulting precipitate. Defatted whey can be further processed by UF, which also improves the performance in the subsequent membrane processes. The defatted WPC has a foaming capacity similar to that of egg white and the same protein content. Its applications can be as raw material in the pastry and

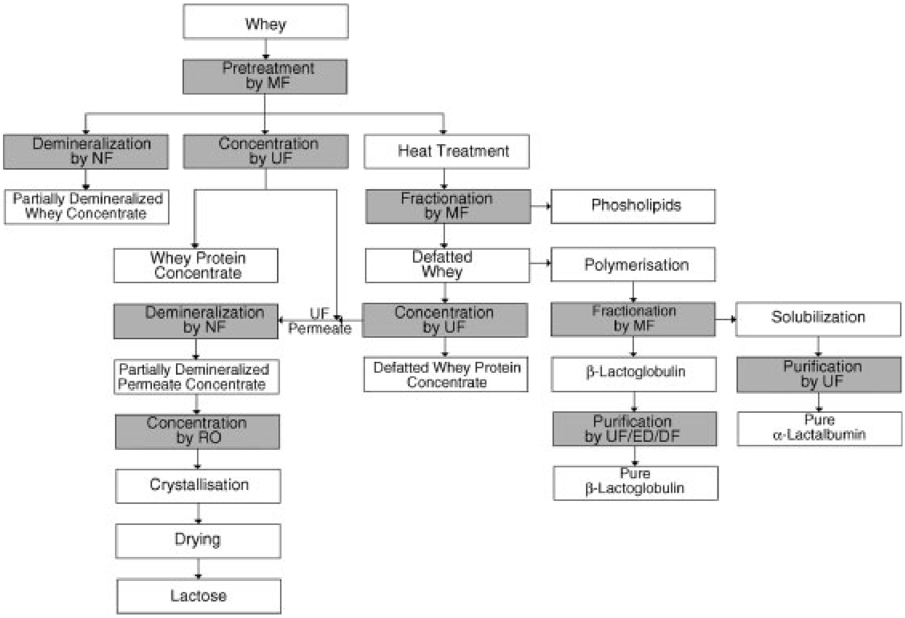

Figure 1.4 Applications of membrane technology in whey processing.

icecream production. The MF retentate, which contains a high amount of phospholipids, can be used as an effective emulsifier agent for food and cosmetic applications. The purified proteins β-lactoglobulin and α-lactalbumin can be obtained from the defatted whey. At low pH (4.0–4.5) and under moderate heat treatment for 30 min at 55 °C, α-lactalbumin polymerizes reversibly entrapping most of the residual lipids and the other whey proteins with the exception of the β-lactoglobulin. The fractionation of β-lactoglobulin from the remaining proteins can then be done by MF with a pore size of 0.2 μm or centrifugation. The resulting soluble phase, rich in β-lactoglobulin, can be further purified by UF coupled with electrodialysis (*ED*) or DF [9]. Purification of α-lactalbumin from the MF retentate can be achieved by solubilization at a neutral pH and subsequently by UF using a membrane with an MWCO of 50 000 Dalton.

It has also been reported that membranes can be applied for the isolation of K-casein-glycomacropeptid (GMP) from cheese whey. GMP can find several applications in the pharmaceutical industry. Studies have shown that GMP avoids the adhesion of *Escherichia coli* cells to the intestine walls, protects against influenza and prevents adhesion of tartar to teeth [12].

It should also be noted that membrane filtration also plays a major role in the lactose manufacture from whey using UF and RO and in the production of low-carbohydrate beverages with high dairy protein content.

1.2.2.4 **Whey Demineralization**

In the dairy industry, the NF process is used to concentrate and partially demineralize liquid whey. Due to the selectivity of the membranes most of the monovalent ions, the organic acids, and some of the lactose will pass the membrane. NF is a very interesting alternative to ion exchange and ED if moderate demineralization is required. One advantage of NF compared to the other two processes is that NF is a simple process, which partially demineralizes and concentrates the whey at the same time. The maximum level of demineralization by NF is about 35% reduction of the ash content with a concentration factor of about 3.5–4. By applying a DF step it is possible to increase the level of demineralization up to 45%. Other applications of NF in whey processing include: concentration and partial demineralization of whey UF permeates prior to the manufacture of lactose and lactose derivatives, converting "salt whey" to normal whey while solving a disposal problem, treating cheese brine solutions to be reused. The potential applications of membrane separation in whey processing are shown in Figure 1.4.

1.2.2.5 **Cheese Manufacturing**

Another early application of membrane technology in the dairy industry was in cheese manufacturing for production of Feta cheese and brine treatment by UF. Nowadays, membrane-processed milk is also successfully used in the manufacturing of quark and cream cheeses. Together with WPC production, the use of UF milk for the production of cheese is the most widespread application of membranes in the dairy industry.

The advantages of UF concentrated milk in cheese making compared to traditional methods are the following:

- increases the total solids, which increases the cheese yield and therefore decreases the production costs in terms of energy and equipment;
- reduces the rennet and starter culture requirements since UF-milk has a good ability of enzymatic coagulation;
- reduces the wastewater processing costs of the cheese plant;
- improves the quality and composition control;
- increases the nutritional value due to the incorporation of the whey protein in the cheese.

UF in cheese processing can be used in three ways [6]:

1) *Preconcentration* – The standardized cheese milk is concentrated by a factor of 1.2–2 and it can be used for most cheese types. This allows the capacity of the cheese vats and whey draining equipment to be doubled. However, the cheese yield will not be significantly improved since only 4.5–5% of the protein content is increased. It is used to produce Cheddar, Cottage Cheese and Mozzarella, and it can be used to standardize cheese milk and manipulate its mineral composition, resulting in a more consistent quality in the final product.
2) *Partial concentration* – The standardized cheese milk is concentrated by a factor 2–6. It is used in the manufacture of Cheddar cheese by using for example, the APV-SiroCurd process, in which the milk is concentrated five times with DF in order to standardize the salt balance [13]. It is also used to produce other cheese types like Queso Fresco, structure Feta, Camembert and Brie.

3) *Total concentration* – The standardized cheese milk is concentrated to the total solids content in the final cheese. This provides the maximum yield increase and since there is no whey drainage, the cheese can be manufactured without the need for a cheese vat. It is used to produce cast Feta, quark, cream cheese, Ricotta and Mascarpone.

The UF permeate, which contains mainly lactose, can be concentrated by RO. The permeate from the RO process can be polished by another RO unit. After pasteurization or UV light treatment, the permeate from the polisher can be used at the plant as process water, thus reducing the water costs of the plant.

Although UF has advantages in cheese production, the increase of whey content in the cheese due to the concentration of all milk proteins can have a negative effect on the ripening of semihard and hard cheeses [14, 15]. Therefore, UF should be viewed as a complementary process to cheese manufacturing and not as an alternative process.

1.3 Fermented Food Products

In the production of the fermented food products, for example beer, wine and vinegar, membranes have initially established themselves as a clarification step after the fermentation. Initially, dead-end filters were used in the production of fermented food products followed by the first trials of cross-flow filtration for the clarification of beer, wine and vinegar in the 1970s. However, the first industrial application in this segment was the dealcoholization of beer by RO in the 1980s. In the last decade, membrane filtration has established itself for the clarification of wine, beer and vinegar and based on its now proven reliability in other production steps.

1.3.1 Beer

The conventional brewing process starts in the brew house with the stepping of the malt with hot water to produce wort, a thick sweet liquid. The wort is then passed to the wort boiler in which it is brewed/boiled for up to 2 h followed by clarification and cooling. The clarified and cooled wort is combined with yeast and passed on to the fermentation tanks in which the yeast converts the grain sugar to alcohol and as such produces beer. Before being transferred to the bright beer tanks, the beer is commonly clarified. The finished beer might then be fine-filtered and pasteurized before bottling. In the case of beer dealcoholisation, the alcohol removal takes place before the beer clarification. The overall brewing process with potential applications of cross-flow membrane filtration is shown in Figure 1.5.

1.3.1.1 Beer from Tank Bottoms/Recovery of Surplus Yeast

After fermentation, yeast is settling at the bottom of the fermentation vessels. The settled tank bottoms account for 1.5–2% of the total beer volume and, apart from the

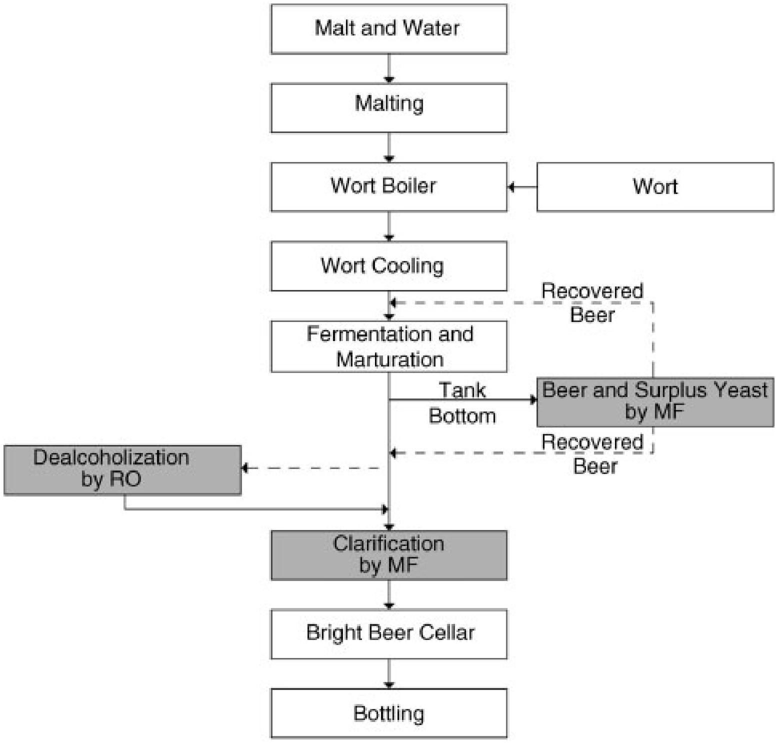

Figure 1.5 Beer production with membrane technology.

yeast, contain a high proportion of beer that is lost if not recovered. In order to recover the beer and concentrate the yeast up to 20% DM, a continuous membrane process has been developed, which separates the beer from the yeast by cross-flow MF with plate-and-frame modules or tubular modules. The layout of this process with plate-and-frame modules is shown in Figure 1.6.

The investment and operating costs of the beer recovery plant are balanced by the beer recovered from the yeast. For a typical brewery with an annual production of

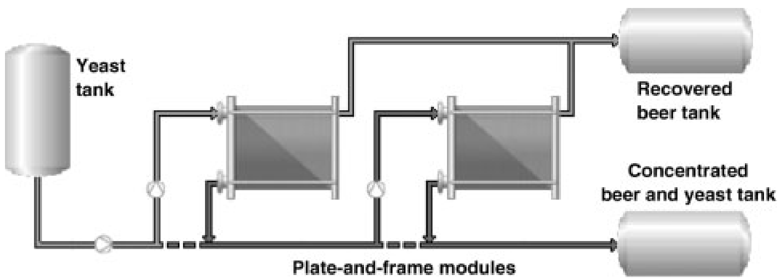

Figure 1.6 Recovery of beer and surplus yeast from tank bottoms.

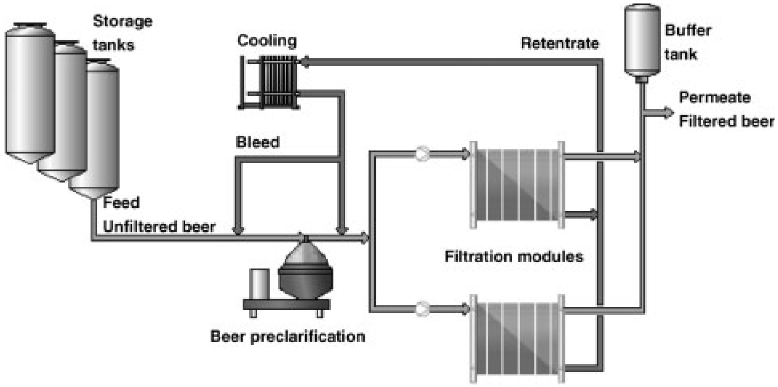

Figure 1.7 Concept of beer clarification by MF.

2 million hl, the recovered beer amounts to 24 000 hl, or about 1% of the annual production [16]. Furthermore, the recovered yeast has an increased dryness that supports further processing.

1.3.1.2 Beer Clarification

In the traditional brewing process, the clarification of the beer after fermentation and maturation is often achieved by a separator followed by kieselguhr filtration, a process that is associated with handling and disposal of the powder as well as large amounts of effluents. To overcome these problems, cross-flow MF with plate-and-frame cassettes has been adopted to remove yeast, micro-organisms and haze without affecting the taste of the beer. The concept of this process is shown in Figure 1.7.

1.3.1.3 Beer Dealcoholization

The demand for low-alcohol and alcohol-free drinks has been constantly growing over the last decade. The market development, for example in Germany shows an increase in the annual consumption of alcohol-free drinks from 130.4 l per person in 1980 to 248.4 l per person in 1999, while in the same period the consumption of alcoholic drinks decreased from 179.5 to 156.3 l per person [17]. RO can be used to reduce the alcohol concentration 8–10 times, while maintaining the beer flavor. The dealcoholization of beer by RO is divided into four steps:

1) *Preconcentration* – the beer is separated into a permeate stream containing water and alcohol and a retentate stream consisting of concentrated beer and flavours.
2) *Diafiltration* – addition of desalted and deoxygenized water to balance the volume removal with the permeate combined with continuous water and alcohol removal with the permeate.
3) *Alcohol adjustment* – fine tuning of taste and alcohol content by addition of desalted and deoxygenized water.
4) *Post-treatment* – to balance taste losses due to removal of the taste carrier alcohol, components such as hops and syrups are added to the dealcoholized beer.

All the steps are operated at temperatures of 7–8 °C or lower, resulting in a high-quality beer, the flavor of which is not affected by a heating process. After dealcoholization, the beer is clarified before bottling.

1.3.2 Wine

The traditional wine-making process starts with the crushing and pressing of the grapes followed by must correction, if required. The grape juice from the pressing is centrifuged and transferred to the fermentation tanks, where the fermentation process starts under the addition of yeast. When the fermentation is completed, the yeast fraction from the wine is removed and the wine is moved into barrels for aging. After the aging, the mature wine is clarified, tartar stabilized, sterile filtered and bottled. Membrane processes can replace several of the different separation steps involved in the traditional wine production as shown in Figure 1.8. When the taste of the wine has been deteriorated or dealcoholization of the wine is desired, then these steps are taken before the sterile filtration.

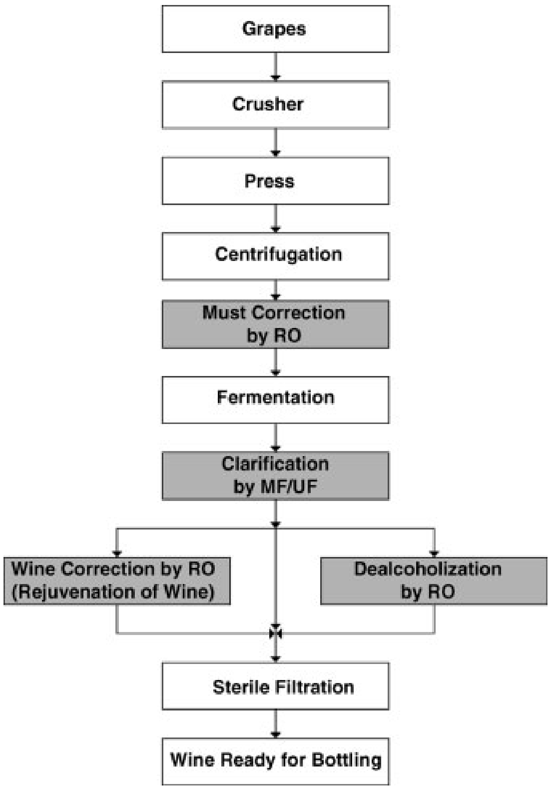

Figure 1.8 Membrane processes in the wine production.

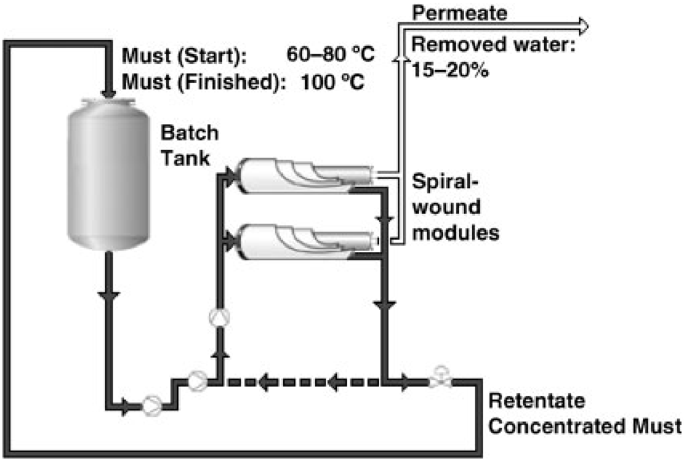

Figure 1.9 Batch plant for must correction by RO.

1.3.2.1 **Must Correction**

As an alternative to chaptalization or other treatments, RO can be applied to increase sugar contents in the wine without addition of nongrape components at ambient temperature and to adjust and balance the composition of the must. The use of RO leads to enrichment in tannins and organoleptic components by water reduction between 5 and 20%. This method is particularly suitable to reverse the dilution of the must quality due to rain during the harvest by the selective removal of excess water. However, applying this method to must from grapes of stalled maturity due to cold weather was found to be less effective, since apart from sugar, acid and green tannins are also concentrated [18]. In general, the use of this method is limited by the legislation in the different countries. In Figure 1.9, the concept for a must correction plant is shown.

1.3.2.2 **Clarification of Wine**

The traditional fining after fermentation often involves several steps of centrifugation and kieselguhr filtration to obtain the desired quality. The use of MF/UF can reduce the number of steps by combining clarification, stabilization and sterile filtration in one continuous operation and eliminates the use of fining substances and filter material. The key to success in the clarification of wine is the membrane selection with regard to fouling behavior and pore size. Another important factor is the membrane pore diameter. In Table 1.1, a selection of critical wine compounds and their sizes is given.

Typically, MF membranes with pore diameters between 0.20 and 0.45 μm are used for white wine and between 0.45 and 0.65 μm for red wine filtration.

1.3.2.3 **Rejuvenation of Old Wine (*Lifting*)**

Aging might deteriorate the taste of wine vinified to be consumed young. A diafiltration process by RO can be applied to lift the wine by removing the negative

Table 1.1 Wine compounds and sizes [19–22].

Component	Size
Large suspended solids	50–200 μm
Yeast	1–8 μm
Bacteria	0.5–1.0 μm
Polysaccharides	50 000–200 000 D
Proteins, tannins, polymerized anthocyanins	10 000–100 000 D
Simple phenols, anthocyanics	500–2000 D
Ethanol, volatiles	20–60 D

aroma components causing the stale taste with the permeate. The wine is treated by an RO unit, which concentrates the wine slightly by removing mainly water, little alcohol and the negative aroma components. The volume lost by the permeate may be replaced by continuously adding demineralized water to avoid remineralization of the wine. The diafiltration process slightly decreases the alcohol content of the wine but improves the quality of the old wine so that it can be sold at a higher price or blended with younger wine. The advantage of this lifting process is that it does not change the structure and composition of the wine, while the effect of the alcohol reduction is minor.

1.3.2.4 **Alcohol Removal**

Similar to the beer market, the demand for low alcohol wine has increased in recent years. Initial trials in the production of alcohol-free wine can be dated back to 1908 when Jung [23] took out a patent on the thermal dealcoholization of wine. Presently, RO is used to remove ethanol and water, which have a relatively low molecular weight in comparison to the other compounds in wine, see Table 1.1, which passes through the membrane, while the larger compounds of the wine matrix are rejected. The process is similar to the dealcoholization of beer, see Section 1.3.1.3, and can be similarly subdivided in preconcentration, diafiltration and alcohol adjustment. Apart from producing alcohol-free wines, this technique can be used to adjust the alcohol level in wine. Wine makers often allow their grapes to ripen until an optimum rich flavor is achieved. At this stage, the grape juice often contains high sugar levels, which result in high alcohol content after fermentation. The alcoholic aroma, however, suppresses other flavors in the wine. By use of RO, the wine can be slightly concentrated by removing water and part of the alcohol. This allows wine makers to harvest grapes depending on the grape flavor ripeness and independent of their sugar contents.

1.3.3
Vinegar

The production of vinegar is an old process, referred to in the history as far back as Babylon 5000 BC. Over the years, the product has been developed according to nationality and tradition, resulting in widely different methods of production.

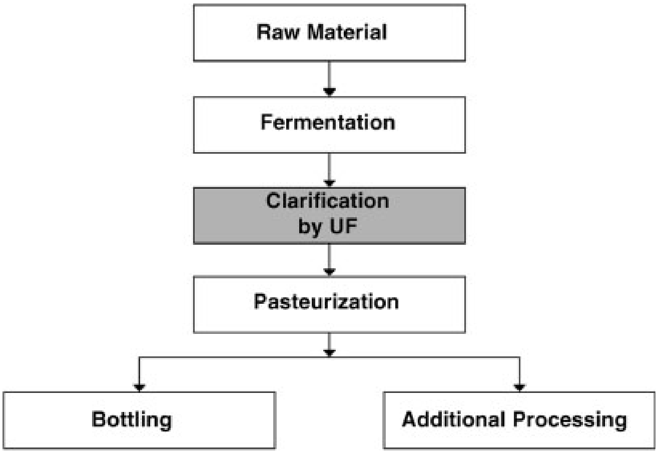

Figure 1.10 Membrane technology in vinegar production.

Vinegar is produced by an aerobe fermentation of bacteria (*genus acetobacter*) reacting on dilute solutions of ethyl alcohol such as cider, wine, fermented fruit juice or dilute distilled alcohol. The different raw materials (apples, grapes, malt, rice, etc.) each contribute to giving the vinegar its special aroma and flavor. In the traditional production process, vinegar requires a reaction time between 3 and 6 months for formation and sedimentation. For some vinegar types, fining agents are also necessary, which are added to the vinegar after fermentation. The final filtration takes place after storage in order to remove the colloids formed. In Figure 1.10, the production process of vinegar including membrane technology is shown.

1.3.3.1 Clarification of Vinegar

The clarification of vinegar by UF is positioned directly after the fermentation step and can substitute many steps in the traditional production. The vinegar fining by UF can be applied for a wide range of vinegar types and results in a vinegar product on the permeate side, that has similar color and organoleptic qualities to the original vinegar but no turbidity. Additionally, proteins, pectins, yeast, fungi, bacteria and colloids are removed and thus the filtration/sedimentation and the clarification are substituted and the storage time reduced. Hence, the permeate from the UF step can be directly pasteurized before bottling or additional processing. However, UF cannot give the vinegar the aroma, which is normally obtained during storage. This aroma is secured by the storage time in the wholesale and retail stages instead.

1.4 Fruit Juices

The general production flow in the fruit juice industry starts with grinding or crushing of the fruits into an optimal and uniform size of particles and then pressing

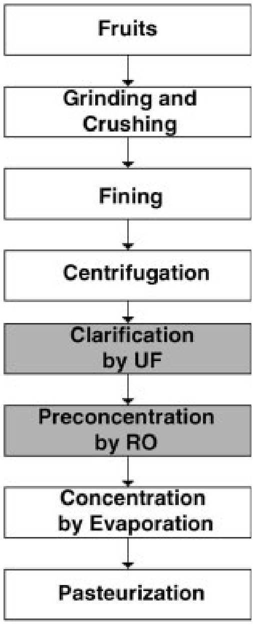

Figure 1.11 Membrane processes in fruit juice production.

out the fruit mash. The traditional fining process consists of long retention time in tanks followed by kieselguhr filtration and requires large amounts of enzymes, gelatin and other chemicals. After clarification/fining, the fruit juice is concentrated to reduce costs for transportation and storage. The common approach to concentrate fruit juice is by using an evaporator combined with an aroma-recovery unit concentrating the apple juice from originally 11–12 Brix to over 70 Brix. The concentrated fruit juice can then be optionally pasteurized before transportation. The general fruit juice production process including membrane processes is shown in Figure 1.11.

1.4.1 Fruit-Juice Clarification

The clarification of fruit juice, mainly apple but also grape, pineapple and orange juice by UF has proven to be an attractive substitute for the traditional fining and filtering process from an economic and qualitative point of view since the 1970s. The UF process removes the suspended solids and other high molecular solids and the filtered juice obtains a clarity and excellent quality, which has not previously been obtainable. Thus, the UF process substitutes the fining step in the traditional process. In order to achieve high yield, high capacity and excellent quality, an enzyme treatment and proper prefiltration must be carried out before the UF system is utilized. Until now, the industrial standard is to use polymeric and

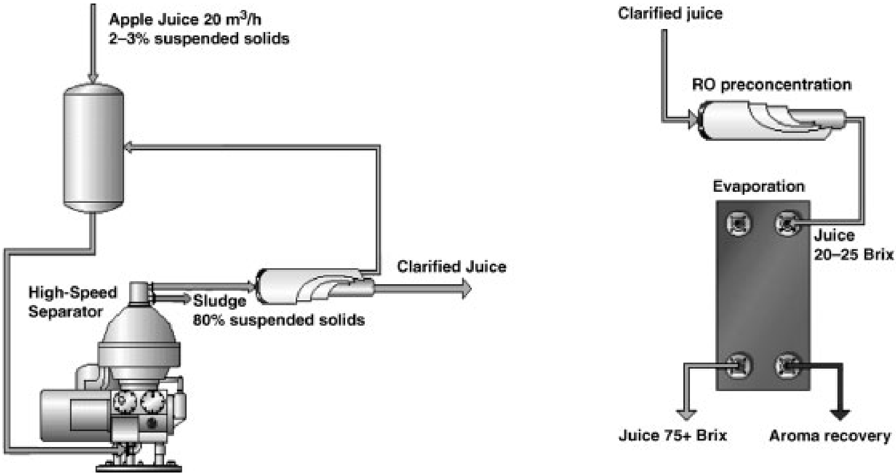

Figure 1.12 Juice clarification (*left*) and juice concentration (*right*).

ceramic tubular modules for the clarification of the juice. However, this module type is associated with low packing density and high membrane replacement costs. Furthermore, this process is commonly run in batch mode and diafiltration water has to be added in the final stage of the clarification to maximize the process yield. More recently, a new concept has been developed, which combines a high-speed separator with spiral-wound UF modules to overcome these limitations [17], see Figure 1.12.

1.4.2
Fruit-Juice Concentration

For the concentration of apple juice, the combination of RO and evaporation can provide an interesting process combination. RO as initial step can remove more than 50% of the water content prior to evaporation, while maintaining 98–99% of sugar and acid as well as 80–90% of volatile flavours in the concentrate, see Figure 1.12. By applying RO, concentration levels of 20–25 Brix can be achieved, while the subsequent evaporation can boost these levels to above 75 Brix. By applying this concept, only 7–9 kWh per m^3 fruit juice are required, which represents an energy saving of 60–75% compared to direct evaporation. Furthermore, the permeate from the RO unit can be recycled as process water.

1.5
Other Membrane Applications in the Food Industry

Apart from the production processes discussed above there are many other applications of membrane processes in the food industry. The first part of this section provides an overview of other key membrane applications in the food industry directly related to the product stream. The aim is not to give a complete listing of all possible applications but to document the diverse applicability of membranes in the food production. The second part of this section focuses on the membrane applications in the food industry related to process water and wastewater.

1.5.1 Membrane Processes as Production Step

The continuous improvement and proven use of membranes in the industry has established membrane technology as a molecular separation unit in a wide range of applications in the food industry. In Table 1.2, a selection of other established membrane applications in the food industry from the continuously growing list of applications is presented.

1.5.2 Membrane Processes for Water and Wastewater

The food industry is one of the largest water-using industries. In the industry, water is used as an ingredient, for initial and intermediate cleaning of the product, and as a key agent in the sanitation of the plant. Depending on the purpose, the requirements for the water vary significantly. The water used in the food industry can be generally classified into three types:

1) Process water – potable water used as an ingredient, is part of or in direct contact with the food.
2) Boiler and cooling water – soft water to avoid scaling and fouling of the cooling and heating equipment.
3) General purpose water – potable, often chlorinated water to rinse raw materials, prepared products, and equipment.

After usage, the different water streams have to be treated as for recycling or for discharge. Membrane processes play an important role in both the pretreatment of the water before usage and post-treatment of the water before recycling or discharge. In Table 1.3, some applications of membranes in the pretreatment and post-treatment of water are summarized.

1.6 Future Trends

It is predicted that membrane processes will continue to grow at average annual growth rates of 5–8% in the foreseeable future. Apart from the worldwide acceptance and use of membrane processes, the key drivers for this development can be related to three key areas, which will be discussed below.

Table 1.2 Selection of other membrane applications in the food industry.

Production step	Membrane processes	Comments
Animal blood plasma		
Concentration and purification of blood plasma	UF	Concentration up to 30% total solids (TS). Low molecular weight components are removed with permeate, for example, salts. Diafiltration can increase purity.
Recovery of peptides from blood-cell fraction	UF	Concentration of high molecular weight peptides in retentate.
Concentration of blood cell fraction	NF/RO	Volume reduction before spray drying.
Egg		
Whole-egg concentration	UF	Concentration up to 40–44% TS. Low molecular weight components are removed with permeate, for example, salts and sugars.
Egg-white concentration	UF	Concentration up to 20–21% TS. Purification by removing salts, glucose and other low molecular components with permeate.
	RO	Concentration up to approx. 24% TS. Product loss less than 0.05% of the solids in the feed.
Gelatin and gums		
Agar and agarose concentration	UF	Concentrate up to 2% TS (agarose) and 4–5% TS (agar). Removes more than 50% of water.
Carrageenan concentration	UF	Concentration up to 3–4% carrageenan. Purification and decolorization by removing low molecular carrageenan, salt, color and sugars.
Apple and citrus pectin concentration	UF	Concentration up to 4–7%. Purification by removing low molecular components, for example, salt and sugars.
Gelatin concentration	UF	Concentration of gelatin up to 25% depending on grade of hydrolytic conversion and bloom value.

Table 1.3 Process and wastewater.

Production step	Membrane processes	Comments
Water pre-treatment		
Desalination/softening of process, boiler and cooling	NF/RO	RO removes minerals, particles plus most of the bacteria and pyrogens.
Preparation of diafiltration water	RO	Diafiltration water is high-quality water in accordance with process water standards.
Pyrogen removal	UF, NF, RO	Membranes with MWCO less than 10 000 remove most pyrogen.
Water post-treatment		
Concentration of sugar water	RO	Concentration of sugars to reduce BOD. Water and sugars might be recycled in the process.
Concentration of food proteins	UF	Concentrated food proteins, for example from the washing step can be concentrated and reused.
Condensate polisher	UF, NF, RO	Concentration of the evaporator condensate, for example in case of carry-over with high BOD/COD.
Concentration of UF permeate	RO	UF permeate contains the low molecular components such as sugars and salts.
Biological treatment	MF/UF	Membrane bioreactor (MBR) with water removal by MF/UF.

1.6.1 New Applications of Membrane Processes

The development of new applications of the established membrane processes MF, UF, NF and RO will be driven by economical and environmental targets. An additional driver for membrane processes is the high growth rate of the market for functional foods, a segment in which membranes has a high potential. In Table 1.4, some of the most recent research trends on membrane applications for MF, UF, NF and RO in the food industry are summarized.

1.6.2 New Membrane Processes

In recent years, three new membrane processes have been developed for applications in the food industry. The processes and their potential in the food industry are shown in the following.

Table 1.4 New applications of MF, UF, NF and RO in the food industry [9, 24–26].

Application	Membrane processes
Dairy	
Concentration of whole and skim milk	RO
Partly demineralized WPC (baby food, special WPC products)	NF
Production of whey protein concentrates and isolates	UF
Defatting of whey for high protein WPC	MF
Standardization of the protein content in cheese milk	MF
Wine	
Preclarification of grape juice	MF/UF
Fruit juices	
Clarification of pulpy tropical fruit juices	MF
Concentration of tomato juice	MF and RO
Other applications	
Concentration of chicken blood plasma	
Filtration of extra virgin olive oil	MF/UF
Dry degumming of vegetable oil	UF/NF

1.6.2.1 **Pervaporation**

While the use of pervaporation for the dehydration of organic compounds is state-of-the-art in the industry, the use of pervaporation for the recovery of organic compounds from aqueous solutions is still limited. The key features of pervaporation are the mass transfer of components through a commonly non-porous polymeric or zeolite membrane combined with a phase change from liquid to vapor. The driving force of pervaporation is an activity difference between the feed and permeate side, while the mass transfer can be described based on the solution diffusion model. For the food industry, three potential applications have been under investigation:

1) Removal of alcohol from wine – a concept has been patented by Lee *et al.* [27] by using hydrophilic membranes and is carried out similarly to alcohol removal by RO.
2) Aroma recovery from raw material (fruit juices, beer, herbal and flowery extracts) – a commercial process has been developed and successfully tested at a fruit-juice concentrate company [28].
3) Recovery of aroma components during fermentation – pilot-scale experiments during the fermentation of wine demonstrated the feasibility to recover the complex wine aroma [29].

Pervaporation is, however, despite its successes and potentials, so far not established in the food industry.

1.6.2.2 **Electrodialysis**

Electrodialysis is used to separate uncharged molecules from charged molecules and is therefore used for, for example, the separation of salts, acids, and bases from aqueous solutions. The key advantage over other membrane processes is the selectivity of electrodialysis towards charged molecules without affecting uncharged molecules. The driving force of the process is based on a gradient of the electrical potential and the separation is achieved based on the Donnan exclusion mechanism using ion-exchange membranes. This mechanism enables electrodialysis to enrich and concentrate electrically charged ions from aqueous solutions. Potential applications in the food industry are, for example:

1) Tartaric stabilization of wine by removing potassium, calcium cations and tartrate anions – has been commercialized and is recognized by the International Wine office as "good practices" [30].
2) Lactic-acid recovery from fermentation broth – realized on a commercial scale to improve productivity.
3) Whey demineralization – effective demineralization after concentration by NF, used in the dairy industry.

The use of electrodialysis in some applications is well established in the food industry but the market share of electrodialysis is small compared to MF, UF, NF and RO.

1.6.2.3 Membrane Contactors – Osmotic Distillation

The concept of membrane contactors was developed during the 1970s, however, the commercialization of the Celgard Liqui-Cel® hollow-fiber module in 1993 led to the breakthrough of this technology. Membrane contactors are devices that achieve a gas/liquid or liquid/liquid mass transfer of one phase to another without dispersion by passing phases on both sides of a microporous membrane. Controlling the pressure difference between the two phases carefully, one of the phases can be immobilized in the pores of the membranes and an interface between the two phases can be established at the mouth of each pore. The driving force of the process is the concentration and/or pressure difference between the feed and the permeate side and mass transfer is based on distribution coefficients. Selected applications in the food industry are:

1) Bubble-free carbonation of soft-drinks – realized in the Pepsi bottling plant in West Virginia to carbonize about 424 l of beverage per minute.
2) CO_2 removal followed by nitrogenatation – used in the beer production to preserve the beer and to obtain a dense foam head.
3) Deoxygenized water – water for the dilution of high-gravity brewed beer [31].
4) Alcohol removal by osmotic distillation – has been tested for wine but not commercialized.
5) Concentration of fruit juices by osmotic distillation – achieves concentrations greater than 60 Brix.

Membrane contactors are currently one of the most active fields of membrane process and application development with many interesting spin-offs for the food industry.

1.6.3 Integrated Process Solutions: Synergies and Hybrid Processes

The development of integrated process solutions such as synergies and hybrid processes is one relatively unexplored area of process development. Until now, commonly only one unit of operation is considered to achieve a predefined separation. Combinations of conventional processes such as centrifugation, evaporation, liquid–liquid extraction and adsorption with membrane processes are rarely used, even though they might offer economical benefits to the end user. However, by integrating membrane processes in their product range, more and more system builders combine the conventional processes with membrane technology. Hence, it seems reasonable to assume that the economic benefits of such process combinations and a wider understanding within the industry of their potentials will support the long-term growth of membrane technology.

Overall, cross-flow membrane processes have established themselves in the food industry and many exciting developments will ensure their importance for the future.

Acknowledgements

The author would like to thank Dr Olga Santos for her valuable input to the section on the dairy industry and Prof. Gun Trägardh for the critical review of the manuscript. Further, the author would like to thank Hanne Jonck for proofreading the manuscript.

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