

An Overview of Membrane Technology in Dairy & Food Industry

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Abstract

Membrane technology is widely used in dairy and food industry. The membrane processes like microfiltration (0.1 to 10 μm); ultrafiltration (0.01 to 0.1 μm); nano-filtration (nano-voids or less than 1 nm) & reverse osmosis (0.001 – 0.0001 μm) are generally being used for pre-treatment, separation, fractionation, purification, recovery, standardization, clarification, concentration, partial or full demineralization, cold pasteurization, etc. which are owing to their property to produce high-value biological products, low temperature processing, retention & rejection selectivity, economy, and their environment friendly operation in comparison to conventional methods. Additionally, the knowledge of various factors related to the membrane operation and the feed like the nature of feed & foulants, configuration, requirement & material of membrane, density & size of pores, operational conditions like pressure, temperature, velocity & concentration factor, retention & rejection phenomenon, etc. are also the key components for the optimum application and diversification of membrane technology.

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List of Abbreviations

CP	Concentration polarization
CF	Concentration Factor
MWCO	Molecular weight cut off
kDa	Kilo Dalton
IUPAC	International Union of Pure and Applied Chemistry
ED	Electro-dialysis
MF	Micro-filtration
Nm	Nanometer
Mm	Micrometer
UF	Ultrafiltration
m ²	Meter square
m ³	Meter cube
A	Area
NF	Nanofiltration
%	Percentage
<	Less than
>	More than
RO	Reverse osmosis
TMP	Transmembrane pressure
EPS	Extracellular polymeric substances
°C	Degree centigrade
μ	Dynamic viscosity
ΔP	Pressure drop

S	Specific area per unit volume
T	Tortuosity of capillaries
Mg	milli gram
L	Litre
IgG	Immunoglobulin
N	Netwon
MMV	Maubois, Macquot and Vassal
NaCl	Sodium chloride
KCl	Potassium chloride
PPO	Polyphenol oxidase
°Brix	Degree brix
kWh	Kilo watt hour
HCl	Hydro chloric acid
NaOH	Sodium hydroxide
K	Potassium
Na	Sodium
Ca	Calcium
Mg	Magnesium
CM	Concentrated must
RCM	Rectified concentrated must
KHT	Potassium hydrogen tartrate
PAA	Polyacrylic acid
PEI	Polyethyleneimine
MS	Mass Spectroscopy
L	Leavo
D	Dextro
MD	Membrane Distillation
LEP	Liquid entry pressure

3.1 Introduction

Historical aspects of membrane technology are very vast. Membrane technology placed an important role to produce novel and functional food ingredients. A lot of laboratory work had been carried out on separation technology before its implementation at industrial scale in 1960s. Various studies were carried out to understand the separation phenomenon and its effectiveness on the industrial level process, started in the 18th century. Implementation of synthetic membrane at industrial level was started in 1960s and effective implementation was carried out in mid of 18th century. With the development of technology, various types of membrane were used for different application of purification and separation. Membrane technology is widely used in dairy and food applications since 1990s and it grows with a rate of 6-7% per year since last 5-7 years. Various membrane processes are based on requirements like ultrafiltration (for fractionation, partial demineralization), reverse osmosis (for concentration), nanofiltration (for demineralization), microfiltration (for cold pasteurization, separation of large molecules) are used. Membrane processing delivers numerous advantages in the processing of high-value biological products, like processing at desirable temperature and lower pressure, retains the nutritional quality of materials, economical operation, better yield, and environment friendly in comparison to conventional methods. From the last decades, the requirement of foods comprises of three main keys, like nutrition, dietetic, and health. Therefore, to formulate novel foods, membrane technology has an important role. Abbe Nolet coined the term osmosis in 1748, and described the permeation phenomenon of water [1]. Based on requirement, different types of materials were used to design different types of membrane modules. Bechhold prepared the membrane with different pore size by using nitrocellulose in 1907 [2]. The first significant application of the membrane for desalination of water was used at the end of World War 2. Loeb-Sourirajan transformed the use of the membrane process for desalination of water at industrial scale and developed first spiral wound modules from cellulose acetate based asymmetric/anisotropic reverse osmosis membranes having high-flux and defect-free [3]. From the last 2-3 decades, membrane technology is widely used for various applications, but its use in food industry increased significantly. A 25-30% of membrane technology turnover is covered only by food sector. Application of membrane technology in dairy sector is around 40% for different applications like, purification, separation, fractionation etc. for the production of novel food ingredients. Out of various dairy processes, milk protein standardization placed its contribution of around 10%. Other applications of membrane techniques are production

and clarification of beer, wine, and fruit juices to produce quality product. Several other applications of membrane techniques in dairy and food industry are discussed in detail in this chapter.

3.2 Terminology in Membrane Processing

3.2.1 Membrane

Membrane is a sieving process, which allows the selective permeation of solute molecules through it, based on its pore size and molecular weight cut off.

3.2.2 Permeate

The part of the feed that passes through the membrane and collected separately is called permeate. In some of the membrane processes permeate is the main desired product. For E.g. Water that is permeating from the reverse osmosis plant which meant for the purification of the water.

3.2.3 Retentive/Retentate

The part of the solution or feed that is not able to pass through the pores of membrane and obtained in the concentrated form is called the retentive/retentate. The term concentrate is also used in some of the literature.

3.2.4 Fouling

Fouling is deposition/accumulation of the feed material on the surface or in the pores of membrane, which results in decrease the overall performance of membrane during processing.

3.2.5 Concentration Polarization

It is the change in the concentration (either decrease or increase) of specific component from the feed at the boundary layer close to the surface of the membrane due to the gathering of solutes, which results in the formation layer of solutes adjacent to the surface of membrane. Due to the formation of the layer, a concentration gradient is set up b/w the solute layer and bulk solution. Due to setting up of steep concentration gradient, back transport of solutes to the bulk solution takes place.

3.2.6 Concentration Factor

It is the number of times the component of the feed gets increased in the final product or the retentate.

$$CF = \frac{C_r}{C_f}$$

Where: C_r is the final concentration of the component in the feed (retentate) and C_f is the initial concentration of the component in the feed.

3.2.7 Feed

It is the fluid or the solution which enters the membrane module or the plant for the separation or concentration or purification or fractionation.

3.2.8 Flux

Flux is the quantity of the permeate or the quantity of the component of the permeate that passes through per unit of the membrane area per unit of time.

3.2.9 Pore Size

It is an opening in the membrane which can of various sizes.

3.2.10 Molecular Weight Cut-Off

It is the lowest molecular weight at which minimum 90% of solute molecules of given molecular weight is retained by the membrane.

3.3 Types of Membrane

Morphology of the membrane is of two types, one is an anisotropic or asymmetric membrane and the other is an isotropic or symmetric membrane. Symmetrical membranes can be of the following types.

3.3.1 Microporous Membrane

The solid material which is having pores or voids is considered as the porous membrane. It is well known that all solid materials are capable of providing a porous medium. According to the International Union of Pure

and Applied Chemistry (IUPAC) classification of the membrane material is done based on their pore size. Membrane having pore size under 2 nm, falls under the category of microporous membrane. Pore size falls in the range of 2-50 nm comes under the category of mesoporous membrane, and from 50-1000 nm comes under the category of macroporous membrane [4]. By managing the pore size, pore volume can be maintained. There are two categories of porous solids, one is crystalline and another is amorphous. By estimating the chemical composition and behavior, physio-chemical properties of that specific material can be determined, thus the membrane properties largely depend upon several factors like, chemical and structural characteristics of that material and their pore characteristics. The microporous membrane has a similar function to the conventional filter. Particles with the largest size than the largest pores are not allowed to pass through it and are completely rejected. Particles larger than the smallest pore and smaller than the larger pore are partially rejected.

3.3.2 Nonporous, Dense Membrane

This membrane works on the principle of diffusion phenomenon mainly driven due to concentration, or electrical potential gradient. Based on the comparative (relative) transport rate, components can be separated. Effectiveness of separation largely depends on diffusion rate (diffusivity) and interaction with membrane material. Hence, on the basis of concentration difference, permeate can be separated using nonporous membrane.

3.3.3 Electrically Charged Membranes

The electrically charged membrane could be either be microporous or dense, but in most cases, they are very finely microporous, contains fixed positive or negative charge on the surface. Anion exchange membrane contains positive charge on the surface, while cation exchange membrane contains negative charge on the surface. When fluid passes through the membrane, opposite charge present in fluid binds to the membrane, and fluid of single charge can be obtained. In this case, separation takes place as the ions with a similar charge as that of the fixed ions are excluded by the membrane. Membrane efficiency largely affected by the concentration of ions and charge density. These membranes are used for processing electrolytic solutions in electro-dialysis.

3.3.4 Anisotropic Membranes (Asymmetrical)

In this type of membrane there is a difference in layered structures, porosity, and pore size over the whole membrane cross-section i.e. it is

unsymmetrical [5]. Asymmetric membranes contains a thin surface layer supported with a thick microporous layer. The thin layer performs the work of the separation and used as the selective layer. High permeate flux will be obtained in this type of membranes due to low thickness. Asymmetrical membranes, composite membranes and supported liquid membranes falls under the category of anisotropic membranes.

3.3.5 Ceramic, Metal and Liquid Membranes

With the development in membrane technology, use of non-conventional methods for membrane manufacturing and polymers as base materials increases significantly. To achieve the higher thermal stability and solvent resistance during process like ultrafiltration and microfiltration, ceramic membranes are used. For separation of gases like hydrogen, non-porous metal membranes (especially Palladium membranes) are used for effective separation of hydrogen from gaseous mixture. To support the liquid transport process, liquid films are comes under application.

3.4 Processes in Membrane Technology

3.4.1 Microfiltration (MF)

It is basically a filtration process which is driven by pressure for the separation of the fine particles, microorganisms and the emulsion droplets. The diameter of the separated particle ranges from 0.1 to 10 μm [6–8]. It is done under the pressure gradient of 1-3 bars. The wide range of the pore allows the separation of the versatile fields like virus, bacteria, aerosol and innumerable macromolecules from fluids. The membrane in MF is permeable to the fluid but retain the particles, which cause the separation. Microfiltration can also be used as pretreatment for Nano filtration or reverse osmosis [9].

3.4.2 Ultrafiltration (UF)

It is one of the membrane separation process in which the pore size of the membrane ranges from 1 to 100 nm (0.01 - 0.1 μm). Ultrafiltration has pore size between the Nano filtration and the Microfiltration. MF and UF membranes both have porous nature, but the structure of the UF membrane is always asymmetrical, as it contains small pore size and lower surface porosity, which results in development of higher hydrodynamic resistance.

Permeate flux of UF membranes can be calculated using Darcy's law and is given as

$$J = A(\Delta P)$$

Where:

A = Membrane permeability constant

ΔP = Trans membrane pressure

The value of the A depends upon porosity of membrane, thickness, and pore size. Calculated values of A for open and dense types of membranes are $5 \text{ m}^3/\text{m}^2.\text{day}.\text{bar}$ and $0.5 \text{ m}^3/\text{m}^2.\text{day}.\text{bar}$, respectively [10].

At lower trans-membrane pressure, flux varies linearly with trans-membrane pressure, and at higher values it is independent of pressure after achievement of threshold value [11].

3.4.3 Nano-Filtration (NF)

It is comparatively newly originated pressure driven separation process. NF falls between the UF and RO, in terms of rejection of molecular and ionic components on the basis of MWCO and pore size of membrane. NF membranes contains small pore size (nano-voids or $0.01 - 0.001 \mu\text{m}$) with larger free space [12–14] which are available for transportation of feed material. Modelling of nano-filtration process is hard to describe due to its complicated processing conditions and different separation parameters as compared to UF and RO [15, 16]. NF rejects multivalent ions (>99% rejection rate) and high molecular weight organic compounds with the lower rejection rate of monovalent ions (<70%).

3.4.4 Reverse Osmosis (RO)

Osmosis is a natural phenomenon, which is originated as early as 1748. According to this movement of the solvent takes place from lower to higher concentration, until achievement of equilibrium condition, as separated via semi permeable membrane [17]. Chemical potential difference is the major driving force for the transportation of water. The reverse osmosis ($0.001 - 0.0001 \mu\text{m}$) can be achieved by application of the pressure more than the osmotic pressure, which causes the flow of the water in the reverse direction i.e. from the solution with the higher solute concentration to the solution with the lower solute concentration.

3.5 Membrane Modules

Productivity of the membranes can be exploited by assembling it into adequate modules by the optimization of the process variables. The main objective of the membrane design is to realize the higher value for specific membrane area per unit volume, which results in higher flow rate. Geometry of membrane module largely affects the parameters like concentration polarization, fluid dynamics phenomenon, membrane performance, and thermal conditions during processing.

The design of the module should provide high rate of heat and mass transfer, it should minimize the concentration and polarization and polarization due to the temperature. It should ensure low fouling density. To overcome the problem of concentration polarization, higher feed velocity is desired, so that higher turbulence created which helps in the reduction of concentration polarization.

Different types of membrane modules have been suggested according to the requirements but among these following are the main modules [18] and their schematic configuration and mode of operation is presented in Figure 3.1.

- Shell-and-tube type modules for hollow fiber or tubular membranes;
- Spiral wound type for flat-sheet membranes; and
- Plate and frame modules type for flat-sheet membranes

Amongst above shell-and – tubular model (A) is widely studied and used because of its simplicity and easy manufacturing, and high surface area to volume ratio. The tubular and the hollow fiber membrane can operate in two types of the configuration. If the flow of the feed is from outside the fiber it is called as the outside-in configuration where permeate is received from the inside of the fiber. If the feed flows from the inside of the hollow fiber and the permeate is received from the outside of the fiber then it is called as the inside-out configuration. Due to the wider variability in pore size and channel diameter, different types of feed materials can be processed, even feed containing suspended particles (using Outside-in configuration). Main drawback of this type of modules is the lower flux rate and low processing life of membrane fibers [18, 19].

In case of the plate and frame (C) and spiral wound modules (B) flat sheet membranes can be assembled. These types of membranes are comparatively thin than the spiral wound membrane and that's why can provide

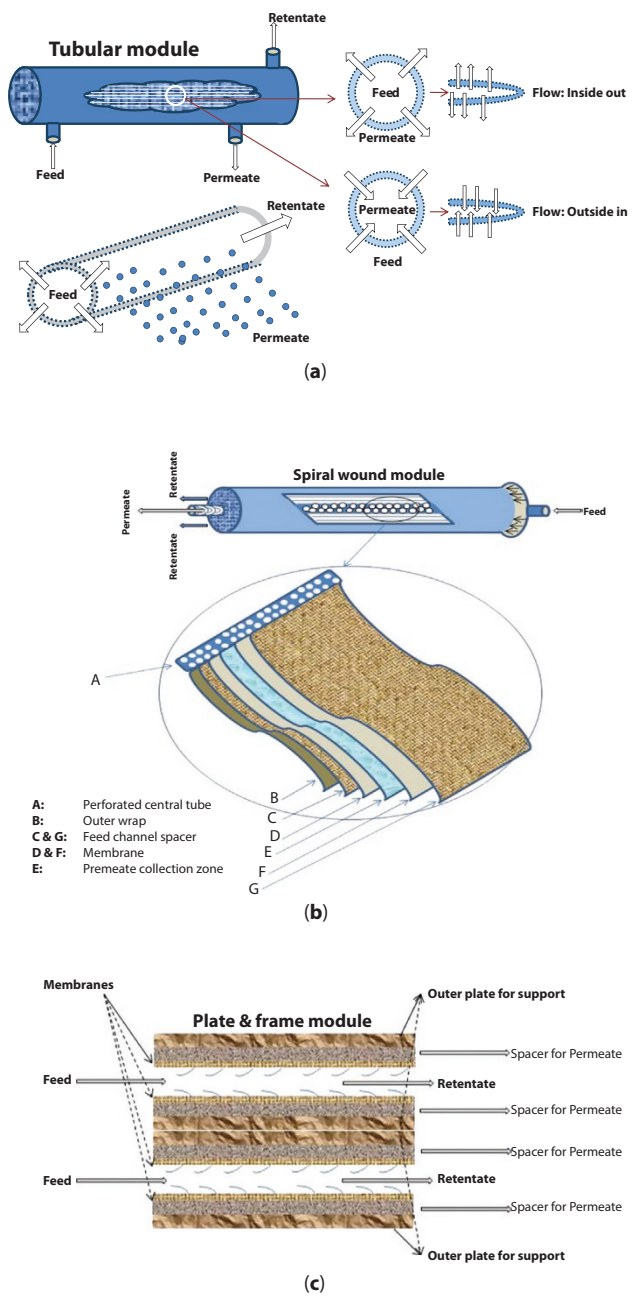


Figure 3.1 Schematic configuration and mode of operation of various type of membrane module (a) tubular module, (b) spiral wound module & (c) plate & frame module.

higher permeability with the requirement of porous support which provides the mechanical strength.

Plate and frame membrane has advantages such as it can provide higher tangential flow rate which in turn lowers the concentration and polarization and fouling effect and this type of membrane can be easily replaced. Low packing density and poor energy efficiency are some disadvantages of the plate and frame type of membrane [20–22].

3.6 Mechanism of Mass Transfer in Membrane Separation

In the field of novel technology, membrane processing has its place. The membrane has a significant means to uplift the growth of processing sectors due to its simplicity, efficiency, and economy. The membrane is a pressure-driven process, has potential application in clarification, concentration, fractionation, and molecular separation. Reduced permeate flux with processing time is one of the major problems which restricts the extensive use of membrane technology. This major occurrence is well-known as membrane fouling. Membrane fouling is the most serious and major problem in membrane processing, and also it is the key challenge for membrane manufacturers and researchers to overcome the fouling of the membrane. Fouling of membrane creates the obstacles like reduced mass transfer, higher processing time and cost, short life of the membrane, and increased cleaning time.

The reduced permeate flux corresponds to the pure water flux/pure solvent flux is due to two main reasons. First is the phenomenon of concentration polarization and another is membrane fouling.

3.6.1 Concentration Polarization (CP)

During membrane processing, due to the hydraulic transport fluid feed comes towards the membrane surface. On the basis of pore size and molecular weight cut off (MWCO), a part of the solvent goes to permeate along with or without some solutes. Along with permeate, a part of solutes moves towards the surface of membrane. Due to the gathering of solutes, a layer of solutes adjacent to the surface of membrane is formed. Due to the formation of the layer, a concentration gradient is set up b/w the solute layer and bulk solution. Due to setting up of steep concentration gradient, back transport of solutes to the bulk solution takes place. At the condition

of steady-state where the convective (towards the membrane) and diffusive (away from the membrane) transport balance each other, the concentration of solutes in the concentration polarization layer attained to the maximum. This maximum concentration is known as gel concentration. After the attainment of gel concentration permeate flux starts decreasing and becomes independent of transmembrane pressure (TMP) [23]. Concentration polarization largely depends upon operating conditions like local hydrodynamic and mass transport conditions [24]. Based on several assumptions like uniform CP layer and constant permeate flux, classical film theory (stagnant film model) explains the phenomenon of CP [25]. This theory is not applicable for cross-flow membrane filtration due to the reason that in this type there is a gradual increase in the CP layer with filtration channel. As in concentration polarization flux gradually decreases, due to this reason constant flux assumption also arises some significant errors in the modeling [26]. Due to these reasons, classical film theory fails to explain the CP phenomenon. Some efforts were also made by researchers to present the model using different numerical methods [27], but those were not so effective. The mass transport model will be discussed later in this chapter.

3.6.2 Membrane Fouling

Fouling of membrane is the major factor that affects the efficiency of membrane processing [28]. Concentration polarization is a time-dependent reversible phenomenon, while fouling is an irreversible phenomenon. As a result of fouling, flux decreased greatly in the early stage and slowly in the posterior stage. Fouling mainly arises due to the accumulation or adsorption of macromolecules like proteins, fat, colloidal particles, fibers, enzymatic residues, microorganisms, salts of inorganic origin, etc. on the surface of the membrane, or due to the precipitation of permeable/soluble solutes within the pores of the membrane due to overcrowding (as shown in Figure 3.2). As a result of precipitation and overcrowding resistance to the permeate flow increases. Due to increasing hydraulic resistance, a decrease in flux rate occurs at the same trans-membrane pressure (TMP). By increasing TMP, permeate flux may be invariable [29], but increases energy requirement. Trans-membrane pressure and permeate flux are the two major indicators for membrane fouling. There is a direct correlation between operation time and irreversible fouling fraction. To obtain the maximum permeate flux repeated chemical cleaning is required. Repeated chemical cleaning ultimately increases the processing cost and decreases the life of the membrane.

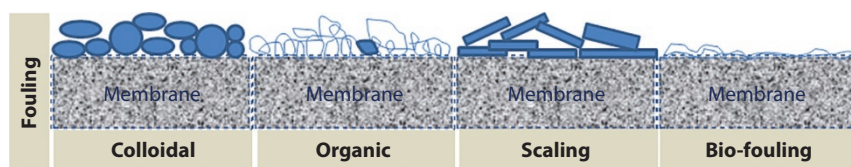


Figure 3.2 Types of membrane fouling (Reproduced from [45]).

Fouling is majorly categorized into back washable or non-back washable and reversible or irreversible. Removal of back-washable fouling takes place by employing the permeate flow in the reverse direction; but non-back washable fouling can't be removed by this technique. It required a chemical cleaning procedure to attain efficient cleaning and better efficiency of the process. Irreversible fouling cannot be removed by employing backwashing, flushing, chemical, or any other methods. Irreversible fouled membrane unable to restore their original flux.

3.6.3 Major Categories of Fouling

3.6.3.1 *Inorganic Fouling*

Inorganic fouling is majorly triggered due to the over-crowding of the inorganic materials. As a result of the gathering of inorganic materials, after attainment of the saturation concentration precipitation of the compounds occurs and the formation of scaling takes place. Ca^{2+} and Mg^{2+} are the major ions responsible for inorganic fouling [30–32].

3.6.3.2 *Organic Fouling*

Due to the accumulation of low molecular weight organic materials, clogging of membrane takes place. Accumulation of organic materials generally takes place on the internal portion of the membrane. By adopting a normal cleaning schedule, organic foulants can be removed. Mo and Huang [33] analyzed the chemical solution after cleaning. He found that the major components which are responsible for organic fouling are low molecular weight organic compounds and calcium.

3.6.3.3 *Colloidal Fouling*

The major limitation of pressure-driven membranes like, microfiltration, ultrafiltration, and reverse osmosis is fouling. Feed generally treated with these membranes contains colloids. Species having a particle size less than

5 μm , which remains stable in suspension or having a charge density like in proteins comes under the category of colloids. In the case of colloids, electro-static interaction plays an important role, which controls the rate of coagulation and diffusivity variation with concentration during diffusion of particles [34, 35]. The deposition of colloidal particles and adsorption of proteins on the surface depends on the interaction forces besides diffusion and hydrodynamics [36]. The rate of deposition of colloidal suspension on the membrane surface largely depends on the surface interaction. Variation in pH during UF treatment of colloidal suspension highly affect the efficiency of the UF process, due to the reason that variation in pH affect the charge density of protein and thus enhances the fouling phenomenon [37, 38]. In the UF of colloidal clay, deposition kinetic largely depends on the suspension salinity [39].

3.6.3.4 *Biological Fouling*

The development of undesirable microbial on the membrane surface is known as biofouling [40]. Raw water sources contain several microorganisms like bacteria, algae, and fungi. Due to the presence of appropriate nutrient growth of these occurs. In the RO system, the most severe problem is biofouling [41, 42]. In simple words, biofilm is the accumulation of microbial aggregates having attachment to the surface. Bacteria produce extracellular polymeric substances (EPS) and form a network of EPS, which results in the formation of biofilm. EPS generally contains polysaccharides, proteins, and nucleic acids [43]. By the application of hydrogen bonds, electrostatic forces, and London dispersion forces, EPS increases the adhesiveness and structural integrity of biofilm. Due to the excellent adhesive and elastic properties, it is difficult to remove the biofilms from the surface of membranes. The presence of Ca^{2+} and Mg^{2+} ions promotes the formation of bridges b/w negatively charged bacteria and the surface of the membrane [44].

To control the formation of biofilms, pretreatments of feed are necessary. Pre-treatments like application of MF to feed so that most microorganisms can be removed from the feed. Another method is the disinfection of feed using biocides or ultra-violet treatment.

3.7 Mechanism of Membrane Fouling

As shown in the flux - time curve (Figure 3.3) for the UF process. In portion I, flux rapidly drops, then followed by a gradual decrease in portion II and

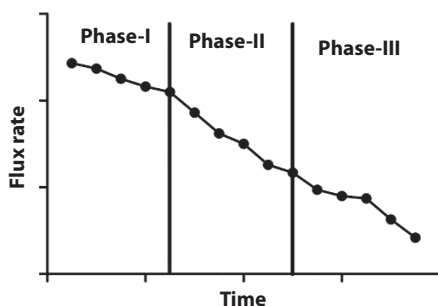


Figure 3.3 Presentation of three-stage flux decline (Reproduced from [50]).

then steady state is achieved in ending in portion III. A decrease in permeate flux of membrane is mainly due to two principal phenomena. The first phenomenon is the blockage of the pore, which increases the resistance towards the permeate flow and the second is the formation of the cake layer after the blockage of pores. The cake layer formation neighboring to the surface of membrane creates the hurdles in the flow of permeate.

At the starting of the membrane process, high permeate flux is obtained because membrane pores are open and clean. As processing time increases, blockage of pores starts due to the retention of particles in the pores. The retention of particles in the pores mainly depends on the size of particles, pore size, and shape of particles [46, 47]. Due to blockage of pores, flux declines rapidly because pore blockage is a fast process and less than one particle can contribute to the full blockage of the pore [48, 49]. Due to increasing resistance to permeate flow by the blockage of pores, particles start accumulates near the membrane surface, which results in the formation of the cake layer. Depending upon the thickness of the cake layer, the rate of permeate flux decreases, and with time decrease continuously.

3.8 Factors Influencing Fouling of Membrane

- (a) Properties of membrane: pore size, surface hydrophobicity, distribution of pore size, and type of membrane material.
- (b) Feed properties: Concentration and nature of feed, feed particle size.
- (c) Operational parameters: operating temperature and pressure, feed rate.

3.8.1 Properties of Membrane

Interaction of water with membrane largely depends on the composition of material and its surface chemistry. Based on the surface chemistry of membrane material, the wetting behavior of the membrane is decided. The presence of active groups enhances the hydrophilicity and charge density of the membrane thus, increases the wettability of the membrane. As a reason for high hydrophilicity, the membrane allows the formation of the water layer on it, so decreasing the probability of membrane fouling. While the absence of active groups enhances the hydrophobicity of the membrane, thus increases the wetting time of the membrane. Due to the lower wettability of the hydrophobic membrane, chances of fouling increase because particles present in an aqueous medium that are responsible for fouling are hydrophobic. Due to low interfacial free energy, these particles tend to form aggregates and enhance the fouling phenomenon. Transmembrane transport of particles and fouling of membrane largely depends upon the morphology of the membrane. Membrane morphology (surface roughness) depends on the factors like size, shape, and surface protuberance. It was observed that higher roughness provides the larger surface area to the foulants for the accumulation thus enhances the fouling, even in the presence of larger turbulence but lower effective shear rate [51, 52]. Permeate flux decreases with increasing the surface roughness [53]. The electrostatic charge of opposite natures of the membrane surface and colloidal particles enhances the membrane fouling. Due to higher magnitude of electrostatic interactions, the accumulation of colloidal particles takes place on the surface of the membrane thus enhances the rate of fouling. To reduce the fouling rate, membranes of opposite charges as of feed solution, so the generation of repulsive forces takes place which results in the decrease in membrane fouling [54].

3.8.2 Feed Properties

Properties of feed solution also affect the membrane performance by inducing fouling. Important feed properties which greatly affect the membrane performance are feed concentration, properties of particles, pH of the solution, the temperature of feed, ionic strength, and feed rate. By increasing the feed concentration fouling rate also increases due to greater accumulation of particles, as discussed in the pore block phenomenon. Larger particle size decreases the deposition but increases the cake formation results in the greater permeate flux. Particle geometry also influences the porosity of cake formation; particles with lower sphericity cake with higher porosity

will be obtained. The pH of the feed solution is an important factor that determines the performance of the membrane. Lower pH results in the conformational change in the protein, also the change in charge density; thus, increases the extent of fouling.

3.8.3 Operating Parameters

Temperature is an important parameter in membrane processing. Vyas, Bennett, and Marshall [55] investigated the effect of temperature on the membrane permeate flux. They found that higher permeate flux was obtained with lower fouling at higher operating temperatures. This might be due to the increasing diffusion rate of feed material. Cross-flow velocity is the apparent velocity of stream, feed corresponding to the surface of the membrane. An increase in crossflow velocity results in an increase of mass transfer rate increases in permeates flux with a lower fouling rate [56]. By increasing the cross-flow velocity, a higher mixing rate will be obtained this will results in the lowering of accumulation of feed particles and hence decreasing the effect of concentration polarization.

Transmembrane pressure (TMP) greatly affects the permeate flux. Higher TMP delivers higher permeate flux. But as processing time increases, concentration polarization increases. At the initial stage of concentration polarization, by increasing TMP, permeate flux increases. But when the gel concentration is attained, the increase in TMP has no positive effect on the permeate flux. At this stage, TMP has attained the value of critical pressure, and permeate flux is denoted with critical flux. It was observed that, problem of fouling can be solved when membrane operated under critical flux condition [57].

3.9 Prevention of Membrane Fouling

3.9.1 Type of Feed and Pre-Treatment

Interaction b/w solutes and membrane significantly contribute to reduction in flux due to the precipitation of colloidal calcium phosphate and adsorption of milk protein on the surface of UF membrane. By changing the pH of milk to lower side converts the colloidal form into soluble form, thus most part of calcium phosphate goes to permeate. On the other hand, increase in pH of milk made the colloidal calcium phosphate insoluble and gets precipitated on the membrane surface, thus contribute to fouling. Protein also carries the high charge density. By changing the pH of feed

containing protein away from their isoelectric points increases the dispersion of proteins and thus lower chances of fouling [58–60].

3.9.2 Operating Parameters

For efficient membrane operation, maximum permeate flux should be obtained from the given area of membrane. Permeate flux depends upon several parameters like feed temperature, feed composition, operating pressure, pH and ionic strength of feed.

3.9.2.1 Operating Pressure

As discussed earlier in concentration polarization, as pressure increases permeate flux increases until gel concentration achieved. At the stage of gel concentration flux becomes independent of applied pressure. This pressure is known as critical pressure and flux is known as critical flux [61, 62]. At this stage, increase in flux velocity is more effective than increasing pressure.

3.9.2.2 Operating Temperature

In UF processing of milk, flux increases with increase in feed temperature. It was observed that by increasing temperature of milk from 10 to 50 °C, flux increases by 3.5 times. Increase in permeate flux is due to higher diffusivity and lower viscosity of milk at higher temperature [63]. UF operation at higher temperature enhances the rate of fouling due to the precipitation of colloidal calcium phosphate [64].

3.9.2.3 Feed Velocity

Rate of fouling decreases as flow rate increases. By increasing flow rate higher turbulence occurs, as a result of which deposited materials flows continuously into permeate, hydraulic resistance created by fouling layer is reduced. Increasing flow velocity is more effective than increasing pressure [65].

3.10 Mass Transfer Model for Filtration Process in Absence of Fouling

Mass transfer through membrane can be classified under two categories in the situation, where fouling is absent. First type is diffusion through dense membrane which is independent of membrane structure and obey Fick's Law of Diffusion and 2nd is the diffusion through porous membrane (Figure 3.4).

3.10.1 Diffusion Theory Through Dense Membrane

It consists of five process, which depends on each other, these are as -

- Diffusion of the solute molecules through the liquid layer of the feed phase on feed side of membrane.
- Solute molecules of feed solution reach to the surface of membrane from feed side (i.e. upstream).
- Diffusion of soluble particles through the membrane matrix occurs.
- On downstream of membrane, desorption phenomenon occurs. Solute molecules get desorbed from the membrane and come on the downstream surface.
- From the boundary layer, diffusion of soluble molecules on permeate side occurs.

Under steady state condition, diffusive flux can be explained by Fick's first law. According to Fick's first law, flux is directly proportional to the concentration gradient [66].

$$\begin{aligned} \text{i.e.} \quad J &\propto (dC/dZ) \\ J &= -D (dC/dZ) \end{aligned}$$

Where, J = Rate of transfer of permeate flux per unit area of membrane;
 C = Concentration of diffusing materials & Z = Space co-ordinate normal to surface.

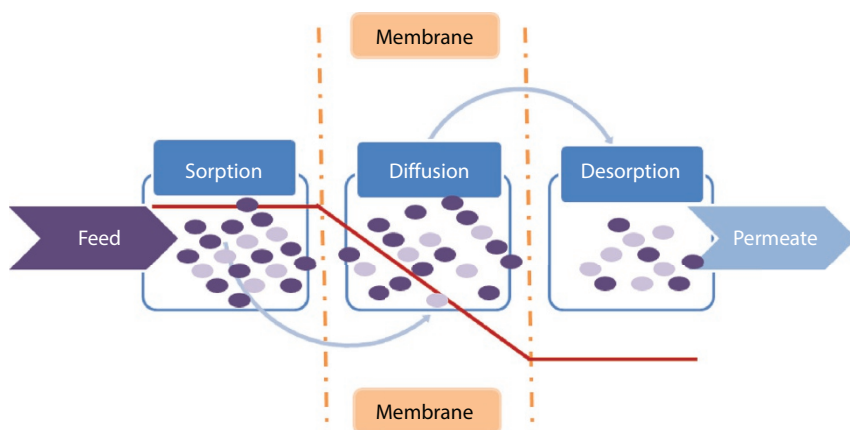


Figure 3.4 Mass transfer through dense membrane (Reproduced from [67]).

3.10.2 Transfer Through Porous Membrane - Convective Transfer - Pore Flow Model

Flow through capillary tubes can be effectively described using pore flow model in which pressure assisted convective flow occurs. In membranes like UF and MF, selective rejection of molecules occurs based on the size of molecules and pore size of membrane. Permeability of molecules through porous membrane can be described in two ways-

- (a) Arrangement of particles in the membrane close to spherical, in this situation Carman - Kozney equation can be applied [68].
- (b) In another approach, differential momentum equation is effectively used to describe the laminar fluid flow through capillaries and Hagen - Poiseuille equation is used to describe the average convective velocity through porous membrane [69, 70].

3.11 Application of the Membrane Technology in Dairy Industry

Dairy industry is the important part of the food industry, which provides the number of nutritionally rich products for the human consumption. Until now various technological advances have simplified the manufacturing of the various dairy products improving its overall quality, acceptability and economic output. Membrane technology is one of that and due to it various processes in the dairy industry are now simplified. It focuses on the environment friendly manner and the cost effectiveness which is must in the dairy industry for various useful processes. Here we can divide the application of the Membrane technology under its four main processes, which are microfiltration, ultrafiltration, nano filtration and finally reverse osmosis.

3.11.1 Microfiltration

3.11.1.1 Waste Water Processing

MF is used in the Dairy industry for the purification of the wastewater so that the load of the polluting components in the wastewater can be decreased up to the permissible level and also the valuable components

from it can be also recovered. We can take the example of the fat rich dairy production where the presence of the fats and oil in the wastewater creates several problems in its biological treatments. Their presence in the wastewater increases the overall processing cost of effluent treatment plant like for aeration and the sludge disposal. In contrary in the case of the MF treatment of this wastewater with 0.2 μm ceramic membrane have seen to reduce the initial chemical oxygen demand from 5000 to 10000 mg/L to less than 250 mg/L. The obtained permeate from this separation can be mixed with the water having low to medium contamination and which later can be subjected to the biological treatment. Retentate produced from MF can be further processed for the production of the soap [71].

3.11.1.2 *Production of the Protein Concentrate*

Due to the precise pore size of the MF membrane and processing at lower temperature, fat and bacteria can be efficiently removed from the feed, which can be further used for production of the high protein products like, protein concentrates and isolates without affecting the desirable properties of final products [72]. Pre-treatment of whey for the production of whey protein concentrate can efficiently remove the residual fat present in whey, which further helps in the enhancement of foaming properties [73].

3.11.1.3 *Isolation*

Immunoglobulin (IgG) can also be isolated from the colostrum whey with the help of the MF. Treatment of the colostrum with (0.1 μm) MF membranes, obtained from the different type of the species can be efficiently used to recover IgG upto 80%. The obtained micro filtered liquid (permeate) named serocolostrum which is free from fat and casein proteins [74].

3.11.1.4 *Separation of Micellar Casein from the Milk*

Concentrated micellar caseins can obtain from both full fat milk and skimmed milk, which can account up to 95% of the total protein. This type of the high casein retentate can be obtained with the help of the microfiltration process along with the diafiltration. When these micellar casein are concentrated, permeate obtained from this process contains native whey proteins. The obtained native whey is microbiologically sterile in nature and almost resembles to the sweet cheese whey [75].

3.11.1.5 *Pretreatment of the Cheese Milk*

MF has shown increase in the cheese firmness and decrease in the coagulation time [76, 77]. The reduction of need to add additives like calcium chloride have also noticed with enabling the stronger heat treatment of the cheese milk [78]. With the standardization of the milk protein level with the MF, quality attributes of cheese can be enhanced [79]. Due to standardized protein level, rennet coagulation time can be optimized and the obtained coagulum will be rigid in nature. MF pre-treatment increased the hardness of cheese (around 40%) as measured using instron universal testing machine [80]. The recoveries of casein and fat in cheese are observed to be increased reducing their loss in the whey. The yield of cheese shown to be increased by 2-4% as a result of increase in the casein content [81].

3.11.2 **Ultrafiltration**

3.11.2.1 *Enzyme Recovery and Concentration*

Ultrafiltration is widely used for the recovery of the enzymes [82]. It is less expensive than the other processes and it also known to prevent the loss of the enzyme activity. It is widely used for the concentration and purification of the protease enzyme [83] showed the possibility of the *Pseudomonas fluorescens* lipase purification by using UF capillary membranes. Separation of the species from the aqueous solution on the basis of size shape and the charge is possible with the UF [84].

3.11.2.2 *Cheese Manufacturing*

UF is used to pre-concentrate the milk before cheese making which provide the benefits such as increased yield of cheese, low energy consumption and volume reduction of the whey [85]. Maubois, Macquot and Vassal in 1969 [86] developed the use of UF for the manufacturing of the cheese. The method is therefore recognized as MMV process. For the manufacture of the lactic acid cheese varieties like Quarg, cream cheese, mascarpone, and *fromages frais* in many plants UF has replaced filtration cloths or centrifugal separators [87]. Cheese manufactured by the UF from fully concentrated milk with the by using mesophilic starter cultures have shown retardation in ripening as compared to the cheese manufactured by the traditional method [88].

3.11.3 Nanofiltration

Demineralization of the whey increased its nutritional value [89]. Nanofiltration is alternative to evaporation and electro-dialysis, which is meant for the demineralization of the whey [90]. NF membrane gives high permeability to the monovalent salts (NaCl, KCl) along with very low permeability to the organic compounds.

NF provides advantage over evaporation and electro dialysis that it pre-form the concentration and demineralization simultaneously. NF results in reduction in cost of energy, wastewater treatment and total cost. The sweet Gouda whey demineralized by NF in respect of the monovalent ions is comparable with the whey demineralized by employing Electro dialysis.

3.11.4 Reverse Osmosis

Concentration of the milk is done in many cases for increasing the shelf life and also concentration results in reduction in the cost of packaging, storage and transportation of milk and milk products. For these purposes, various types of heat exchangers and falling film evaporators are used. These techniques of concentration result in the change in the composition, nutritional properties, rheological properties and heat stability due to the high processing temperature [91]. Increase in the output of the cheese has observed by using UF and RO as a method for pre-concentration [92].

In the dairy industry, RO membrane is used mostly as the concentration technique [93–96]. The main advantage offered by the RO in the dairy industry is reduced energy consumption than the conventional techniques.

3.12 Application of Membrane Technology in Food Industry

As the development in the field of novel technology increased, the use of membrane technology also increased in the dairy and food sectors. Various membrane processes are based on requirements like Ultrafiltration (for fractionation, partial demineralization), Reverse osmosis (for concentration), Nano-filtration (for demineralization), Micro-filtration (for cold pasteurization, separation of large molecules) are used.

Membrane processing delivers numerous advantages in the processing of high-value biological products, like processing at desirable temperature and lower pressure, retains the nutritional quality of materials, economical

operation, better yield, and environment friendly in comparison to conventional methods [97]. Because from the last decades, the requirement of foods comprises of three main keys, like nutrition, dietetic, and health. Therefore, to formulate novel foods, membrane technology has an important role. Every method also has its drawbacks, like limited concentration of products, problems like fouling, and concentration polarization which leads to the inefficient separation of molecules and decrease in permeate flux.

3.12.1 Beverages

Membrane operation is generally used in two or more combinations like sequential filtration of liquids using membranes of varying molecular weight cut off (MWCO), pre-treatments like heat treatment, enzymes, and post-treatments like evaporation, adjustment of pH in case of fruit juices, vegetable juices, and sugar solutions [98–100].

3.12.2 Clarification, Concentration, and Sterilization of Fruit Juices

Several variables like the maturity of the fruit, ripening index, climate, and natural variations affects the composition and processing of fruit juices [101]. Clarification of fruit juices is one of the major challenges. In traditional methods, enzymes are used for clarification purposes; but time and labor requirement is high in this process. Membrane technology using ultrafiltration membrane has several advantages over traditional method; as it retains the enzymes based on their pore size like depectinization enzymes, as well as polyphenol oxidase (PPO). Due to the retention of the enzyme, mainly pectinase less amount of enzyme is required in the process; ultimately reducing the production cost. Preservation of juices is also a major challenge; because preservation by heat treatment causes the problem of haziness in the juices. To avoid such types of problems micro-filtration for cold sterilization of juices can be used.

Juices produced by traditional methods and membranes are almost similar in composition. Heatherbell *et al.* [102] observed that the unpasteurized bottled juice from UF had a superior quality to traditional and UF canned juice; but the problem of sedimentation during storage. Rwabazizi and Wrolstad, [103] found a 55% loss of anthocyanin in UF strawberry clarified juice using 10 kDa membrane; which was quite higher than the traditional filtration method. Drake and Nelson [104] observed lower

turbidity and 5% higher total soluble solids in UF-treated apple juices than the conventional filtration method.

3.12.3 Concentration, De-Acidification, and Demineralization of Juices

To reduce the cost of transportation and also to increase the shelf life of juices; concentration is done. The most common method is used for concentration is vacuum evaporation. But this can cause several changes in the fruit juices like loss of aroma, decrease in the nutritional quality of juice. To avoid such kinds of problems concentration using reverse osmosis (RO) is commercially used. Bengtsson [105] reported the high retention of aroma compounds in polyamide RO membrane. The concentration of apple juice can be achieved by 25° Brix employing reverse osmosis.

Juices of single strength extracted from orange, pineapple, lemon, and grapes are highly acidic with an acid concentration ranges from 1.0-1.2% [106, 107]. Due to high acidity, it is hard to use these juices in single strength or concentrated form for canning purposes [108, 109]. Sourness in juices depends on the ratio of total soluble sugar to the acid content. The concentration of soluble sugar remains almost the same in fruits but citric content varies with the variation in season. The ratio of total soluble sugar to the acid concentration is known as Brix/acid ratio. Brix/acid ratio for acceptable quality of grapes and orange juices are 10 to 11 and 13.5-14.5 respectively [110]. One method to adjust the Brix/acid ratio is the addition of natural sweet juice into sour juice, but this is not much effective method. Therefore, for effective de-acidification of juices, the electro-dialysis technique is generally used. Two stacks containing cation and anion exchangers (bipolar) are used with periodic reversal of voltage to prevent fouling problems. Total energy requirement varies from 0.02-0.1 kWh/equivalent with a current efficiency of 52 to 90%. The efficiency of electro-dialysis mainly depends upon the quality of juice [111, 112]. Due to the high fiber and nutrient content in native/original apple juice, demand is also high, but it is very challenging to produce high-quality cloudy juice. Due to the high fiber content in unclarified juice, a higher concentration of polyphenol oxidase and polyphenol is present. These cause undesirable changes, like enzymatic browning of the apple juice. The activity of polyphenol oxidase can be permanently suppressed by changing the pH of apple juice to 2 and then readjusted to the original pH [113, 114]. Earlier this was done using salts like hydrochloric acid (HCl) and caustic soda (NaOH). But the combination of acid and base leads to the formation of salts in the product and contributes inferior flavors to the product. To avoid this kind

of problem electro-dialysis technique is used nowadays. A bipolar electro-dialysis system with potassium hydroxide is used for the adjustment of pH of unclarified/cloudy apple juice. By using electro-dialysis, pH of juice can be attained up to 2-3.5 so that the activity of polyphenol oxidase can be suppressed and then readjusted to the original pH [115, 116].

3.12.4 Demineralization of Sugar Syrup

Alkali and alkaline earth metals are highly melassigenic in nature. Due to this property, they prevent the crystallization of sugars by holding the sugar in molasses. Alkali metals exhibit a higher melassigenic effect than alkaline earth metals (i.e. $K > Na > Ca > Mg$). Ionized metal content in raw sugar beet or sugar cane juice is up to 3.5% [117–120]. The presence of these metal impurities inhibits the crystallization of sugar and causes fouling in the evaporator. To overcome this problem technologies like ion-exchange resins, synthetic resins, adsorbents, and membranes have been employed, but due to the short life cycle and higher processing cost, these technologies are not much used. Electro-dialysis an emerging technology for reducing ion concentration is generally employed for the demineralization of sugar syrups. A bipolar module is used for this process. The major problem of using electro-dialysis is the higher fouling of membrane modules caused by anionic organic materials which results in the un-appropriate cleaning of assembly, decreasing efficiency, and increasing the resistance of the membrane. The smooth operation of electro-dialysis requires energy about 1.10 kWh/kg of salt removed from the juice [121, 122]. The efficiency of this process varies from 40-45%, which largely depends on the initial quality of juice [123].

3.12.5 Manufacturing of Beverages Using Vegetable Proteins

Several vegetables and their derivatives are widely used for the manufacturing of beverages. Soybean extract called soya milk contains proteins, fat, and glucides as 47%, 24%, and 15% respectively. By employing UF and diafiltration, retentate can be obtained which is a concentrated source of protein (47-60%) and fat (24-34%). This type of retentate can be further processed for the manufacturing of protein hydrolysates; useful for sportsmen and also for the preparation of protein-enriched diets for the peoples having allergy from the parent or native proteins [124]. By employing a combination of membranes and different processing conditions, it is quite easy to separate/fractionate the desirable components from the raw materials. Peptides from wheat gluten hydrolysate can be fractionated based on their charge using acidic conditions and zirconium oxide UF membrane [125].

3.12.6 Rough Beer Clarification

Clarification is one of the most important steps in the manufacturing of beer. Filtration of rough beer is done to eliminate the residue of yeast and colloidal particles, which are mainly responsible for the haziness in beer. Clarification is generally done to provide biological stability and the reformation of the previous form into bright and clear form. By using standard filtration techniques, we can't achieve the superior quality of beer. To produce the superior quality of beer with the economic operation; MF is generally used at a lower temperature almost 0°C to obtain the optimum permeate flux rate [126, 127]. Rough beer clarification has an emerging market for the application of membrane technology. With the opportunities, it is also a challenge for the engineers to avoid the problems of fouling and improvement in the quality of permeate [128, 129], as the rate of permeate flux in MF is quite lower than that of dead-end filtration and also complicated cleaning schedule like enzymatic, alkaline, and oxidative cleaning; consume a lot of time for cleaning.

3.12.7 Preservation of Beer

To maintain the quality and microbiological stability of beer heat treatment is generally done. Flash pasteurization is generally done for the preservation of clarified beer. Some heat-induced flavors may produce during this process, which can be easily eliminated by the application of sterile filters [130]. Nowadays there is a huge demand for cold sterile beer (draught beer). So to meet the quality and market demand requirement, cold sterilization of beer employed MF is done. MF technique eliminates the process like dead-end filtration with cartridges and heat treatment [131, 132] due to some advantages like -

- a) Low operational temperature (0°C)
- b) Maintains the biological, colloidal, and microbiological quality of beer
- c) Economic operation
- d) Maintains the color, flavor, and aroma of beer.

3.12.8 Membrane Processing in the Wine Industry

In the wine manufacturing process, grapes must have their place to produce superior quality wine. Enrichment of must is done before the

fermentation process to overcome the reduced level of sugar. Traditionally this level is makeup by adding sucrose from different sources like beet and cane sugar, concentrated must (CM) of grapes, or rectified CM. Vacuum evaporation is generally used to produce concentrated must; but it has some drawbacks like loss of aroma and production of off-flavors [133]. To counter these types of phenomenon reverse osmosis is used for the concentration of must [134, 135]. If must rectification is considered there is the requirement of ion-exchange assembly, and this can be completely fulfilled by nano-filtration as proposed by Santos *et al.* [136] because nano-filtration can retain most of the sugar in the retentate and reject the acids in permeate from the grapes must. After the must concentration and rectification process, clarification of wine is an important step. Earlier wine clarification was done using diatomaceous-earth filtration, which is a discontinuous and time-consuming process. As there is the valorization of novel technology increases, this is replaced by tangential MF and UF. It has several advantages over conventional filtration in terms of process economy, time consumption, and process efficiency. Yeasts and suspended particles with colloidal nature are the major cause of turbidity in wine [137]. Serrano *et al.* [138] compared the efficiency of the clarification process by tangential MF and the traditional method. They found that tangential MF employed clarification wine had a lower amount of polysaccharide content. Polyphenols and polysaccharides are the major constituents that cause the fouling of organic membranes. Clarification of white wine using tangential MF retains higher amounts of polysaccharides and polyphenols in clarified white wine in comparison to clarified red wine [139, 140].

Another application of membrane technology in winemaking is tartaric stabilization using electro-dialysis. A natural constituent called Potassium hydrogen tartrate (KHT) present in grapes. As alcohol content increases, the solubility of KHT decreases. Due to super-saturation, precipitation of KHT occurs in bottles. To overcome this problem, earlier cold tartaric stabilization was done. This process consists of cooling, seeding, crystallization, and filtration using diatomaceous-earth. The main drawback of this process is that there is no control on the concentration of KHT and also the undesirable precipitation of polyphenols and polysaccharides occurs with the crystallization process. To overcome these types of problems electro-dialysis is done. The main advantage of this process is that there is precise control on the concentration of KHT and no unwanted precipitation of polysaccharides and polyphenols [141].

13.12.9 Membrane Processing in Fish, Poultry, and Gelatin Industry

Ultrafiltration (UF) technique is mainly used in fish industry to fractionate low molecular weight components. UF was applied to improve the bioactivity and fractionation of small peptides having molecular weight ($<7\text{kDa}$) of saithe protein hydrolysate by Chbeaud *et al.* [142]. Waste water originated from fish and poultry industries contains large amounts of small molecular weight compounds. To minimize the organic load, and increasing the recovery of by-products UF is used nowadays. Afonso and Borquez [143] used ceramic membrane of molecular weight cut off 15kDa to reduce the load (organic) of fish meal waste water. Results revealed that organic load was sufficiently reduced and higher recovery of valuable components from waste water.

3.13 Uses of Membrane Technology in Biotechnology

3.13.1 Purification of Proteins

Membrane processes based on poly-electrolytic films and polymer brushes as a support material are widely used in the separation and purification of biotechnological products. Based on the surface hydrophobicity, surface charge, pore size of membrane adsorption of proteins takes place [144]. The advantage of the membrane purification process is that it is a less time-consuming process. Besides this, the surface area used for the separation process is quite lower than that of the separation bed process; due to this reason, this process has a lower binding capacity than beds containing nanoparticles. To improve the separation process using membrane technology, modification based on polymeric films with the brush is done. The principle behind this is that in the presence of water polymers absorb water and by swelling increase in thickness takes place. Due to the increase in thickness binding capacity of the membrane increases, so the efficiency of purification and separation increases.

3.13.2 Purification of Antibody

Columns containing the costing of immobilized protein A and G are generally used for the purification of antibodies. Modified microporous membranes containing PAA (polyacrylic acid)/PEI (poly-ethyleneimine) films, small length peptides with antibodies were used by [145]. Antibodies

placed an important role in biotechnological therapy. The cost of separation and purification of antibodies is quite high. To optimize the processing time and cost membrane processing is used instead of column separation because it took a long time for processing. In the protein purification process immobilization of antibodies in membrane pores may affect the binding capacity and thus ultimately rate of reaction. Electrostatic immobilization of antibodies is unstable but provides higher binding capacity; whereas higher stability and lower binding capacity were seen in the case of covalent immobilization. To improve the efficiency of the process, the two-step immobilization method involves both electrostatic and covalent immobilization to produce a higher binding capacity and stability.

3.13.3 Controlled Protein Digestion - A Substrate for Mass Spectroscopy

Mass Spectroscopy (MS) is a potent technique to detect the proteins and their post-translational modifications. Peptides are the most important substrate for MS in comparison to proteins. The conversion of proteins into peptides is the most crucial step in MS analysis. Earlier, digestion employed enzymes like protease (trypsin) was generally used. The main drawback of this process is the uncontrolled digestion and due to the low concentration of enzymes, it restricts the self -digestion of protease [146]. Researchers made several efforts to develop the digestion process like polymeric microfluidic channels [147, 148] reactors with solid supports like monolith containing enzymes [149, 150] resins [151] and membranes [152]. Membranes thickness ranges from 10-200 μm provides an excellent surface for controlled protein digestion. By varying the residence time in membrane peptides with desirable size can be obtained by lessening or extending the residence time [153]. By reducing the residence time, better results of post-translational modification can be obtained using MS and better flexibility in protein regions can be obtained.

3.13.4 Enantiomer Isolation from Racemic Mixtures

A racemic mixture is the mixture of two enantiomers having a mirror image of each other. Most of the drugs contain enantiomers. One enantiomer may have the same and positive effect as of other enantiomer or have a different and negative effect. Therefore, it is important to separate, isolate, and identify the enantiomers. For separation of enantiomers from the racemic mixture, membranes of regenerated cellulose with chiral

L- proline - copper complexes were used by [154]. The chiral compound can form coordination compounds with different enantiomers based on their stereo-chemistry. In this ligands exchange, the proposed mechanism is generally used based on their different functional group having a varying affinity towards the formation of coordination compounds with the ligands and effective separation of the racemic mixture takes place. This method was applied on D - or L - Phe using the membrane separation technique. The results revealed that the membrane allows a higher permeation rate to D - Phe than L - Phe.

3.14 Membrane Distillation

Among the membrane processes, membrane distillation (MD) is an emerging and popular technology that is widely used as a separation technique nowadays. As distillation also explain the use of thermal conditions. Besides non-thermal and pressure-driven processes, membrane distillation is a thermally pressure-driven process generally used for the distillation of feed solution. In membrane, distillation water is the main component as a feed solution. In MD, one side of the membrane which is microporous and hydrophobic remain in contact with the feed solution. As a result of the temperature gradient, partial pressure gets generated and mass transfer occurs. Permeation of liquid molecules is restricted in MD. Due to the difference in vapor pressure vaporization of liquid molecules take place and the volatile components through micro-porous structure go into permeate side and collected in condensed form. MD is a major alternative to reverse osmosis and has potent application in the desalination of water. MD is more economical and simpler than the traditional desalination process. Due to lower operating pressure than reverse osmosis and lower energy requirements, energy sources like solar and medium mechanical energy sources can be used [155–158]. Majorly four configurations of MD are generally used (as shown in Figure 3.5) based on the recovery of permeate, these are (a) Direct contact MD (b) Air gap MD (c) Sweeping gas MD (d) Vacuum MD. There is the requirement of special types of membranes having optimum surface hydrophobicity, high thermal resistance, high porosity, and adequate liquid entry pressure (LEP). MD technology undergoes some issues like module design optimization, requisite of energy, and need for superior membrane [159–162].

MD has some emerging application like desalination of seawater, recovery of volatile acids from industrial wastes, manufacturing of (milli-Q,

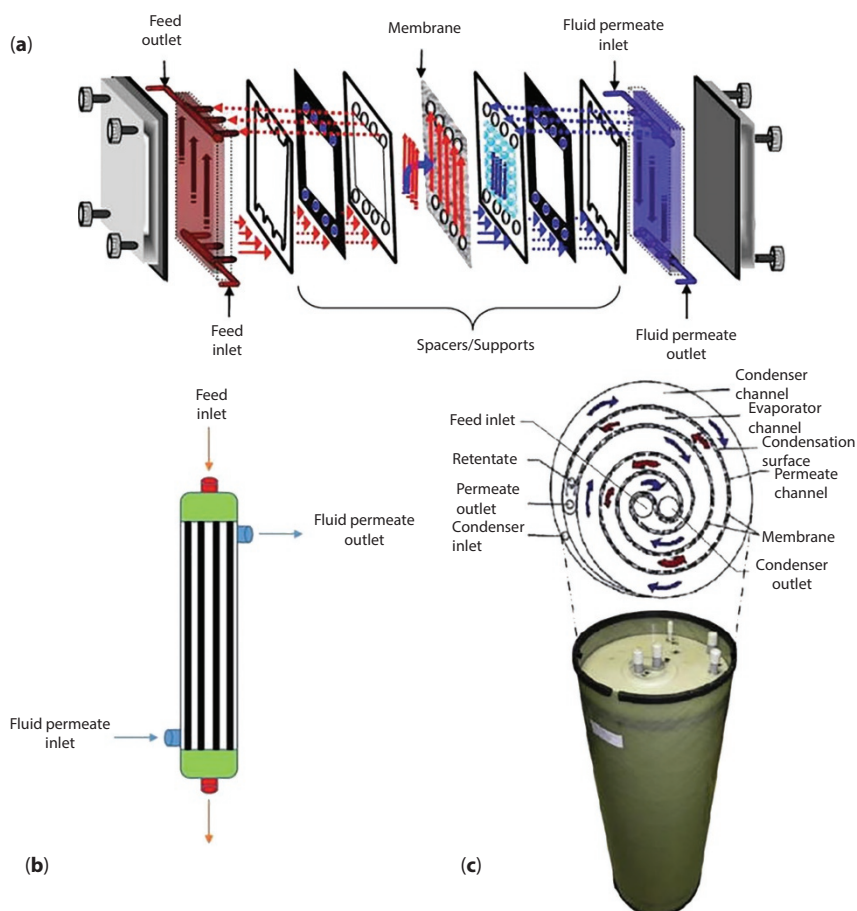


Figure 3.5 Different module of membrane distillation (Adopted from [163]), where a - Plate and Frame type, b - Capillary type, & c - Spiral wound type.

double distilled water), liquid food concentrate preparation (mandarin juice, sugar solution, paneer and cheese whey, apple juice concentration), alcoholic solution treatment, recovery of aroma compounds from (fruit juice and alcohol) fruit juice concentration, separation of a zeotropic mixtures, alcohol removal from fermented beverages, increasing concentration of alcohol, etc. Based on the treatment requirement different MD modules are used. Generally used MD modules are plate and frame, capillary, and spiral wound types.

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