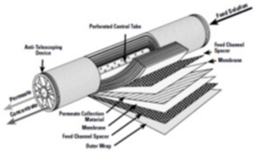
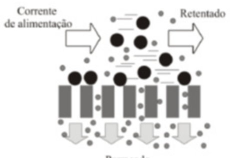
# PROCESSAMENTO POR MEMBRANAS

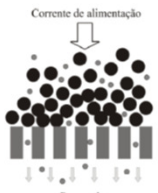
PROFA. DRA. CYNTHIA DITCHFIELD

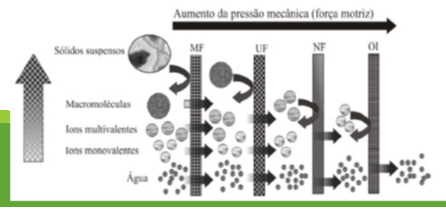


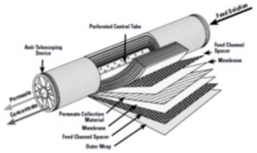
# Processamento por Membranas

- ➢Conceitos
- ➢Equipamentos
- ➢Aplicações



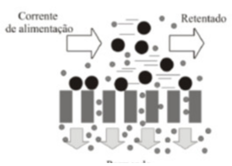



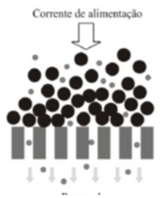



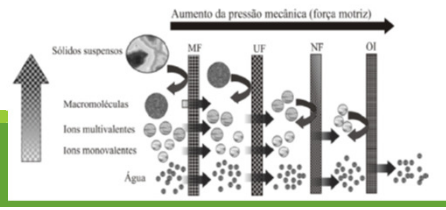


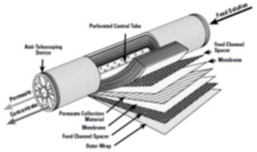
# Processamento por Membranas

- Primeiras membranas com fluxo para uso industrial por volta de 1950
- Técnica de separação de duas fases (Retentado e Permeado)
- Emprega uma membrana semipermeável que atua como barreira restringindo (total ou parcialmente) a passagem de espécies químicas presentes



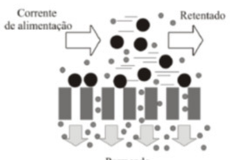



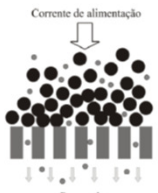


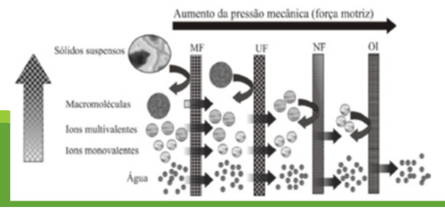
# Processamento por Membranas

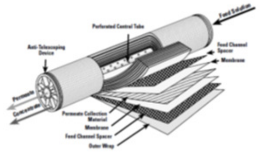
- Permite a concentração, fracionamento e/ou purificação de fluidos gerando duas correntes com composições diferentes

- Diferentes mecanismos realizam a separação como restrição de tamanho e difusividade seletiva

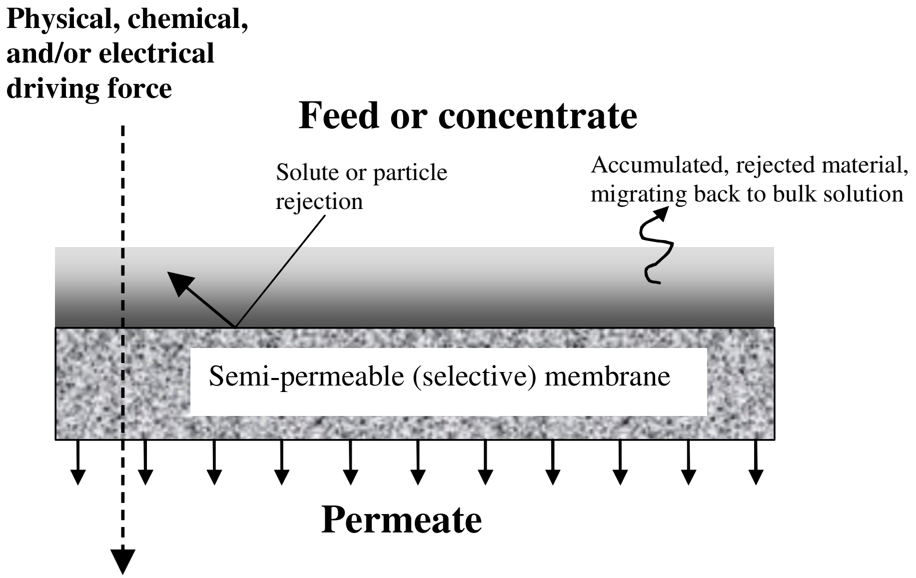


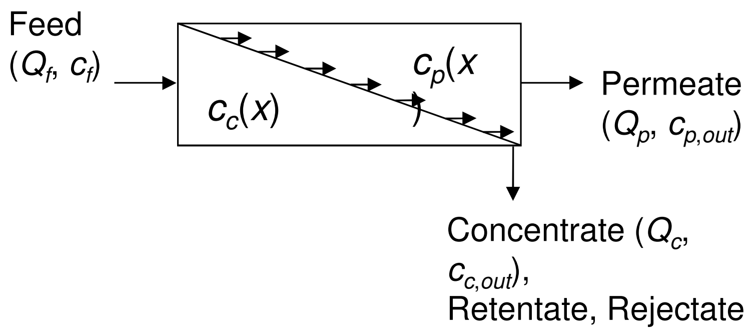



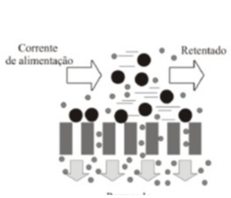



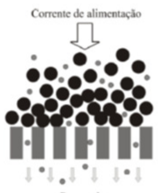


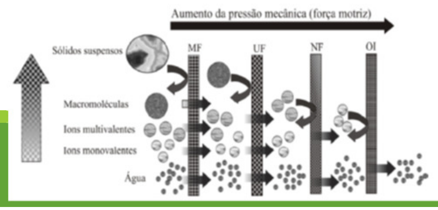
# Processamento por Membranas

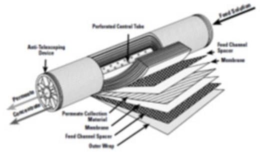


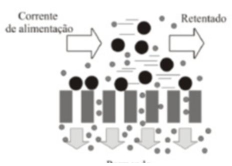



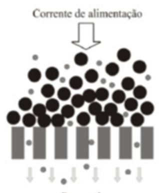



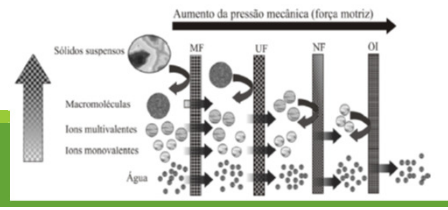


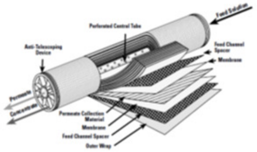
# Processamento por Membranas

- A separação não envolve a mudança de fase
- Temperaturas de processo em geral são baixas (4 a 50) °C
- Operação é relativamente simples e permite ampliação de escala



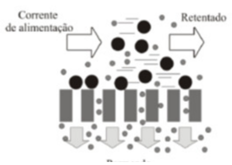



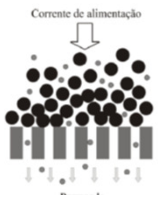


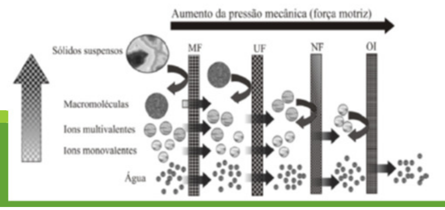
# Processamento por Membranas

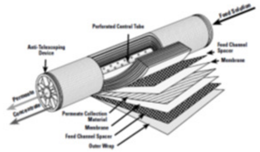
- Uso industrial difundido e a indústria atualmente demanda dos fabricantes de equipamentos membranas para a resolução de problemas específicos

- Os processos de filtração por membranas são classificados de acordo com a faixa de tamanhos que conseguem separar



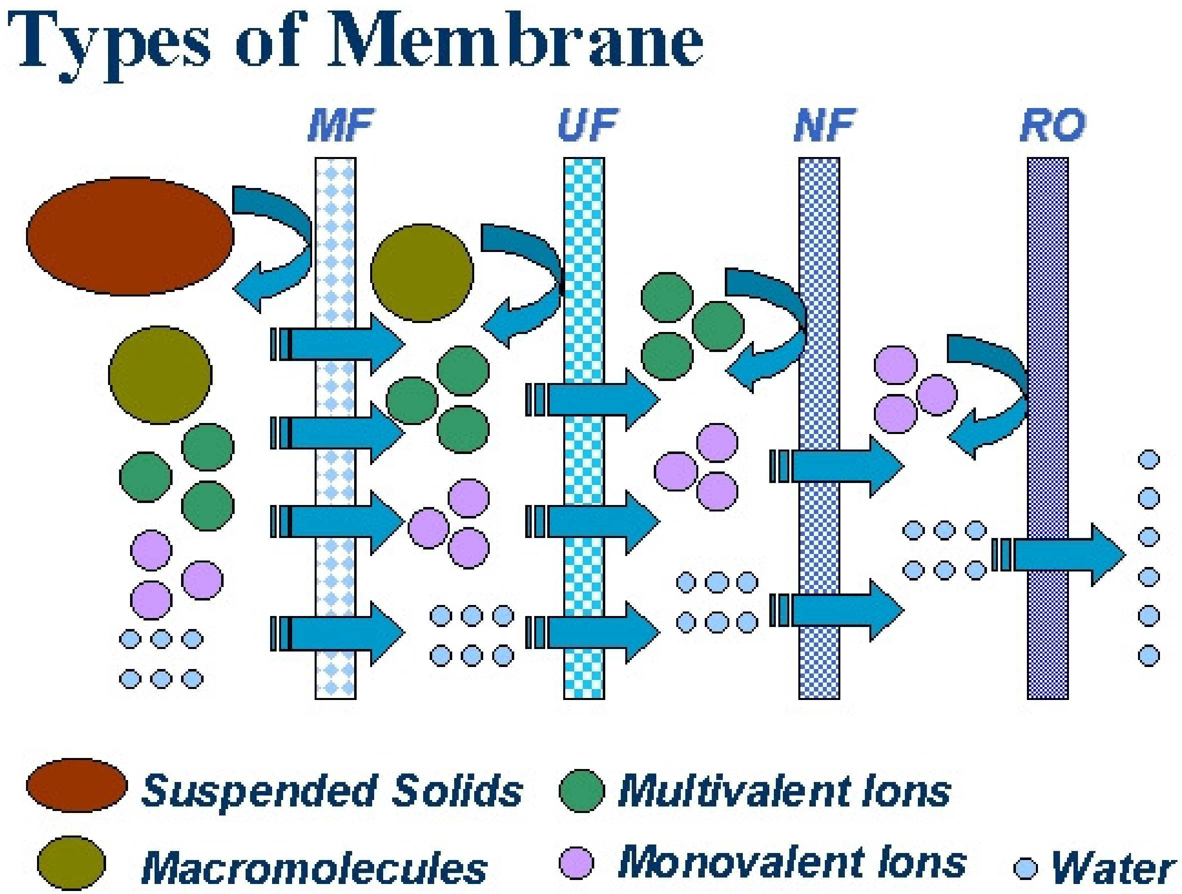



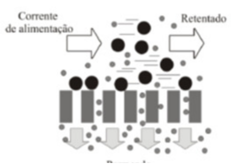



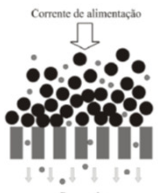


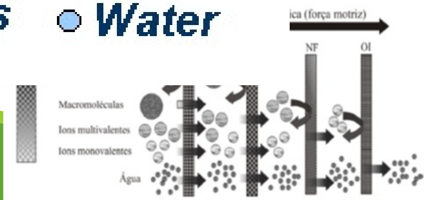
# Processamento por Membranas

- ➢Microfiltração (MF)
- ➢Ultrafiltração (UF)
- ➢Nanofiltração (NF)
- ➢Osmose Reversa ou Osmose Inversa (RO)

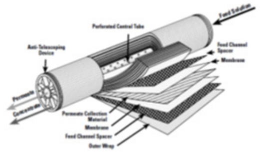


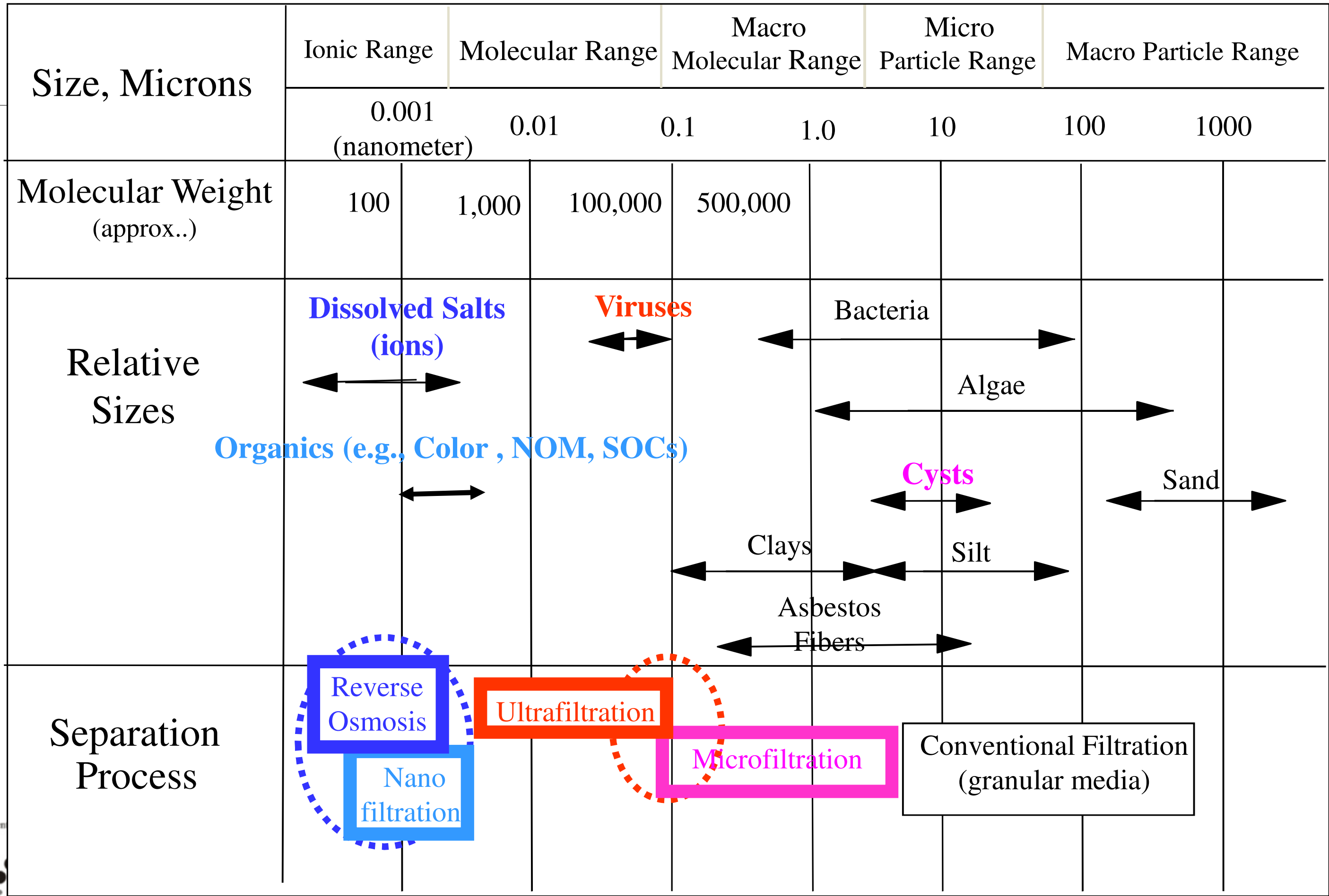



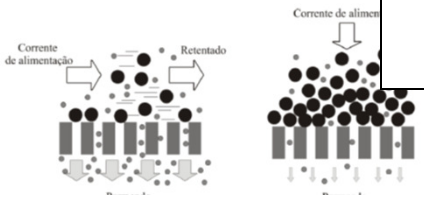



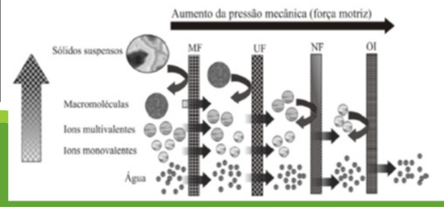



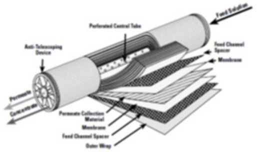
# Processamento por Membranas





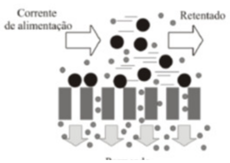



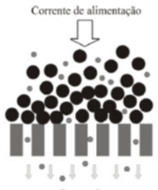



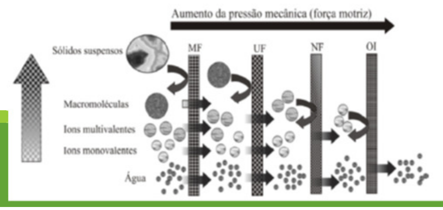


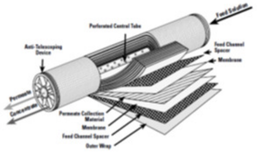
# Processamento por Membranas

- ➢ Microfiltração
  - ✓ Primeiro processo a ser desenvolvido
  - ✓ Largamente empregado
  - ✓ Tamanho de poro: (0,05-10) μm



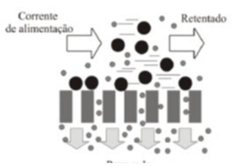



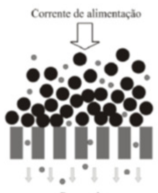


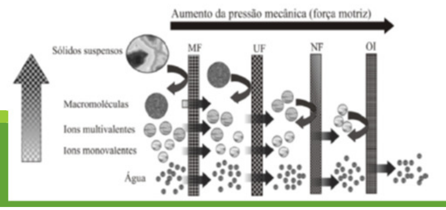
# Processamento por Membranas

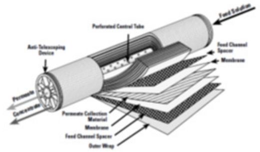
## ➢ Microfiltração

- ✓ Rejeita partículas na faixa entre (0,2-10) μm
- ✓ Consegue reter bactérias, células fragmentadas e coloides
- ✓ Massa molar ≥ 300.000 Daltons (1 Dalton (Da) = 1,660538921(73)×$10^{-27}$ kg)
- ✓ Força motriz: diferença de pressão



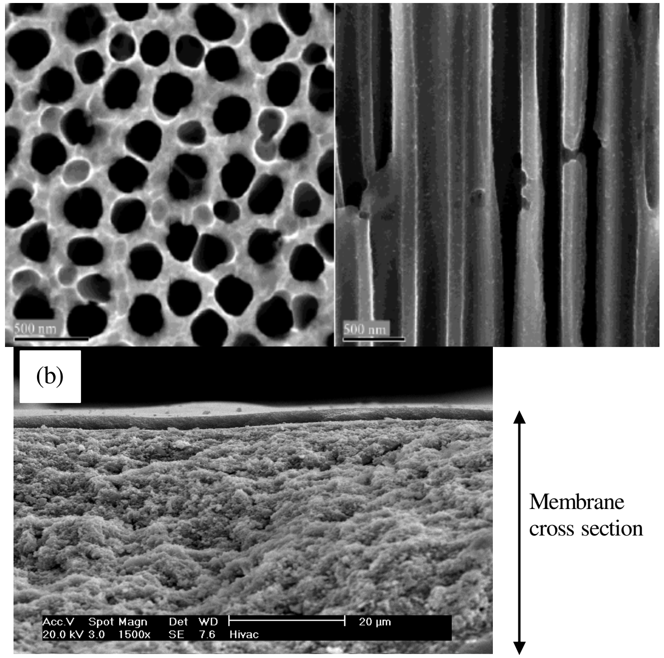



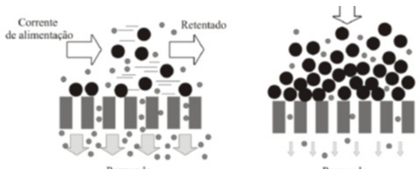



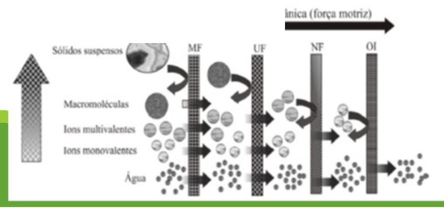


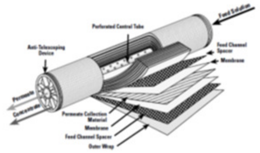
# Processamento por Membranas

- ➢ Microfiltração
  - ✓ Pressão de operação: (0,2-3,5) bar
  - ✓ Fluxo médio: > 200 L/m².h
  - ✓ Mecanismo de separação pela diferença de tamanho
  - ✓ Membrana porosa





# Processamento por Membranas

## ➢Microfiltração

✓Fluxo segue equação de Hagen-Poiseuille ou Kozeny-Carman

- Hagen-Poiseuille:

$$-\frac{\Delta P}{L} = \frac{32\mu v}{D^2}$$

Kozeny-Carman:

$$-\frac{\Delta P}{L} = \frac{k_1 \mu v (1-\in)^2 a_0^2}{\in^3}$$

Em que:

$\Delta p$ é a pressão ($N/m^2$)

v é a velocidade do fluido (m/s)

D é o diâmetro do poro (m)

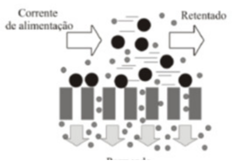
L é a espessura da membrana(m)

μ é a viscosidade (Pa.s)

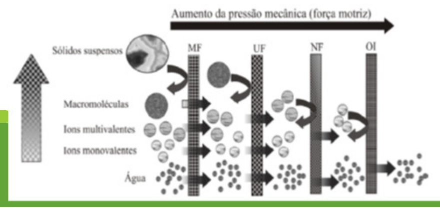
$k_1$ é uma constante para partículas de tamanho e forma definida

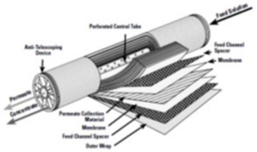
Є é a porosidade da membrana

$a_0$ é a área superficial específica expressa em $m^2$ / $m^3$



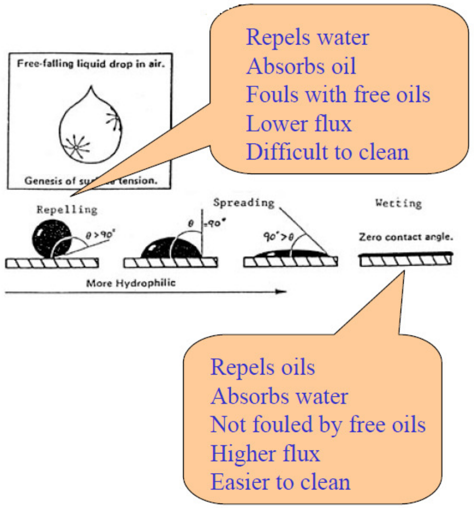






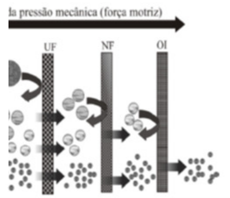
# Processamento por Membranas

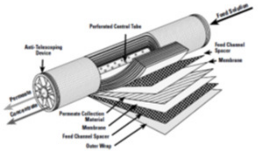
- ➢ Microfiltração




  - ✓ Membranas hidrofílicas x hidrofóbicas

  - ✓ Efeitos de adsorção entre a superfície da membrana e as espécies rejeitadas

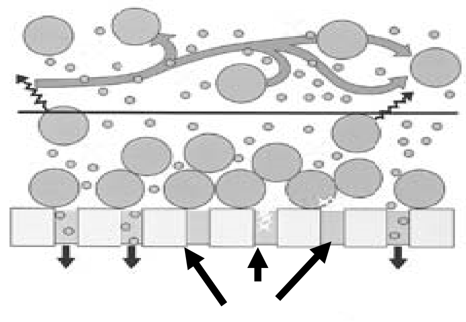





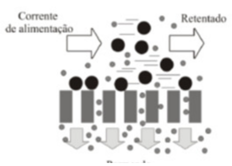
# Processamento por Membranas

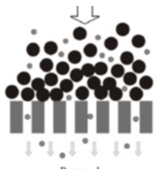
## ➢Microfiltração

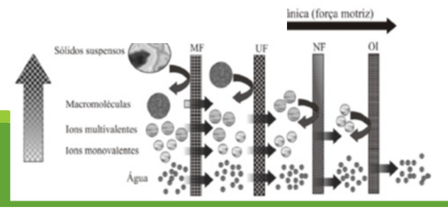
✓Colmatagem: entupimento dos poros da membrana e formação de gel (polarização por concentração) e incrustação  (“fouling”)

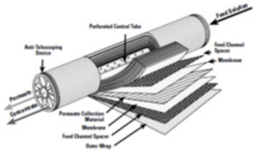



✓Operação em geral em temperatura ambiente



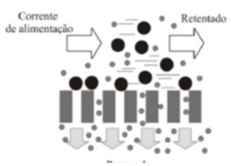



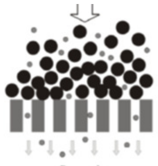


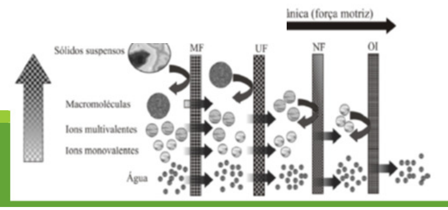


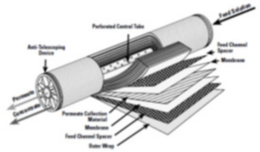
# Processamento por Membranas

- ➢Ultrafiltração
  - ✓Membranas microporosas
  - ✓Tamanho de poro: (1-50) nm
  - ✓Rejeita partículas na faixa entre (15-2000) Å



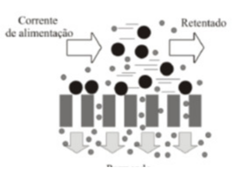


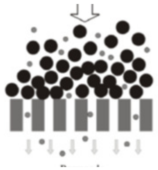


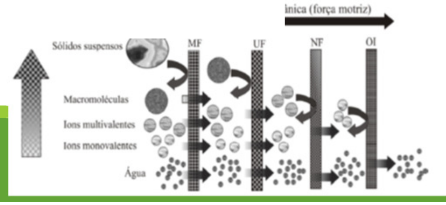
# Processamento por Membranas

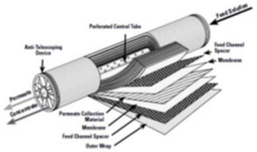
## ➢Ultrafiltração

- ✓Consegue reter polímeros, proteínas (enzimas) e coloides
- ✓Massa molar entre (5.000 até $5 \times 10^6$) Daltons
- ✓Força motriz: diferença de pressão



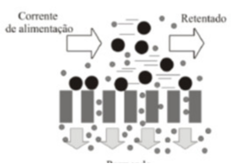


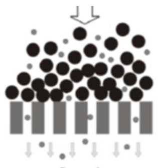


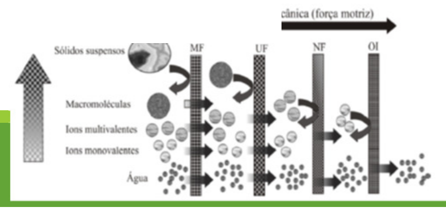
# Processamento por Membranas

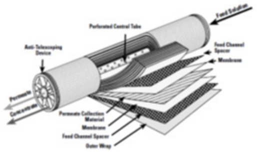
## ➢ Ultrafiltração

- ✓ Pressão de operação: (1-10) bar
- ✓ Fluxo médio: (5 – 200) L/m².h
- ✓ Mecanismo de separação pela diferença de tamanho (principal)
- ✓ Membrana porosa



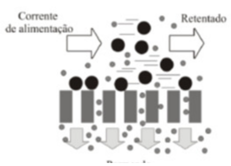


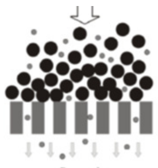


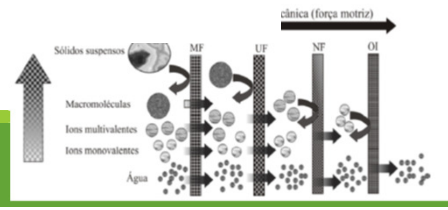
# Processamento por Membranas

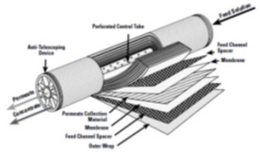
## ➢Ultrafiltração

- ✓Para pequenos tamanhos de poro fenômeno de difusão da solução
- ✓Desempenho é afetado por pressão, temperatura, agitação, concentração e íons presentes
- ✓Colmatagem é um problema sério





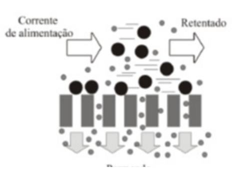


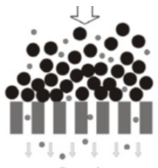
# Processamento por Membranas

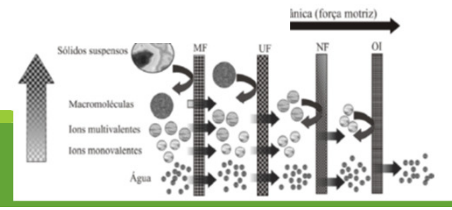
## ➢Ultrafiltração

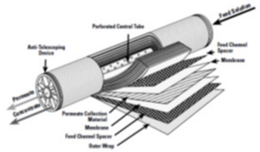
✓Parâmetro característico: diâmetro de corte nominal (*molecular weight cut-off*)

✓Valor da massa molar para o qual a membrana apresenta coeficiente de rejeição de 95 %







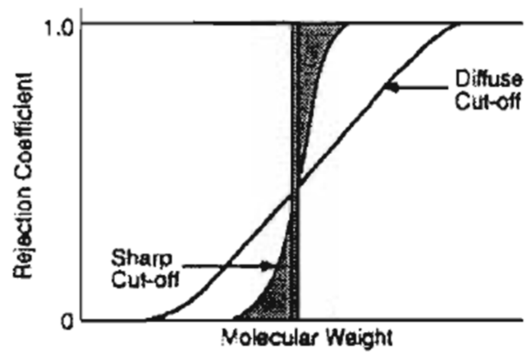
# Processamento por Membranas

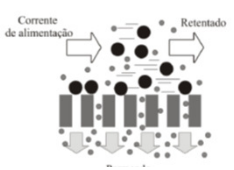
## ➢Ultrafiltração

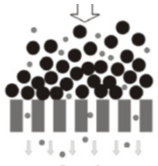
✓Dimensionamento: Utilizar membrana com diâmetro de corte nominal a metade da massa molar da menor espécie a ser retida

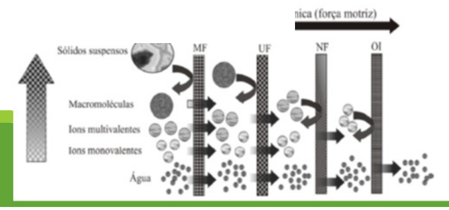
**Relation between MWCO and the pore size for UF membranes.**

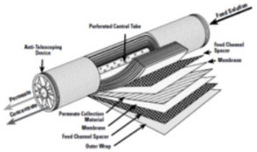
| | Pore Diameter | | |
|---|---|---|---|
| **MWCO (Daltons)** | **μm** | **nm** | **Å** |
| 1000000 | 0.1 | 100 | 1000 |
| 500000 | 0.02 | 20 | 200 |
| 100000 | 0.01 | 10 | 100 |
| 50000 | 0.04 | 4 | 40 |
| 10000 | 0.0025 | 2.5 | 25 |
| 5000 | 0.0015 | 1.5 | 15 |



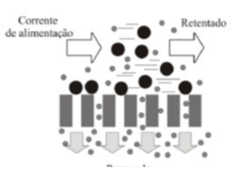


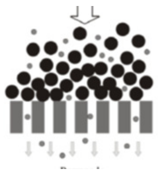


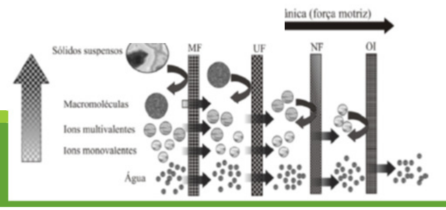
# Processamento por Membranas

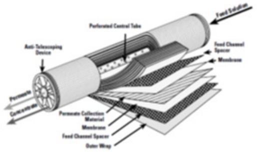
## ➢Nanofiltração

- ✓Processo mais recente
- ✓Faixa de separação entre a ultrafiltração e a osmose inversa
- ✓Tamanho de poro: 2 nm



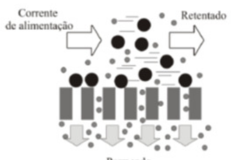


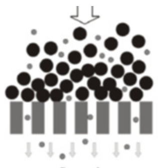


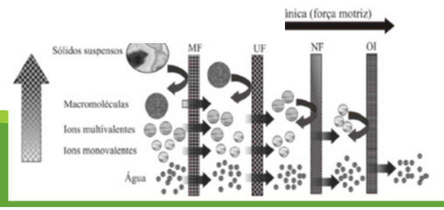
# Processamento por Membranas

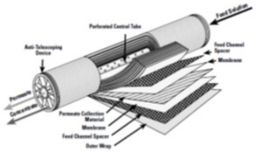
➢Nanofiltração

- ✓Rejeita partículas neutras > 200 g/mol
- ✓Consegue reter íons multivalentes
- ✓Massa molar entre (300-1000) Daltons
- ✓Força motriz: diferença de pressão



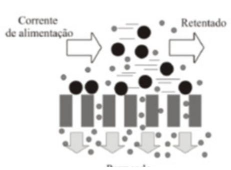


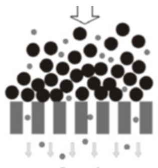


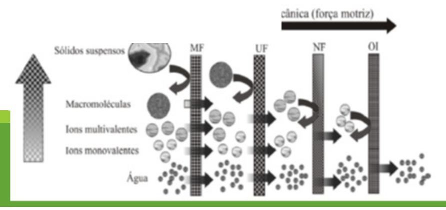
# Processamento por Membranas

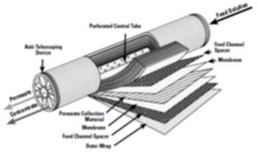
## ➢Nanofiltração

- ✓Pressão de operação: (5-25) bar (moderada)
- ✓Fluxo médio: (20 – 80) L/m².h
- ✓Mecanismo de separação por interação eletrostática (principal) e por diferença de tamanho



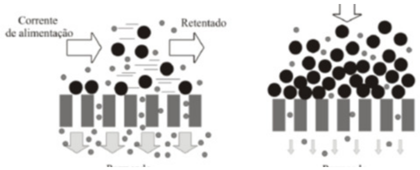



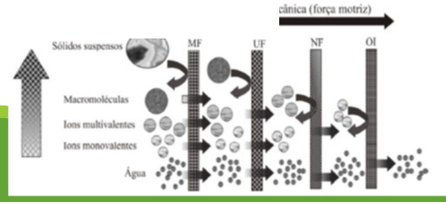


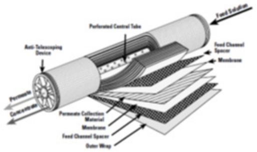


# Processamento por Membranas

- ➢Nanofiltração
  - ✓Moléculas neutras são separadas por diferença de tamanho e os sais multivalentes por carga elétrica
  - ✓Membrana porosa
  - ✓Colmatagem é um problema sério

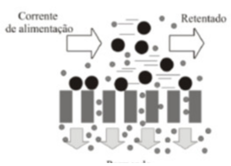


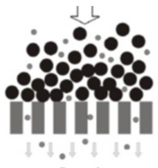



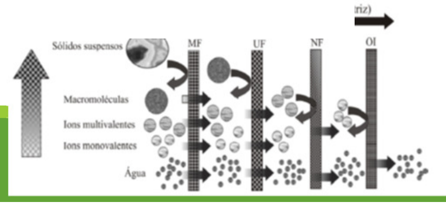


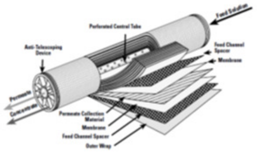
# Processamento por Membranas

- Osmose inversa ou osmose reversa
  - ✓ Processo com menor tamanho possível para aplicação em separação líquido/líquido
  - ✓ Tamanho de poro: < 2 nm
  - ✓ Porosidade em torno de 50 %
  - ✓ Retenção de partículas (1-10) Å



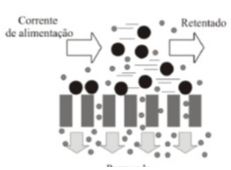



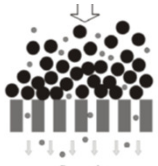


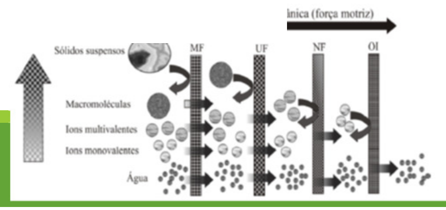


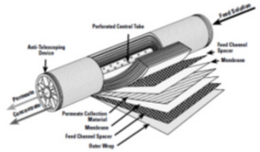
# Processamento por Membranas

- ➢ Osmose inversa ou osmose reversa
  - ✓ Consegue reter íons monovalentes (99%)
  - ✓ Rejeição de vírus e bactérias: até 99,9 %
  - ✓ Força motriz: diferença de pressão







# Processamento por Membranas

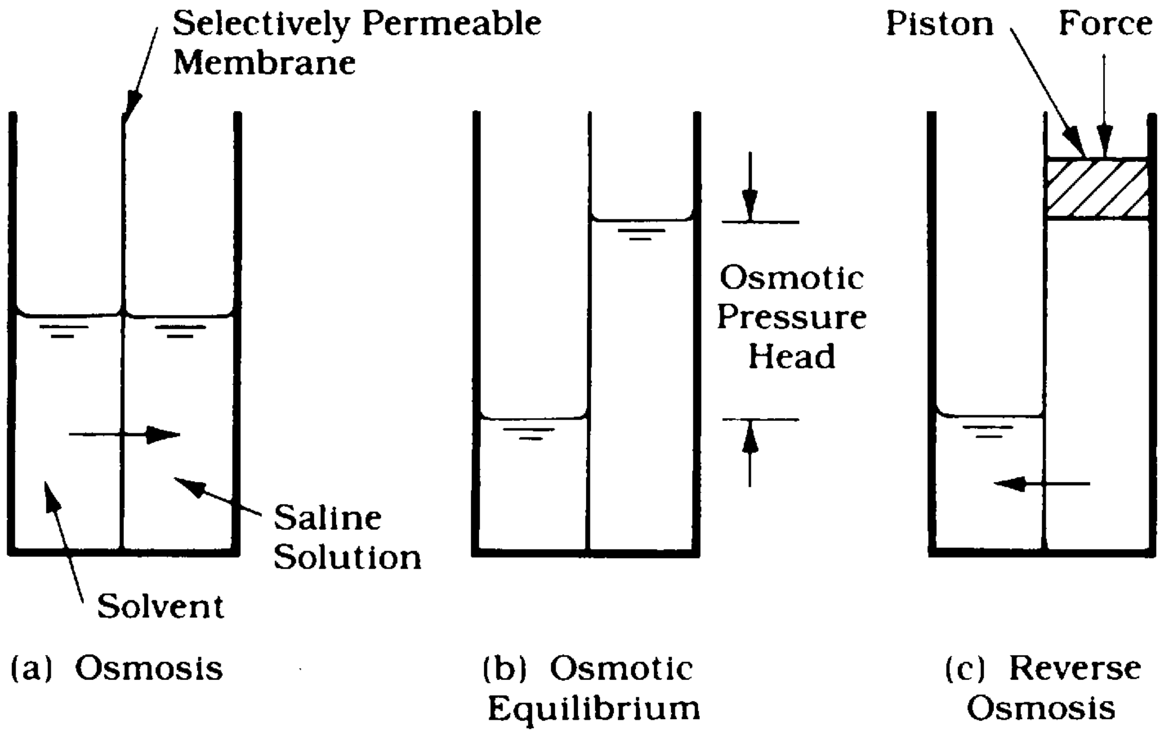
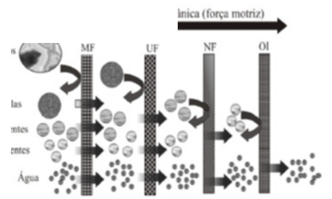
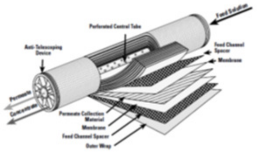


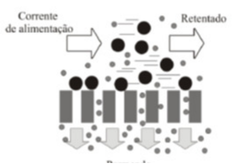

**FIGURE 14.3**
***Osmosis and Reverse Osmosis***

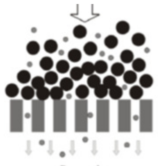



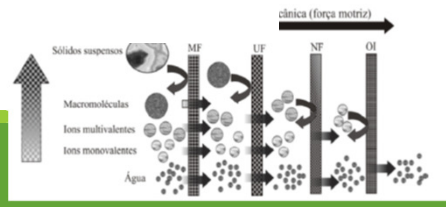


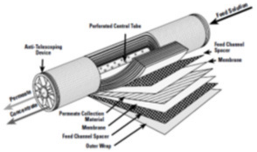
# Processamento por Membranas

- ➢ Osmose Inversa
  - ✓ Pressão de operação: (10-150) bar (alta)
  - ✓ Fluxo médio: (3 – 30) L/m².h
  - ✓ Mecanismo de separação por difusão-solução



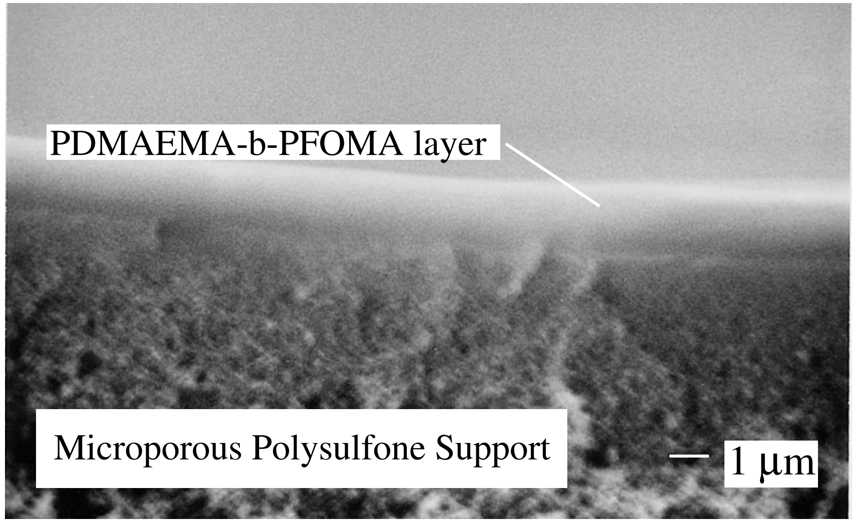



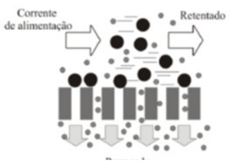


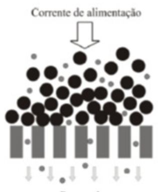


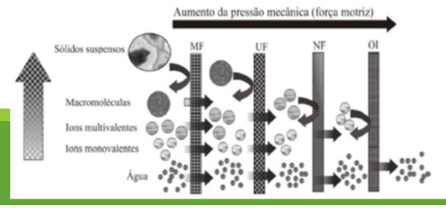
# Processamento por Membranas

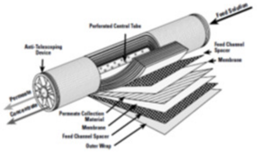
- ➢Osmose Inversa
  - ✓Membrana é densa processo de sorção e dessorção dos componentes na superfície da membrana
  - ✓Afinidade da membrana pelo permeado
  - ✓Colmatagem é um problema sério



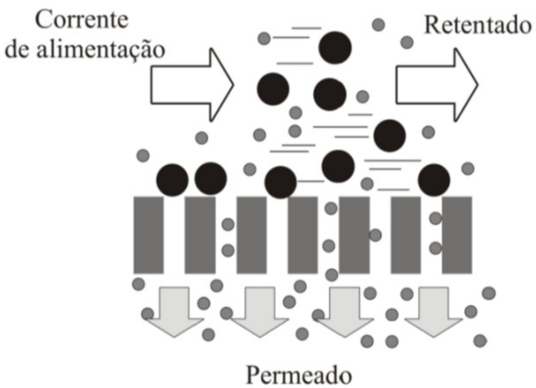





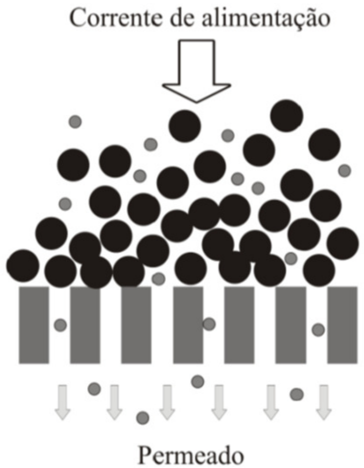
# Processamento por Membranas

## ➢ Parâmetros de Processo

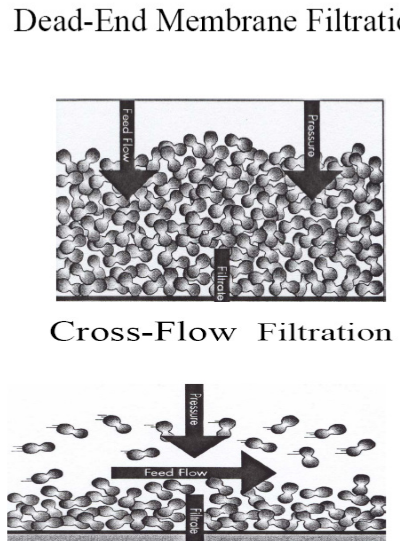
✓ Filtração convencional (perpendicular ou estática) e filtração tangencial

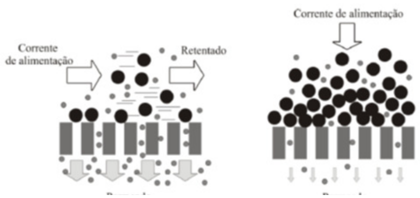


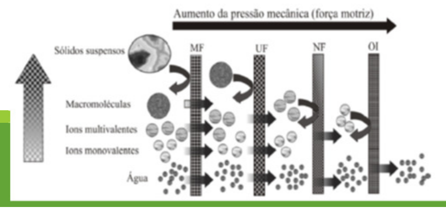

Filtração tangencial

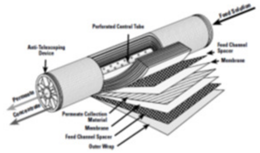



Filtração estática



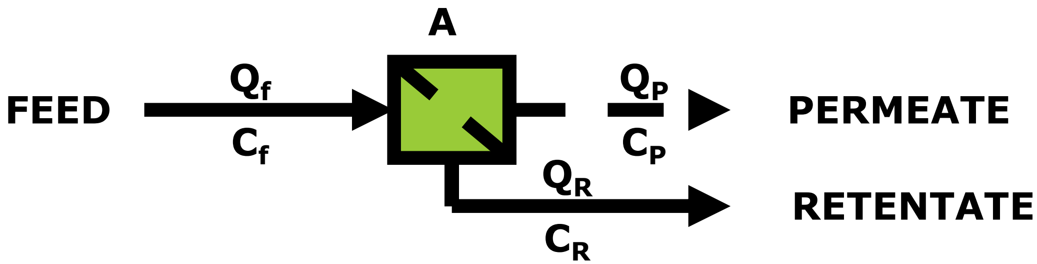





# Processamento por Membranas

- Parâmetros de Processo




✓ Fluxo de permeado (*J*): $J = \frac{Q_p}{A} = \frac{m_p}{t.A}$ para osmose inversa: $J = \frac{c}{\mu}(\Delta P - \Delta\pi)$

✓ Pressão transmembrana ($P_T$) : $\Delta P_T = P_R - P_P = \frac{P_e + P_s}{2}$

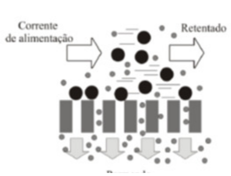
Em que:

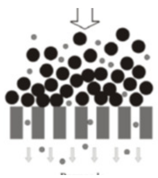
c é o coeficiente de permeabilidade da membrana

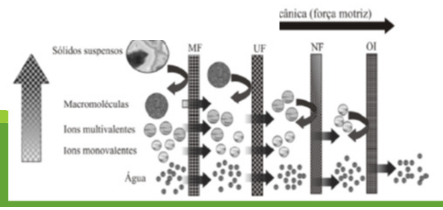
μ é a viscosidade (Pa.s)

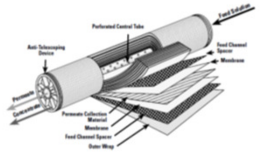
Δp é a pressão transmembrana

Δπ é a diferença de pressão osmótica entre a alimentação e o permeado



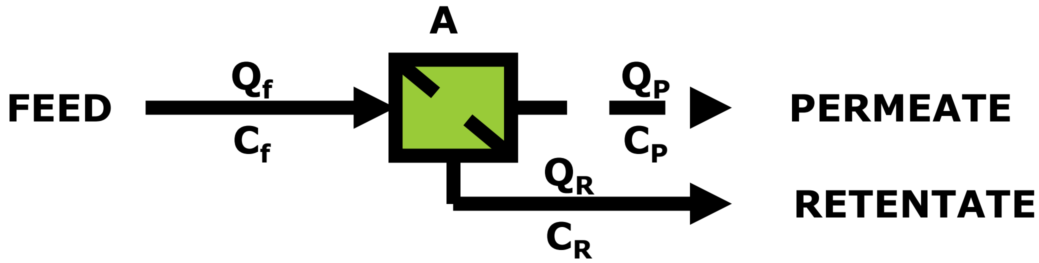







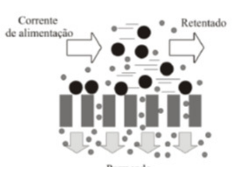
# Processamento por Membranas

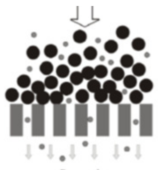
## ➢Parâmetros de Processo

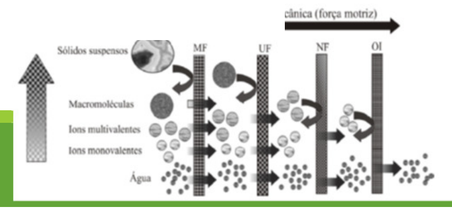


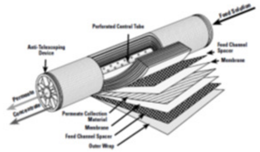

✓Rejeição de uma espécie = $1 - \frac{C_p}{C_f}$

✓Recuperação = $\frac{Q_p}{Q_f}$



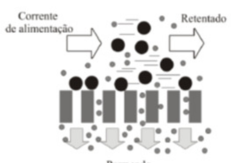


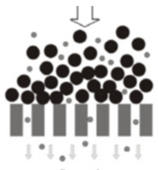


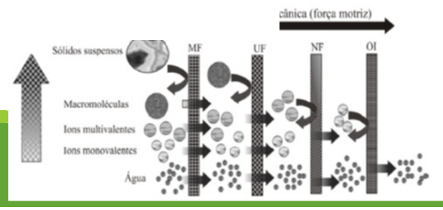
# Processamento por Membranas

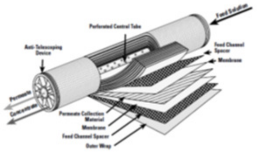
| *Membrane Process* | *Transmembrane Pressure, $\Delta P_{tot}$ (kPa)* | *System Recovery (%)*[a] |
|---|---|---|
| Microfiltration | 10 to 100 | 90 to 99+ |
| Ultrafiltration | 50 to 300 | 85 to 95+ |
| Nanofiltration | 200 to 1500 | 75 to 90+ |
| Reverse Osmosis | 500 to 8000 | 60 to 90 |

[a] Defined as the ratio of permeate flow rate to feed flow rate





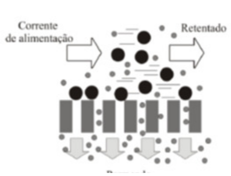


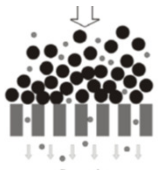
# Processamento por Membranas

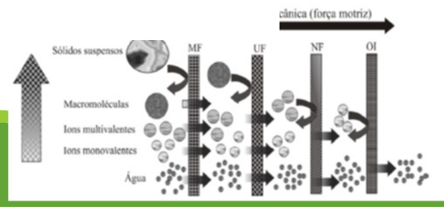
## ➢Parâmetros de Processo

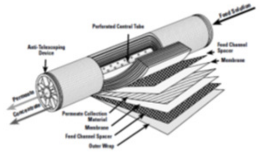
✓Resistência ($R$): $R = \frac{Força\ motriz}{Fluxo} = \frac{\Delta P_T}{J}$ (kg/m².s)

✓Resistência da membrana ($R_m$): $R_m = \frac{R}{\mu} = \frac{\Delta P_T}{\mu . J}$ ($m^{-1}$)



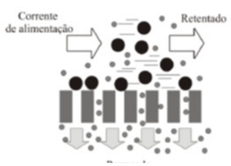


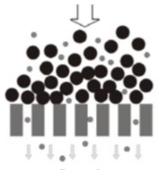


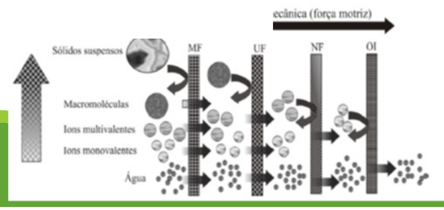
# Processamento por Membranas

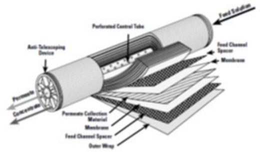
➢ Parâmetros de Processo

| *Process* | *Typical Volumetric Flux*, (L/m$^2$-h) | *Typical Membrane Resistance*, $\mathcal{R}m$ (m$^{-1}$) |
|---|---|---|
| **Microfiltration** | **100-250** | **1x10$^{11}$ – 1x10$^{12}$** |
| **Ultrafiltration** | **30-150** | **1x10$^{12}$ – 1x10$^{13}$** |
| **Nanofiltration** | **20-50** | **1x10$^{13}$ – 1x10$^{14}$** |
| **Reverse osmosis** | **5-40** | **5x10$^{13}$ – 1x10$^{15}$** |







# Processamento por Membranas

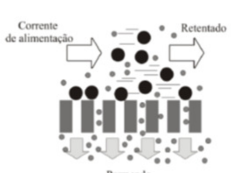
## ➢Parâmetros de Processo

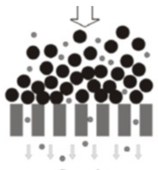
✓Resistividade: $\frac{R}{\delta_{mem}} = \frac{\Delta P_T}{J.\delta_{mem}}$ (kg/m³.s)

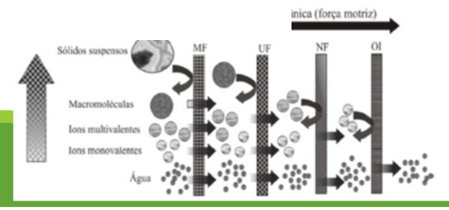
✓Permeabilidade do fluxo total ($k_V$): $k_V = \frac{1}{Resistividade} = \frac{J.\delta_{mem}}{\Delta P_T}$

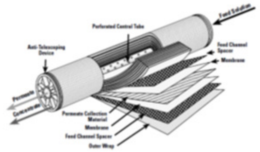
✓Permeabilidade de uma espécie química *i* ($k_i$): $k_V = \frac{J_i.\delta_{mem}}{\Delta P_T}$

Em que: $\delta_{mem}$ é a espessura da membrana



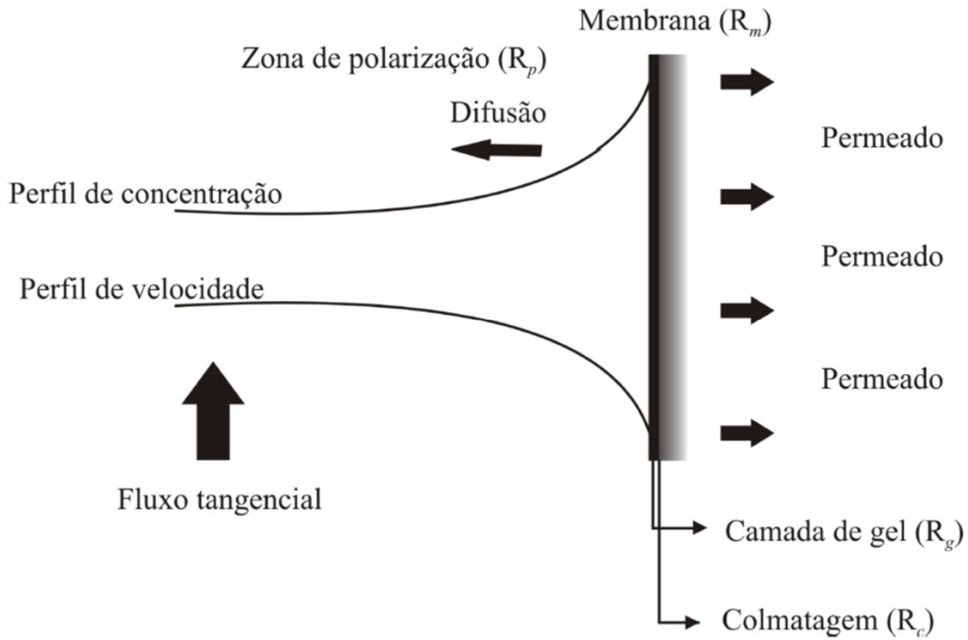


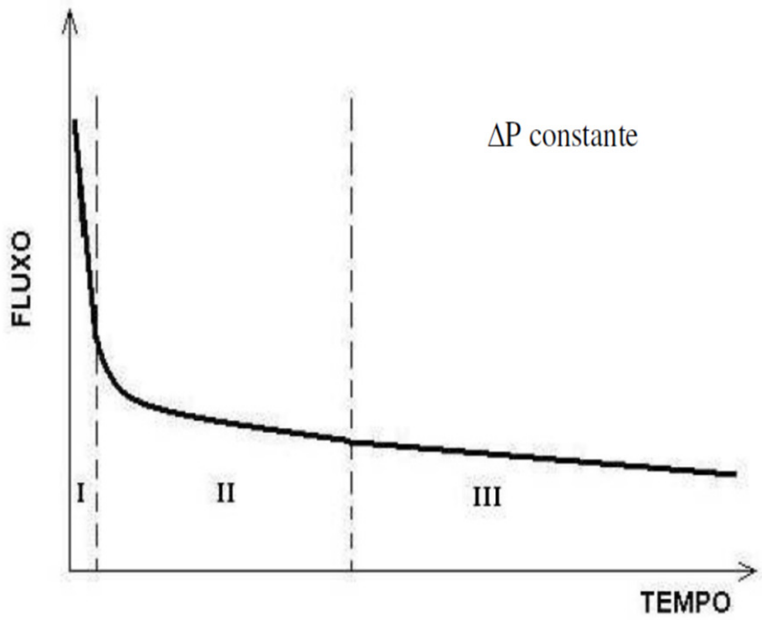


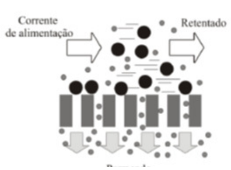
# Processamento por Membranas

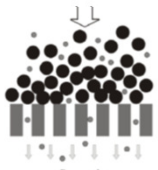
## ➢Parâmetros de Processo

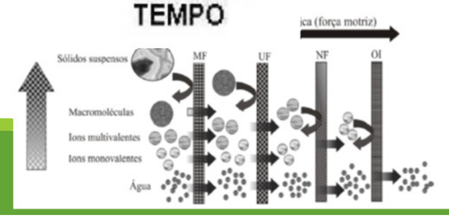
### ✓Fatores que limitam o fluxo do permeado

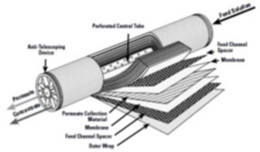


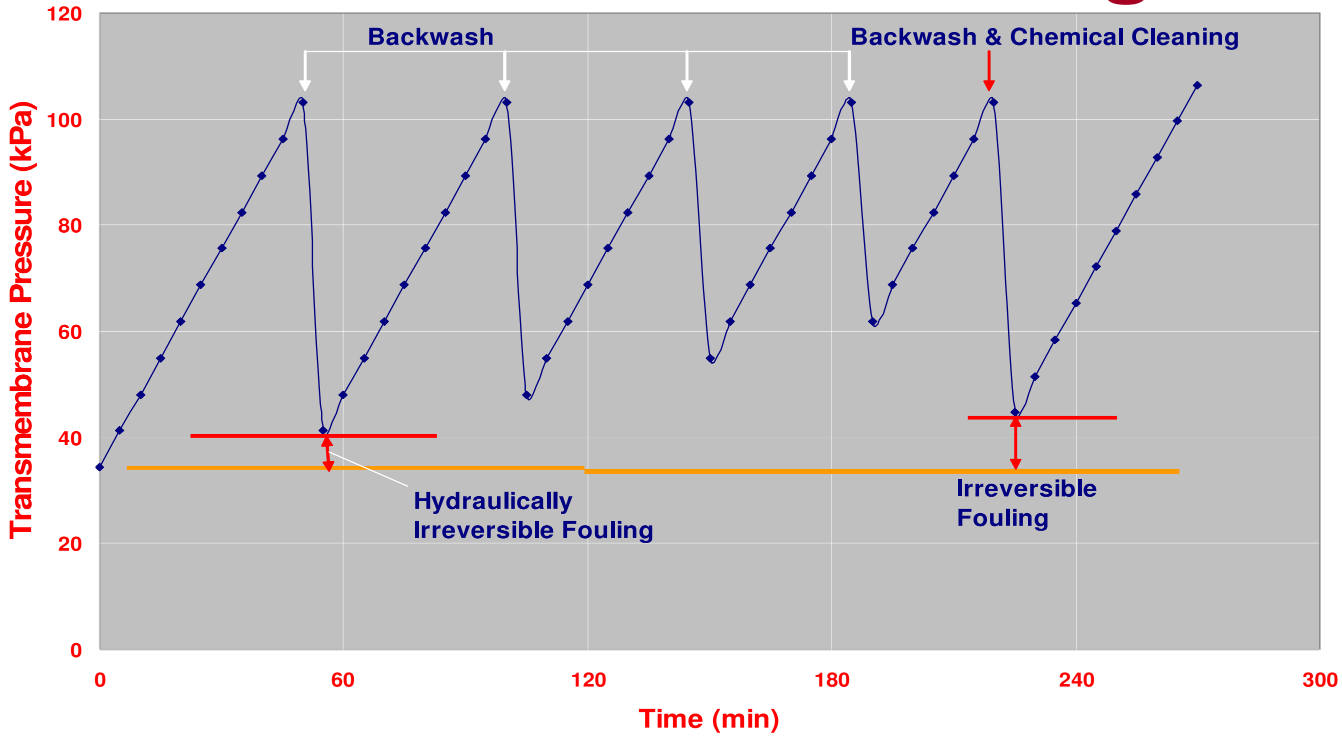


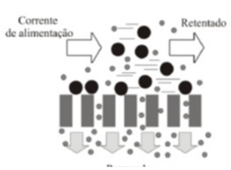


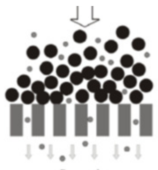


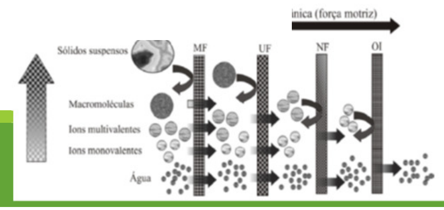
# Processamento por Membranas

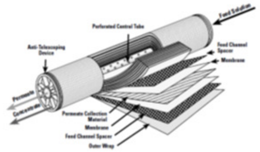
## Membrane Fouling





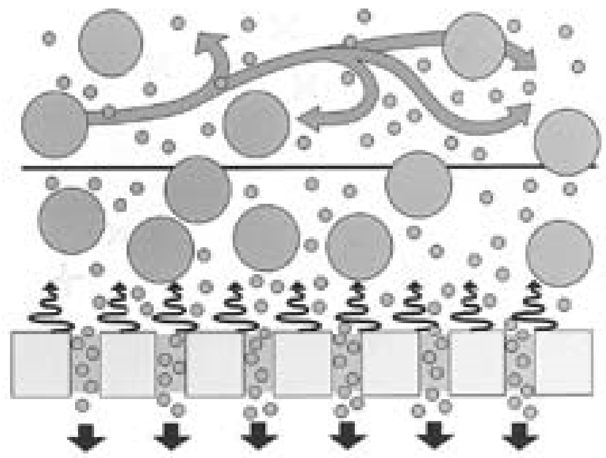


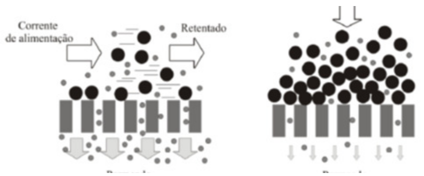
# Processamento por Membranas

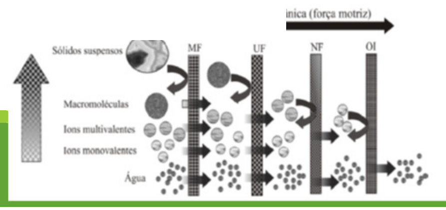
## ➢Parâmetros de Processo

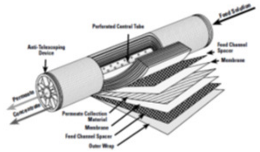
### ✓Controle da colmatagem

- Fluxo tangencial à membrana
- Pulsação periódica da corrente de alimentação
- Pulsação periódica do filtrado (retrolavagem)





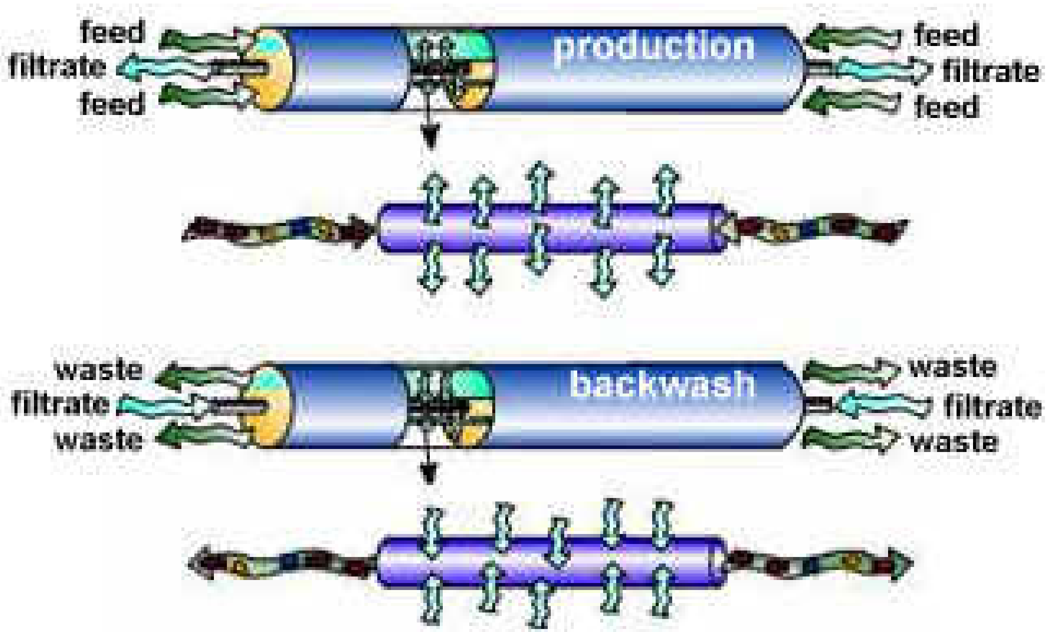


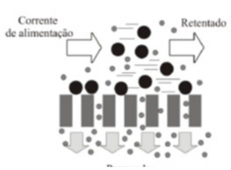
# Processamento por Membranas

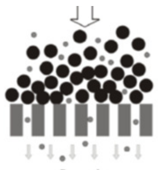
## ➢Parâmetros de Processo

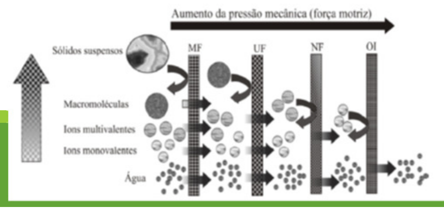
### ✓Controle da colmatagem

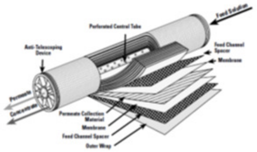
- Rotação da membrana (aumento do cisalhamento)
- Vibração da membrana
- Aplicação de ultrassom



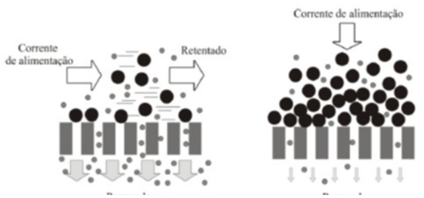


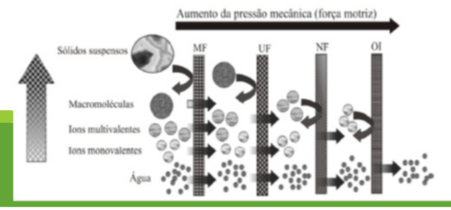


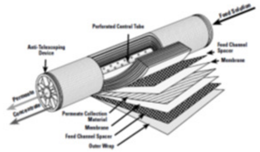
# Processamento por Membranas

## ➢Parâmetros de Operação

- ✓Viabilidade econômica depende da minimização da colmatagem da membrana (fluxo do permeado)
- ✓Parâmetros mais importantes: pressão transmembrana, a temperatura e a velocidade tangencial
- ✓Consumo energético maior com o aumento dos parâmetros

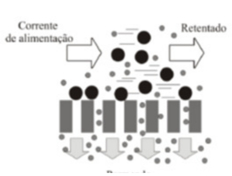


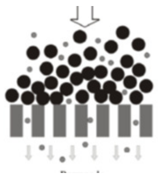



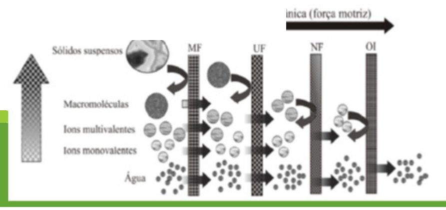


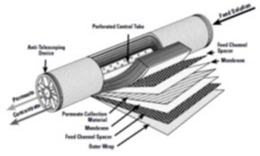
# Processamento por Membranas

- ➢ Parâmetros de Operação
  - ✓ Pressão maior aumenta o fluxo para fluidos com poucos componentes causadores de colmatagem
  - ✓ Maior temperatura aumenta o fluxo pela redução da viscosidade da solução e aumento da difusão através da camada de gel e da própria membrana (limitação: tolerância da membrana e do produto)
  - ✓ Maior velocidade tangencial arrasta partículas e evita a colmatagem aumentando o fluxo de permeado





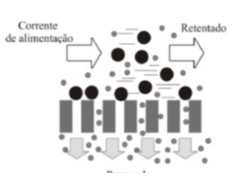


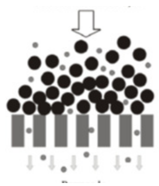
# Processamento por Membranas

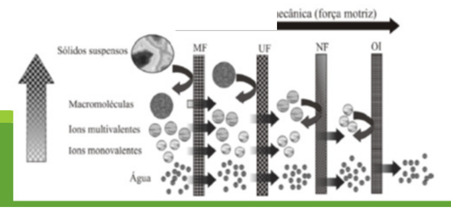
## ➢Equipamentos

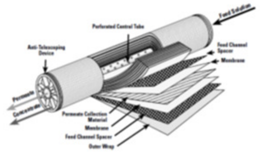
### ✓Material das membranas

- Membranas sintéticas de materiais poliméricos
- Acetato de celulose, polisulfona, polietersulfona, polifluoreto de viniledeno, poliacrilonitrila, polieteramida e policarbonato
- Membranas inorgânicas: cerâmicas (óxido de alumina, óxido de zircônia, dióxido de silício), vidro e metálicas







# Processamento por Membranas

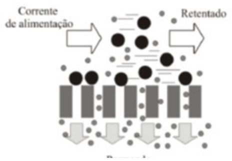
**Properties of Selected Membrane materials**

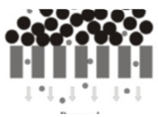
| Material[a] | Maximum temperature (°C) | pH range | Solvent resistance |
|---|---|---|---|
| Cellulose acetate | 30/65 | 2–7.25 | Low |
| Fluoropolymer | 60 | 1.5–12 | High |
| Polyacrylonitrile | 60 | 2–10 | High |
| Polyamide | 60 | 1.5–9.5 | Medium |
| Polyethersulfone | 80 | 1.5–12 | Medium |
| Polysulfone | 80 | 1.5–12 | Medium |
| PVDF | 80 | 1.5–12 | High |
| Alumina oxide[b] | 300 | 0–14 | High |
| Zirconia oxide[b] | 300 | 0.5–13.5 | High |

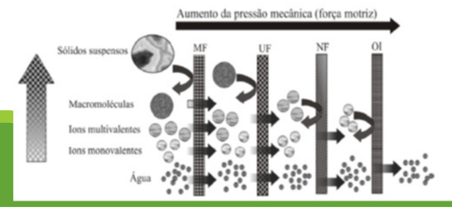
Adapted from Cheryan, M., *Ultrafiltration Handbook*, 1986.

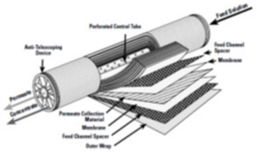
[a] Pressure limitations depend whether the membrane is designed for RO, UF or MF.

[b] Cannot be used with phosphoric acid.





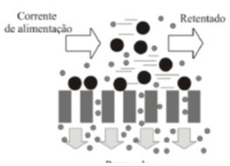


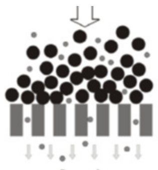
# Processamento por Membranas

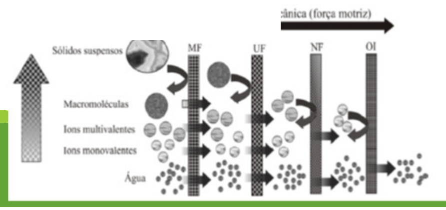
## ➢Equipamentos

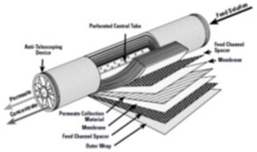
### ✓Arranjo das membranas

- Membranas são organizadas em módulos
- Configurações dos módulos: fibra oca, placa e quadro, espiral e tubular



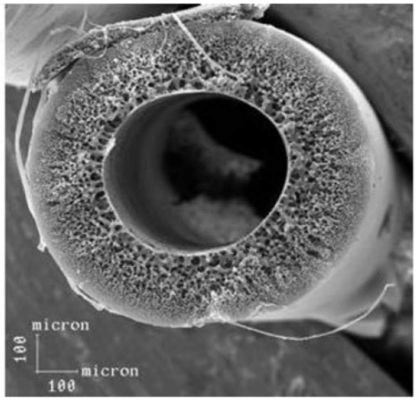


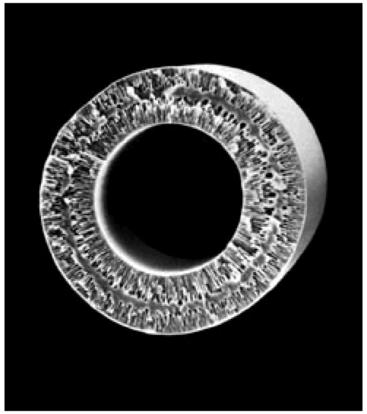


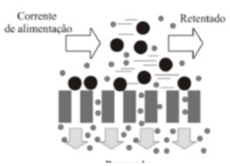
# Processamento por Membranas

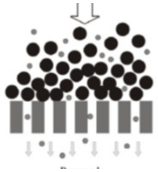
## ➢Equipamentos

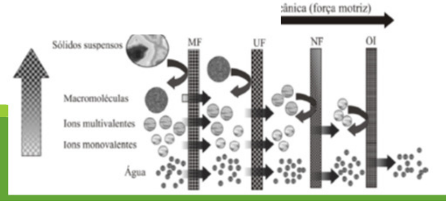
- Fibra oca: elevada relação área de permeação/volume do módulo (menor espaço ocupado e custo)

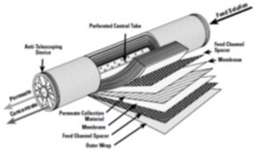






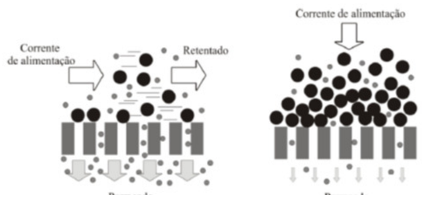


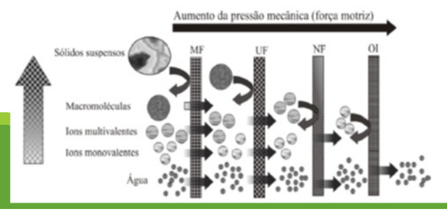
# Processamento por Membranas

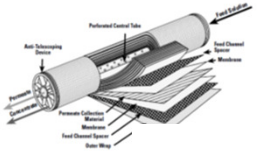
## ➢ Equipamentos

### ✓ Arranjo das membranas

- Placa e quadro: fácil controle do escoamento, custo de construção elevado e baixa relação área de permeação/volume do módulo



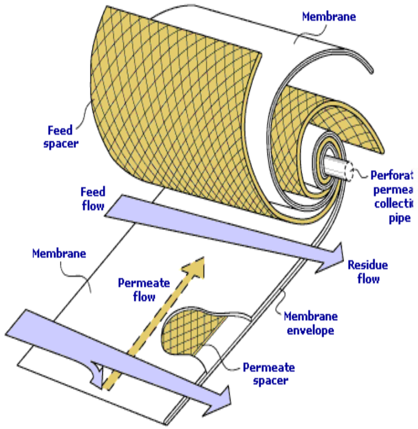


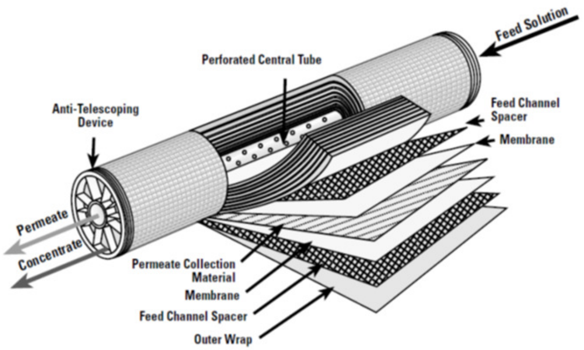
# Processamento por Membranas

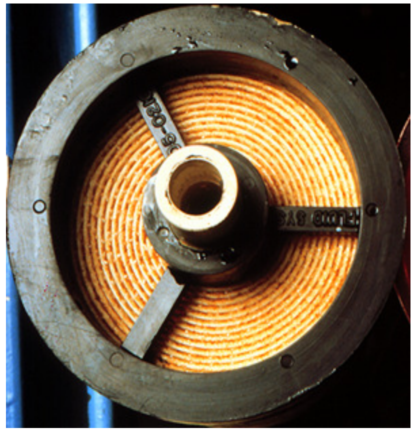
## ➢Equipamentos

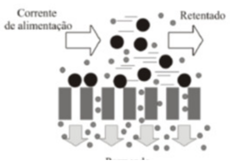
### ✓Arranjo das membranas

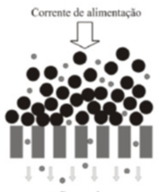
- Espiral: compacto, custo mais baixo, baixo consumo de energia, escoamento ruim (favorece colmatagem)

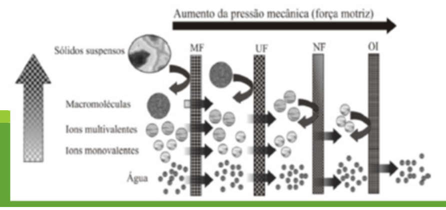


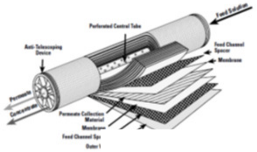





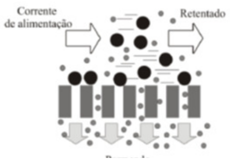


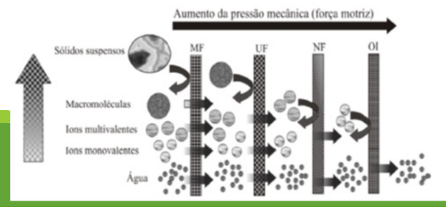
# Processamento por Membranas

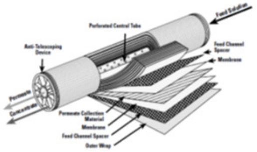
## ➢Equipamentos

### ✓Arranjo das membranas

- Tubular: alta turbulência, escoamento e limpeza melhores, custo elevado, baixa relação área de permeação/volume do módulo, grande espaço ocupado



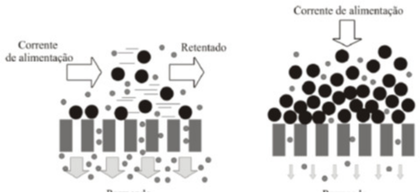


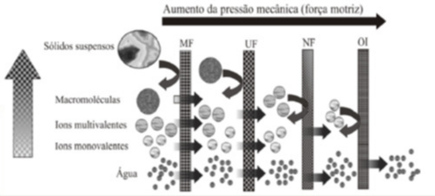
# Processamento por Membranas

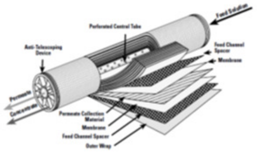
## ➢Equipamentos

### ✓Arranjo das membranas

- Cerâmicas:



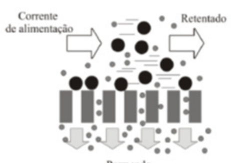


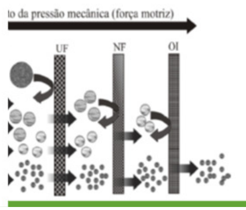


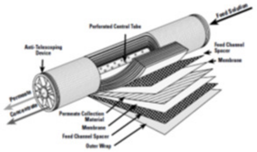
# Processamento por Membranas

**TABLE 2**
**Characteristics of Common Membrane Configurations**

| Characteristic | Hollow fiber | Plate and frame | Spiral wound | Tubular polymeric | Tubular inorganic |
|---|---|---|---|---|---|
| Channel size (mm) | 0.6–1.1 | 0.5–1.0 | 0.86–1.52 | 12.7–25.4 | 2–19 |
| Packing density (area/volume) | High (1000–10000 m²/m³) | Moderate (200–400 m²/m³) | Moderate (300–1000 m²/m³) | Low (100–300 m²/m³) | Low (100–300 m²/m³) |
| Flux | Fair/poor | Excellent/good | Good | Good | Good |
| Energy consumption | Low | Medium/high | Medium | High | High |
| Cost/area | Low | High | Low | High | Very high |
| Membrane replacement cost | Moderate | Low | Moderate/low | High | Very high |
| Hold-up volume | Low | Medium | Medium | High | Medium/high |
| Fouling | High | Medium | Medium | Low | Low/medium |
| Backflushing | Yes | No | No | No | Yes |
| Cleaning in place | Good | Fair/poor | Fair/poor | Excellent | Excellent |
| Polymer choices | Few | Many | Many | Few/Many | Not applicable |
| Other comments | Cannot withstand high pressures | Permeate from membrane elements can be monitored separately | Mesh spacer creates dead spots to flow | Can handle high solids content | Has high resistance to pH, T, and chemicals |



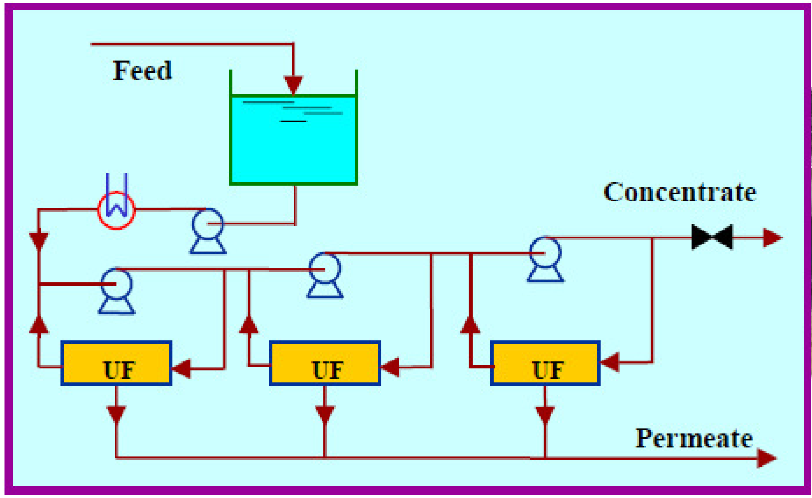



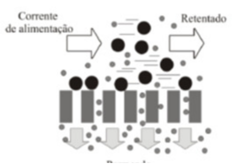


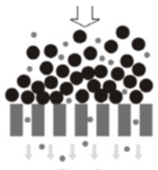
# Processamento por Membranas

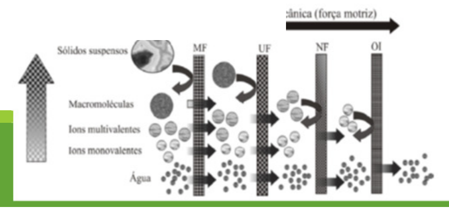
➢ Equipamentos

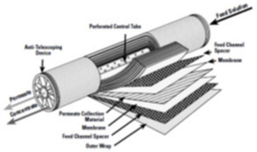
✓ Configurações de Processos



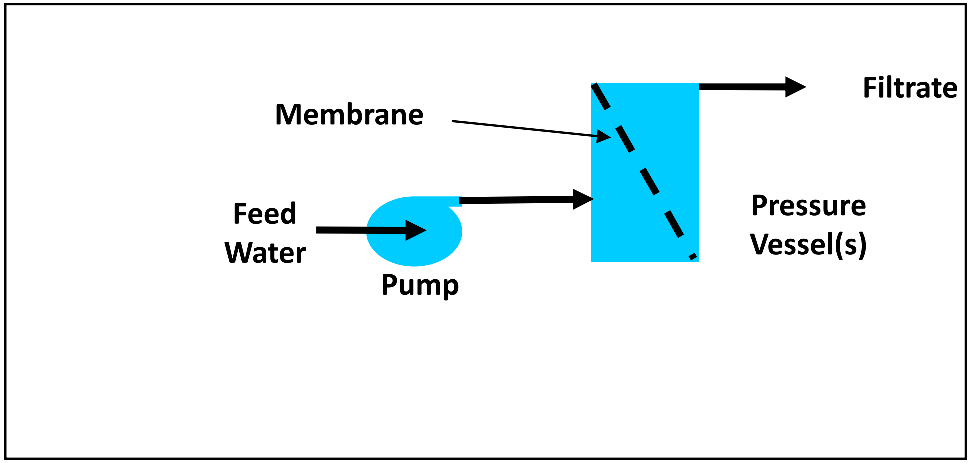




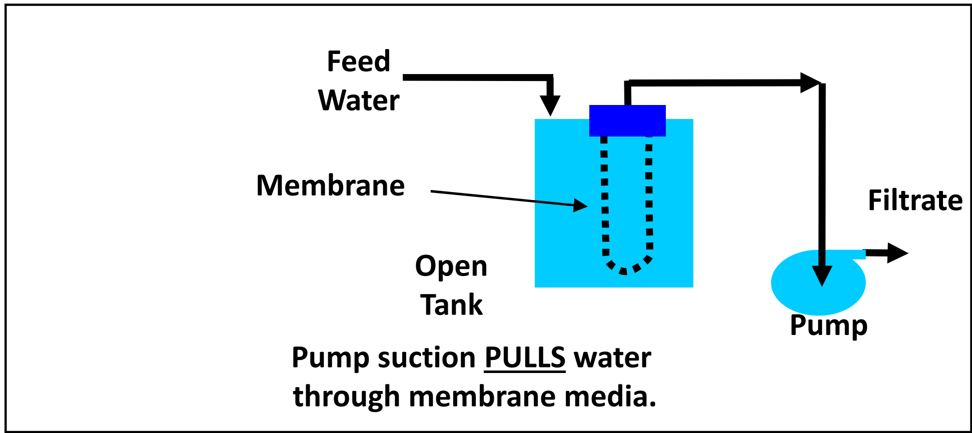
# Processamento por Membranas

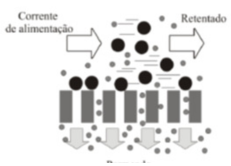
- Equipamentos
  - ✓ Configurações de Processos

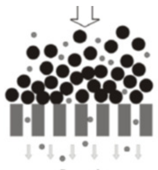
Encased
membrane system

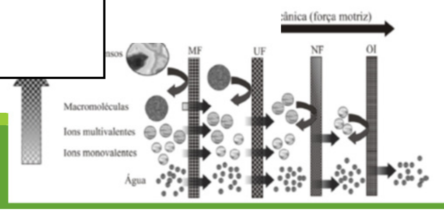


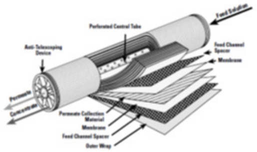

Submerged membrane
system



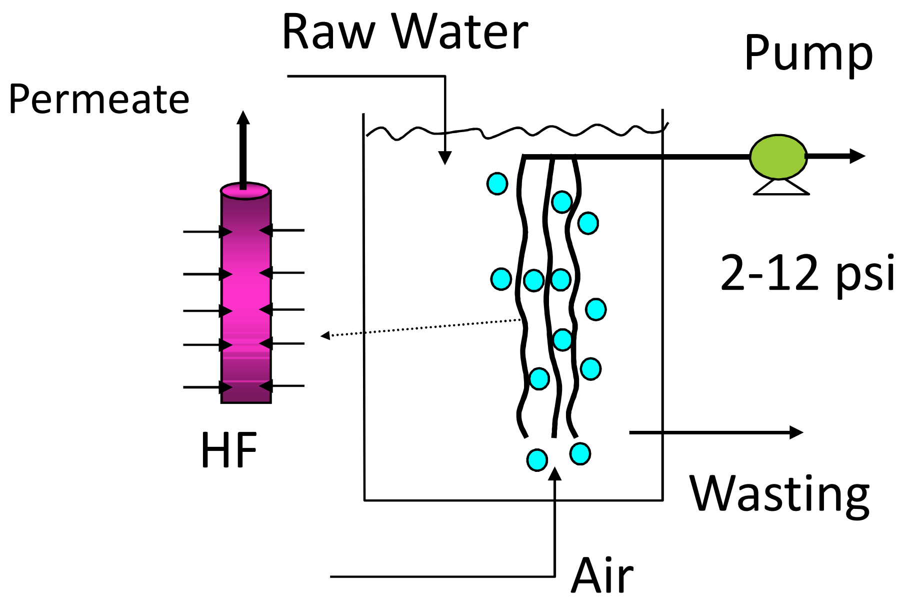


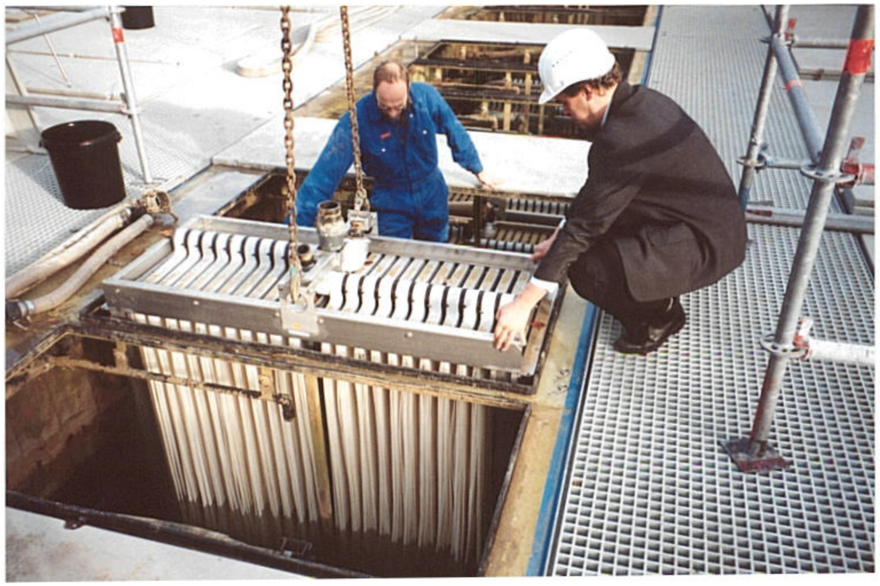


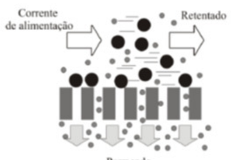
# Processamento por Membranas

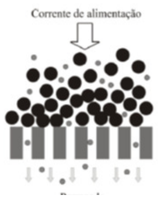
## ➢Equipamentos

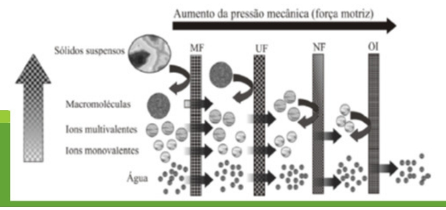
### ✓Configurações de Processos

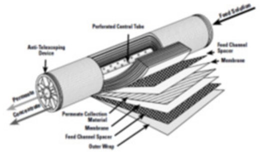




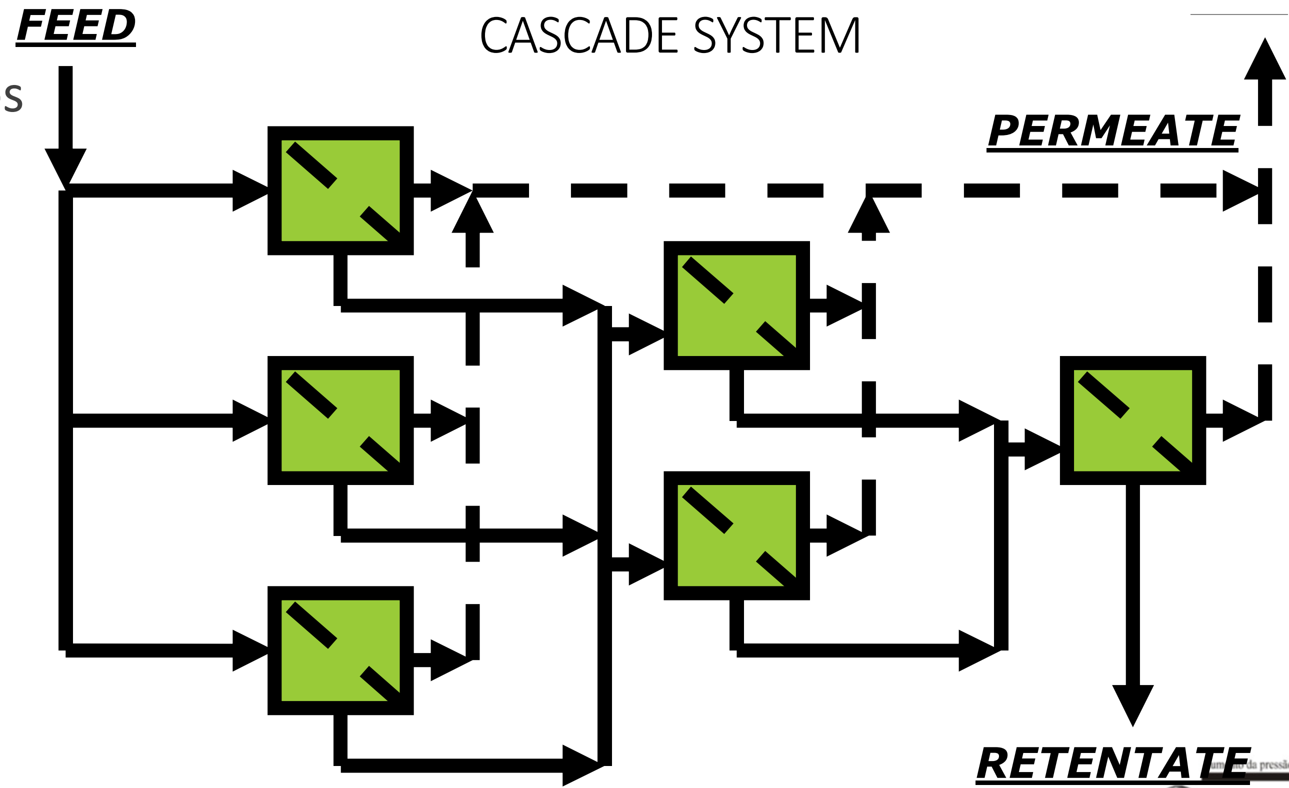



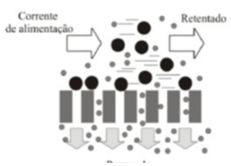


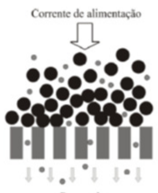
# Processamento por Membranas

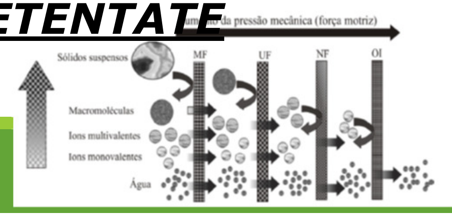
- Equipamentos
  - ✓ Configurações de Processos

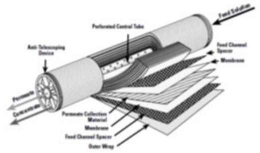
CASCADE SYSTEM



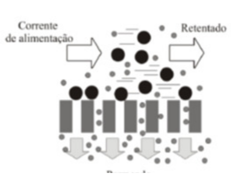


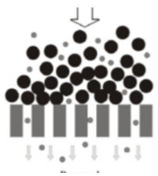
# Processamento por Membranas

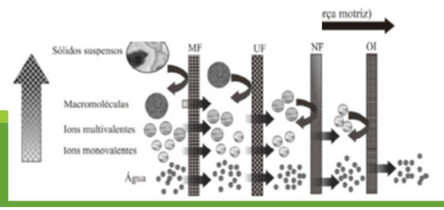
## ➢Outros processos por membranas

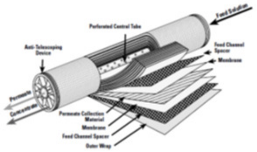
### ✓Eletrodiálise

- Membrana semipermeável que permite a passagem apenas de íons com carga positiva (cátions) ou íons com carga negativa (ânions)



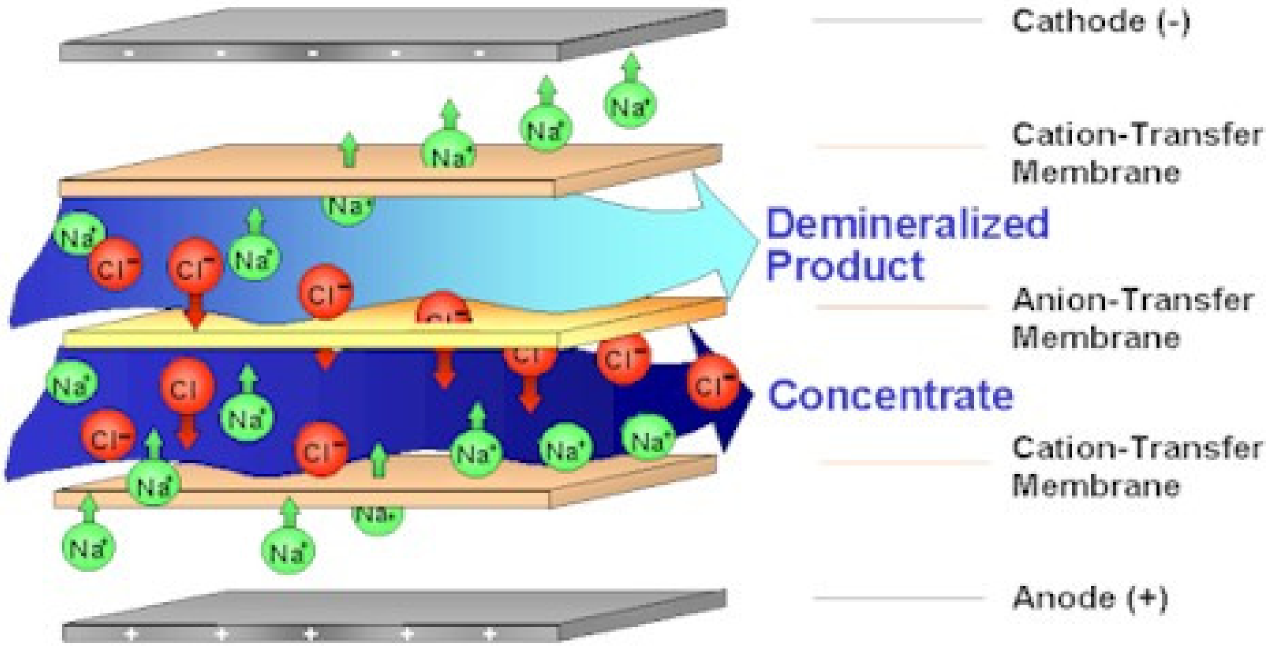



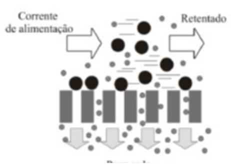


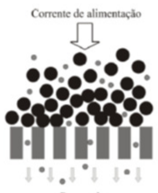


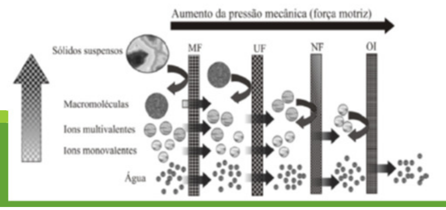
# Processamento por Membranas

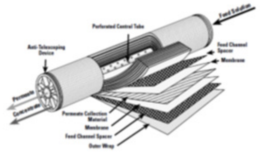
- Eletrodiálise



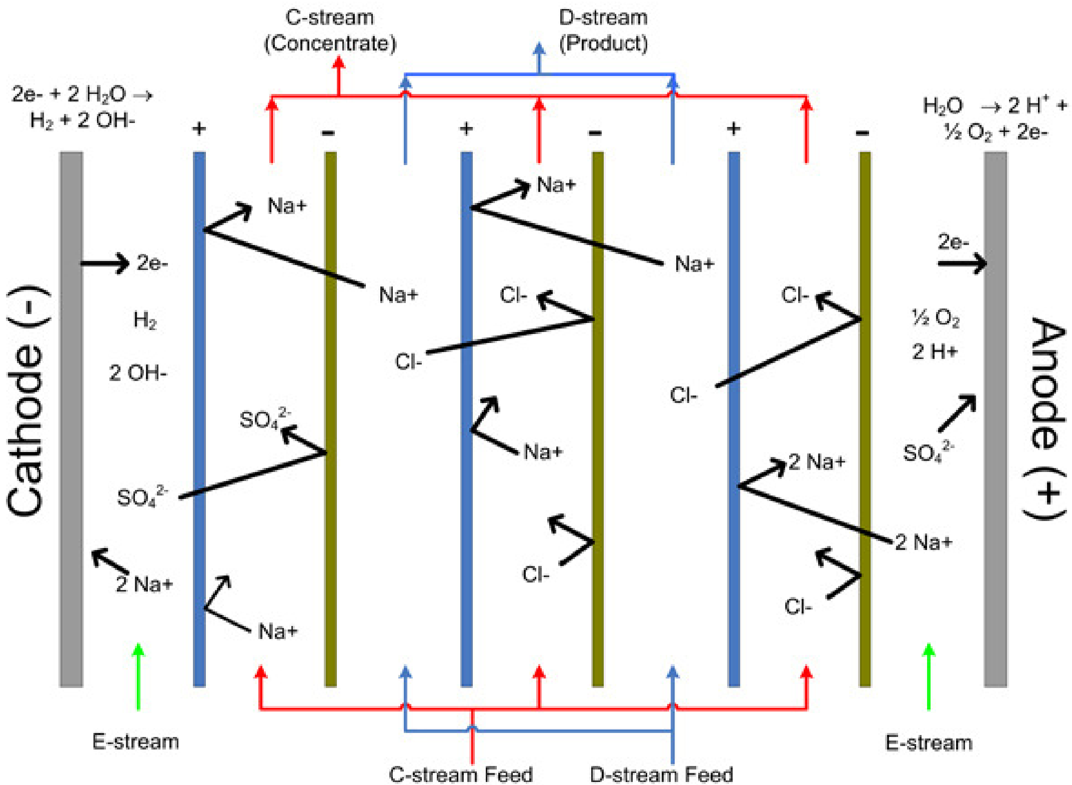



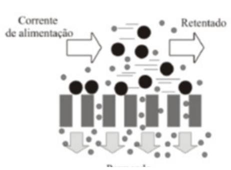



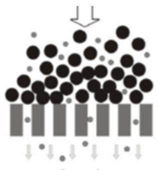


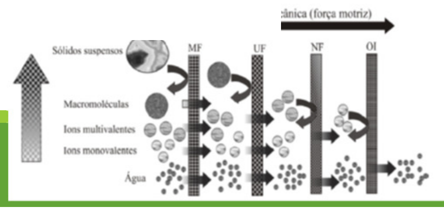
# Processamento por Membranas

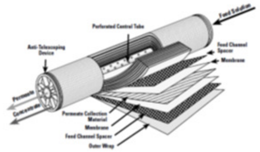
- Eletrodiálise





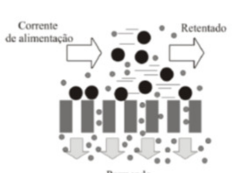


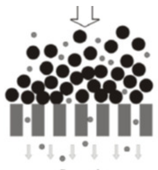
# Processamento por Membranas

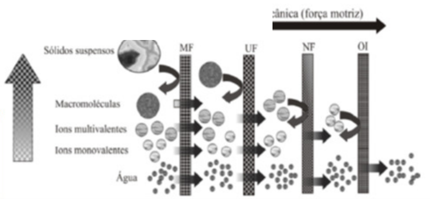
## ➢Outros processos por membranas

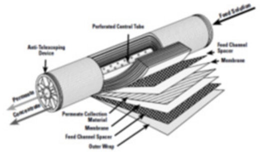
### ✓Osmose Direta (DO ou DOC)

- Concentração de um líquido empregando uma membrana semipermeável densa e hidrofílica
- Duas soluções aquosas (alimentação e agente osmótico) com pressões osmóticas diferentes
- Permite atingir concentrações de até (45-60) °Brix



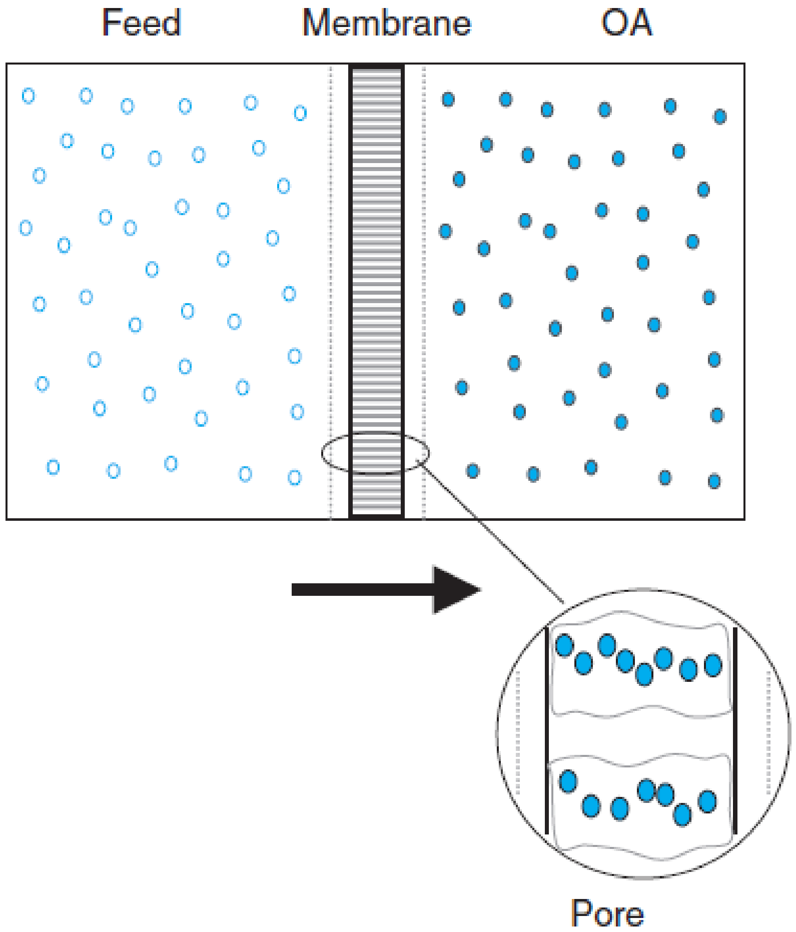



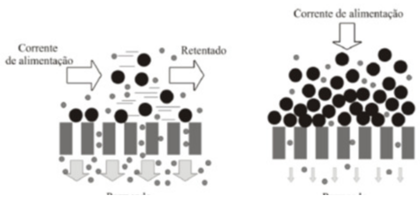


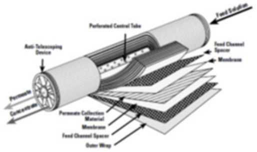


# Processamento por Membranas

✓Osmose Direta (DO ou DOC)



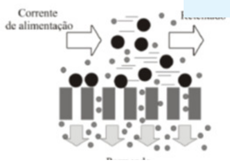



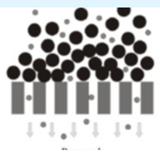



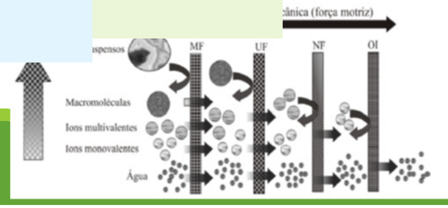
# Processamento por Membranas

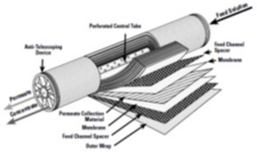
**Table 10.2 Work carried out by various researchers on direct osmosis**

| Type | Juices/water/ colorants | Osmotic agent | Membranes and their operating conditions | Fluxes (l/m$^2$h) | References |
|---|---|---|---|---|---|
| DOC | Grape juice | NaCl | Module: Plate and frame membrane module<br>Cellulose acetate membrane | 2.5 | Popper et al. (1964) |
| DO | Red raspberry juice | HFCS | Module: Osmotek DOC cell<br>S 0.14 m$^2$ | 0.9–1.4 | Wrolstad et al. (1993) |
| DOC | Orange, raspberry, tomato juices | PEG, HFCS | Module: Osmotek DOC module<br>Cellulose triacetate membrane<br>MWCO 100 Da, δ 90 μm | 5–6 | Herron et al. (1994) |
| DOC | Tomato juice | NaCl<br>$CaCl_2$<br>$Ca(NO_3)_2$<br>Sucrose PEG | Module: Tubular membrane module<br>AFC99 aromatic polyamide thin film composite reverse osmosis membrane<br>δ 500 and 600 μm | 0.37–3.1 | Petrotos et al. (1998) |
| DOC | Tomato juice | Brine | Module: Flat sheet membrane module<br>Commercial reverse osmosis membrane,<br>δ 260 μm | 4.5 | Petrotos and Lazarides (2001) |
| DOC | Red radish | HFCS | Module: Pilot plant (Osmoteck Inc., Corvalis OR) | 0.5–2 | Rodriguez-Saona et al. (2001) |





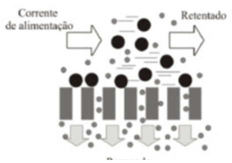


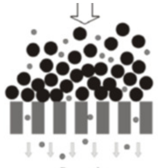
# Processamento por Membranas

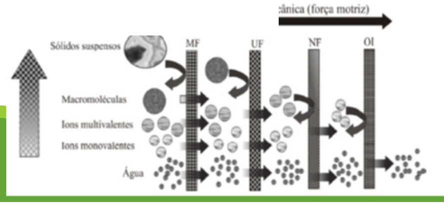
## ➢Outros processos por membranas

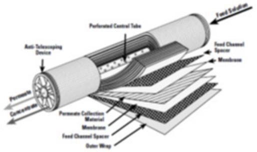
### ✓Pervaporação ou Destilação Osmótica por membranas (OMD)

- Concentração  de um líquido empregando uma membrana microporosa e hidrofóbica
- Duas soluções aquosas (alimentação e agente osmótico) com  pressões de vapor diferentes





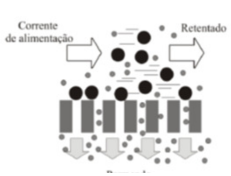


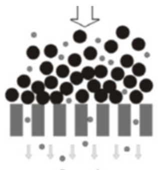
# Processamento por Membranas

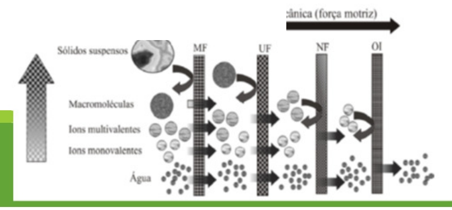
## ➢Outros processos por membranas

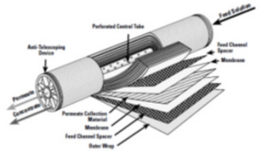
### ✓Pervaporação ou Destilação Osmótica por membranas (OMD)

- Água evapora  na superfície da solução de maior pressão de vapor atravessa a membrana e condensa  na solução de menor pressão de vapor
- Permite atingir concentrações de até 70 °Brix



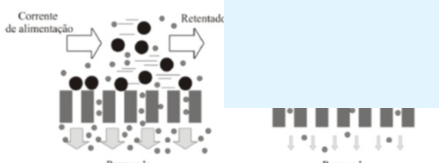


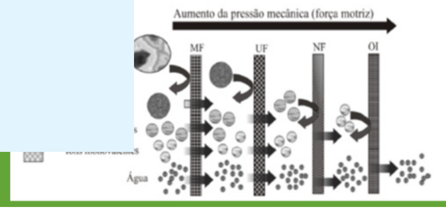


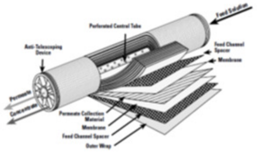
# Processamento por Membranas

**Table 10.1 Work carried out by various researches on osmotic membrane distillation**

| Type | Juices/water/ Colorants | Osmotic agent | Membranes and their operating conditions | Fluxes ($l/m^2/h$) | References |
|---|---|---|---|---|---|
| OMD | Orange juice, seawater | Seawater $MgSO_4$ | Module: Hollow fibre<br>PP membrane; r 700 A; S 0.18 $m^2$, ε 50% | 0.4–7.9 | Lefebvre (1988) |
| OMD | Orange, apple, grape juices | NaCl | Module: Syrinx plate and frame PTFE membrane; r 0.2 μm; S 0.7 $m^2$; δ 100 μm<br>Temperature: 29–40 °C | 0–2.2 | Sheng et al. (1991) |
| OMD | Water | NaCl | Module: Lewis cell (stirred cell)<br>a) Millipore PVDF (GVHP) r 0.2μm; ε 70%; δ 125 μm; S 0.00275 $m^2$<br>b) Millipore PTFE (FHLP) r 0.2 μm; ε 70%; δ 175 μm; S 0.00275 $m^2$<br>c) Gelman PTFE (TF-1000) r 1 μm; ε 80%; δ 178 μm; S 0.00275 $m^2$<br>d) Gelman PTFE (TF-450) r 0.45 μm; ε 80%; δ 178 μm; S 0.00275 $m^2$<br>e) Gelman PTFE (TF-200) r 0.2 μm; ε 80%; δ 178 μm; S 0.00275 $m^2$ | 0–0.5 | Mengual et al. (1993) |
| OMD | Water | NaCl, $MgCl_2$ | Module: Capillary modules (LM2P06, MD020CP2N) in shell-tube configuration<br>a) Accurel PP Q3/2; r 0.2 μm; ε 70%; $S_l$ 0.04 $m^2$<br>b) Accurel PP S6/2; r 0.2μm; ε 70%; $S_l$ 0.104 $m^2$<br>Temperature: 25–50 °C | 0.2–2.5 | Gostoli (1999) |



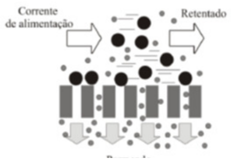





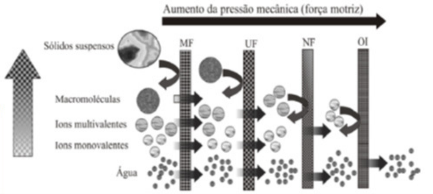
# Processamento por Membranas

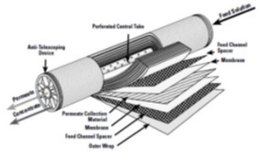
**Table 10.1 Work carried out by various researches on osmotic membrane distillation**

| | | | | | |
|---|---|---|---|---|---|
| OMD | Water | $CaCl_2$ | Module: Flat sheet membrane (Co-current)<br>a) Pall-Gelman TF200 r 0.2 μm; δ 165 μm: ε 60%; S 0.004 $m^2$<br>b) Pall-Gelman TF450 r 0.45 μm; δ 178 μm: ε 60%; S 0.004 $m^2$<br>Temperature: 25°C | 4–12 | Courel et al. (2000a) |
| OE | Passion fruit juice | $CaCl_2$ | Module: Hollow fibres module<br>PP membrane; r 0.2 μm; S 10.2 $m^2$<br>Temperature: 30°C | 0.5–0.75 | Vaillant et al. (2001) |
| OMD | Water | Glycerol, NaCl, $CaCl_2$ | Module: Stirred cell<br>PP membrane; r 0.1 μm; δ 90 mm; ε 55%; S 0.00113 $m^2$<br>Temperature: 20–45°C | 0.4–3.2 | Alves and Coelhoso (2002) |
| OMD | Water, sugarcane juice | NaCl, $K_2HPO_4$, $CaCl_2$ | Module: Flat membrane test cell<br>a) PP membrane; r 0.05 μm; δ 90 μm; S 0.045 $m^2$<br>b) PP membrane; r 0.2 μm; δ 150 μm; S 0.045 $m^2$<br>c) PTFE membrane; r 0.025 μm; S 0.045 $m^2$<br>Acoustic field: 1.2 MHz<br>Temperature: 25–60°C | 0.4–0.93 | Narayan et al. (2002) |





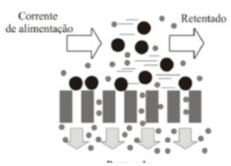


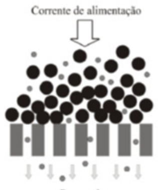


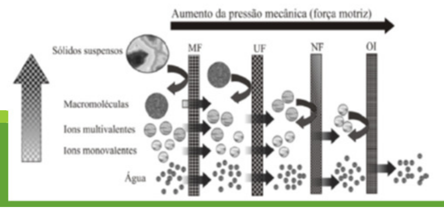
# Processamento por Membranas

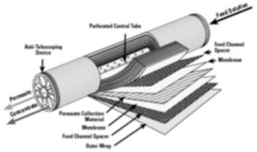
**Table 10.1 Work carried out by various researches on osmotic membrane distillation**

| | | | | | |
|---|---|---|---|---|---|
| OMD | Phycocyanin | $CaCl_2$, $K_2HPO_4$ | Module: Flat membrane test cell<br>a) PP membrane; r 0.05 μm; δ 90 μm; S 0.0115 $m^2$<br>b) PP membrane; r 0.2 μm; δ 150 μm; S 0.0115 $m^2$<br>Temperature: 25°C | 1.4–1.9 | Naveen et al. (2003a) |
| OE | Water | Brine | Module: Ceramic tubular membrane<br>r 0.2 and 0.8 × $10^{-6}$ m<br>Temperature: 25–35°C | 0.15–1.4 | Brodard et al. (2003) |



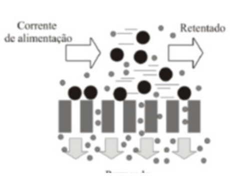


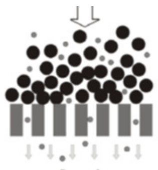
# Processamento por Membranas

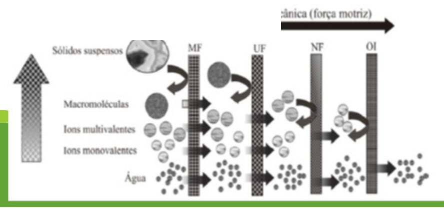
## ➢Aplicações

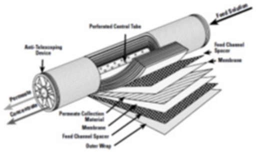
### ✓Laticínios

- Ultrafiltração  de leite e soro de leite para concentração de proteínas
- Remoção de gordura do soro de leite por uma sequência de processos UF/MF/UF
- Remoção de bactérias do leite por MF





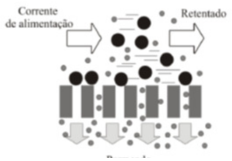


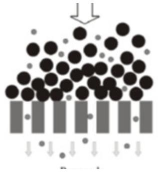
# Processamento por Membranas

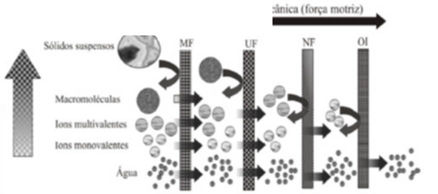
## ➢Aplicações

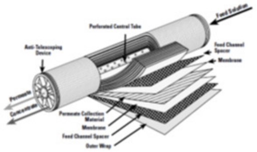
### ✓Laticínios

- Fracionamento de caseínas por MF
- UF na produção de queijos: pré-concentração, concentração parcial, concentração total
- NF de soro de leite (desmineralização parcial e concentração)





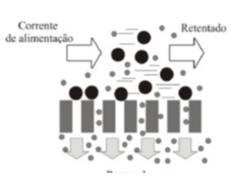


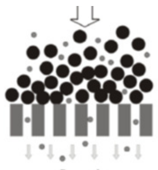
# Processamento por Membranas

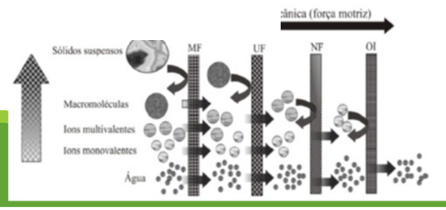
## ➢Aplicações

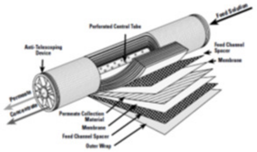
### ✓Sucos de fruta e vinho

- Clarificação do suco por UF ou MF (suco de maçã, uva, pera, abacaxi, *cranberry* e cítricos)
- Pasteurização de sucos por UF ou MF
- Concentração de sucos por pervaporação, RO, DO e UF





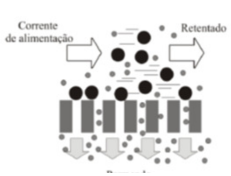


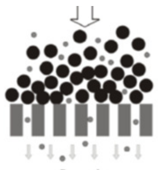
# Processamento por Membranas

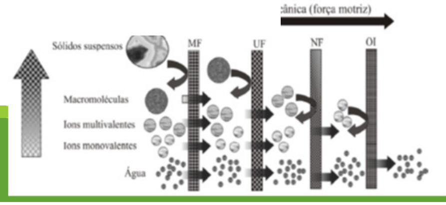
➢Aplicações

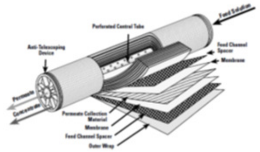
✓Sucos de fruta e vinho

- Estabilização tartárica de vinho e sucos de uva por ED
- Remoção de etanol por RO ou pervaporação





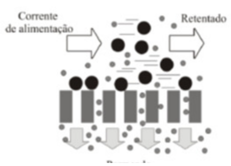


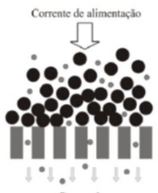
# Processamento por Membranas

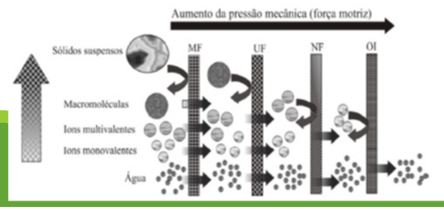
## ➢Aplicações

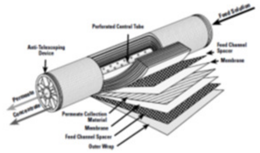
### ✓Cerveja

- Clarificação  por MF
- Recuperação de cerveja dos fundos de tanque por MF
- Pasteurização da cerveja por MF
- Remoção de etanol por RO





# Processamento por Membranas

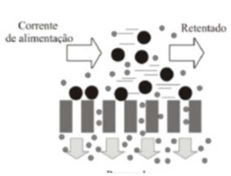
## ➢Aplicações

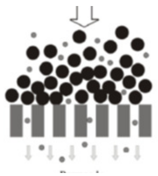
### ✓Óleo comestível

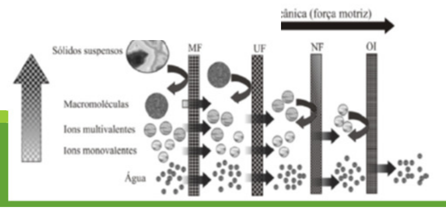
- Refino de óleos vegetais por UF e MF

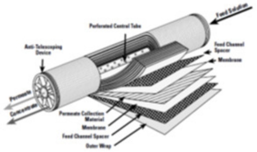
### ✓Processamento de águas residuárias

- Recuperação de compostos
- Redução do volume de efluentes gerados





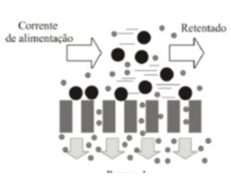


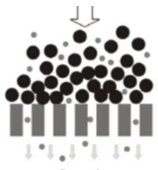
# Processamento por Membranas

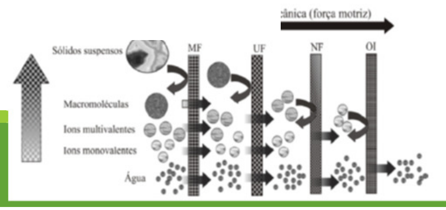
## ➢Aplicações

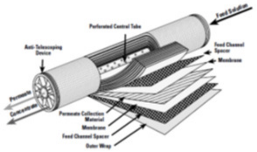
### ✓Outras aplicações

- Concentração de clara de ovo por UF
- Remoção da dureza da água e  desalinização por NF





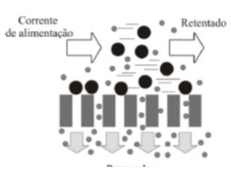


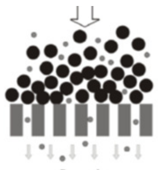
# Processamento por Membranas

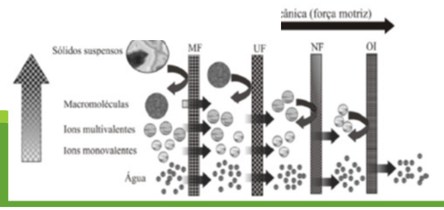
## ➢Limitações

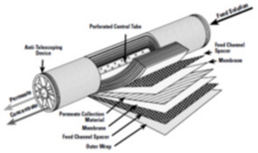
### ✓MF, UF, NF, RO

- Polarização por concentração, colmatagem, danos por cisalhamento em proteínas, restrição de concentração máxima (25-30) °Brix







# Processamento por Membranas

## ➢Limitações

### ✓OMD e DO

- Membranas precisam ser mais seletivas, apresentar melhores características de difusividade e permitir ciclos de operação mais longos
- Dimensionamento e otimização dos módulos e processos para melhorar o fluxo