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# 1 **Water reuse in the food processing industries: a review** 2 **on pressure-driven membrane processes as** 3 **reconditioning treatments**

4  
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## 13 **Keywords**

14 water recycling, water reuse, food industry, membrane processes.

## 15 **Abstract**

16 Establishing general rules for short wastewater recycling loops in the food industries is a  
17 challenging task . This work provides an overview on water consumption, effluent  
18 discharge and the main water consuming unit operations in this sector. Pressure-driven  
19 membrane processes as treatment technologies will be ~~are~~ focused on and nanofiltration  
20 and reverse osmosis appear unavoidable. An original synthesis of the membranes used, the

21 best operating conditions and the corresponding performances are is broken down by  
22 food sector and by effluent load. Recycling is mostly proposed ~~Most of the time recycling~~  
23 ~~is proposed~~ for floor washing, heating/cooling, vessel pre-cleaning, even though criteria  
24 for potable water are not fulfilled ~~potable water criteria are not reached~~. Water of a quality  
25 which is sufficient for recycling can be obtained with a single ~~one~~ membrane treatment  
26 stage only when ~~few-charged~~ weakly concentrated (COD < 1 g/L) non-fat effluents are  
27 concerned, originating from flushing, bottle washing or rinsing water after vegetable  
28 peeling. This critical review can be used as a guideline for recycling projects and points to  
29 ~~indicates~~ the remaining challenges and improvements to be made. ~~challenging progresses~~.

30

## 31 **Nomenclature**

32 AC = Activated Carbon

33 AR = Attributable Risk

34 BAT = Best Available Techniques

35 BOD = Biological Oxygen Demand

36 BREF = BAT Reference document

37 CF = Coagulation/Flocculation

38  $C_{\text{feed}}$  = Concentration of the pollutant in the feed solution

39 CIP = Cleaning In Place

40 COD = Chemical Oxygen Demand

41  $C_p$  = Concentration of the pollutant in the permeate

- 42 Cr = Concentration of the pollutant in the retentate
- 43 DAF = Dissolved Air Flotation
- 44 FDM = Food, Drink and Milk industries
- 45 FO = Forward Osmosis
- 46  $F_p$  = Permeate Flowrate
- 47  $J_p$  = Permeate flux
- 48 LCA = Life Cycle Analysis
- 49 MF = MicroFiltration
- 50 MWCO = Molecular Weight Cut-Off
- 51 NF = NanoFiltration
- 52 PCB = PolyChlorinated Biphenyls
- 53 PL = Pulsed Light
- 54 PreF = PreFiltration
- 55 QMRA = Quantitative Microbial Risk Analysis
- 56 R = solute retention rate
- 57  $S_m$  = Membrane surface
- 58 TKN = Total Kjeldahl Nitrogen
- 59 TMP = TransMembrane Pressure
- 60 TN = Total Nitrogen
- 61 TOC = Total Organic Carbone
- 62 TP = Total Phosphorus
- 63 TSS = Total Suspended Solids

64 UF = UltraFiltration

65 US = UltraSonication

66 UV = UltraViolet

67 RO = Reverse Osmosis

68 WWTP = WasteWater Treatment Plant

## 69 **1. Introduction: Benchmarking on water management in food** 70 **plants**

71 Human activities and particularly industrial activities contribute to climate change and  
72 severe water scarcity (Huang et al., 2021). The latter is predicted ~~projected~~ to get worse in  
73 the coming years in North Africa, Middle East, Pakistan, India and northern China (Asano et  
74 al., 2007; Meneses et al., 2017) and restrictions on the amount of water extracted from  
75 ground water and surface sources is becoming ~~become~~ unavoidable in temperate  
76 countries. Consequently, in order to ensure sustainable water management, ~~water~~  
77 ~~resources sustainability~~, UNESCO has fixed as one of its main targets to reduce by 20% the  
78 amount of water used by industries by 2030 (UNESCO, 2014). Being a major consumer of  
79 water and specifically ~~mainly~~ drinking water (Casani et al., 2005; Valta et al., 2016; Vanham  
80 et al., 2019), the food industry is particularly ~~dramatically~~ concerned by this issue and must  
81 ~~needs to~~ make significant efforts to reduce its water consumption. To this end, ~~in Europe~~  
82 the European Commission conducted a survey in Europe of the specific water consumption  
83 and wastewater discharge in some food industries (European Commission, 2019). Like  
84 other publications concerning the food industry, ~~As other reviews dealing with food~~

85 industry (Klemes et al., 2008; Muro et al., 2012; Ölmez, 2013), it highlights the fact that  
86 water management is greatly dependent on the sector (Table 1) and that data vary  
87 considerably depending on the reference.

88 Additionally, each food sector has different water uses depending on the characteristics of  
89 raw materials ~~raw materials characteristics~~ and on the transformation processes, as seen in  
90 Table 2 for beverage, fruits and vegetables, meat processing and dairy industries.  
91 Moreover, practices may vary in one given sector from country to country, as highlighted  
92 by Wojdalski et al. (Wojdalski et al., 2013) in the dairy industry: in this case, water  
93 consumption was shown to vary according to the degree of process automation of the  
94 country, the production factors and the equipment requirements (electric power, water  
95 consumption...). For instance, for ~~in~~ milk powder or cheese, water consumption (expressed  
96 in liters of water per liter of processed milk) ranges from ~~between~~ 0.69 to ~~and~~ 1.90 in  
97 Denmark whereas it is between 4.60 and 6.30 in Norway. It ~~is also~~ depends on ~~function of~~  
98 the plant size, as ~~in~~ at the Amul Dairy (India) for example, where the cleaning use  
99 (including CIP, floor wash, crate wash and railway tanker wash) reaches 4.5 million liters  
100 (Tiwari et al., 2016) representing 77% of the overall water consumption compared with  
101 ~~instead of~~ the average 49% mentioned in Table 2. These observations for the dairy industry  
102 can be generalized to other food industries.

103 Given the situational analysis above, in order to reduce water consumption in the food  
104 sector, two complementary strategies are envisaged ~~to be intended~~: i) The development of  
105 new water-efficient production processes ii) The re-design of water networks in the plants,  
106 including water recycling or reuse. To make the different options clear, it may be useful to

107 reiterate ~~restate~~ the definitions applied (recycling, reuse, reconditioning, etc.). The official  
108 ~~precise~~ definitions can be found ~~are collected~~ in Table 3. If there is a possibility that ~~In the~~  
109 ~~case where~~ effluents may be polluted with undesired substances and/or particles from ~~the~~  
110 food ingredients, or from ~~but also with~~ soils or pesticides, then recycling is preferred.

111 In several countries (such as Singapore, Australia, Israel, China and U.S. ~~U.S.A.~~ states such as  
112 Florida and California), many food industries have already set up water reuse and recycling  
113 projects (Meneses et al., 2017), and water reuse guidelines applicable ~~in~~ to the food  
114 industry are available. In Australia, the “water reuse guideline for food businesses in NSW  
115 considering reusing water” (NSW-Food-Authority., 2008) indicates both the feasible  
116 recycling solutions and a methodology to check that these solutions are not harmful to the  
117 product’s qualities. ~~don’t harm the product’s qualities.~~ In Europe, the European  
118 Commission has developed a guide regarding the minimum requirements for water reuse  
119 (European Commission, 2018).

120 ~~It has to be noted that~~ Water recycling strategies are considered at different levels ~~scales,~~  
121 from a geographic region to a unit operation in a plant. At the regional level, ~~region-scale,~~  
122 wastewater may be collected from several water treatment plants to provide water – after  
123 treatment - ~~water~~ to power stations, industrial users and even main drinking water supply  
124 storage, as in the Brisbane region (Australia) where the Western Corridor Recycled Water  
125 Project (WCRWP) was launched in 2009 (Apostolidis et al., 2011). This concept of “water  
126 mining” dates back to the 90s (Johnson et al., 1996), and requires a tight coordination  
127 between the different sectors and a good synchronisation ~~accordance~~ between their  
128 respective water fluxes, both those produced and those required. At the factory level ~~scale,~~

129 effluent is generally collected and mixed before a global treatment and possible an  
130 ~~eventual~~ recycling for non-food uses, outside the factory ~~like~~ for agricultural irrigation for  
131 example, or inside ~~like~~ for floor cleaning as illustrated by Apostolidis in the case of a  
132 brewery in Austria (Apostolidis et al., 2011). Though not as common, effluent recovery at  
133 the unit operation level ~~operation-unit scale~~ and its recycling within ~~inside~~ the production  
134 line is also possible, as ~~it~~ is the case in Cleaning In Place (CIP) where it is a current practice  
135 to use effluent from the rinse stage for the prewash stage (European Commission, 2019).  
136 Such short water recycling loops within or as close as possible to a unit operation ~~or as~~  
137 ~~close as possible to it~~ allow to set up a treatment process which is more specific to the  
138 ~~present~~ pollutants present, leading to higher treatment performances. ~~As a matter of~~ In  
139 fact, collecting and mixing wastewater from different unit operations generally leads to a  
140 only moderate efficiency of the treatment processes. Furthermore, pumping and transport  
141 of wastewater to a wastewater treatment plant (WWTP) or to the rejection point are expen-  
142 sive (Manzocco et al., 2015). Consequently, it would appear to be pertinent ~~It consequently~~  
143 ~~seems really relevant~~ to develop these short recycling loops.

144  
145 However, there is a lack of ~~broad~~ tools in this context to help re-design the water networks  
146 and choose, optimize and simulate the recycling or reuse scenarios. Considering the  
147 above-mentioned variations of the quality and quantity of wastewater ~~wastewater's quality~~  
148 ~~and quantity~~ even within a given food sector, a factory-by-factory study is needed. Recent-  
149 ly, as part of ~~in the lifetime of~~ a French research program (MINIMEAU ANR-17-CE10-0015,  
150 2018-2022), Nemati-Amirkolaii et al. developed some tools based on a Water Pinch analy-



151 sis to help choose ~~choosing~~ the best water recycling loops in a factory, with the aim of  
152 minimizing ~~to minimize~~ water consumption and wastewater production (Nemati-Amirkolai  
153 et al., 2019). In the same program, in order to appreciate the performances to be reached  
154 by the water reconditioning treatments, Garnier et al. proposed a methodology for the de-  
155 velopment of a new recycling project and the definition of both the most convenient and  
156 the cleanest technology for treatment, regarding ~~as regard to~~ the desired quality of the  
157 water to be recycled (Garnier et al., 2019).

158 With regard to this, ~~In this regard~~, an overview of the physical-chemical treatment  
159 solutions available in ~~the~~ scientific literature for food industry effluent needs to be  
160 established, ~~with a focus~~ focusing on the type of industry and considering water  
161 reconditioning at unit operation level. The choice of a treatment solution and its  
162 operational conditions necessarily involve the definition of the compounds to be removed  
163 from the effluent and of the targeted quality for the reused/recycled water. Consequently,  
164 ~~a literature~~ data analysis on effluent quality for each food industry sector needs to be  
165 performed. Finally, the membrane processes ~~are considered known to be simple to set up~~  
166 ~~and run in various industrial sectors, including among which the food transformation~~  
167 ~~sector and including wastewater treatment.~~ They present several advantages, mainly their  
168 modularity, robustness, compactness and the very limited pollution they generate as  
169 compared to ion-exchange or adsorption processes (Cui et al., 2010; Frenkel, 2010; Guiga  
170 and Lameloise, 2019; Pabby et al., 2008; Samaei et al., 2018). ~~Furthermore, they~~ They are  
171 considered simple to set up and are already well-known by the industrialists of ~~this~~  
172 ~~sector~~the food sector, as they have been ~~are~~ widely used since the 70s - 80s in the dairy

173 industry and since the 90s in several other food industries for the processing of fluid  
174 products (Daufin et al., 2001). Consequently, the present review focuses on these  
175 processes, and specifically on the pressure-driven membrane processes as reconditioning  
176 solutions of aqueous effluent produced in the food sector.

177 Several literature reviews exist that touch on this issue, but none of them target membrane  
178 applications for reducing water consumption in the food sector. In fact, some of the  
179 available articles deal with the general question of water reuse and recycling irrespective of  
180 the production sector and treatment process (Apostolidis et al., 2011; Asano et al., 2007;  
181 Lens et al., 2002). Others focus ~~are focused~~ on the food sector but do not address  
182 performances and efficiency of the membrane processes (Barbera and Gurnari, 2018;  
183 Casani et al., 2005; Klemes et al., 2008; Meneses et al., 2017; Ölmez, 2013; Wojdalski et al.,  
184 2013). In 2021, Pervez et al. proposed a short review on membrane processes for  
185 wastewater treatment in the food sector (Pervez et al., 2021) but this article considers very  
186 few case studies based on pressure-driven membrane processes and gives a more general  
187 view on membrane technologies: membrane distillation, electrodialysis, and electrospun  
188 nanofiber membranes. Finally, in 2012 Muro et al. (Muro et al., 2012) proposed a relevant  
189 review on wastewater treatment by membrane processes in the food industries. It  
190 provides global levels of pollution for each food industry, indicates the main retained  
191 solutes by each membrane category, the mean permeate fluxes for different case studies  
192 and the remaining pollutant concentration ranges obtained. However, this review remains  
193 descriptive and does not lead to any overview or guidelines for the feasibility of recycling  
194 the effluents produced.

195 Some studies ~~works~~ closer to our objectives deal with one specific food industry or case  
196 study: dairy (Galvão, 2018; Song et al., 2018), fresh-cut vegetables (Manzocco et al., 2015),  
197 brewery (Simate et al., 2011) or beverage (Tay and Jeyaseelan, 1995). ~~They Each of them~~  
198 They each provide valuable data and information for ~~each~~ the sector concerned ~~under~~  
199 ~~concern~~, and warrant gathering and comparison. ~~these deserve to be gathered and~~  
200 ~~compared to build an overview of the place of membrane processes in this context. In~~  
201 ~~2021, Pervez et al. proposed a short review on membrane processes for wastewater~~  
202 ~~treatment in the food sector (Pervez et al., 2021) but this article considered very few case~~  
203 ~~studies based on pressure-driven membrane processes. Finally, in 2012 Muro et al. (Muro~~  
204 ~~et al., 2012) proposed a relevant literature review on wastewater treatment by membrane~~  
205 ~~processes in the food industries. It gives the global levels of pollution for each food~~  
206 ~~industry, the main retained solutes by each membrane category, the mean permeate fluxes~~  
207 ~~for different case studies and the remaining pollutant concentration ranges obtained.~~  
208 ~~However, this review remains descriptive and does not provide an overview of the possible~~  
209 ~~guidelines for the feasibility of recycling effluents produced at different unit operations~~  
210 ~~and in different food industries.~~

211 ~~The present paper uses the above mentioned works and other multiple case studies to~~  
212 ~~build up a synthesis on recycling of aqueous effluents in the food sector: the major~~  
213 ~~effluents to treat, their composition and the relevance of the use of pressure-driven~~  
214 ~~membrane processes. It categorizes the case studies. This has been done That is what we~~  
215 ~~have done~~ in the present paper, which proposes a classification of the effluent by food  
216 industry, by origin (unit operation) and by charge (COD level). ~~—and. proposes an~~

217 ~~analysis~~When necessary, raw data was ~~were~~ processed and analysed in terms of treatment  
218 efficiency (residual pollution and permeate fluxes) ~~and concrete recycling possibilities (in~~  
219 ~~accordance with the regularoty texts and the identified possible derogations)~~. Treatment  
220 and recycling trends then emerge depending on the effluent type (in accordance with the  
221 ~~regularoty~~ regulatory texts and the identified possible derogations), as well as ~~on the~~ This  
222 ~~allows to conclude on the definition of the relevant cases for recycling and the limits of~~  
223 application of the membrane processes. It also highlights the remaining challenges in this  
224 field.

## 225 **2. Identification of the key parameters in the wastewater to be** 226 **reused or recycled**

227 When reusing or recycling water, knowing the quantity and detailed composition of the  
228 water to be treated as well as the quality of water required for each unit operation is  
229 essential ~~In case of reuse or recycling, knowing the quantity and the detailed composition~~  
230 ~~of the water to be treated and the water quality required for each unit operation is an~~  
231 ~~essential information~~ for the ~~theoretical~~ optimization of the water network as well as for  
232 choosing an appropriate treatment process when necessary. For WWTP purposes, average  
233 concentrations and specific loads of wastewater produced by European food industries are  
234 defined through global parameters (European Commission, 2019), such as Biological  
235 Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS),  
236 Total Organic Carbon (TOC), Total Nitrogen (TN) and Total Phosphorus (TP). Adapted to  
237 the design of a WWTP, these parameters are not suitable for selecting and scaling ~~to select~~

238 ~~and scale~~ a more specific process whose ~~which~~ objective may be to obtain an acceptable  
239 water quality for recycling in the food industry - possibly up to a potable water quality  
240 level - ~~neither to follow~~ or for tracking the elimination of one or several specific pollutants.  
241 Indeed, in many countries, the regulatory authority stipulates applying ~~to follow~~ the  
242 precautionary principle, meaning that potable water should be used when it is in ~~en~~  
243 ~~coming into~~ contact with food, as is the case in the European Community for which 75% of  
244 the water used ~~consumed~~ by the food industry is potable water (Barbera and Gurnari,  
245 2018; Valta et al., 2016). Quality evaluation of the treated water then requires the analysis  
246 of additional global parameters (colour, conductivity, odour, oxidability, turbidity and TOC)  
247 but also of more specific species such as organic micro-pollutants (pesticides, disinfectants,  
248 oils, PCB...), bromate, copper, nitrates, aluminium or iron. Consequently, wastewater quality  
249 has to be studied more accurately in order to scale treatment processes to ensure the  
250 safety of the treated water.

251 Examples of precise compositions of wastewater from food industries are given in ~~the~~  
252 literature but analysis remains to be adapted on a case-by-case basis. Table 4 gathers main  
253 wastewater origins and compounds present for the main food sectors, which may help to  
254 select the compounds to be analysed more specifically. ~~They can be organic such as sugars~~  
255 ~~(fructose, sucrose, lactose...)~~ or acids (citric, malic, lactic...), have a proteic or a lipidic origin,  
256 ~~be minerals, and~~ They are of course directly related to the type of food. Comparison of the  
257 measured levels with the expected water quality for recycling establish which compounds  
258 or "key parameters" should ~~to~~ be removed in priority as well as the choice of the treatment  
259 process and its operational conditions. Additionally, pollutants of small molecular weight

260 are often more difficult to eliminate due to their size, especially through membrane  
261 treatment. This is the case of most of the organic acids found in the wastewater of fruit and  
262 vegetable processing or dairy industries, or of the ethanol found in the wastewater of  
263 breweries and wineries. This may also be the case for organic micro-pollutants and their  
264 degradation products that do not significantly contribute to the global parameters (COD)  
265 but are present in the effluent of most of the food industry sectors. Consequently, their  
266 accumulation in the recycled water after several cycles of treatment must be investigated  
267 and controlled.

### 268 **3. Physical-chemical treatment possibilities for water** 269 **reconditioning**

#### 270 **3.1. Examples of recommendations and existing practices**

271 Some general guidelines exist worldwide for water management in the food industries,  
272 either produced by community ~~communitary~~ authorities (European Commission, 2018,  
273 2019) or published as handbooks by authors (Klemes et al., 2008). The example of the  
274 European Community is interesting. Indeed, the European Union commissioned a study on  
275 the Best Available Techniques (BAT) Reference document (BREF) used in the Food, Drink  
276 and Milk (FDM) Industries. For water management, this study summarizes the recycling and  
277 reuse practices in 495 factories (European Commission, 2019), that we have synthesized  
278 ~~managed to synthesize~~ in Table 5. As mentioned above ~~above-mentioned~~ and gathered in  
279 Table 2, Klemes et al. (2008), among other authors, also contributed to build an overview

280 on water consumption in different food industries, providing valuable benchmarks to  
281 manufacturers of each industry. ~~providing to manufacturers of each industry valuable~~  
282 ~~benchmarks.~~

283 From these different syntheses, the dairy industry stands out as the main and first sector  
284 where recycling has been extensively studied and where applications were implemented on  
285 an ~~at~~ the industrial scale (Daufin et al., 2001; Kolev Slavov, 2017). Water recycling after  
286 treatment by membrane processes is assessed (mainly UF followed by RO), and several  
287 examples exist: for instance, condensate from evaporation plants (for concentrated milk  
288 production) could be recycled as high-quality water stream after RO filtration (Mavrov and  
289 Belieres, 2000; Muro et al., 2012). ~~Elsewhere in~~In this sector, simulation and experimental  
290 studies were carried out at India's largest plant. ~~the India's largest plant undertook~~  
291 ~~simulation and experimental studies~~ (Tiwari et al., 2016). The wastewater from CIP of the  
292 vessels used for butter clarification (*ghee* obtained by the elimination of the aqueous  
293 phase) could be recycled after coagulation and adsorption for its own pre-washing step.  
294 The blow-down wastewater from the cooling tower could be recycled for the same use  
295 after a membrane filtration such as RO (Tiwari et al., 2016).

296 For the other food sectors, the fruit and vegetable industry provides some examples where  
297 blanching water can be reused for preliminary cleaning of freezing tunnels (European  
298 Commission, 2019; Klemes et al., 2008). 90% of the total water used in this sector is for  
299 cleaning and rinsing after peeling and many authors claimed that 90% of the water used  
300 could be saved if all the wastewater arising from the washing steps was recycled essentially  
301 for device cleaning (Lehto et al., 2014; Manzocco et al., 2015).

302 In several cases, for any food sector, disinfection ~~may be~~ appears critical before recycling.  
303 In addition to the conventional sodium hypochlorite treatment, the BREF for the Food,  
304 Drink and Milk sectors (European Commission, 2019) describes two emerging disinfection  
305 techniques in the fresh-cut vegetable industry : ozone/UV treatments before fresh-cut  
306 vegetable washing, and the use of Neutral Electrolyzed Oxidizing water (NEOW) for salad  
307 disinfection.

### 308 **3.2. Analysis of the membrane process applications for food** 309 **wastewater reconditioning**

310 As observed in ~~arises through~~ the previous examples, membrane processes have been  
311 used for a long time and are often chosen for the treatment of wastewater from the food  
312 industry. ~~the use of membrane processes is often chosen for the treatment of wastewater~~  
313 ~~from the food industry and for a long time~~ (Daufin et al., 2001). Depending on the  
314 membrane filtration process and the membrane molecular weight cut-off (MWCO),  
315 different types of pollutants or particles can be removed (Table 6).

316 The performances of the chosen membrane filtration process ~~Whatever the membrane~~  
317 ~~filtration process, its performances~~ for a given Transmembrane Pressure (TMP) are  
318 evaluated by the pollutants retention or removal efficiency R, expressed as :

$$319 \quad R = \frac{C_r - C_p}{C_r} \cdot 100 (\%) \quad (1)$$

320 Where  $C_r$  (or  $C_{\text{feed}}$ ) and  $C_p$  are the concentrations of the key parameter concerned ~~under~~  
321 ~~concern~~ respectively in the retentate (or feed) and in the permeate.

322 The permeate flux  $J_p$  obtained under a given TMP is also an essential parameter as it



323 accounts for the purified water productivity :

324

$$325 \quad J_p = \frac{F_p}{S_m} \quad (\text{L.h}^{-1}.\text{m}^{-2}) \quad (2)$$

326

327 Where  $F_p$  is the permeate flowrate ( $\text{L.h}^{-1}$ ) and  $S_m$  the effective membrane area ( $\text{m}^2$ ).

328

329 UF, NF and RO are usually the main treatments used as polishing steps to remove the  
330 soluble organic load and minerals. However, they need to be preceded by relevant pre-  
331 treatments to improve their efficiency (technically and economically) .~~These steps which~~  
332 allow elimination of ~~to eliminate~~ TSS, turbidity or O&G (Frenkel, 2010; Muro et al., 2012)  
333 thus avoiding premature NF and RO membrane fouling or its physical damage. ~~After~~  
334 ~~possible rough pre-treatments steps such as settling, sand filtration, sieving or cartridge~~  
335 ~~filtration (prefiltration, PreF) for example, MF is generally used as a membrane prefiltration~~  
336 ~~to eliminate the smallest particulates. A post-treatment such as chemical or physical~~  
337 ~~disinfection ensures the water safety and its suitability for food contact.~~

338 Examples of reconditioning pre-treatments and treatment studies with membrane  
339 processes are gathered in Table 7 and categorized by food industry, wastewater origin  
340 (unit operation~~unit~~) and global charge (COD level). The applied treatments are  
341 characterized (membrane type or cut-off, salt rejection, permeate fluxes and residual  
342 concentrations) and the potential recycling application is given when available.

343

344 **3.2.1. Pre-treatment: Total Suspended Solids (TSS) and turbidity removal**

345 Different solutions can be found to eliminate all particles from coarse to ultrafine particles,  
346 generally including a ~~including as most often used techniques~~ a rough pre-treatment or  
347 clarification step, consisting in settling, sand filtration, sieving, or Coagulation/Flocculation  
348 (CF) (Azbar and Yonar, 2004; Azmi et al., 2013; Coskun et al., 2013; Ioannou et al., 2013;  
349 Mavrov et al., 1997; Pauer et al., 2013). Generally, depending on the clarifier technology,  
350 the turbidity removal efficiency varies from 90% to 99% through CF. ~~followed by~~  
351 ~~clarification or granular media filtration~~. It is usually followed by depth prefiltration through  
352 microfiltration with cartridge filters, cross-flow microfiltration or ultrafiltration, combined or  
353 not (Barbera and Gurnari, 2018). As can be seen in Table 7 for food industry effluents,  
354 prefiltration (PreF) and/or microfiltration (MF) from 100  $\mu\text{m}$  down to 0.2  $\mu\text{m}$  is one of the  
355 most widespread pre-treatment processes encountered, regardless of ~~whatever~~ the  
356 industrial effluent source (Azmi et al., 2013; Bortoluzzi et al., 2017; Fährnich et al., 1998;  
357 Gebreyohannes et al., 2015; Ioannou et al., 2013; Malmali et al., 2018; Mavrov and Belieres,  
358 2000; Riera et al., 2013; Rogener et al., 2003; Sridhar et al., 2002; Suárez et al., 2014; Suárez  
359 and Riera, 2015; Tay and Jeyaseelan, 1995). ~~It may be preceded by a clarification step~~  
360 ~~(sedimentation, dissolved air flotation (DAF) or centrifugation) with or without~~  
361 ~~Coagulation/Flocculation (CF)~~

362 For wastewater from brewery bottle-washing (Rogener et al., 2003), ~~combined flocculation~~  
363 ~~/belt filtration, cross or depth MF, UF, hydrocyclone or anthracite / sand filtration are~~  
364 ~~compared~~. results show that combining anthracite / sand filter and bag filters (coarse and  
365 fine depth filtration) is the best solution ~~for this kind of effluent~~. Belt filter is also found  
366 efficient to remove glass residues, parts of labels and coarse impurities from the mineral

367 water bottle-washing wastewater (Mavrov and Belieres, 2000).

368 CF with and without chemicals is usually used as pre-treatment of wastewater from root  
369 vegetables (Lehto et al., 2014), and sand filtration is also found competitive for carrot  
370 wastewater treatment, provided the velocity in the sand filter is low enough to allow  
371 pathogenic fungi removal (Mebalds and Hamilton, 2002). Results from Garnier et al. (2020)  
372 show that wastewater from carrot rinsing after peeling could be pre-treated by settling or  
373 trommel screening, followed by MF or UF, leading to about 90% of TSS and up to 28% for  
374 COD (Garnier et al., 2020), consistent with Reimann (2002) and Pauer et al. (2013) results  
375 with ~~pre-treatment ensured by UF~~ (in that case considered as pre-treatment).

376 In the vegetable oil refining industry sector (Coskun et al., 2013), UF may also be  
377 encountered but centrifugation and CF are the main pre-treatment processes studied. In  
378 this sector, Dissolved Air Flotation (DAF) is shown to be efficient to assist grease and oil  
379 flotation, further separated with a flat scraper, ~~Results on effluents from two fat and~~  
380 ~~vegetable oils industries in Turkey (Azbar and Yonar, 2004) show that it allows to reach~~  
381 leading to 50% of COD removal. It is improved to 90% for COD, BOD<sub>5</sub>, TSS, Total Kjeldahl  
382 Nitrogen (TKN) and O&G if DAF is combined with chemicals (Azbar and Yonar, 2004).  
383 Nevertheless, concentrations ~~after DAF and chemical treatments~~ in the pretreated effluent  
384 remain very high and not suitable ~~convenient~~ for reuse as process water.  
385 Coagulation/Flocculation at a rather basic pH followed by settling also allows to decrease  
386 COD and turbidity (Khouni et al., 2020; Louhichi et al., 2019). But these processes are  
387 efficient only for free and dispersed-oil elimination.

388 Finally, UV may be used ~~before membrane treatment to inhibit bacterial build-ups or algal~~

389 bloom and limit thereby the fouling risks (Mavrov and Belieres, 2000; Mavrov et al., 1997).  
390 Finally, Eventually it is interesting to note that for flushing water in the dairy industry, no  
391 pre-treatment is found necessary in the examples given of in Table 7, whatever the COD  
392 level. This may be explained by the fact that these effluents mainly contain dissolved  
393 organic compounds. This makes it possible to perform simpler treatment processes with  
394 fewer steps, which makes these effluents good candidates for treatment and recycling. This  
395 is also the case for low contaminated washing water of fresh-cut vegetables, for which a  
396 pre-treatment step followed by MF is sufficient before NF or RO treatment. On the  
397 contrary, for highly loaded effluents (COD > 10 g/L) whose pre-treatment requires a  
398 complicated chain of processes with different fluxes, correlating them with a continuous  
399 processing polishing unit seems industrially difficult. The recycling solution could then  
400 require a storage step. This is probably the case for the proposed pre-treatment of sausage  
401 cooling water (Table 7) where sedimentation + MF + H<sub>2</sub>O<sub>2</sub> + UV were shown necessary.  
402 This treatment example is certainly efficient at a laboratory or pilot scale but seems  
403 unfeasible at an industrial scale.

### 404 **3.2.2. Treatment by membrane processes**

405 ~~The numerous and various case studies presented~~ As shown in Table 7, membrane  
406 technologies (UF, NF and RO) are used as polishing and reconditioning processes show  
407 ~~that~~ for wastewater treatment in all food sectors. ~~consider and study membrane processes~~  
408 ~~as polishing and reconditioning treatment.~~ In some cases, especially when the effluent  
409 presents a low charge (COD < 1 g.L<sup>-1</sup>) or when it does not result from contact with food  
410 ingredients (vapour condensates, washing of mineral water bottles), the quality of treated

411 wastewater may allow an authorization for reuse (Mavrov and Belieres, 2000).  
412 On the contrary, in the most difficult cases such as charged vegetable oil wastewater, ~~the~~  
413 ~~performed treatments only allow to discharge~~ the treated water can only be discharged  
414 into the receiving environment (Khouni 2020) or ~~to use used them~~ for irrigation (Ochando-  
415 Pullido 2018).

416 Between those two situations, most investigations result in relatively good permeate  
417 qualities for which the prospective reuse destinations proposed should be submitted to  
418 the local authorities to obtain a derogation for its reuse in the process. ~~Nevertheless,~~  
419 ~~s~~Some other "degraded" reuse opportunities are ~~performed~~ proposed, such as floor  
420 washing (Kyrychuk 2014). Yet, in many cases, drinking water quality is considered as  
421 reached, as the quality obtained meets applicable standards. However, direct contact with  
422 food ingredients is avoided, and uses mainly concern heating, cooling, first  
423 cleaning/washing, or bottle first washing.

424 For the dairy industry, the most common effluents produced are flushing water (water-  
425 diluted milk) and tank washing water. The former are particularly interesting because their  
426 treatment would allow the recovery of milk components in addition to purified water. The  
427 latter can be treated to recover both water and cleaning solutions (ex. NaOH).  
428 Nanofiltration with MWCO 150 – 300 Da allows the retention of generally more than 90%  
429 of the COD, reaching even 99%, COD being mainly composed of lactose and nitrogenous  
430 molecules (proteins, TKN), that are efficiently retained (Brião et al., 2019; Kyrychuk et al.,  
431 2014; Song et al., 2018; Vourch et al., 2008). Then TMP between 10 – 20 bar is usually used  
432 for up to 100 L.h<sup>-1</sup>.m<sup>-2</sup> permeate flux. However, depending on the initial concentration of

433 pollutants, which is widely uneven depending if on whether flushing waters or vapor  
434 condensates are concerned, the obtained permeates may still contain unacceptable  
435 concentrations for a drinking water type, with up to several hundred ppm in lactose or ~~few~~  
436 ~~hundred mg.L<sup>-1</sup>~~ TOC (Balannec et al., 2002; Balannec et al., 2005; Bortoluzzi et al., 2017). For  
437 those more concentrated streams, a simple NF or RO treatment may be enough to  
438 produce water for heating, cooling or cleaning purposes; but more often NF plus RO or a  
439 double NF is required. For the lower loads (COD < 1 g.L<sup>-1</sup>), a quality close to drinking water  
440 is reached (TOC < 3 - 10 mg.L<sup>-1</sup>) with a simple or a double-stage RO, under 20 – 30 bar,  
441 corresponding to a permeate flux of about 30 L.h<sup>-1</sup>.m<sup>-2</sup> (Brião et al., 2019; Kyrychuk et al.,  
442 2014; Mavrov et al., 2001; Song et al., 2018; Vourch et al., 2005, 2008). Additionally, authors  
443 indicate that effluent storage before treatment (24 h) lowers the effectiveness of RO or  
444 NF+RO operations (Vourch et al., 2008). This is generally due to the biodegradation of  
445 organic solutes, representing nutrient media for micro-organisms. This microbial  
446 development leads to the synthesis of lower molecular weight solutes, resulting in a  
447 decreased effectiveness of the membrane process. ~~into smaller molecules, leading to lower~~  
448 ~~COD retention by the membranes.~~ This result is interesting as it confirms that it is essential  
449 to give special attention to the synchronisation of fluxes to avoid storage, as already  
450 mentioned (section 3.2.1).

451 Concerning the beverage industry, wastewater with low organic loads (< 1 g.L<sup>-1</sup>) can be  
452 treated through NF run at lower TMP (8 – 10 bar), ~~which allows to obtain a~~ but high  
453 permeate flux in the range 80 - 100 L.h<sup>-1</sup>.m<sup>-2</sup> depending on the membrane, while  
454 eliminating up to 100% of the COD content (Braeken et al., 2004; Mavrov and Belieres,

455 2000; Rogener et al., 2003). However, only RO leads to a "drinking water quality", preceded  
456 or not by a NF step. If recycling is intended for bottle washing, ~~it may be noticed that the~~  
457 hardness of the rinsing water must be reduced to ~~decreased~~ below  $0.9 \text{ mmol.L}^{-1} \text{ Ca}^{2+}$   
458 (Klemes et al., 2008) to avoid calcium deposit on bottles.

459 For wastewater with higher organic loads (generally corresponding to the washing water of  
460 barrels, tanks, reservoirs or bottles that were previously in contact with beverage), a single  
461 NF or RO treatment operation proved insufficient to reach drinkable water quality, with  
462 residual COD values at  $97 - 210 \text{ mg.L}^{-1}$ , mainly due to ethanol in the cases of brewery and  
463 winery, and conductivities at  $146 - 3320 \text{ }\mu\text{S.cm}^{-1}$  (Braeken et al., 2004; Ioannou et al., 2015).  
464 Nevertheless, in some cases such as the winery industry, RO retentates contain high  
465 amounts of polyphenols that can be recovered and used for food or non-food applications  
466 (Ioannou et al., 2013). This second type of valorisation would make the treatment effort  
467 economically sustainable, especially when high pressures are applied or when a double-  
468 stage of NF/RO is necessary.

469 In the case of fruit and vegetable, two very different situations are encountered. On the  
470 one hand, peeling and washing effluent represents the highest fluxes, ~~while their~~ with  
471 moderate organic charge ~~is moderate~~ (few  $\text{g.L}^{-1}$  or  $< 1 \text{ g.L}^{-1}$ ). UF treatment then appears  
472 insufficient to treat this effluent with retention ~~R~~ below 40% - and residual COD at about  
473  $800 \text{ mg.L}^{-1}$  - or insufficient removal of micro-organisms (Mundi and Zytner, 2015; Reimann,  
474 2002). ~~UF followed by~~ A complementary RO treatment at TMP ~~←~~ up to 17 bar allows to  
475 obtain 92% to 98% of COD removal for a residual COD content below  $60 \text{ mg.L}^{-1}$ , but with  
476 low permeate fluxes at  $6 \text{ to } 41 \text{ L.h}^{-1}.\text{m}^{-2}$  and authors conclude that reuse may be possible

477 ~~to a possible reuse for a first washing of food ingredients (Reimann, 2002), and in any case~~  
478 ~~before blanching (Garnier et al., 2020). On the other hand, cooking and blanching effluent,~~  
479 ~~due to the enhanced mass transfer at the high temperatures applied, is highly~~  
480 ~~concentrated. Table 7 shows the example of soybean cooking water with 70 - 85 g.L<sup>-1</sup> COD,~~  
481 ~~requiring high-pressure NF treatments (20 bar) with tight membranes (150-300 Da). The~~  
482 ~~permeate fluxes then obtained are moderate (35 - 61 L.h<sup>-1</sup>.m<sup>-2</sup>) and they latter still contain~~  
483 ~~very high COD concentrations (8 - 10 g.L<sup>-1</sup>) (Pauer et al., 2013). (Pauer et al., 2013) for~~  
484 ~~which the ~~Even though Authors~~ authors indicate a possible "degraded" reuse such as floor~~  
485 ~~cleaning, excluding any use in the food transformation process. But even then, a risk~~  
486 ~~analysis should absolutely be run to ensure that this recycling has no negative impact on~~  
487 ~~foods and employees safety.~~

488 Concerning the poultry and meat production, a single or double NF operation (depending  
489 on the effluent) at moderate TMP (3 - 6 bar) and permeate fluxes around 20 L.h<sup>-1</sup>.m<sup>-2</sup>, often  
490 completed with a disinfection (UV) step, seem enough to treat the low charge sausage  
491 cooling waters (COD < 0.5 g.L<sup>-1</sup>) ~~seem to be treated enough to be~~. It allows its recycling  
492 ~~recycled~~ as water of drinking quality, with TOC content below 2.5 mg.L<sup>-1</sup> in certain cases  
493 (Fährnich et al., 1998; Mavrov and Belieres, 2000; Mavrov et al., 1997). ~~The treatment then~~  
494 ~~consists of a single or a double NF operation depending on the effluent, at moderate TMP~~  
495 ~~(3-6 bar) and permeate fluxes around 20 L.h<sup>-1</sup>.m<sup>-2</sup>, often completed with a disinfection (UV)~~  
496 ~~step~~. Fährnich (1998) notes that in case of storage tank use before treatment, the latter  
497 should undergo a daily CIP operation to avoid microbial development. We can conclude  
498 that even though it is weakly concentrated, effluent storage should always be avoided.



499 In the case of more concentrated effluents, UF alone (30 kDa) or followed by a reverse  
500 osmosis treatment is proposed for water recycling or discharge, but without any further  
501 detail. Globally, these effluents originating from a direct contact with poultry and meat,  
502 present a particular risk of presence of pathogenic micro-organisms and an UF treatment  
503 alone seems to be insufficient for a reuse authorization.

504 However, vegetable oil effluent seems to be the most difficult to treat. Oil extraction  
505 processes are very different depending on the vegetable treated. Here are obviously are  
506 only presented examples generating wastewater, but it is worth noting that many  
507 processes generate organic solvent effluents that are also investigated for treatment and  
508 reuse. Apart from oil process wastewater with  $\text{COD} < 1 \text{ g.L}^{-1}$ , pre-treatment is  
509 systematically required for highly loaded effluent. Then, UF treatment alone only allows to  
510 discharge permeates into the receiving environment. RO or tight NF membrane treatments  
511 are required for reuse in the process and need to be applied at high TMP (up to 25 bar for  
512 NF and 55 bar for RO). Permeate fluxes vary significantly, from 39 to  $100 \text{ L.h}^{-1}.\text{m}^{-2}$   
513 depending on the initial effluent quality. However, NF performances are insufficient  
514 regarding the remaining COD amounts at  $2 - 3 \text{ g.L}^{-1}$  when the initial COD is about  $13 \text{ g.L}^{-1}$   
515 (Ochando-Pulido et al., 2018). Only RO and even a double-stage RO treatment allow to  
516 obtain a suitable permeate quality for reuse with a residual COD below  $50 \text{ mg.L}^{-1}$  (Sridhar  
517 et al., 2002). Forward osmosis is also tested on olive mill wastewater (Gebreyohannes et al.,  
518 2015), to reduce the total discharged volume and to recover phenolic compounds. At last  
519 Finally, for the most concentrated wastewater ( $\text{COD} 53 - 67 \text{ g.L}^{-1}$ ) only RO treatment allows  
520 to reach permeates suitable for discharge, with a still high residual COD of  $0.7 \text{ g.L}^{-1}$ . A

521 critical technical aspect must be highlighted concerning wastewater from vegetable oil  
522 processing: it is the negative impact of organic solvents, even in low amounts, on the  
523 membrane integrity and thus its lifetime (Low and Shen, 2021). Additionally, fouling issues  
524 arise with these effluents, making the use of membrane processes unlikely at the industrial  
525 scale.

526 ~~Eventually, forward osmosis (FO) is arousing an ever greater interest in the scientific~~  
527 ~~community, with the advantage of a reversible fouling contrary to other membrane~~  
528 ~~processes, where it becomes irreversible due to foulant compaction by hydraulic pressure~~  
529 ~~(Gebreyohannes et al., 2015). It can be used for wastewater treatment as well as for food~~  
530 ~~processing (Cath et al., 2006). It was studied for the treatment of dairy and vegetable oils~~  
531 ~~effluents (Gebreyohannes et al., 2015; Song et al., 2018). Nevertheless, permeate fluxes~~  
532 ~~remain low. Combined with a recovery process such as RO or bio-electrochemical system,~~  
533 ~~FO can be used to produce pure water from wastewater.”~~

534

535 As a conclusion, the analysis above demonstrates that membrane processes for short-loop  
536 treatment/recycling of water in the food industry seem relevant when this wastewater  
537 presents a slight-low COD load (< few g/L) and is preferentially not fat. Otherwise, it is  
538 important to evaluate the opportunity to valorize the residual solutes concentrated in  
539 retentates to ensure a global sustainability of the treatment process. For all the other cases,  
540 alternative treatment processes must be considered (other physical-chemical treatments or  
541 biological treatments).

542 Furthermore, when BOD/COD ratio is high, it would be preferable to avoid storage to limit

543 microbial degradation of the effluent, that leads to smaller molecules, more difficult to  
544 eliminate by membrane processes.

545 In all cases, recycling with a direct food contact does not yet seem ~~seems not yet~~ to be  
546 common and is even prohibited by several national and community regulations, to uphold  
547 ~~ensure~~ the precautionary principle. However, our analysis brings out diverse uses of the  
548 treated wastewater, such as heating, cooling, in boilers, or in first washing/rinsing steps of  
549 ingredients or vessels before rinsing with drinking water.

### 550 **3.2.3. Post-treatments: Disinfection**

551 Disinfection is used to inactivate or to destroy micro-organisms present in the water. It is  
552 usually installed at the end of the treatment process scheme but can also be installed for  
553 instance before membrane treatment to limit fouling: in this case it inhibits bacterial build-  
554 ups or algal bloom and limits thereby the fouling risks (Mavrov and Belieres, 2000; Mavrov  
555 et al., 1997). ~~as already mentioned (Mavrov and Belieres, 2000)~~ To design a disinfection  
556 process, inactivation target is defined and expressed as the decimal reduction rate of the  
557 microorganisms number. In the fresh-cut vegetable industry, a 5 log reduction of  
558 pathogenic bacteria is generally considered as a minimum for allowing washing water to  
559 be recycled (Manzocco et al., 2015).

560 Disinfection can be chemical or physical. Ozone is mainly used for its huge oxidizing effect,  
561 and chemicals containing chlorine compounds are necessary for its persistency  
562 (hypochlorite and related compounds, chloramines, chlorine dioxide, acidified sodium  
563 chlorite). In the case of physical disinfection, different technologies such as Ultraviolet Light  
564 (UV), Pulsed Light (PL) and UltraSonication (US) are possible, used alone or combined.

565 Some authors have reviewed the advantages and limitations / drawbacks of each solution  
566 (Klemes et al., 2008; Manzocco et al., 2015).

567 Table 8 brings together examples of disinfection post-treatment in the food industry, after  
568 membrane treatment. Disinfection with chlorination or UV is mainly proposed, even if  
569 membrane treatment also ensures disinfection by physical removal of any microorganism.

## 570 **4. Conclusion**

571 On the basis of numerous case studies available in the literature and some literature  
572 reviews, the present work allowed to build a synthesis of the applications of membrane  
573 processes to treat food industry effluent in order to recycle it into the food production  
574 processes.

575 This synthesis classified the applications according to the COD level and the efficiency of  
576 the treatment (permeate flux and composition), for each food industry. This made it  
577 possible to ~~delimit~~ define the cases where the applied treatment leads to obtaining a water  
578 quality suitable for recycling, even though potable water criteria are not reached. The main  
579 recycling applications found deal with non-food contact, due to current regulatory  
580 limitations: recycling for floor washing, heating, cooling, bottle or vessel pre-cleaning. This  
581 work also allowed to identify the cases where membrane treatments seem to be  
582 simultaneously technically efficient and cost effective: these are the cases where only one  
583 membrane treatment stage is sufficient to obtain water quality complying with local  
584 recycling requirements. This generally corresponds to ~~few-charged~~ low COD content  
585 (COD < 1 g/L) non-fat effluent, generally originating from flushing, bottle washing or

586 vegetable rinsing water ~~after peeling~~. For more loaded effluent, the valorization of solutes  
587 recovered in the retentates would be a solution ~~becomes essential~~ to obtain economically  
588 efficient treatment processes.

589 Finally, the data of purified water flux, applied pressure and pollutant rejections collected  
590 in this work for certain membrane types, make it possible to undertake an initial scale-up  
591 study.

592 Once the overall reconditioning treatment is selected for a given new application, pilot  
593 tests have still to be run in order to confirm if the treated water quality fits with the  
594 intended purpose. Of course, the treated cases in the present work are mostly research  
595 cases dealing with the feasibility of membrane treatment and some critical aspects such as  
596 flux decline, fouling, energy consumption or life cycle analysis are not brought to the fore  
597 even though they represent key parameters for industrial scale running. Simulations of the  
598 long term permeate productivity and quality obtained would then allow to validate the  
599 recycling strategy and show if a given pollutant accumulation may occur, possibly having a  
600 detrimental impact and questioning the treatment process choice. Moreover, a risk  
601 analysis, such as Quantitative Microbial Risk Assessment (QMRA) or Attributable Risk (AR),  
602 has to be performed (Lens et al., 2002) in order to establish the impacts on materials and  
603 products, including that on existing wastewater treatment. A Life-Cycle Assessment (LCA)  
604 would finally allow to estimate the overall benefits gained with the ~~planned~~ planned  
605 solution when compared to the existing scheme.

606 Otherwise, whereas scaling phenomena may happen with hard water, membrane  
607 technologies may lead to softened water (low calcium and magnesium content)

608 responsible for corrosion. Care should then be taken to obtain the right calcium-carbonate  
609 balance of the treated water (Hallopeau & Dubin method).

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858 **Tables:**

859 **Table 1:** Water consumption and specific wastewater discharge in some European food  
 860 factories (European Commission, 2019)

861

<b>Food Industry</b>	<b>Product</b>	<b>Unit</b>	<b>Specific water consumption</b>	<b>Specific wastewater discharge (yearly average)</b>
Dairy	Milk	m <sup>3</sup> .ton <sup>-1</sup> of raw materials	0.33-12.61	0.3-3.0
	Cheese	"	0.24-4.9	0.75-2.5
	Powder milk	"	0.50-4.27	1.2-2.7
Fats and oils	Oilseed / vegetable oil	m <sup>3</sup> .ton <sup>-1</sup> of oil produced	0.2-4.5	0.15-1.9
	Olive oil	"	2.16-10.29 (3 installations)	0.33-8
Fruits, vegetables and agricultural	Potatoes	m <sup>3</sup> .ton <sup>-1</sup> of products	10	4.0-6.0 (excluding potatoes flakes and powder)
	Tomato	"	2.5-9	8.0-10.0 (excluding tomato powder and with recycling)
	Fruits and vegetables	"	1-15	0-35
	Sugar beet	m <sup>3</sup> .ton <sup>-1</sup> of beets	0-0.9	0.5-1.0
	Soft drinks and nectar / juice	m <sup>3</sup> .hL <sup>-1</sup> of products	0-0.3 (maximum at 5.1)	0.08-0.20
Beverage	Beer	m <sup>3</sup> .hL <sup>-1</sup> of products	0.2-0.6 (maximum at 3)	0.15-0.50
Other	Wet pet food	m <sup>3</sup> .ton <sup>-1</sup> of products	2.64-4.88	1.3-2.4

862 **Table 2:** Examples of specific uses of water in different food sectors (Klemes et al., 2008)

863

<b>Water consuming activity</b>	<b>Beverage (%)</b>	<b>Meat processing (%)</b>	<b>Vegetable (%)</b>	<b>Dairy (%)</b>
Ingredient	60	0	0	0
Plant cleaning	25	48	15	49
Cooling towers	2	2	5	6
Process operations	8	47	78	42
Auxiliary use	5	3	2	3

864 **Table 3:** Definitions of specific terms used

Specific terms	Definition	Source
Reuse	<p>"Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived."</p> <p>➤ Wastewater is reused without treatment.</p>	(European Commission, 2019)
Recycling	<p>"Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes."</p> <p>➤ Wastewater is treated before using it again.</p>	(European Commission, 2019)
Reconditioning treatment	<p>"The treatment of water intended for reuse by means designed to reduce or eliminate microbiological, chemical, and physical contaminants, according to its intended use."</p> <p>➤ Wastewater is treated with purifying processes.</p>	(Codex.Alimentarius, 1999)
Reused water	Wastewater which is reused or recycled.	(Codex.Alimentarius, 1999)

865

866

867 **Table 4:** Overview of the main origins of the wastewater for some food industries, and  
 868 parameters and compounds found therein

Type of industry	Main origins of wastewater	Parameters and compounds present in wastewater	References
Winery	Washing, cooling and cleaning equipment, facilities	Ethanol, Sugars Phenolic compounds Total Nitrogen (TN)  $PO_4^{3-} / K^+ / Na^+$	(Klemes et al., 2008) (Buelow et al., 2015) (Ioannou et al., 2015)
Dairy	Clean-in-Place (CIP) Heat treatments: pasteurising, Ultra-High Temperature (UHT) processes, chilling, cooling, steam production	TSS, COD, TOC, TN, TKN, TP, color  Proteins (caseins)/ Carbohydrates (lactose) / Lipids / Urea / Organic acids (citric, lactic...) / Oil and Grease (O&G)  Conductivity, pH  $NH_4^+ / PO_4^{3-} / Na^+ / Cl^- / Ca^{2+} / Mg^{2+} / K^+ / Na^+$  Detergents and sanitizing agents	(Balannec et al., 2002) (Balannec et al., 2005) (Barbera and Gurnari, 2018) (Galvão, 2018) (Bortoluzzi et al., 2017) (Klemes et al., 2008) (Riera et al., 2013) (Song et al., 2018) (Suàrez and Riera, 2015)
Fats and oils	Degumming Deacidification Deodorisation steps Blowdown of the boiler De-oiling of the bleaching earth	COD, BOD, TOC, Total Dissolved Solids (TDS), TSS, color, turbidity  (O&G/ Phenolic compounds / Nitrogen compounds / Pesticides  Conductivity, pH  $SO_4^{2-} / S^{2-} / PO_4^{3-} / Ca^{2+} / Mg^{2+} / K^+ / Mn^{2+} / Fe^{2+} / Cu^{2+} / Zn^{2+} /$ Heavy metals Catalyst used in the hydrogenation process	(Azbar and Yonar, 2004) (Azmi et al., 2013) (Gebreyohannes et al., 2015) (Klemes et al., 2008) (Pandey et al., 2003) (Sridhar et al., 2002)
Fruit and vegetables	Washing and sanitation operations such as: ➤ removing soil from unpeeled vegetables ➤ cleaning of surfaces ➤ cleaning, rinsing and cooling of processed vegetables	TSS (soil), color  Sugars / Starches / Organic acids / Pesticides  Brines  Pathogenic microorganisms	(Barbera and Gurnari, 2018) (Klemes et al., 2008) (Lehto et al., 2014) (Millan-Sango et al., 2017) (Nelson et al., 2007) (Sinha et al., 2011)

Type of industry	Main origins of wastewater	Parameters and compounds present in wastewater	References
Breweries	Expired, wasted beer and brewery washing and in particular bottle and keg washing	<p>TDS, TSS, COD, BOD, TOC, TN, TP, color, turbidity</p> <p>Sugars / Soluble starch / Proteins / Ethanol / Volatile fatty acids / Phenolic compounds</p> <p>Conductivity, pH</p> <p><math>\text{Na}^+ / \text{Cl}^- / \text{Ca}^{2+} / \text{Mg}^{2+} / \text{Fe}^{2+} / \text{NO}_2^- / \text{Al}^{3+} / \text{SO}_4^{2-} / \text{F}^-</math></p> <p>Pathogenic microorganisms</p>	<p>(Barbera and Gurnari, 2018)</p> <p>(Bloor et al., 1995)</p> <p>(Braeken et al., 2004)</p> <p>(Ferrarini et al., 2001)</p> <p>(Goldammer, 2008)</p> <p>(Ioannou et al., 2013)</p> <p>(Klemes et al., 2008)</p> <p>(Mavrov and Belieres, 2000)</p> <p>(Rao et al., 2007)</p> <p>(Rogener et al., 2003)</p> <p>(Simate et al., 2011)</p> <p>(Tay and Jeyaseelan, 1995)</p>
Soft drink	Bottle washing, equipment washing and rinsing, filter washing, Regeneration of softener and decarbonator	<p>TSS, BOD, COD</p> <p>Sugars / Pectins / Flavourings and colouring additives</p>	<p>(Barbera and Gurnari, 2018)</p> <p>(Hsine et al., 2005)</p>

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871 **Table 5:** Examples of the practices of recycling or reuse in the food industry (European  
872 Commission, 2019)

Type of industry	Country	Reuse / recycling	Origin of wastewater	Targeted operation	
Dairy	Finland	Reuse	Cooling water	Cooling water	
	Finland (several cases)		Last flush of the CIP cycle	First flush of the next CIP cycle	
	Germany		Rinsing water after cleaning	Pre-rinsing	
	Denmark (several cases) / Finland	Recycling (nd*)	Condensate of whey	Not indicated	
	Denmark / Ireland	Recycled after filtration on RO	Condensates generated in evaporation and drying operations	Not indicated	
	Italy	Italy	Recycling (nd)	High pressure steam condensate water	Boiler water
			Recycling after filtration by UltraFiltration (UF)+RO	Wastewater	Not indicated
Fats and oils	Germany	Recycling after energetic usage	Condensate from vapour production	Process water	
		Recycling after evaporation	Wastewater	Process water	
	Italy	Recycling (nd)	Wastewater	Cleaning or cooling water	
Fruits and vegetables	France	Reuse	Cooling water	Cooling water	
	Belgium	Recycling (nd)	Wastewater	Cleaning or cooling water	
		Recycling after UF + RO	Wastewater	Not indicated	
Brewing industry	France	Recycling (nd)	Rinsing water after cleaning	Pasteurisation unit	
	Belgium	Recycling (nd)	Hot water generated from cooling system	Mashing operation	
	Spain	Recycling after electrochemical treatment	Cooling water	Cooling water	
Soft drinks and juice made form concentrate	France	Reuse	Washing water	Same or different washing	
		Recycling (nd)	Rinsing water after cleaning	Cooling	
	Belgium	Recycling after RO	Condensates generated in evaporation and drying operations	Not indicated	

<b>Type of industry</b>	<b>Country</b>	<b>Reuse / recycling</b>	<b>Origin of wastewater</b>	<b>Targeted operation</b>
Starch production	France	Reuse	Washing water	Same or different washing
	Spain	Recycling (nd)	Rinsing water after cleaning	Auxiliary services
Sugar beet manufacturing	Spain	Reuse	Washing water	Same or different washing
	United Kingdom	Reuse	Condensates	Borehole-extracted water (according to certain conditions)
Animal feed	France	Recycling after filtration on reverse osmosis	Condensates generated in evaporation and drying operations	Not indicated
	Netherlands	Recycling (nd)	Cooling water	Boiler feed water
Meat processing	Belgium	Recycling (nd)	Cooling water	Cleaning water
Ethanol production	Germany	Recycling (nd)	Wastewater	Cleaning or cooling water

873 (\*) nd: not defined

874 **Table 6:** Rejected solutes depending on the membrane type (Berland and Juery, 2002;  
875 Muro et al., 2012)

<b>Membrane type</b>	<b>Retained solutes</b>
Microfiltration (MF)	bacteria, fat, oil, grease, colloids, organic microparticles, Cryptosporidium and Giardia, sand, TSS and turbidity
Ultrafiltration (UF)	all the solutes retained with MF plus proteins, pigments oils, sugars, organic microparticles and virus
Nanofiltration (NF)	all the solutes retained with UF plus pigments, sulphates, divalent cations, divalent anions, lactose, sucrose, sodium chloride and pesticides
Reverse Osmosis (RO)	all the solutes retained with NF plus salts and inorganic ions

**Table 7:** Membrane treatment examples used for water recycling and their performances, in the food processing industry

Domain	Load	Origin	Pre-treatment	Membrane treatment step (R% NaCl - MWCO)	TMP (bar)	J <sub>p</sub> (L.h <sup>-1</sup> m <sup>-2</sup> )	Residuals through treatment step (R %)	Permeate use / Conclusion	Reference
<b>DAIRY (cow)</b>	<b>COD ≤ 1 g.L<sup>-1</sup></b>	<b>Flash coolers</b>	PreF 100 μm	NF 200 Da	30	80 – 100	COD 10-34 mg.L <sup>-1</sup> (70-90%) TOC 10 mg.L <sup>-1</sup> (65-78%) Cond 17-35 μS.cm <sup>-1</sup> (75-97%)	Boiler	(Riera et al., 2013)
			MF (5, 1, 0.2 μm) + AC	RO (99.5%)	6 - 15	40 - 80			(Suàrez et al., 2014; Suàrez and Riera, 2015)
		<b>vapor condensates</b>	Cartridge filter + UV	NF + NF	4 (2 <sup>nd</sup> NF)	16	COD < 10 mg.L <sup>-1</sup> (80%) TOC < 4 mg.L <sup>-1</sup> (65%) Cond 2 - 35 μS.cm <sup>-1</sup> (75-80%)	“... technology was granted approval for water reuse in the food industry”	(Mavrov and Belieres, 2000)
		<b>Unknown origin</b>	PreF 25 μm	RO (99.5%)	20 - 30	14 - 21	TOC 130-300 mg.L <sup>-1</sup> (65-84%) Lactose 3-10 mg.L <sup>-1</sup> (>99%)	MF+RO : Heating or cooling operations	(Bortoluzzi et al., 2017)
	<b>COD ~ 1 - 3 g.L<sup>-1</sup></b>	<b>Flushing water</b>	-	NF 200 - 300 Da RO (99.5%)	10	5-6	Lactose 20 mg.L <sup>-1</sup> (99.7%) Prot N.D.	(NF+) RO: “washing floors”	(Kyrychuk et al., 2014)
				FO (0.3-0.37 nm) + MD (450 nm)	-	3-10	TOC 1-3 mg.L <sup>-1</sup> (>99%)	Higher quality than urban recycled water	(Song et al., 2018)
		<b>(Skimmed/ whole milk)</b>	-	RO (99.5%)	20	30	COD < 30 mg.L <sup>-1</sup> (>98%) TOC < 7 mg.L <sup>-1</sup> (>99.8%) Prot < 10 mg.L <sup>-1</sup> (>97%) Lactose 5-40 mg.L <sup>-1</sup> (> 95%) Fat < 30 mg.L <sup>-1</sup> (>88%) Cond 8 - 50 μS.cm <sup>-1</sup> (> 97%)	Heating, cooling, cleaning ; RO+RO → potable water quality	(Brião et al., 2019; Kyrychuk et al., 2014; Vourch et al., 2008)
					10	18			
					10-20	12-23			
	-	(NF or RO) + RO (99.5%)	20	34	TOC < 3.3 mg.L <sup>-1</sup> (> 99.9%) Cond < 9 μS.cm <sup>-1</sup> (> 98.7%)	Heating, cooling, cleaning	(Vourch et al., 2005)		

		<b>Diluted flushing water</b>	-	<b>NF</b> (200 Da) ; <b>RO</b> (99.3%)	10-20	28-37 12-23	Lactose 30-47 mg.L <sup>-1</sup> (> 93%) COD 21-42 mg.L <sup>-1</sup> (> 98%)	Cooling towers	(Brião et al., 2019)
		<b>Unknown origin</b>	PreF 25 µm	<b>NF90</b> (200-400 Da)	20-30	50 - 100	COD 1 g.L <sup>-1</sup> (20-50%) TKN < 60 m.L <sup>-1</sup> (30-60%) Lactose < 15 mg.L <sup>-1</sup> (>99%)	MF+NF : Heating or cooling	(Bortoluzzi et al., 2017)
	<b>COD &gt; 10 g.L<sup>-1</sup></b>	<b>Flushing water</b>	-	<b>NF</b> (150 - 300 Da)	10 - 20	5 - 20	COD < 120 mg.L <sup>-1</sup> (>90%) Prot N.D. Lactose < 400 mg.L <sup>-1</sup> (>98%)	Boiler (if NF+RO or RO+RO)	(Balannec et al., 2002; Balannec et al., 2005)
			-	<b>RO</b>	15 - 35	4 - 40			(Balannec et al., 2002; Balannec et al., 2005)
<b>BEVERAGE</b>	<b>COD &lt; 1 g.L<sup>-1</sup></b>	<b>Bottle washing (unknown industry)</b>	Cartridge filter 30 µm	<b>UF</b>  <b>RO</b>	4.5 - 6.5  35 - 37	178  68	COD 30 mg.L <sup>-1</sup> (95.6%) Turbi < 0.1 NTU (~100%) Color < 5.0 Hazen units (~100%) TDS 170.0 mg.L <sup>-1</sup> (95%)	UF: Bottle washing plants RO: “water quality comparable to city water supply”	(Tay and Jeyaseelan, 1995)
		<b>Brewing room rinsing water</b>	-	<b>NF</b> (150-300 Da)	8	43 - 77	COD 1 – 24 mg.L <sup>-1</sup> (~100%) Cond 535 – 1 818 µS.cm <sup>-1</sup> (60-75%) pH= 11.2-11.6	Insufficient permeate quality	(Braeken et al., 2004)
		<b>Bottles washing (Brewery)</b>	Filtration with anthracite and sand + PreF 25 µm	<b>RO</b> (no information on the type of membrane)	10	10	Cond 21-93 µS.cm <sup>-1</sup> (96-99%) COD 4-14 mg.L <sup>-1</sup> (97-99%) CFU/mL = 70* pH = 5.0-10.4	RO permeate has “drinking water quality” after UV disinfection. “Could be reused for cleaning purposes”.	(Rogener et al., 2003)
		<b>Presoaking water from bottle washing machines (mineral water bottles)</b>	Cartridge filters, UV disinfection	<b>NF + LPRO</b> (no information on the type of membrane)	-	-	Cond 18 µS.cm <sup>-1</sup> (>98.7%) COD 1.8 mg.L <sup>-1</sup> (>99%) TOC 3.6 mg.L <sup>-1</sup> (>96%) NO <sub>2</sub> <sup>-</sup> < 0.1 mg.L <sup>-1</sup> (~98%)	“Authorized water reuse in the food industry”: For bottle rinsing machine prior to fresh water rinsing; or for cleaning purposes	(Mavrov and Belieres, 2000)
	<b>COD ~ 1 - 5 g.L<sup>-1</sup></b>	<b>Brewery - Bottle washing</b>	-	<b>NF</b> (150-300 Da)	8	43 - 85	COD 97-210 mg.L <sup>-1</sup> : 66-167 mg.L <sup>-1</sup> from ethanol (60-75-%) Cond 782-3320 µS.cm <sup>-1</sup> (37-79%) pH = 11.8-12.5	Insufficient permeate quality	(Braeken et al., 2004)

		Bright beer reservoir rinsing water	-			38 - 105	COD 136-147mg.L <sup>-1</sup> : 78-147 mg.L <sup>-1</sup> from ethanol (95-96%) Cond 146-357 μS.cm <sup>-1</sup> (80-90%) pH = 5.5-6.7		
		Winery - washing and rinsing operations of fermentation tanks and barrels	Centrifugation and MF (1 μm)	RO (99.5%)	10	27 - 40	COD 140 mg.L <sup>-1</sup> (97.4%) BOD <sub>5</sub> 9 mg.L <sup>-1</sup> (97.9%) TN 3.3 mg.L <sup>-1</sup> (67%) TP 0.5 mg.L <sup>-1</sup> (76.2%) TSS 4 mg.L <sup>-1</sup> (93.9%) TS 200 mg.L <sup>-1</sup> (96%) Cond 182 μS.cm <sup>-1</sup> (94.6%) <i>Daphnia magna</i> N.D. (100%)	RO permeates can be used for irrigation or disposed of in surface water.	(Ioannou et al., 2013)
FRUITS AND VEGETABLES	COD ~ 0.3 - 5 g.L <sup>-1</sup>	Low-contaminated wash water of fresh-cut vegetables	-	MF submerged (PVDF nominal pore size 0.2 μm)	0.9	19 - 24	pH = 7.1-7.2 TS 100 mg.L <sup>-1</sup> (54.1%) Free chlorine 0 mg.L <sup>-1</sup> (100%) Tot_chlorine 0.16 mg.L <sup>-1</sup> (98 %); <u>Color</u> : green	“Suitable for recycling”	(Nelson et al., 2007)
			UF (SiC-0.05 or SiC-0.1) 2 bar/155 L.h <sup>-1</sup> m <sup>2</sup>	RO (99.5%) SW30HR TW30	17	6 26	COD 52-60 mg.L <sup>-1</sup> (92.4-93.4%)	“Quality complying with the German regulations”; reused for first washing.	(Reimann, 2002)
		Carrot peeling	PreF (169 μm + 79 μm) + MF (0.5 μm)	RO (99.2%)	≤15	41	COD < 12 mg.L <sup>-1</sup> (98%) Conducti < 8μS.cm <sup>-1</sup> (98.3%) Sugars < 4 mg.L <sup>-1</sup> (99.2%)	“Reuse in the vegetable plants prior to the blanching step”	(Garnier et al., 2020)
	COD = 70 - 85 g.L <sup>-1</sup>	Soy bean cooking water	Centrifugation or UF+UF	NF (150-300 Da)	20	35-61	Sucrose N.D. (100%) COD 8.3 - 10 gO <sub>2</sub> .L <sup>-1</sup> (>80%)	(Centri or UF) + NF: water reuse	(Pauer et al., 2013)
POULTRY AND MEAT PRODUCTION	COD < 0.5 g.L <sup>-1</sup>	Sausage cooling water	Sedimentation skimming + MF (3 μm) + H <sub>2</sub> O <sub>2</sub> + UV	NF (polyamide membrane)	5 - 6	18.8 - 27	Turbi < 1 FNU (100%) Cond 95-350 μS.cm <sup>-1</sup> (61.1 – 95.7%) COD 2-3 mg.L <sup>-1</sup> (92.7-98.3%) TKN < 1 mg.L <sup>-1</sup> (100%)	post-treatments (UV oxidation/disinfection → Drinking water quality	(Mavrov et al., 1997)
			Skimming + PreF (50 and 3 μm) + UV	NF + NF	5 3	18 - 20.5 11.4 - 13.2	TOC 5 – 58 mg.L <sup>-1</sup> (55.1%) Cond 52-145 μS.cm <sup>-1</sup> (91.1%) Nitrite 0.05-0.18 mg.L <sup>-1</sup> (65.8%)	NF+NF+ disinfection → drinking water quality	(Fährnich et al., 1998)
			Belt filter, cartridge filters, UV	NF + NF	5.4 1.4	2 4	Cond = 7-120 μS.cm <sup>-1</sup> ~92%) TOC = 1.4 – 2.5 mg.L <sup>-1</sup> (99%) Cl <sup>-</sup> = 0.7-2.1 mg.L <sup>-1</sup> (~98%)	“Authorization for water reuse in the food industry” (cleaning)	(Mavrov and Belieres, 2000)
		Bird	PreF (300 μm)	UF 30 kDa	0.67	40 – 60	BOD ~ 30 mg.L <sup>-1</sup> (93%)	-	(Malmali et

	COD = few g.L <sup>-1</sup>	washing; Chilling wastewater				50 – 70 160 – 350	COD ~ 70 mg.L <sup>-1</sup> (94%) TSS 0 (100%); FOG 0 (100%)		al., 2018)
		Water from animal protein concentration / washing of ion exchange resins	-	UF 5 kDa + RO (POI-02)	3.5-4.5	17-19 39-44	pH= 6.8 – 7.5 Cond= 45 – 75 µS.cm <sup>-1</sup> Turbi= 0.10-0.15 NTU TS= 10 - 40 mg.L <sup>-1</sup> Ca <sup>2+</sup> < 5 mg.L <sup>-1</sup>	“Feasibility for water recovery”	(Hernández et al., 2019)
VEGETABLE OILS	COD < 1 g.L <sup>-1</sup>	-	-	UF 30 kDa	2	60 (?)	COD 50 mg.L <sup>-1</sup> (90 %) TOC 40 mg.L <sup>-1</sup> (86 %) TSS 0 mg.L <sup>-1</sup> (100 %)	Treated water suitable for discharge	(Mohammadi and Esmaelifar, 2004)
		-	Neutralization + coagulation	UF (PVDF 200 kDa) + RO (99% NaCl)	5 30	33.4 39.1	Turb 0.05 NTU (99.9%) SS 198 mg.L <sup>-1</sup> (96.5%) BOD <sub>5</sub> 30 mg.L <sup>-1</sup> (98.9%) pH=6.67	RO permeates comply with the “WHO standards” for water reuse	(Azmi et al., 2013)
	COD = few g.L <sup>-1</sup>	Palm oil mill	+ MF (0.2 µm)	RO (PPT-9908)	55.2	52.5	TDS 62 mg.L <sup>-1</sup> (99.4%) COD 46 mg.L <sup>-1</sup> (98.2%) BOD 0 mg.L <sup>-1</sup> (100%) Cond 86 µS.cm <sup>-1</sup> (99.3%)	RO+RO needed for reuse.	(Sridhar et al., 2002)
		Olive mill	PreF (35 and 15 µm) + MF (0.4 µm) or MF (0.4 µm) + immobilized pectinase	FO (CTA) Draw solution: 3.7 M MgCl <sub>2</sub>	104 (π)	4	TOC 130 mg.L <sup>-1</sup> (96.8%) TIC 1.6 mg.L <sup>-1</sup> (99.3%) TPh 13 mg.L <sup>-1</sup> (98.4%)	Pectins totally removed. 30% flux enhancement when pectinase is used as pre-treatment	(Gebreyohannes et al., 2015)
			Centrifugation	NF (150-300 Da)	25	64	COD 2.5-3 g.L <sup>-1</sup> (86-89 %) Phenolic compounds 10 mg.L <sup>-1</sup> (95 %)	Irrigation use	(Ochando-Pulido et al., 2018)
	Soybean oil	GAC	RO	-	100	COD 380-528 mg.L <sup>-1</sup> (94 - 97 %) Turbidity 1.22-1.84 NTU (> 99.78%)	-	(Elhady et al., 2020)	
	COD ~ 50 – 67 g.L <sup>-1</sup>	Olive mill	Centrifugation + UF (UC 030)	(UF+) RO (99.5% or 99.0%)	25	(15.3) 14.6 (21.2) 17.5	Cond ~ 300 µS.cm <sup>-1</sup> (>95.6%) COD < 0.7 g.L <sup>-1</sup> (97.5%)	Useless UF	(Coskun et al., 2013)
Soybean oil		Coagulation-flocculation	UF 150 kDa	1.2	40 - 60	TOC 277 - 473 mg.L <sup>-1</sup> Turbidity < 7.2 NTU (>99.7%)	Insufficient quality for discharge into receiving environment	(Khouni et al., 2020)	

							Color 0 (100%)	or for agricultural use	
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\* CFU= Colony Forming Units

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879 **Table 8:** Examples of disinfection used as a post-treatment after membrane treatment

<b>Type of industry</b>	<b>Main process</b>	<b>Posttreatment</b>	<b>Reference</b>
Dairy	NF + NF	UV	(Chmiel et al., 2000; Mavrov and Belieres, 2000; Mavrov et al., 2001)
Meat	NF + NF	UV	(Fährlich et al., 1998)
Bottle washing	UF or RO	Without	(Tay and Jeyaseelan, 1995)
	NF + LPRO	UV	(Mavrov and Belieres, 2000)
	RO	UV	(Rogener et al., 2003)