Water reuse in the food processing industries: a review on pressure-driven membrane processes as reconditioning treatments

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Keywords

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

Abstract

Establishing general rules for short wastewater recycling loops in the food industries is a challenging task . This work provides an overview on water consumption, effluent discharge and the main water consuming unit operations in this sector. Pressure-driven membrane processes as treatment technologies will be focused on and nanofiltration and reverse osmosis appear unavoidable. An original synthesis of the membranes used, the best operating conditions and the corresponding performances are broken down by food sector and by effluent load. Recycling is mostly proposed for floor washing, heating/cooling, vessel pre-cleaning, even though criteria for potable water are not fulfilled. Water of a quality which is sufficient for recycling can be obtained with a single membrane treatment stage only when weakly concentrated (COD < 1 g/L) non-fat effluents are concerned, originating from flushing, bottle washing or rinsing water after vegetable peeling. This critical review can be used as a guideline for recycling projects and points to the remaining challenges and improvements to be made.

Nomenclature

AC = Activated Carbon

AR = Attributable Risk

BAT = Best Available Techniques

BOD = Biological Oxygen Demand

BREF = BAT Reference document

CF = Coagulation/Flocculation

Cfeed = Concentration of the pollutant in the feed solution

CIP = Cleaning In Place

COD = Chemical Oxygen Demand

Cp = Concentration of the pollutant in the permeate

Cr = Concentration of the pollutant in the retentate

DAF = Dissolved Air Flotation
FDM = Food, Drink and Milk industries
FO = Forward Osmosis
Fp = Permeate Flowrate
Jp = Permeate flux
LCA = Life Cycle Analysis
MF = MicroFiltration
MWCO = Molecular Weight Cut-Off
NF = NanoFiltration
PCB = PolyChlorinated Biphenyls
PL = Pulsed Light
PreF = PreFiltration
QMRA = Quantitative Microbial Risk Analysis
R = solute retention rate
Sm = Membrane surface
TKN = Total Kjeldahl Nitrogen
TMP = TransMembrane Pressure
TN = Total Nitrogen
TOC = Total Organic Carbone
TP = Total Phosphorus
TSS = Total Suspended Solids
UF = UltraFiltration

US = UltraSonication

UV = UltraViolet

RO = Reverse Osmosis

WWTP = WasteWater Treatment Plant

1. Introduction: Benchmarking on water management in food plants

Human activities and particularly industrial activities contribute to climate change and severe water scarcity (Huang et al., 2021). The latter is predicted to get worse in the coming years in North Africa, Middle East, Pakistan, India and northern China (Asano et al., 2007; Meneses et al., 2017) and restrictions on the amount of water extracted from ground water and surface sources is becoming unavoidable in temperate countries. Consequently, in order to ensure sustainable water management, UNESCO has fixed as one of its main targets to reduce by 20% the amount of water used by industries by 2030 (UNESCO, 2014). Being a major consumer of water and specifically drinking water (Casani et al., 2005; Valta et al., 2016; Vanham et al., 2019), the food industry is particularly concerned by this issue and must make significant efforts to reduce its water consumption. To this end, the European Commission conducted a survey in Europe of the specific water consumption and wastewater discharge in some food industries (European Commission, 2019). Like other publications concerning the food industry (Klemes et al., 2008; Muro et al., 2012; Ölmez, 2013), it highlights the fact that water management is greatly dependent on the sector (Table 1) and that data vary considerably depending on the reference.

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

Given the situational analysis above, in order to reduce water consumption in the food sector, two complementary strategies are envisaged: i) The development of new water-efficient production processes ii) The re-design of water networks in the plants, including water recycling or reuse. To make the different options clear, it may be useful to reiterate the definitions applied (recycling, reuse, reconditioning, etc.). The official definitions can be found in Table 3. If there is a possibility that effluents may be polluted with undesired substances and/or particles from food, or from soils or pesticides, then recycling is preferred. In several countries (such as Singapore, Australia, Israel, China and U.S. states such as Florida and California), many food industries have already set up water reuse and recycling projects (Meneses et al., 2017), and water reuse guidelines applicable to the food industry are available. In Australia, the “water reuse guideline for food businesses in NSW considering reusing water” (NSW-Food-Authority, 2008) indicates both the feasible recycling solutions and a methodology to check that these solutions are not harmful to the product’s qualities. In Europe, the European Commission has developed a guide regarding the minimum requirements for water reuse (European Commission, 2018).

Water recycling strategies are considered at different levels, from a geographic region to a unit operation in a plant. At the regional level, wastewater may be collected from several water treatment plants to provide water – after treatment - to power stations, industrial users and even main drinking water supply storage, as in the Brisbane region (Australia) where the Western Corridor Recycled Water Project (WCRWP) was launched in 2009 (Apostolidis et al., 2011). This concept of “water mining” dates back to the 90s (Johnson et al., 1996), and requires a tight coordination between the different sectors and good synchronisation between their respective water fluxes, both those produced and those required. At the factory level, effluent is generally collected and mixed before global treatment and possible recycling for non-food uses, outside the factory for agricultural irrigation for example, or inside for floor cleaning as illustrated by Apostolidis in the case of a brewery in Austria (Apostolidis et al., 2011). Though not as common, effluent recovery at the unit operation level and its recycling within the production line is also possible, as is the case in Cleaning In Place (CIP) where it is current practice to use effluent from the rinse stage for the prewash stage (European Commission, 2019). Such short water recycling loops within or as close as possible to a unit operation allow to set up a treatment process which is more specific to the pollutants present, leading to higher treatment performances. In fact, collecting and mixing wastewater from different unit operations generally leads to only moderate efficiency of the treatment processes. Furthermore, pumping and transport of wastewater to a wastewater treatment plant (WWTP) or to the rejection point are expensive (Manzocco et al., 2015). Consequently, it would appear to be pertinent to develop these short recycling loops.

However, there is a lack of tools in this context to help re-design the water networks and choose, optimize and simulate the recycling or reuse scenarios. Considering the above-mentioned variations of the quality and quantity of wastewater even within a given food sector, a factory-by-factory study is needed. Recently, as part of a French research program (MINIMEAU ANR-17-CE10-0015, 2018-2022), Nemati-Amirkolaii et al. developed some tools based on a Water Pinch analysis to help choose the best water recycling loops in a factory, with the aim of minimizing water consumption and wastewater production (Nemati-Amirkolaii et al., 2019). In the same program, in order to appreciate the performances to be reached by the water reconditioning treatments, Garnier et al. proposed a methodology for the development of a new recycling project and the definition of both the most convenient and the cleanest technology for treatment, regarding the desired quality of the water to be recycled (Garnier et al., 2019).

With regard to this, an overview of the physical-chemical treatment solutions available in scientific literature for food industry effluent needs to be established, focusing on the type of industry and considering water reconditioning at unit operation level. The choice of a treatment solution and its operational conditions necessarily involve the definition of the compounds to be removed from the effluent and of the targeted quality for the reused/recycled water. Consequently, data analysis on effluent quality for each food industry sector needs to be performed. Finally, the membrane processes present several advantages, mainly their modularity, robustness, compactness and the very limited pollution they generate as compared to ion-exchange or adsorption processes (Cui et al., 2010; Frenkel, 2010; Guiga and Lameloise, 2019; Pabby et al., 2008; Samaei et al., 2018). They are considered simple to set up and are already well-known by the industrialists of the food sector, as they have been widely used since the 70s - 80s in the dairy industry and since the 90s in several other food industries for the processing of fluid products (Daufin et al., 2001). Consequently, the present review focuses on these processes, and specifically on the pressure-driven membrane processes as reconditioning solutions of aqueous effluent produced in the food sector.

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

Some studies closer to our objectives deal with one specific food industry or case study: dairy (Galvão, 2018; Song et al., 2018), fresh-cut vegetables (Manzocco et al., 2015), brewery (Simate et al., 2011) or beverage (Tay and Jeyaseelan, 1995). They each provide valuable data and information for the sector concerned, and warrant gathering and comparison.

This has been done in the present paper, which proposes a classification of the effluent by food industry, by origin (unit operation) and by charge (COD level). When necessary, raw data was processed and analysed in terms of treatment efficiency (residual pollution and permeate fluxes). Treatment and recycling trends then emerge depending on the effluent type (in accordance with the regulatory texts and the identified possible derogations), as well as the limits of application of the membrane processes. It also highlights the remaining challenges in this field.

2. Identification of the key parameters in the wastewater to be reused or recycled

When reusing or recycling water, knowing the quantity and detailed composition of the water to be treated as well as the quality of water required for each unit operation is essential for the optimization of the water network as well as for choosing an appropriate treatment process when necessary. For WWTP purposes, average concentrations and specific loads of wastewater produced by European food industries are defined through global parameters (European Commission, 2019), such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Organic Carbon (TOC), Total Nitrogen (TN) and Total Phosphorus (TP). Adapted to the design of a WWTP, these parameters are not suitable for selecting and scaling a more specific process whose objective may be to obtain an acceptable water quality for recycling in the food industry - possibly up to a potable water quality level - or for tracking the elimination of one or several specific pollutants. Indeed, in many countries, the regulatory authority stipulates applying the precautionary principle, meaning that potable water should be used when it is in contact with food, as is the case in the European Community for which 75% of the water used by the food industry is potable water (Barbera and Gurnari, 2018; Valta et al., 2016). Quality evaluation of the treated water then requires the analysis of additional global parameters (colour, conductivity, odour, oxidability, turbidity and TOC) but also of more specific species such as organic micro-pollutants (pesticides, disinfectants, oils, PCB…), bromate, copper, nitrates, aluminium or iron. Consequently, wastewater quality has to be studied more accurately in order to scale treatment processes to ensure the safety of the treated water.

Examples of precise compositions of wastewater from food industries are given in literature but analysis remains to be adapted on a case-by-case basis. Table 4 gathers main wastewater origins and compounds present for the main food sectors, which may help to select the compounds to be analysed more specifically. They are of course directly related to the type of food. Comparison of the measured levels with the expected water quality for recycling establish which compounds or “key parameters” should be removed in priority as well as the choice of the treatment process and its operational conditions. Additionally, pollutants of small molecular weight are often more difficult to eliminate due to their size, especially through membrane treatment. This is the case of most of the organic acids found in the wastewater of fruit and vegetable processing or dairy industries, or of the ethanol found in the wastewater of breweries and wineries. This may also be the case for organic micro-pollutants and their degradation products that do not significantly contribute to the global parameters (COD) but are present in the effluent of most of the food industry sectors. Consequently, their accumulation in the recycled water after several cycles of treatment must be investigated and controlled.

3. Physical-chemical treatment possibilities for water reconditioning

3.1. Examples of recommendations and existing practices

Some general guidelines exist worldwide for water management in the food industries, either produced by community authorities (European Commission, 2018, 2019) or published as handbooks by authors (Klemes et al., 2008). The example of the European Community is interesting. Indeed, the European Union commissioned a study on the Best Available

Techniques (BAT) Reference document (BREF) used in the Food, Drink and Milk (FDM) Industries. For water management, this study summarizes the recycling and reuse practices in 495 factories (European Commission, 2019), that we have synthesized in Table 5. As mentioned above and gathered in Table 2, Klemes et al. (2008), among other authors, also contributed to build an overview on water consumption in different food industries, providing valuable benchmarks to manufacturers of each industry.

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

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

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

3.2. Analysis of the membrane process applications for food wastewater reconditioning

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

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

$$R = \frac{C_r - C_p}{C_r} . 100\ (\%) \tag{1}$$

Where C_r (or C_{feed}) and C_p are the concentrations of the key parameter concerned respectively in the retentate (or feed) and in the permeate.

The permeate flux J_p obtained under a given TMP is also an essential parameter as it accounts for the purified water productivity :

$$J_p = \frac{F_p}{S_m} \qquad (\mathrm{L.h^{-1}.m^{-2}}) \qquad (2)$$

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

UF, NF and RO are usually the main treatments used as polishing steps to remove the soluble organic load and minerals. However, they need to be preceded by relevant pre-treatments to improve their efficiency (technically and economically) which allow elimination of TSS, turbidity or O&G (Frenkel, 2010; Muro et al., 2012) thus avoiding premature NF and RO membrane fouling or its physical damage.

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

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

Different solutions can be found to eliminate all particles from coarse to ultrafine, generally including a rough pre-treatment or clarification step, consisting in settling, sand filtration, sieving, or Coagulation/Flocculation (CF) (Azbar and Yonar, 2004; Azmi et al., 2013; Coskun et al., 2013; Ioannou et al., 2013; Mavrov et al., 1997; Pauer et al., 2013). Generally, depending on the clarifier technology, the turbidity removal efficiency varies from 90% to 99% through

CF. It is usually followed by depth prefiltration through microfiltration with cartridge filters, cross-flow microfiltration or ultrafiltration, combined or not (Barbera and Gurnari, 2018). As can be seen in Table 7 for food industry effluents, prefiltration (PreF) and/or microfiltration (MF) from 100 µm down to 0.2 µm is one of the most widespread pre-treatment processes encountered, regardless of the industrial effluent source (Azmi et al., 2013; Bortoluzzi et al., 2017; Fähnrich et al., 1998; Gebreyohannes et al., 2015; Ioannou et al., 2013; Malmali et al., 2018; Mavrov and Belieres, 2000; Riera et al., 2013; Rogener et al., 2003; Sridhar et al., 2002; Suàrez et al., 2014; Suàrez and Riera, 2015; Tay and Jeyaseelan, 1995).

For wastewater from brewery bottle-washing (Rogener et al., 2003), results show that combining anthracite / sand filter and bag filters (coarse and fine depth filtration) is the best solution. Belt filter is also found efficient to remove glass residues, parts of labels and coarse impurities from the mineral water bottle-washing wastewater (Mavrov and Belieres, 2000).

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

In the vegetable oil refining industry sector (Coskun et al., 2013), UF may also be encountered but centrifugation and CF are the main pre-treatment processes studied. In this sector, Dissolved Air Flotation (DAF) is shown to be efficient to assist grease and oil flotation, further separated with a flat scraper, leading to 50% of COD removal. It is improved to 90% for COD, BOD_5, TSS, Total Kjeldahl Nitrogen (TKN) and O&G if DAF is combined with chemicals (Azbar and Yonar, 2004). Nevertheless, concentrations in the pretreated effluent remain very high and not suitable for reuse as process water. Coagulation/Flocculation at a rather basic pH followed by settling also allows to decrease COD and turbidity (Khouni et al., 2020; Louhıchı et al., 2019). But these processes are efficient only for free and dispersed-oil elimination.

Finally, it is interesting to note that for flushing water in the dairy industry, no pre-treatment is found necessary in the examples given in Table 7, whatever the COD level. This may be explained by the fact that these effluents mainly contain dissolved organic compounds. This makes it possible to perform simpler treatment processes with fewer steps, which makes these effluents good candidates for treatment and recycling. This is also the case for low contaminated washing water of fresh-cut vegetables, for which a pre-treatment step followed by MF is sufficient before NF or RO treatment. On the contrary, for highly loaded effluents (COD > 10 g/L) whose pre-treatment requires a complicated chain of processes with different fluxes, correlating them with a continuous processing polishing unit seems industrially difficult. The recycling solution could then require a storage step. This is probably the case for the proposed pre-treatment of sausage cooling water (Table 7) where sedimentation + MF + H_2O_2 + UV were shown necessary. This treatment example is certainly efficient at a laboratory or pilot scale but seems unfeasible at an industrial scale.

3.2.2. Treatment by membrane processes

As shown in Table 7, membrane technologies (UF, NF and RO) are used as polishing and reconditioning processes for wastewater treatment in all food sectors. In some cases, especially when the effluent presents a low charge (COD < 1 $g.L^{-1}$) or when it does not result from contact with food ingredients (vapour condensates, washing of mineral water bottles), the quality of treated wastewater may allow an authorization for reuse (Mavrov and Belieres, 2000).

On the contrary, in the most difficult cases such as charged vegetable oil wastewater, the treated water can only be discharged into the receiving environment (Khouni 2020) or used for irrigation (Ochando-Pullido 2018).

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

For the dairy industry, the most common effluents produced are flushing water (water-diluted milk) and tank washing water. The former are particularly interesting because their treatment would allow the recovery of milk components in addition to purified water. The latter can be treated to recover both water and cleaning solutions (ex. NaOH). Nanofiltration with MWCO 150 – 300 Da allows the retention of generally more than 90% of the COD, reaching even 99%, COD being mainly composed of lactose and nitrogenous molecules (proteins, TKN), that are efficiently retained (Brião et al., 2019; Kyrychuk et al., 2014; Song et al., 2018; Vourch et al., 2008). Then TMP between 10 – 20 bar is usually used for up to 100 $L.h^{-1}.m^{-2}$ permeate flux. However, depending on the initial concentration of pollutants, which is widely uneven depending on whether flushing waters or vapor condensates are concerned, the obtained permeates may still contain unacceptable concentrations for a drinking water type, with up to several hundred ppm in lactose or TOC (Balannec et al., 2002; Balannec et al., 2005; Bortoluzzi et al., 2017). For those more concentrated streams, a simple NF or RO treatment may be enough to produce water for heating, cooling or cleaning purposes; but more often NF plus RO or a double NF is required. For the lower loads (COD < 1 gL^{-1}), a quality close to drinking water is reached (TOC < 3 - 10 $mg.L^{-1}$) with a simple or a double-stage RO, under 20 – 30 bar, corresponding to a permeate flux of about 30 $L.h^{-1}.m^{-2}$ (Brião et al., 2019; Kyrychuk et al., 2014; Mavrov et al., 2001; Song et al., 2018; Vourch et al., 2005, 2008). Additionally, authors indicate that effluent storage before treatment (24 h) lowers the effectiveness of RO or NF+RO operations (Vourch et al., 2008). This is generally due to the biodegradation of organic solutes, representing nutrient media for micro-organisms. This microbial development leads to the synthesis of lower molecular weight solutes, resulting in a decreased effectiveness of the membrane process. This result is interesting as it confirms that it is essential to give special attention to the synchronisation of fluxes to avoid storage, as already mentioned (section 3.2.1).

Concerning the beverage industry, wastewater with low organic loads (COD < 1 $g.L^{-1}$) can be treated through NF run at lower TMP (8 – 10 bar), but high permeate flux in the range 80 - 100 $L.h^{-1}.m^{-2}$ depending on the membrane, while eliminating up to 100% of the COD content (Braeken et al., 2004; Mavrov and Belieres, 2000; Rogener et al., 2003). However, only RO leads to a "drinking water quality", preceded or not by a NF step. If recycling is intended for bottle washing, the hardness of the rinsing water must be reduced to below 0.9 mmol.L^{-1} Ca^{2+} (Klemes et al., 2008) to avoid calcium deposit on bottles.

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

In the case of fruit and vegetable, two very different situations are encountered. On the one hand, peeling and washing effluent represents the highest fluxes, with moderate organic charge (few g.L^{-1} or < 1 g.L^{-1}). UF treatment then appears insufficient to treat this effluent with retention below 40% - and residual COD at about 800 mg.L^{-1}- or insufficient removal of micro-organisms (Mundi and Zytner, 2015; Reimann, 2002). A complementary RO treatment at TMP up to 17 bar allows to obtain 92% to 98% of COD removal for a residual COD content below 60 mg.L^{-1}, but with low permeate fluxes at 6 to 41 L.h^{-1}.m^{-2}. Authors conclude that reuse may be possible for a first washing of food ingredients (Reimann, 2002), and in any case before blanching (Garnier et al., 2020). On the other hand, cooking and blanching effluent, due to the enhanced mass transfer at the high temperatures applied, is highly concentrated. Table 7 shows the example of soybean cooking water with 70 - 85 g.L^{-1} COD, requiring high-pressure NF treatments (20 bar) with tight membranes (150 - 300 Da). The permeate fluxes then obtained are moderate (35 - 61 L.h^{-1}.m^{-2}) and the latter still contain very high COD concentrations (8 - 10 g.L^{-1}) (Pauer et al., 2013) for which the authors indicate a possible "degraded" reuse such as floor cleaning, excluding any use in the food transformation process.

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

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

However, vegetable oil effluent seems to be the most difficult to treat. Oil extraction processes are very different depending on the vegetable treated. Here obviously are only presented examples generating wastewater, but it is worth noting that many processes generate organic solvent effluents that are also investigated for treatment and reuse. Apart from oil process wastewater with COD < 1 g.L^{-1}, pre-treatment is systematically required for highly loaded effluent. Then, UF treatment alone only allows to discharge permeates into the receiving environment. RO or tight NF membrane treatments are required for reuse in the process and need to be applied at high TMP (up to 25 bar for NF and 55 bar for RO). Permeate fluxes vary significantly, from 39 to 100 L.h^{-1}.m^{-2} depending on the initial effluent quality. However, NF performances are insufficient regarding the remaining COD amounts at 2 - 3 g.L^{-1} when the initial COD is about 13 g.L^{-1} (Ochando-Pulido et al., 2018). Only RO and even a double-stage RO treatment allow to obtain a suitable permeate quality for reuse with a residual COD below 50 mg.L^{-1} (Sridhar et al., 2002). Forward osmosis is also tested on olive mill wastewater (Gebreyohannes et al., 2015), to reduce the total discharged volume and to recover phenolic compounds. Finally, for the most concentrated wastewater (COD 53 - 67 g.L^{-1}) only RO treatment allows to reach permeates suitable for discharge, with a still high residual COD of 0.7 g.L^{-1}. A critical technical aspect must be highlighted concerning wastewater from vegetable oil processing: it is the negative impact of organic solvents, even in low amounts, on the membrane integrity and thus its lifetime (Low and Shen, 2021). Additionally, fouling issues arise with these effluents, making the use of membrane processes unlikely at the industrial scale.

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

Furthermore, when BOD/COD ratio is high, it would be preferable to avoid storage to limit microbial degradation of the effluent, that leads to smaller molecules, more difficult to eliminate by membrane processes.

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

3.2.3. Post-treatments: Disinfection

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

Disinfection can be chemical or physical. Ozone is mainly used for its huge oxidizing effect, and chemicals containing chlorine compounds are necessary for its persistency (hypochlorite and related compounds, chloramines, chlorine dioxide, acidified sodium chlorite). In the case of physical disinfection, different technologies such as Ultraviolet Light (UV), Pulsed Light (PL) and UltraSonication (US) are possible, used alone or combined. Some authors have reviewed the advantages and limitations / drawbacks of each solution (Klemes et al., 2008; Manzocco et al., 2015).

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

4. Conclusion

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

This synthesis classified the applications according to the COD level and the efficiency of the treatment (permeate flux and composition), for each food industry. This made it possible to define the cases where the applied treatment leads to obtaining a water quality suitable for recycling, even though potable water criteria are not reached. The main recycling applications found deal with non-food contact, due to current regulatory limitations: recycling for floor washing, heating, cooling, bottle or vessel pre-cleaning. This work also allowed to identify the cases where membrane treatments seem to be simultaneously technically efficient and cost effective: these are the cases where only one membrane treatment stage is sufficient to obtain water quality complying with local recycling requirements. This generally corresponds to low COD content (COD < 1 g/L) non-fat effluent, generally originating from flushing, bottle washing or vegetable rinsing. For more loaded effluent, the valorization of solutes recovered in the retentates would be a solution to obtain economically efficient treatment processes.

Finally, the data of purified water flux, applied pressure and pollutant rejections collected in this work for certain membrane types, make it possible to undertake an initial scale-up study. Once the overall reconditioning treatment is selected for a given new application, pilot tests have still to be run in order to confirm if the treated water quality fits with the intended purpose. Of course, the treated cases in the present work are mostly research cases dealing with the feasability of membrane treatment and some critical aspects such as flux decline, fouling, energy consumption or life cycle analysis are not brought to the fore even though they represent key parameters for industrial scale running. Simulations of the long term permeate productivity and quality obtained would then allow to validate the recycling strategy and show if a given pollutant accumulation may occur, possibly having a detrimental impact and questioning the treatment process choice. Moreover, a risk analysis, such as Quantitative Microbial Risk Assessment (QMRA) or Attributable Risk (AR), has to be performed (Lens et al., 2002) in order to establish the impacts on materials and products, including that on existing wastewater treatment. A Life-Cycle Assessment (LCA) would finally allow to estimate the overall benefits gained with the planned solution when compared to the existing scheme.

Otherwise, whereas scaling phenomena may happen with hard water, membrane technologies may lead to softened water (low calcium and magnesium content) responsible for corrosion. Care should then be taken to obtain the right calcium-carbonate balance of the treated water (Hallopeau & Dubin method).

Acknowledgements

This research was supported by the French Technological Joined Network (RMT) *ACTIA Ecofluides*. It was supported by French state funds managed by the French National Agency for Research (ANR) through the MINIMEAU Project (ANR-17-CE10-0015): https://minimeau.fr/

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Tables:

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

Food Industry	Product	Unit	Specific water consumption	Specific wastewater discharge (yearly average)
Dairy	Milk	m^3.ton^{-1} 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^3.ton^{-1} 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^3.ton^{-1} 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^3.ton^{-1} of beets	0-0.9	0.5-1.0
	Soft drinks and nectar / juice	m^3.hL^{-1} of products	0-0.3 (maximum at 5.1)	0.08-0.20
Beverage	Beer	m^3.hL^{-1} of products	0.2-0.6 (maximum at 3)	0.15-0.50
Other	Wet pet food	m^3.ton^{-1} of products	2.64-4.88	1.3-2.4

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

Water consuming activity	Beverage (%)	Meat processing (%)	Vegetable (%)	Dairy (%)
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

Table 3: Definitions of specific terms used

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

Table 4: Overview of the main origins of the wastewater for some food industries, and 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, stream 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	TDS, TSS, COD, BOD, TOC, TN, TP, color, turbidity Sugars / Soluble starch / Proteins / Ethanol / Volatile fatty acids / Phenolic compounds Conductivity, pH Na^+ / Cl^- / Ca^{2+} / Mg^{2+} / Fe^{2+} / NO_2^- / Al^{3+} / SO_4^{2-} / F^- Pathogenic microorganisms	(Barbera and Gurnari, 2018) (Bloor et al., 1995) (Braeken et al., 2004) (Ferrarini et al., 2001) (Goldammer, 2008) (Ioannou et al., 2013) (Klemes et al., 2008) (Mavrov and Belieres, 2000) (Rao et al., 2007) (Rogener et al., 2003) (Simate et al., 2011) (Tay and Jeyaseelan, 1995)
Soft drink	Bottle washing, equipment washing and rinsing, filter washing, Regeneration of softener and decarbonator	TSS, BOD, COD Sugars / Pectins / Flavourings and colouring additives	(Barbera and Gurnari, 2018) (Hsine et al., 2005)

Table 5: Examples of the practices of recycling or reuse in the food industry (European 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	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

Type of industry	**Country**	**Reuse / recycling**	**Origin of wastewater**	**Targeted operation**
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

(*) nd: not defined

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

Membrane type	Retained solutes
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-treatement	Membrane treatment step (R% NaCl - MWCO)	TMP (bar)	J_p ($L.h^{-1} m^{-2}$)	Residuals through treatment step (R %)	Permeate use / Conclusion	Reference
DAIRY (cow)	**COD ≤ 1 $g.L^{-1}$**	**Flash coolers**	PreF 100 µm	**NF** 200 Da	30	80 – 100	COD 10-34 $mg.L^{-1}$ (70-90%) TOC 10 $mg.L^{-1}$ (65-78%) Cond 17-35 $µS.cm^{-1}$ (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)
		vapor condensates	Cartridge filter + UV	**NF + NF**	4 (2nd NF)	16	COD < 10 $mg.L^{-1}$ (80%) TOC< 4 $mg.L^{-1}$ (65%) Cond 2 - 35 $µS.cm^{-1}$ (75-80%)	"… technology was granted approval for water reuse in the food industry"	(Mavrov and Belieres, 2000)
		Unknown origin	PreF 25 µm	**RO** (99.5%)	20 - 30	14 - 21	TOC 130-300 $mg.L^{-1}$ (65-84%) Lactose 3-10 $mg.L^{-1}$ (>99%)	MF+RO : Heating or cooling operations	(Bortoluzzi et al., 2017)
	COD ~ 1 - 3 $g.L^{-1}$	**Flushing water**	-	**NF** 200 - 300 Da **RO** (99.5%)	10	5-6	Lactose 20 $mg.L^{-1}$ (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 $mg.L^{-1}$ (>99%)	Higher quality than urban recycled water	(Song et al., 2018)
			-	**RO** (99.5%)	20 10 10-20	30 18 12-23	COD < 30 $mg.L^{-1}$ (>98%) TOC < 7 $mg.L^{-1}$ (>99.8%) Prot < 10 $mg.L^{-1}$ (>97%) Lactose 5-40 $mg.L^{-1}$ (> 95%) Fat < 30 $mg.L^{-1}$ (>88%) Cond 8 - 50 $µS.cm^{-1}$ (> 97%)	Heating, cooling, cleaning ; RO+RO ➔ potable water quality	(Brião et al., 2019; Kyrychuk et al., 2014; Vourch et al., 2008)
		(Skimmed/ whole milk)	-	**(NF or RO) + RO** (99.5%)	20	34	TOC < 3.3 $mg.L^{-1}$ (> 99.9%) Cond < 9 $µS.cm^{-1}$ (> 98.7%)	Heating, cooling, cleaning	(Vourch et al., 2005)

		Diluted flushing water	-	**NF** (200 Da) ; **RO** (99.3%)	10-20	28-37 12-23	Lactose 30-47 mg.L^{-1} (> 93%) COD 21-42 mg.L^{-1} (> 98%)	Cooling towers	(Brião et al., 2019)
		Unknown origin	PreF 25 µm	**NF90** (200-400 Da)	20-30	50 - 100	COD 1 g.L^{-1} (20-50%) TKN < 60 m.L^{-1} (30-60%) Lactose < 15 mg.L^{-1} (>99%)	MF+NF : Heating or cooling	(Bortoluzzi et al., 2017)
	COD > 10 g.L^{-1}	**Flushing water**	-	**NF** (150 - 300 Da)	10 - 20	5 - 20	COD < 120 mg.L^{-1} (>90%) Prot N.D. Lactose < 400 mg.L^{-1} (>98%)	Boiler (if NF+RO or RO+RO)	(Balannec et al., 2002; Balannec et al., 2005)
			-	**RO**	15 - 35	4 - 40			(Balannec et al., 2002; Balannec et al., 2005)
BEVERAGE	**COD < 1 g.L^{-1}**	**Bottle washing (unknown industry)**	Cartridge filter 30 µm	**UF** **RO**	4.5 - 6.5 35 - 37	178 68	COD 30 mg.L^{-1} (95.6%) Turbi < 0.1 NTU (~100%) Color < 5.0 Hazen units (~100%) TDS 170.0 mg.L^{-1} (95%)	UF: Bottle washing plants RO: “water quality comparable to city water supply”	(Tay and Jeyaseelan, 1995)
		Brewing room rinsing water	-	**NF** (150-300 Da)	8	43 - 77	COD 1 – 24 mg.L^{-1} (~100%) Cond 535 – 1 818 µS.cm^{-1} (60-75%) pH= 11.2-11.6	Insufficient permeate quality	(Braeken et al., 2004)
		Bottles washing (Brewery)	Filtration with anthracite and sand + PreF 25 µm	**RO** (no information on the type of membrane)	10	10	Cond 21-93 µS.cm^{-1} (96-99%) COD 4-14 mg.L^{-1} (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)
		Presoaking water from bottle washing machines (mineral water bottles)	Cartridge filters, UV disinfection	**NF + LPRO** (no information on the type of membrane)	-	-	Cond 18 µS.cm^{-1} (>98.7%) COD 1.8 mg.L^{-1} (>99%) TOC 3.6 mg.L^{-1} (>96%) NO_2^- < 0.1 mg.L^{-1} (~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)
	COD ~ 1 - 5 g.L^{-1}	**Brewery - Bottle washing**	-	**NF** (150-300 Da)	8	43 - 85	COD 97-210 mg.L^{-1}: 66-167 mg.L^{-1} from ethanol (60-75-%) Cond 782-3320 µS.cm^{-1} (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^{-1}: 78-147 mg.L^{-1} from ethanol (95-96%) Cond 146-357 µS.cm^{-1} (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^{-1} (97.4%) BOD$_5$ 9 mg.L^{-1} (97.9%) TN 3.3 mg.L^{-1} (67%) TP 0.5 mg.L^{-1} (76.2%) TSS 4 mg.L^{-1} (93.9%) TS 200 mg.L^{-1} (96%) Cond 182 µS.cm^{-1} (94.6%) *Daphnia magna 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^{-1}**	**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^{-1} (54.1%) Free chlorine 0 mg.L^{-1} (100%) Tot_chlorine 0.16 mg.L^{-1} (98 %); Color: green	"Suitable for recycling"	(Nelson et al., 2007)
			UF (SiC-0.05 or SiC-0.1) 2 bar/155 L.h^{-1} m^{-2}	**RO** (99.5%) SW30HR TW30	17	6 26	COD 52-60 mg.L^{-1} (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^{-1} (98%) Conducti < 8µS.cm^{-1} (98.3%) Sugars < 4 mg.L^{-1} (99.2%)	"Reuse in the vegetable plants prior to the blanching step"	(Garnier et al., 2020)
	COD = 70 - 85 g.L^{-1}	**Soy bean cooking water**	Centrifugation or UF+UF	**NF** (150-300 Da)	20	35-61	Sucrose N.D. (100%) COD 8.3 - 10 gO$_2$.L^{-1} (>80%)	(Centri or UF) + NF: water reuse	(Pauer et al., 2013)
POULTRY AND MEAT PRODUCTION	**COD < 0.5 g.L^{-1}**	**Sausage cooling water**	Sedimentation skimming + MF (3 µm) + H$_2$O$_2$ + UV	**NF** (polyamide membrane)	5 - 6	18.8 - 27	Turbi < 1 FNU (100%) Cond 95-350 µS.cm^{-1} (61.1 – 95.7%) COD 2-3 mg.L^{-1} (92.7-98.3%) TKN < 1 mg.L^{-1} (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^{-1} (55.1%) Cond 52-145 µS.cm^{-1} (91.1%) Nitrite 0.05-0.18 mg.L^{-1} (65.8%)	NF+NF+ disinfection ➔ drinking water quality	(Fähnrich et al., 1998)
			Belt filter, cartridge filters, UV	**NF** + **NF**	5.4 1.4	2 4	Cond = 7-120 µS.cm^{-1} ~92%) TOC = 1.4 – 2.5 mg.L^{-1} (99%) Cl^{-} = 0.7-2.1 mg.L^{-1} (~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^{-1} (93%)	-	(Malmali et

	COD = few g.L^{-1}	**washing; Chilling wastewater**				50 – 70 160 – 350	COD ~ 70 mg.L^{-1} (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^{-1} Turbi= 0.10-0.15 NTU TS= 10 - 40 mg.L^{-1} Ca^{2+} < 5 mg.L^{-1}	**"Feasibility for water recovery"**	(Hernández et al., 2019)
VEGETABLE OILS	**COD < 1 g.L^{-1}**	-	-	**UF** 30 kDa	2	60 (?)	COD 50 mg.L^{-1} (90 %) TOC 40 mg.L^{-1} (86 %) TSS 0 mg.L^{-1} (100 %)	Treated water suitable for discharge	(Mohammadi and Esmaeelifar, 2004)
	COD = few g.L^{-1}	-	Neutralization + coagulation + MF (0.2 µm)	**UF** (PVDF 200 kDa) **+ RO** (99% NaCl)	5 30	33.4 39.1	Turb 0.05 NTU (99.9%) SS 198 mg.L^{-1} (96.5%) BOD$_5$ 30 mg.L^{-1} (98.9%) pH=6.67	RO permeates comply with the "WHO standards" for water reuse	(Azmi et al., 2013)
		Palm oil mill		**RO** (PPT-9908)	55.2	52.5	TDS 62 mg.L^{-1} (99.4%) COD 46 mg.L^{-1} (98.2%) BOD 0 mg.L^{-1} (100%) Cond 86 µS.cm^{-1} (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$_2$	104 (π)	4	TOC 130 mg.L^{-1} (96.8%) TIC 1.6 mg.L^{-1} (99.3%) TPh 13 mg.L^{-1} (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^{-1} (86-89 %) Phenolic compounds 10 mg.L^{-1} (95 %)	Irrigation use	(Ochando-Pulido et al., 2018)
		Soybean oil	GAC	**RO**	-	100	COD 380-528 mg.L^{-1} (94 - 97 %) Turbidity 1.22-1.84 NTU (> 99.78%)	-	(Elhady et al., 2020)
	COD ~ 50 – 67 g.L^{-1}	**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^{-1} (>95.6%) COD < 0.7 g.L^{-1} (97.5%)	Useless UF	(Coskun et al., 2013)
		Soybean oil	Coagulation-flocculation	UF 150 kDa	1.2	40 - 60	TOC 277 - 473 mg.L^{-1} Turbidity < 7.2 NTU (>99.7%)	Insufficient quality for discharge into receiving environment	(Khouni et al., 2020)

							Color 0 (100%)	or for agricultural use	

* CFU= Colony Forming Units

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

Type of industry	**Main process**	**Posttreatment**	**Reference**
Dairy	NF + NF	UV	(Chmiel et al., 2000; Mavrov and Belieres, 2000; Mavrov et al., 2001)
Meat	NF + NF	UV	(Fähnrich 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)