A review of technologies and applications for water purification in the food & beverage industry

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Abstract: Food & Beverage (F&B) industry is known as a water intensive sector. Thousands of litres per hour of pure water are necessary to produce the final drinks, for the line and backup process requirements of medium size production plants. Due to health restrictions and the F&B standard, the physical, chemical and biological quality of process water has to fit with high level of purity. To this purpose, all F&B plants require a dedicate water purification unit making raw water (both primary and recovered) ready-for-use. Such units are process plants based on mechanical and chemical purification technologies, mainly. This paper aims at revising the state-of-art of research and practice in this field. Starting from the process description and the expected water quality level, a matrix analysis, according to a panel of classification drivers, allows outlining the current research streams and the most popular technologies. The industrial sector, the fluid features and the adopted technology are among the investigated drivers. Results highlight a wide range of solutions, often combined in series to increase the final effect. Lacks are in applications dedicated to the wastewater purification, implementing local close-loops to decrease the overall F&B water intensity.

Keywords: Water purification, Food & Beverage, Process industry, Matrix analysis, Review.

1. Introduction

Water is the key of Earth's life and lies behind all anthropic activities. The availability of pure water is essential for social, technological and economic progress. The FAO Aquastat database provides wide information about the origin, use and disposal of this basic resource (FAO, 2016). A scattered scenario appears. Water withdrawal ranges between <100m^3/inhab/yr for Centre Africa and >800m^3/inhab/yr for North America and the Western Europe. Furthermore, at global level, over 70% of the ~4 million m^3/yr water withdrawal is for agricultural uses, 20% goes to industry and the remainder supplies municipal needs. Such balance is changing, progressively, due to industrialization. Starting from the developed countries, the incidence of the secondary sector on the water balance is increasing rapidly. Europe leads this transition. 2014 data states that industry water intensity is of about 57%, while agriculture is at 22% (Aquastat, 2014).

Industry is hungry of water and highly pure water. All the coded Eurostat industrial sectors require water within the production processes and/or incorporate water into the delivered final products. Multiple evidences fix *'top six'* industrial sectors in terms of water consumption, i.e. food & beverage (F&B), textiles, paper and paper products, energy, petroleum and chemicals, basic metals, motor vehicles and transport equipment (Eurostat, 2015).

F&B industry uses pure water for washing, preparing, cooking and handling food produces, to clean the primary packages containing food and drink with thousands of litres per hour of water need for a middle side F&B production plant. Water is pure if contaminants of any type, e.g. biological, chemical, etc., are below safety limits for the human health and the safe process assessment (Grimm et al., 1998). Raw water in input to the process has ground or underground origin and it is withdrawn, locally, by the process industry itself. Uses of the civil/residential water grid are rare due to the required quantities and for economic reasons. Furthermore, wastewater at the end of the process is discharged, i.e. open loop, after post treatments to match the existing regulations about wastewater quality levels. The quality of raw water entering the F&B industry makes it not ready-to-use due to low purity. F&B production sites have local purification plants treating water before its use within the main process. Such industrial auxiliary units include mechanical and chemical functional modules, arranged in series, dedicated to specific contaminants, e.g. suspended solids, solutes, microbiological charge, etc. Wide research and applications exist about these units to increase performances, reduce stops and maintenance best fitting the industrial sector peculiarities. Both base research on new materials and technologies and applied research on customized plants exist.

This paper proposes a review and analysis of the existing literature, prototypal solutions and full-scale applications. Deep focus is on the F&B sector. Starting from the description of the standard water pollutants and overall plant structure a set of drivers allows classifying the current research trend stressing the most promising streams and the existing open challenges driving the forthcoming efforts in this field.

According to the introduced topic and purpose, the reminder of this paper is organized as in the following: the next Section 2 introduces the groups of water pollutants and purification technologies. Section 3 provides the drivers to study and classify the existing literature. Section 4 presents a matrix analysis of the recent developments in the field drawing trends and action lines. Finally, Section 5 concludes this paper with operative suggestions and future research opportunities.

2. Water pollutants and key purification technologies

The origin and previous use of the F&B process water heavily affects its level of purity, the pollutants inside and it drives the choice of the purification technologies. Abstracting from local peculiarities, the following sub-sections provide an overview of the most common categories of impurities within ground and underground raw water entering F&B industry processes. Finally, widely adopted purification technologies are introduced.

2.1 Pollutant categories

Solids are the first group of water contaminants. Such large group includes both dissolved (DS) and suspended (SS) substances of organic and inorganic origin. Examples of organic DS are humic acid, tannin and pyrogens, while dissolved reactive silica and salt ions exemplify inorganic DS. On the other hand, algae, fungi and bacteria are organic SS, while silt, rust, floc and clays are inorganics. Conductivity/resistivity analyses allow estimating the total DS and SS, while chemical analyses allow identifying the concentration of dissolved minerals and organics (Alvarez et al., 1997; Brunner, 2014).

Microbiological contamination is the second category of water pollutant. A distinction between viable and nonviable organisms indicates the possibility of this pollutant to proliferate within water. Bacterial colonies, pyrogenic contamination, e.g. endotoxins, are common microbiological compounds within raw water. LAL test to track endotoxins, total organic carbon (TOC), biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are key indicators of the environmental health of process water. Large use of these indicators is done when analysing F&B process wastewater because of the high risk of water microbiological contamination during the process (Diná Alfonso and Bórquez, 2002).

The third group of contaminants includes minerals, from ions. Common mineral contaminants are iron, manganese, sulphates, carbonates, nitrates and nitrites, phosphates, silica, aluminium, sodium, potassium, etc. The detection of the level of such impurities is by concentration measures, water hardness and alkalinity measures. High differences occur in the quality and quantity of such impurities depending on the water origin and eventual previous use.

Heavy metals are the fourth harmful category of pollutants. Lead, arsenic, cadmium, selenium and chromium cause severe human health risks and badly interfere with the F&B processes.

Final pollutants of interest include dissolved gases, as carbon dioxide, hydrogen sulphide and radon, radioactive constituents, i.e. radionuclides, dissolved and volatile organic compounds (DOC and VOC, respectively). Depending on their nature, DOC and VOC may cause severe effect on human health. The most of them is carcinogen.

2.2 Purification technologies

Macedonio et al. (2012) provide an extensive survey about water purification technologies from different water sources stressing the crucial role of membranes in the current scenario. Basically, membranes purify water according to the *'mechanical sieve theory'* (Wilf, 2008) even if chemical reactions and biological pollutant degradation become possible depending on the membrane materials.

Membrane technologies include filtration and reverse osmosis (RO). Filtration is distinguished, further, in micro-, ultra- and nanofiltration depending on the dimensions of the membrane pores. Figure 1 matches such dimensions to the detected pollutants.

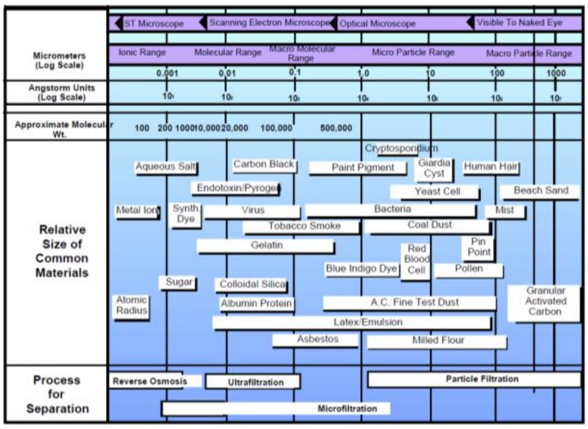
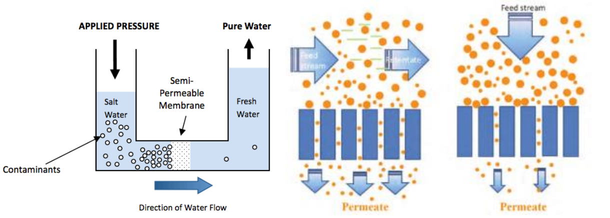


Figure 1: membrane technologies (Munir, 2006)

When the source water passes through the filter, under the so-called trans-membrane pressure provided by the gravity or a pump, the pollutants, e.g. bacteria, viruses, are held (Gao et al., 2011). After ultrafiltration, the water is generally ready to drink. For F&B industry use, RO is adopted, frequently, to remove the most of the solutes as evident in the following review analysis. In RO, the application of an external pressure to a concentrated solution forces the water molecules through a semi-permeable membrane retaining the contaminants (El-Manharawy and Hafez, 2000). The following Figure 2 presents the RO and filtration principles and the two most common filtration technologies, i.e. dead-end and cross-flow (see Munir, 2006, for details).



(a) *(b)*

Figure 2: RO *(a)* and filtration *(b)* technologies

The microbiological contamination removal is through an UV functional unit. UV radiation inactivates the most of microorganisms. The degree of inactivation depends on the UV dose and time exposure (in μW·s/cm^2). Standard modular UV units are already widely diffuse at highly competitive cost.

Finally, in addition to such technologies, distillation, thermal processes and new frontiers adopting innovative principles, e.g. biotechnological reactors, are at a prototypal level of readiness.

3. Water technology classification drivers

To provide a comprehensive review and comparison among the existing contributions on water purification a set of classification drivers is introduced. They are the common metrics of analysis of the literature. Analytically:

- Study target. Both industrial applications and research papers are considered. Such driver directly refers to the technology readiness level of the proposed purification methodology.
- Industrial sector. Attention to the beverage and food sector is payed. Nevertheless, in presence of possible extensions to further industrial areas, the analysis highlights cross-sectorial applicability.
- Process fluid. This driver distinguishes among raw water, from ground or underground, wastewater, i.e. recovered process fluids at the industry site to implement local close-loops, and juices/water based fluids (with large water percentage – highly diluted).
- Key investigated technology. According to the trends outlined in Section 2, deep attention goes to filtration and RO as the most immediately applicable technologies. Some frontiers are included as 'other(s)' if they are beyond the so-called experimental proof of concept. In addition, mandatory basic pre-treatments, e.g. chemical addition, pre-filtration etc., and post-treatments, e.g. UV, clean in place (CIP), etc., are neglected because they are common in practice.

4. Matrix analysis

Following the introduced classification drivers, a deep review of the literature, from 1992 to present, allows drawing the matrix of Table 1 crossing the references to the metrics of analysis. The search of the articles is within high standard scientific electronic databases (EDs) as Elsevier (sciencedirect.com), Tailor & Francis (tandfonline.com), Emerald (emeraldinsight.com), Springer (springerlink.com) and Inderscience (inderscience.com) using the introduced pollutants and purification technologies as keywords to drive the search. Attention is, mainly, on indexed international journals presenting frequently cited papers.

In Table 1 ticks indicate if the correspondent paper addresses or not the driver of analysis. Multiple ticks within the same driver indicate a combination of technologies and/or process fluid. The global overview of the matrix shows the research trends in this research field. Some interpretative keys are in the following.

- Multiple examples of industrial applications are proposed indicating an advanced technology readiness level of water purification technologies. This is particularly true for RO technology already widely adopted in both large and small-scale F&B plants and still effective in the modern purification systems.
- The frontier of the research, studied from different perspectives in a wide number of research papers, is on innovative materials for membranes, on the integration of multiple technologies for a low-maintenance, low-carbon and low-energy purification plant and on wastewater local recovery even under critic conditions in terms of water contaminants, e.g. meat, dairy and fruit industries.
- The integration of ultrafiltration and RO within the series of the plant functional modules is widely adopted in the F&B sector. This is to remove the suspended solids and, then, the solutes. UV is, generally, at the last stage. Globally, the integration of complementary technologies is becoming a *must* to get highly pure water.
- Wide interest is in water desalination, even from seawater, due to their large applicability, worldwide; see reference from *Desalination* journal.
- Despite deep studies applied to the beverage industry exist; research is more limited for the food industry mainly because of the lower attention to the water problems.
- Research on wastewater is still limited respect to raw water (including water within water-based products); it is concentrated in the most recent years even if the pioneering studies dated early '90s state the water intensity of the F&B sector.
- Rising attention is on alternative purification technologies with very-low environmental impact. Good examples use bioreactors strongly reducing the need of chemicals. Weaknesses of such solutions are in the process time, the need of batches instead of continuous water flows and the maintenance activities on the active agents. Upgrades are mandatory before their use within the F&B industry.

Table 1: matrix analysis on water purification technologies and applications

Year	Author(s)	Study target: Industrial Application	Study target: Research Paper	Industrial sector: Beverage	Industrial sector: Food	Industrial sector: Multiple/ Cross-sectorial	Process fluid: Raw water	Process fluid: Wastewater	Process fluid: Juices/ Water-based	Process fluid: Multiple/ Cross-sectorial	Key investigated technology: Microfiltration [0.1-0.5]µm	Key investigated technology: Ultrafiltration [0.005-0.05]µm	Key investigated technology: Nanofiltration [0.0005-0.005]µm	Key investigated technology: Reverse Osmosis	Key investigated technology: Other(s)
1992	Capannelli et al.	✓		✓					✓			✓			
1995	Al-Mazidi		✓			✓	✓	✓							
1996	A1-Malack & Anderson		✓			✓				✓	✓				
1996	Jiraratananon & Chanachai		✓	✓					✓			✓			
1996	Snow et al.		✓			✓	✓					✓	✓	✓	
1997	Alvarez et al.	✓		✓					✓					✓	
1997	Jiraratananon et al.		✓	✓					✓			✓			
2000	El-Manharawy & Hafez		✓	✓			✓							✓	
2000	Mavrov & Bélières	✓			✓			✓					✓	✓	
2001	Al-Jayyousi & Mohsen	✓		✓			✓							✓	
2001	El-Manharawy & Hafez		✓	✓			✓	✓						✓	
2002	De Bruijn et al.		✓	✓					✓			✓			
2003	De Barros et al.		✓	✓					✓			✓			
2004	Galambos et al.	✓			✓			✓					✓	✓	
2004	Uche et al.	✓			✓		✓							✓	Distillation
2005	Bohdziewicz & Sroka	✓			✓			✓						✓	
2005	Mehta & Zydney	✓				✓				✓		✓			
2005	Yazdanshenas et al.	✓		✓					✓			✓			
2006	Baruah et al.		✓			✓				✓	✓				
2006	De Bruijn & Borquez	✓		✓					✓			✓			
2006	Cassano et al.	✓		✓					✓			✓			Distillation
2007	Cassano et al.		✓	✓					✓			✓			
2007	Cassano et al.		✓	✓					✓			✓			
2007	Rai et al.		✓	✓					✓			✓			
2007	Rektor et al.	✓		✓					✓					✓	
2008	Cassano et al.		✓	✓					✓			✓			
2008	Frenkel		✓			✓	✓	✓			✓	✓	✓	✓	
2008	Mirza		✓			✓				✓			✓	✓	
2008	Vourch et al.	✓			✓			✓						✓	
2009	Di Giacomo & Taglieri	✓		✓					✓					✓	
2009	Gokmen et al.		✓	✓					✓			✓			
2009	Zularisam et al.		✓	✓			✓					✓			
2010	Astudillo et al.		✓			✓				✓	✓	✓	✓		
2010	El-Kamah et al.	✓		✓				✓							Thermal
2010	Kanani et al.	✓				✓				✓		✓			
2010	Onsekizoglu et al.		✓	✓					✓						Distillation
2010	Yazdanshenas et al.	✓		✓					✓			✓			
2011	Habibi et al.		✓	✓					✓		✓				
2011	Razi et al.		✓		✓					✓	✓				
2013	Kujawski et al.	✓		✓					✓					✓	
2013	Sudhakaran et al.		✓	✓			✓				✓	✓	✓	✓	
2014	Mahmoud et al.		✓			✓	✓				✓	✓	✓	✓	
2014	Sorlini et al.	✓		✓			✓				✓	✓	✓	✓	Thermal
2015	Alkaya & Demirer	✓		✓				✓	✓		✓	✓		✓	
2015	Raj & Murthy		✓		✓			✓							Chemical
2016	Ghimpusan et al.		✓		✓			✓						✓	Biological
2016	Meneses & Flores	✓			✓			✓				✓		✓	
2016	Mohammad et al.		✓	✓			✓				✓	✓	✓	✓	

5. Conclusions

This paper presents a matrix analysis, based on relevant classification drivers, to review the literature about water purification technologies and applications for the food & beverage (F&B) industry. Starting from the introduction on the water purification issue, the pollutant categories and the most diffused technologies and methods to provide high standard water to the F&B main plant, the matrix analysis detects the research directions and open challenges.

The review of the literature, from 1992 to present, shows high attention to raw water and water based fluid treatment within the beverage industry. Minor studies are about wastewater recovery, especially for the food industry, to implement water saving local closed-loops. Base research on materials and the design of dedicated recovery functional modules are encouraged together with prototypal and full-scale plant set up to field test solutions to this challenging goal allowing strong water savings and decreasing the environmental impact, i.e. water footprint, of the F&B industry. Finally, base research and proof of concept for innovative non-mechanical green technologies are to be investigated further making such solutions ready to their industrial application.

Acknowledgements

This work is developed within the CIP Eco-innovation project no. Eco/13/630314/LESS-WATER BEV.TECH, co-funded by the Eco-innovation Initiative of the European Union, in partnership with A DUE S.p.A. and CVAR Ltd.

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