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Description of the Deliverable n. 12 of Work Package 6

This deliverable reports about the publication of the second two scientific reports, as scheduled, on relevant scientific journals in the field of energy, water management and production process design and optimisation.

These activities are particularly important for the dissemination of the new technology among the international academic community.

The project outcomes are going to be presented and discussed at two international conferences, as follows:

#	Title of Paper	Authors	Conference / Presentation	Proceedings
3	Environmental assessment of an innovative plant for the wastewater purification in the beverage industry	Marco Bortolini Lucia Botti Mauro Gamberi Riccardo Manzini Cristina Mora Alberto Regattieri (Department of Industrial Engineering, Alma Mater Studiorum - University of Bologna, Italy)	24th International Conference on Production Research ICPR 2017 (Poznań, Poland), July 30th - August 3rd, 2017 www.24icpr2017.put.poznan.pl	Published on DEStech indexed on Web of Science
4	Design, prototyping and assessment of a wastewater closed-loop recovery and purification system	Marco Bortolini Mauro Gamberi Cristina Mora Francesco Pilati Alberto Regattieri (Department of Industrial Engineering, Alma Mater Studiorum - University of Bologna, Italy)	Multidisciplinary Digital Publishing Institute, 2017 http://www.mdpi.com/2071-1050/9/11/1938	MDPI for peer-reviewed and open access journals

ENVIRONMENTAL ASSESSMENT OF AN INNOVATIVE PLANT FOR THE WASTEWATER PURIFICATION IN THE BEVERAGE INDUSTRY

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Abstract
Nowadays, efforts to reduce the resource depletion and environmental emissions from the anthropic activities, are mandatory for sustainable development pattern. Among the key resources to save, pure water is as important as critic due to its scarcity and its essential role for life and growth. Furthermore, during the last decades, rising attention from institutions and industries is toward solutions for the water intensity decrease and wastewater recovery.
This paper proposes the environmental assessment of an innovative wastewater collection and purification plant tailored to a mid-size beverage industry aiming at locally closing the loop of the water chain, allowing its recirculation and local reuse. After the description of the functional module features, sizes and design, based on a prototype actually working in Italy, the paper follows the ISO 14040 standards to develop an environmental assessment of the industrial system, quantifying the impact rising from the manufacturing and the assembly phases.

Keywords: Wastewater purification, Life Cycle Assessment, Design for the Environment, Water saving, Food and beverage industry.

1. INTRODUCTION

Nowadays the urgency in reduction of emissions and of depletion of resources makes necessary to pay attention to Design for Environment and Eco-design, in order to encourage a sustainable development.
In accordance with the World Commission of Environmental and Development (WCED, 1987), sustainable development is “a pattern of resource use that aims to meet human needs while preserving the environment so that these needs can be met not only in the present, but also for future generations” [1].
The reduction in the use of raw materials and natural resources, the spread of energy efficient processes and components are necessary from both the economic and the environmental viewpoints. Between the natural resources particular attention need the water, that is known as the ‘blue gold’, the key of life, and its availability is crucial for the equal growth of communities (UN Millennium Development Goal Report, 2011) [2]. Among the key resources to save, pure water is as important as critic due to its scarcity in large geographical areas and its essential role for life, progress and growth. So, during the last decades, rising attention from institutions, industry and the public opinion is toward solutions for the water intensity decrease and wastewater recovery.
Wastewater recovery is a must at the EU level, with the aim to save the environment – water footprint of processes; to comply with the EU regulations; to match high technical/economic target in product/market.

Focusing on the European Union (EU) area, the highest amount of water consumption is from industry.

Furthermore, among all industrial activities, Food & Beverage industry is known as a very water intensive sector (~100.000 liters/hour of raw water generating thousands of litres of wastewater per day).

Within F&B, standard mid-size plants require over 45m3/h of pure water, i.e. reverse osmosis water, to produce common beverages as juices and carbonated soft drinks. Actually, such water is pumped from wells and drained after use (open loop).
This paper proposes the environmental assessment of an innovative wastewater collection and purification plant tailored to a mid-size beverage industry aiming at locally closing the loop of the water chain, allowing its recirculation and local reuse. After a legislative overview about the European and Italian strategies on food and water production (paragraph 2), the authors conduct a literature review on the Life Cycle Assessment analysis in industrial application (paragraph 3). Then a description of the functional module features, sizes and design, based on a prototype actually working in Italy is made (paragraph 4). Following paragraph 5 presents the environmental assessment of the industrial wastewater recovery plant quantifying the key categories of impact and effect on the environment rising from the manufacturing and the assembly phases.

2. LEGISLATIVE OVERVIEW

2.1. The European strategy on food and water production

People ingest water directly or indirectly, as other foods, taking all the substances contained in it and swallowing microbiological contaminants and chemicals. The Council of the European Communities ([3],[4]) control the quality of the water used for human consumption, aiming to guarantee a high level of health protection for the European community. Specifically, the food law applies to food and feed traded both on the internal market and internationally. The food production chain and the food safety issues cover a wide range of critical aspects, from the primary production to the final consumption, going through its transport and distribution. The European Food Safety Authority promotes, applies and controls the procedures in matters of food safety. Specifically, the protection of the human health from the adverse effects of any contamination of water intended for human consumption is one of the main goals of the European strategy for food safety. Furthermore, the comprehension of the scarcity of natural resources and of the vulnerability of biosphere health induced a deep re-thinking of the concept of development, as a process harmonised with the environment, in the interests of present and future generations. In a sustainable growth perspective, the European Parliament ([5]) from the Council Directive 98/83/EC sets the goal to increase efficiency standards for water using products up to the 16% by 2030.

2.2 The Italian approach

The Italian regulations on water production is fragmented. Several national regulations address the water production chain, defining the Italian strategy and responsibilities at national and local levels.

The Presidency of Italian Republic actuates the Council Directive 80/778/EEC [3] with Legislative Decree 2 febbraio 2001, n. 31 [6], regulating the management of the water for human consumption, specifying the water quality control methods, the responsibilities in industry and the control Authority. The Italian legislation prohibits the use of recovered and purified wastewater within F&B and pharmaceutical industries except in the case of a local recover. Specifically, the Minister of Environment and Land Protection has defined the Decree GAB/DEC/ 93/06 on Technical standards for wastewater reuse [7]. In the Art. 3 (eligible use), such decree states that the treated wastewaters can be used for watering, civil use and industrial use. Finally, the Legislative Decree 11 maggio 1999, n. 152 [8] transfers the responsibility of setting rules for water saving, control and reuse to the local regions.

3. LITERATURE REVIEW

Increasing the eco-efficiency of the global economy and decreasing the environmental impact associated with the industrial processes is a crucial goal for the developed countries. Companies are one of the key players in the pursuit of a more sustainable society.

This Section introduces a brief literature review on Life Cycle Engineering (LCE) and Life Cycle Assessment (LCA), showing the importance of LCA in the Eco-Design and some applications of LCA in industry.

Jeswiet defines the “Life Cycle Engineering” (LCE) as “the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimising the product life cycle and minimising pollution and waste” [9].

The same author defines LCE as a multitude of topics such as: sustainability, economics, market, economic progress, social concern, environment, protect the environment, minimise pollution/waste, resource conservation, engineering activities, optimisation, eco-design, green design, product life cycle, product/process assessment. Wenzel and Alting [10] and Rosen and Kishawy [11] define three dimensions of levels on eco-efficiency in LCE: product, process and practices. Consequently, Life Cycle Engineering addresses the eco-efficiency by focusing on the design of product and its manufacturing process by using organisational practices.

3.1. LCA and Eco-Design

Eco-Design, or Design for Environment, focuses on the resource preservation, the environmental protection and the human health during the whole product life cycle [12], [13]. Regardless of the restrictions imposed by the regulations and the standards in force, the compliance with the best practices in eco-design may provide competitive leverage in the market, given its sustainability advantages [14]. Bovea and Pérez-Belis have developed an extended taxonomy of Eco-Design tools based on literature contributions concerning the environmental design methodology [15]. Their study includes twenty main Eco-Design methodologies. More than the 50% of such methods are based on the use of LCA for the product environmental profile assessment. The literature on the use of LCA for the Eco-Design shows both potential benefits and the limits of the LCA-based approach [16]. However, today LCA is a standardized methodology and its application is popular in several industries, from agriculture to food packaging. The following Section 3.2 shows some applications of LCA in different industries.

3.2. LCA in industry

LCA is widely adopted in industry. Several researches show the use of LCA for the water treatment industry [17]–[23]. In the last years, the study of the environmental impact assessment of the processes related to the agricultural industry has increased significantly. Such interest is justified by the importance of the food production to the environmental impact generation. Roy et al. have proposed an extended review on LCA studies related to the food production, classifying several contributions on the basis of the food product features [24]. Hospido et al. have analysed milk production in Spain. Their research shows that the feed production phase is a hotspot of milk life cycle [25]. Specifically, the production of silage, representing the 21% by weight of the animal feed, is estimated to be responsible for 29% of global warming and acidification, and 23% of the eutrophication effects of the total milk production process. Accorsi et al. propose an original conceptual framework for the integrated design of a food packaging and distribution network. In such paper, LCA methodology is used to evaluate the carbon footprint associated with the life cycle of packages in a distribution network [26].

Finally, in their study, Cascini et al. have shown a streamlined version of LCA, the Carbon Footprint Assessment, for the analysis of the whole refrigeration system life cycle. Their results demonstrate that the use-phase contributes significantly to the total environmental impact, and that indirect emissions resulting from refrigerating unit electric energy consumption are larger than those associated with refrigerant leakage.

4. THE PLANT

The analysis concerns an innovative plant for water treatment and wastewater recovery and purification in the food & beverage industry. The key aspects of the plant are: water saving, wastewater recycling, solid waste minimisation and recovery. The rated drinkable water production of the plant object of this project is 50’000 l/h all spent in beverage preparation, divided in Non-Carbonated Beverage (NCB) and Carbonate Soft Drinks (CSD). Design and modelling of NCB or CSD water-saving production plant components will be developed considering the main goal of total water consumption minimisation and waste water amount reduction.

The target is a mid-size F&B Italian company producing soft drinks, non-carbonated beverages, juices and vegetable sauces. The annual water intensity is 2.4 billion liters/year actually supplied from five wells and managed in open-loop.

The block diagram of the pilot plant is reported In Figure 1.

The main components of the system are Carbon Filter, Tanks, Prefiltration, Ultrafiltration, Reverse Osmosis, Ultraviolet Treatment, Cleaning in Place (CIP),Pump for water recovery.

The water streams of the plant are:

- Fillers: 3 lines, 30,000 l/h, continuous;
- Osmosis retentate: 15,000 l/h, continuous;
- CIP: 4,000 l/h, discontinuous & highly polluted;
- Cooling towers: 2,000 l/h, continuous;
- Syrup room: 1,000 l/h discontinuous.

4.1. Ultrafiltration (UF) system

“UF is recognized as a low-pressure membrane filtration process; it is usually defined to be limited to membranes with pore diameters from 0.005μm to 0.1μm. When the source water is passing through the filter under a trans-membrane pressure provided by the gravity or a pump, the bacteria and most viruses can be removed, […] the drinking water quality can be satisfied for consumers, and the use of chemicals, capital, and operating cost can be reduced.”[27]

The overall operating conditions and output of the ultrafiltration system are:

- Pressures: 0.03 ÷ 3 bar
- Pore diameter: 0.005 ÷ 0.1 μm
- Withholding molecular amount: 1 ÷ 500 kDalton
- Membrane structure: porous anisotropic structure.

- Typical removed impurities: suspension, colloids, bacteria, dissolved organics (*partially*)
- Unremoved solutes: fine minerals, soluble salts, metal ions
- Flow rate: 40 ÷ 90 l/m^2h (depending on the treated water) Hagen-Poiseuille Carman-Kozeny equations.

4.2. Reverse osmosis system

The ultrafiltration treatment eliminated from our water all suspended solids and most of the microbial contamination, but did not act in any way on the contaminants dissolved in the water to be treated.

To remove the contaminant solutes from the water it is necessary to use a reverse osmosis plant. Reverse osmosis uses a different principle than the purely mechanical ultrafiltration one, in this case osmotic membranes are used that are permeable to water and not to solutes present in it. Applying a higher pressure than the osmotic one to the water to be treated a migration of water is obtained in the opposite direction to the natural one, i.e., from the more concentrated part to the less concentrated one. In this way two waters are obtained, one rich in solutes that will be discarded and one poor in solutes that will be sent to the customer's treated water storage tank. For the osmotic membrane sizing the authors rely on a well-known calculation programme "Rosa" by DOW. The output is 25000 l / h of water having the following characteristics:

- turbidity: < 0.1 NTU
- total suspended solids: < 0.1 mg/l
- total dissolved solids (TDS): 50 mg/l

The selected membranes are the BW30-400 a model specifically designed to work with water having a dissolved solids content of greater than 2000 mg / l, was also considered a flow factor of 0.85 to consider the fouling of the membranes to three years.

The complete scheme of the prototypal wastewater recovery plant is reported in Figure 2.

5. LIFE CYCLE ASSESSMENT

The LCA is a useful tool for the evaluation of the environmental impact associated to a specific product life cycle. Topics and steps of the LCA methodology are regulated by the International Organization for Standardization (ISO). According to the ISO 14040:2006 (E) the complete LCA framework includes four steps: goal and scope definition; inventory analysis; impact assessment; interpretation of results. In this study SimaPro 7.3.3 by Pré Consultants is the software used as support. This LCA considers: raw material extraction processes; manufacturing and assembly of components; transports. Life cycle impact assessment is carried out using three methods: Eco-indicator 99 Hierarchical version (EI99H), ReCiPe H/A and IPCC 2007 Global Warming Potential (GWP). The first one focuses on the evaluation of midpoint indices: damage on human health, measured in "DALY" (Disability Adjusted Life Years); ecosystem quality, quantified in PAF·m2·year (Potentially Affected Fraction); resource preservation, evaluated in "MJ surplus". Therefore, through weighting and normalisation, EI99H elaborates an endpoint index (Pt) that measures the total environmental impact of the analyses object: 1000 Pt corresponds to the average environmental burden introduced by an European citizen in one year. The ReCiPe method comprises two sets of impact categories with associated sets of characterisation factors. Eighteen impact categories are addressed at the midpoint level. At the endpoint level, most of these midpoint impact categories are further converted and aggregated into the following three endpoint categories: damage to human health (HH), measured in "DALY"; damage to ecosystem diversity (ED), measured in Ecosystem species*yr; damage to resource availability (RA), measured in Resources Surplus Cost.

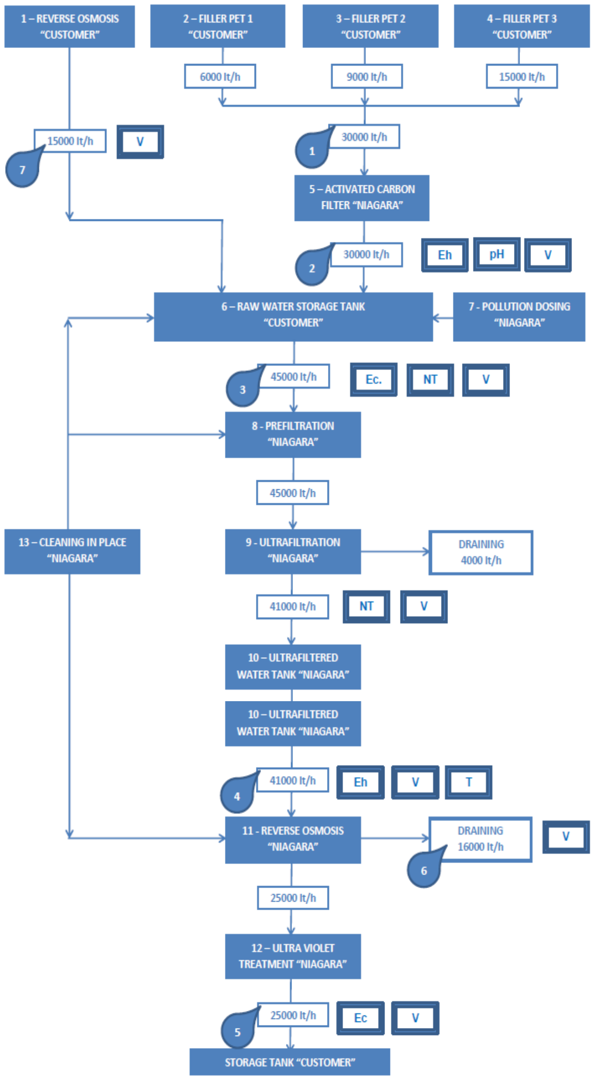

Figure 1: Block diagram of the pilot plant

Finally Global Warming Potential is defined as "the climatic warming potential of a greenhouse gas relative to that of carbon dioxide and is calculated in terms of the 100-year warming potential of 1 kg of a gas relative to 1 kg of CO2" (Directive 2006/842/EC). The GWP of a gas is measured in mass of equivalent carbon dioxide CO2(eq)).

5.1. Goal and Scope definition

The main objective of this LCA is the environmental impact evaluation of the manufacturing and the assembly phases of the industrial system, with the final aim of identifying the life cycle stages and plant components that, directly and indirectly, introduce the greatest impact on the final results. The characterization of the most relevant contributions is mainly intended to redesigning the plant in a greener perspective.

For the present study, the functional unit is the construction of an innovative plant for water treatment and wastewater recovery and purification in the food & beverage industry. The confines of the system are from "the cradle to the gate of the industry", so the use phase and the disposal at the end of life are not included in this analysis.

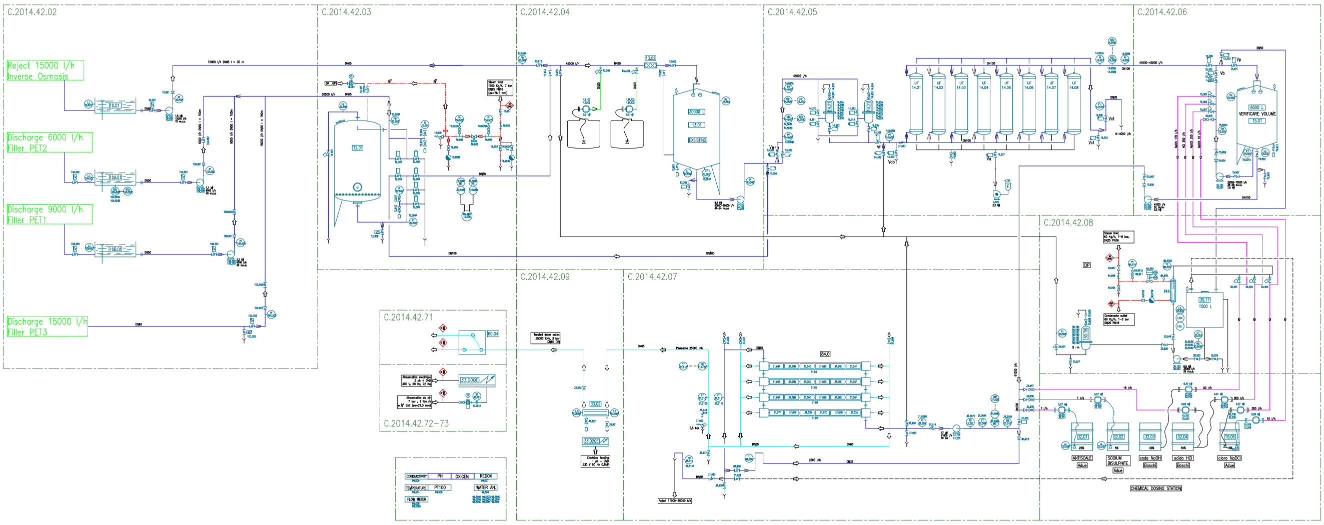

Figure 2: Scheme of the prototypal wastewater recovery plant

5.2. Inventory Analysis (LCI)

The Inventory analysis considers raw material extraction processes; manufacturing and assembly of components; transports. Process data, material and energy consumption information derive from direct observation or reliable assumptions, while pollutant emission and waste generation values are mined from Ecoinvent databank. In a few cases, in order to limit mismatches between data bank information and actual data on employed materials and processes, some simplifying hypotheses are made.

The plant is subdivided in the following functional parts:

- Cleaning In Place (CIP)
- Carbon Filter
- Pump for water recovery
- Reverse Osmosis
- Tank 8000 l
- Tank 3000 l
- Ultrafiltration
- Ultra Violet Treatment (UV)
- Electrical system

For each of these functional parts, all the constitutive components and materials are considered for the analysis.

The inventory analysis, in this phase, incudes all the constitutive components and materials, with the exception of some elements with low influence on the global impact or of difficult characterisation, such as: the electrical system, the electronic measurement instruments, the gaskets, the heat exchanger, the aspiration spear, the hatchway, the PVC reduction, the electronic components.

Although the complexity of the plant, it is possible to list the main materials of which it is composed: Steel (S), Aluminium (AISI 304L), Polypropylene (PP), Polyamide (PA), Polyester, Polycarbonate, Polyvinylfluoride film (PVDF).

Thanks to the use of databanks, all the processes necessary to extraction and transformation of raw materials are considered in this analysis. All the processes required for manufacturing and assembly of the plant are included in this study. The main processes are: welding (with gas Argon), folding, cold impact extrusion, drawing of pipes, thermoforming, sheet rolling, wire drawing, injection moulding.

The amounts of energy consumption and secondary materials used for manufacturing activities is also taken from the producer.

The transportation phase is considered for all the components and materials: the metal sheet, the valves “Bardiani”, the piping and junctions, the osmosis houses, the uv, the pre-filtration housing, the pre-filtration canisters, the pump bodies come from Europe. The pump motors come from China, the ultrafiltration membrane come from Rimini (Italy), osmosis canister come from USA, the active carbon come from Thailand.

In order to provide for lack of information, average geographical distances between suppliers and manufacturer are considered. Particularly the distances of the European suppliers are calculated as a mean of the distances between the manufacturer, located at Fornovo di Taro (Italy) and Sweden, Germany and Spain. The vehicles considered for the transportations are lorry >16t, fleet average and lorry 3.5-7.5t, EURO4.

5.3. Impact Assessment

Life cycle impact assessment of the plant is carried out using Eco-indicator 99 Hierarchical version (EI99H), ReCiPe H/A and IPCC 2007 and Global Warming Potential (GWP).

Eco-indicator 99 Hierarchical version

Table 1 show the damage assessment of the single functional parts of the plant. In the proposed results life cycle is split in the eight functional parts: Cleaning In Place (CIP), Carbon Filter, Pump for water recovery, Reverse Osmosis, Tank 8000 l, Tank 3000 l, Ultrafiltration, Ultra Violet Treatment (UV). Reverse Osmosis, Ultrafiltration and Carbon Filter are the represents the components with the highest environmental burden. In particular the component that bring the highest damage is Reverse Osmosis, that have the major impact in Ecotoxicity and Climate Change categories; Carbon Filter introduces significant damages in Land Use; Ultrafiltration generates significant damage in Radiation and in Oxone layer.

The same results are visible in Figure 3. Figure 4 reports the same results in the impact categories’ perspective. Considering the Single Point indicator as assessment index, 4321,17 Pt is the environmental impact values due to the production of Reverse Osmosis.

ReCiPe H/A

The results of the impact assessment are confirmed also by the analysis conduct with the ReCiPe H/A method. Reverse Osmosis is the most damaging component and it has the major impact in Climate Change Human Heath and Climate Change Ecosystem; Ultrafiltration generates significant damage in Radiation and in Oxone layer.

Carbon Filter introduces significant damages in Agricultural land occupation and Particulate matter formation. Considering the Single Point indicator as assessment index, 3206,60 Pt is the environmental impact values due to the production of Reverse Osmosis system.

In Figure 6 and 7 are reported the damage assessment respectively of the subgroups of the water recovery plant and on impact categories. ***IPCC 2007 Global Warming Potential***

The same conclusion can be achieved considering the analysis with GWP method. The whole water recovery plant produces 60872 kg CO_2 eq. Also in this method the Reverse Osmosis is the group with the major impact. Particularly the manufacturing of this component produces 32400 kg CO_2 eq that represent the 53,2% of the total kg CO_2 eq. The ultrafiltration group is the second in term of GWP emissions. Table 2 and Figure 7 report the results of the GWP analysis.

Table 1: Damage assessment of the water recovery plant with Eco-indicator 99 method

Impact Categories	**Carbon Filter**	**CIP**	**N.4 Pump for Water Recovery**	**Reverse Osmosis**	**Tank 30k**	**Tank 8k**	**Ultrafiltration**	**UV**	**total**
Carcinogens	130,76	195,67	157,33	1056,66	363,12	330,07	304,85	0,02	**2538,48**
Resp. organics	0,32	0,04	0,02	0,38	0,03	0,10	0,30	0,00	**1,19**
Resp. inorganics	1181,50	111,34	77,76	1652,64	66,25	196,42	444,33	6,48	**3736,73**
Climate change	35,71	20,81	13,74	311,67	5,01	35,64	163,29	1,53	**587,40**
Radiation	1,16	0,13	0,08	1,51	0,12	0,22	2,89	0,00	**6,10**
Ozone layer	0,01	0,00	0,00	0,03	0,00	0,01	0,05	0,00	**0,11**
Ecotoxicity	51,57	41,63	30,00	467,30	33,73	65,69	52,92	2,21	**745,05**
Acidification/ Eutrophication	33,17	3,24	2,27	50,11	1,74	6,84	20,03	0,19	**117,59**
Land use	157,88	0,89	0,51	7,41	0,87	1,72	7,69	0,00	**176,97**
Minerals	6,62	25,02	18,33	127,36	41,46	38,84	27,13	0,04	**284,80**
Fossil fuels	114,82	46,78	29,07	646,09	19,06	94,83	487,06	2,28	**1439,98**
total	**1713,51**	**445,56**	**329,11**	**4321,17**	**531,39**	**770,35**	**1510,54**	**12,74**	**9634,38**

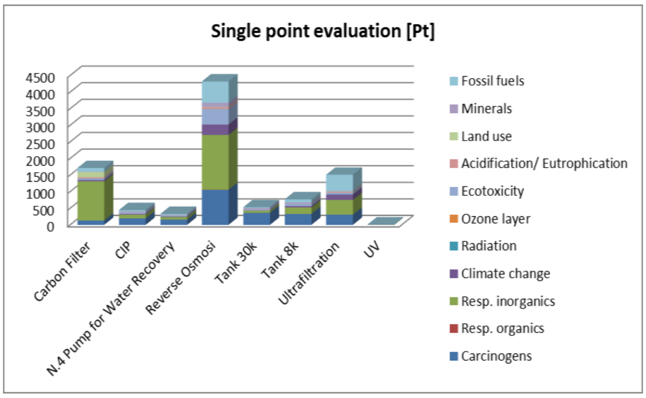

Figure 3: Damage assessment of the subgroups - Eco-indicator 99 method (Single Point)

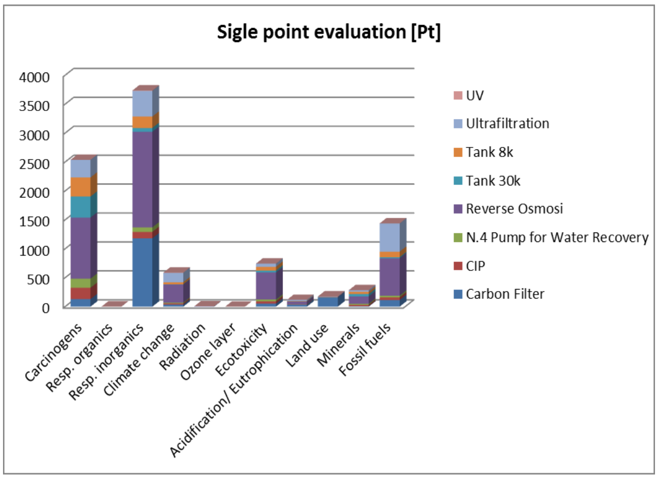

Figure 4: Damage assessment on impact categories - Eco-indicator 99 method (Single Point).

5.4. Interpretation of Results

In an Eco-design perspective, some elements of the actual prototype design can be modifying in order to obtain minor environmental impact of the plant.

Particularly, since Reverse Osmosis, Ultrafiltration and Carbon Filter are the parts with the greatest impact, the manufacturing and assembly phases of these components are considered in order to find the processes or the sub-components generating the majority of the damage. Figure

9 reported the damage assessment (normalization) of the single component Reverse Osmosis. The major damaging contribution is due to the pressure vessel and pump components. So future change in manufacturing of this component is desirable for a more sustainable design.

Referring to Ultrafiltration the impact assessment of this component is reported in figure 9, where it is evident that the negative impact is mainly due to ultrafiltration membrane.

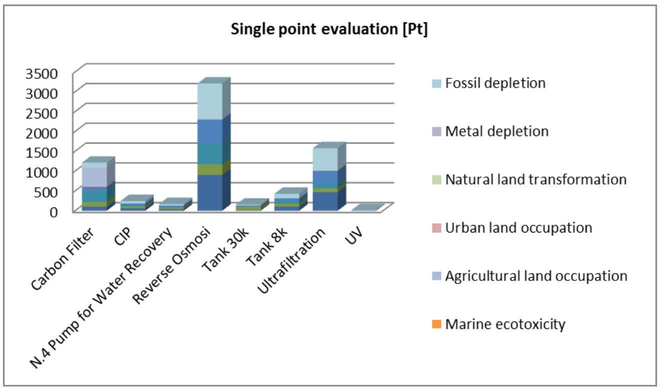

Figure 5: Damage assessment of the subgroups of the water recovery plant with ReCiPe H/A method

Figure 6: Damage assessment on impact categories of the water recovery plant with ReCiPe H/A method

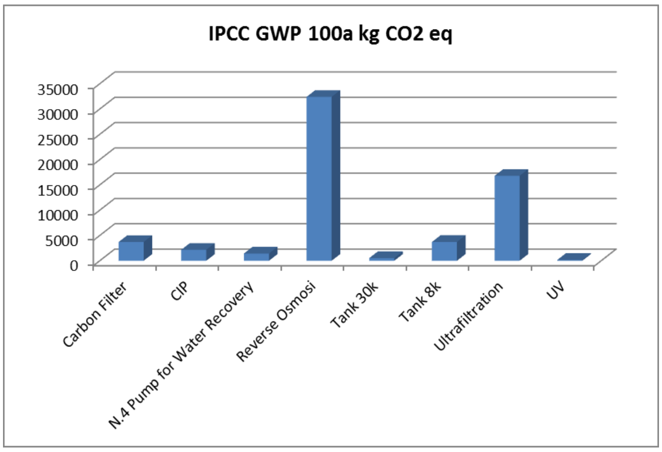

Figure 7: Impact assessment of the subgroup of the water recovery plant with GWP 100a method

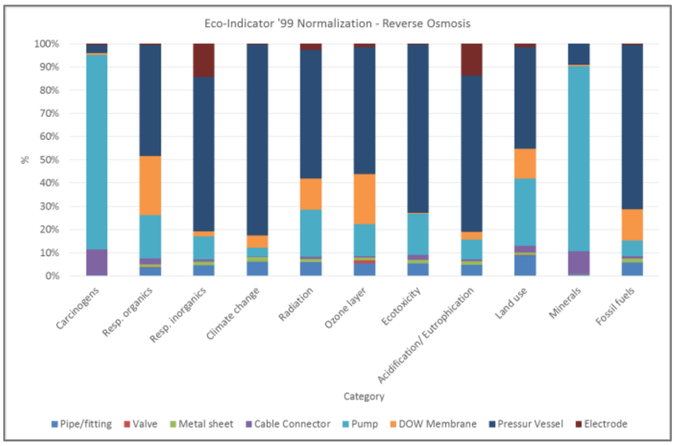

Figure 8. Impact Assessment of Reverse Osmosis in Eco-Indicator 99 method – Normalization

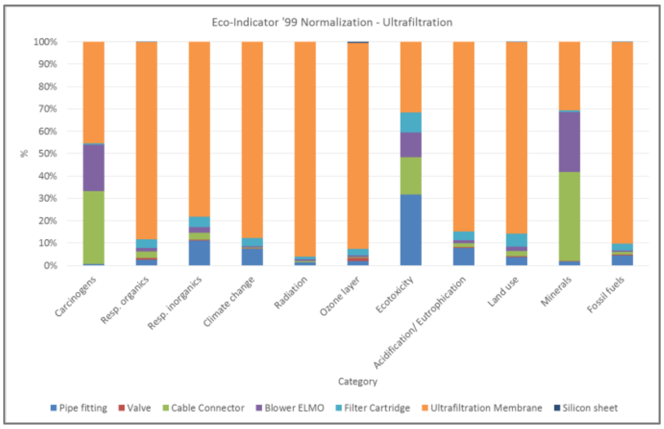

Figure 9. Impact Assessment of Ultrafiltration in Eco-Indicator 99 method – Normalization

6. CONCLUSIONS

In this paper, an innovative plant for water treatment and wastewater recovery and purification in the food & beverage industry is presented.

After the description of the functional module features, sizes and design, the environmental impact on different damage categories introduced during its life cycle is analysed and estimated through the adoption of LCA methodology.

The analysis concern the evaluation of the environmental impact of the manufacturing and the assembly phases, in an eco-design perspective. So the confines of the system are from "the cradle to the gate of the industry".

The analysis is conduct according with the International Organization for Standardization (ISO) and with the support of the software SimaPro 7.3.3 by Pré Consultants. Three different methods of evaluation are considered: Eco-indicator 99 Hierarchical version (EI99H), ReCiPe H/A and IPCC 2007 Global Warming Potential (GWP).

The impact assessment analysis demonstrates that the functional subgroup with the major impact is the Reverse Osmosis group, considering all the three methods. Particularly this subgroup is responsible of the 53,2% of the total kg CO_2 eq. emitted, of the 44,85% of damage Pt in Ecoindicator99 and of 45,78% of damage Pt in ReCiPe H/A. The other subgroups mainly damaging are Carbon Filter and the Ultrafiltration groups.

As regards these three subgroups, the phases with major impact are the construction of the ultrafiltration membranes for the Ultrafiltration group, the pump ad the pressure vessel for the reverse osmosis group.

Table 2: Damage assessment of the subgroup of the water recovery plant with GWP 100a method

Impact Category	Unit	Total	Carbon Filter	CIP	N.4 Pump for Water Recovery	Reverse Osmosis	Tank 30k	Tank 8k	Ultrafiltration	UV
IPCC GWP 100a	kg CO2 eq	60872,6	3696,9	2165,9	1430,2	32400,5	525,84	3711,5	16782,78	158,78

The impact categories of Eco-indicator 99 method, characterised by major damage, are Resp.Inorganics (38,69%) Carcinogens (26,35%) and Fossil Fuels (14,95%). As regards ReCiPe H/A the impact categories mainly interested are Fossil Deplation (25,65%), Climate Change Human Health (24,14%) and Climate change Ecosystem (15,79%).

7. FUTURE DEVELOPMENT

The future development of this study concern the inclusion of the Electrical and Electronical System in the Inventory Analysis. The whole life cycle of the plant have to be included in the analysis, with particular attention to the use phase, in which the water recovery could have a positive effect on the environmental impact for the ground water's consumption avoided. So a comparison between a traditional system without water recovery and the system with the prototype object of this study is desirable.

Then, in light of the results of the environmental impact of the manufacturing and assembly of the wastewater recovery plant, the authors will propose some changes to the prototype design, in an eco-design perspective, equal performance. Finally these design alternative could be included in a sensitive analysis, with the aim of define the better configuration in an environmental point of view.

8. ACKNOWLEDGMENTS

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Design, Prototyping, and Assessment of a Wastewater Closed-Loop Recovery and Purification System

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Abstract: Efforts to decrease the water use within industry are mandatory to pursue product and process sustainability. Particularly, the European Union (EU) is at the top level for water consumption in industry, while some sectors, such as the food and beverage (F&B), are highly water-intensive with hundreds of liters per hour of consumed and, then, drained water. This article provides a systematic overview of the most innovative insights coming from an EU Eco-Innovation project dealing with greening the F&B industry through the design, prototyping, technical, economic, and environmental assessment of a wastewater closed-loop recovery and purification system. The system, tailored for a standard mid-size F&B company using 2–3 billion L/year of raw water, collects, purifies and recirculates the key produced wastewater streams with an overall recovery efficiency of about 56%. The proposed purification technology comes from the most efficient combination of membrane-based filtration methods, reverse osmosis (RO), and ultraviolet modules. Evidence from the technical design, full-scale on-site technology prototyping, net-present-value (NPV) analysis and system life-cycle-assessment (LCA) are presented concluding about the convenience of adopting the proposed solution to reduce costs and impacts on the environment.

Keywords: wastewater purification; food and beverage industry; water reuse; water saving; ultra-filtration; economic assessment; life-cycle-assessment; EU project

1. Introduction and Background

Nowadays, the urgency in decreasing the natural resource depletion makes necessary to invest in innovative and sustainable process plants and technologies. According to the United Nations sixth sustainable development goal, pure water requires specific efforts because of its key role for the equal growth of communities, feeding the most of the anthropic activities [1]. In this context, the FAO Aquastat database provides wide information about the origin, use and disposal of this basic resource [2], while rising attention from institutions, industry and the public opinion is toward solutions for the water intensity decrease and wastewater recovery, purification and reuse. Focusing on the European Union (EU), industry is responsible of the most of the water consumption, while the food and beverage (F&B) sector is very water intensive, i.e., ~100.000 L/h of input raw water generating thousands of liters of wastewater every day. Sustainable innovations in F&B, leading to the reduction of the required primary water, are desirable and encouraged [3,4]. Technologies focusing on wastewater recovery, purification according to the top standards [5,6] and local reuse create virtuous closed-loops [7].

The current literature trend outlines multiple technologies for water purification. The authors, in [8], present a systematic review and classification on the topic outlining that solutions based on mechanical filtration and/or reverse osmosis (RO) potentially match the constraints of the F&B

industry, i.e., high flow rate and high water quality standards. Examples and solution feasibility studies and prototypes are in [9–13]. Nevertheless, full-scale systems targeted and validated on the F&B industry needs are still missing and, most importantly, rarely adopted in practice with the final effect of an exponential increase of the water consumption and draining. Efforts to overcome these limits are mandatory.

This paper contributes to address the introduced lacks presenting the scientific evidences of an EU Eco-Innovation Project aiming at the design, full-scale prototyping, and assessment of an innovative system for the F&B industry wastewater closed-loop recovery and purification. The system combines advanced purification technologies allowing reducing the necessary input raw water and decreasing the overall system water footprint. According to this purpose, Section 2 presents the system design and prototyping, Section 3 proposes the full-scale prototype field-test and technical validation within an Italian mid-size F&B company, Section 4 presents the system economic assessment, while Section 5 summarizes the system life-cycle-assessment (LCA). The paper conclusions and research next steps are provided in Section 6.

2. System Design and Prototyping

The first mandatory step deals with the definition of the purification technology to adopt in relation to the plant capacity, in m^3 per hour of entry wastewater, and the wastewater quality. To this purpose, an industrial survey over a significant set of mid-size F&B industries allows getting the main drained wastewater streams together with the continuity of the flow and the pollutant categories. Table 1 summarizes the survey outcomes.

The survey reveals that the contaminants are different in nature and concentration, e.g., organic compounds (fruit juices, sugar, ascorbic and citric acids), chemicals from washing and disinfecting of the equipment (caustic soda, nitric acid, peroxides, and chlorine), salts, and metals at high concentration from the RO retentate, etc.

Starting from these data and with the aim of designing a continuous process addressing the most quantitatively relevant water flows, the target recovery and purification plant flow rate is set to 45 m^3/h so that the RO retentate and the filler drained wastewater can be fully processed. Nevertheless, in terms of pollutants, these two water flows do not represent a significant F&B sample because of the presence of the other organic and chemical compounds. For this reason, the chosen purification technology is designed to be able to process all five water sources and specific field tests verify such condition by artificially creating different types of wastewater dosing concentrates of production wastes. In this way, no lack of generality occurs guaranteeing the system flexibility to multiple operative contexts.

Table 1. Wastewater sources and features for F&B companies.

Category	RO Retentate	Fillers	Clean in Process	Syrup Room	Cooling Towers
Avg flow rate [m^3/h]	15	30	4	1	2
Continuous flow	Yes	Yes	No	No	Yes
Total hardness [mg/L]	1240	78	728	767	841
Oxidability (Kubel) [mg/L]	<0.5	<0.5	0.9	3530	<0.5
Conductivity [µS/cm]	3080	158	2810	1625	841
pH	7.7	3.7	11.5	4.1	7.8
Redox potential [mV]	238	509	54	201	-
Suspended solids [mg/L]	1.5	5.5	1120	1280	<1.0
Turbidity [NTU]	<0.4	<0.4	745	134	1
Total alkalinity [mg/L]	978	32	865	281	82

2.1. System Functional Design

The system functional design is highly dependent on the chosen combination of purification technologies allowing the output water to have the physical, chemical, and microbiological conditions fitting to the F&B industry safe use, according to the regulations in force. To this purpose, the authors develop a review, covering the last three decades, of the existing water purification technologies applied to the F&B industry outlining strengths and weaknesses and presenting an original matrix analysis to identify trends and the technology readiness level (TRL) of each of them. The full discussion of such study is out of this paper boundaries and it is available in [8].

Merging the survey on the wastewater sources from the F&B industry and the review on the available technologies for water purification, the overall rationale of the prototypal system is outlined in the schematic in Figure 1.

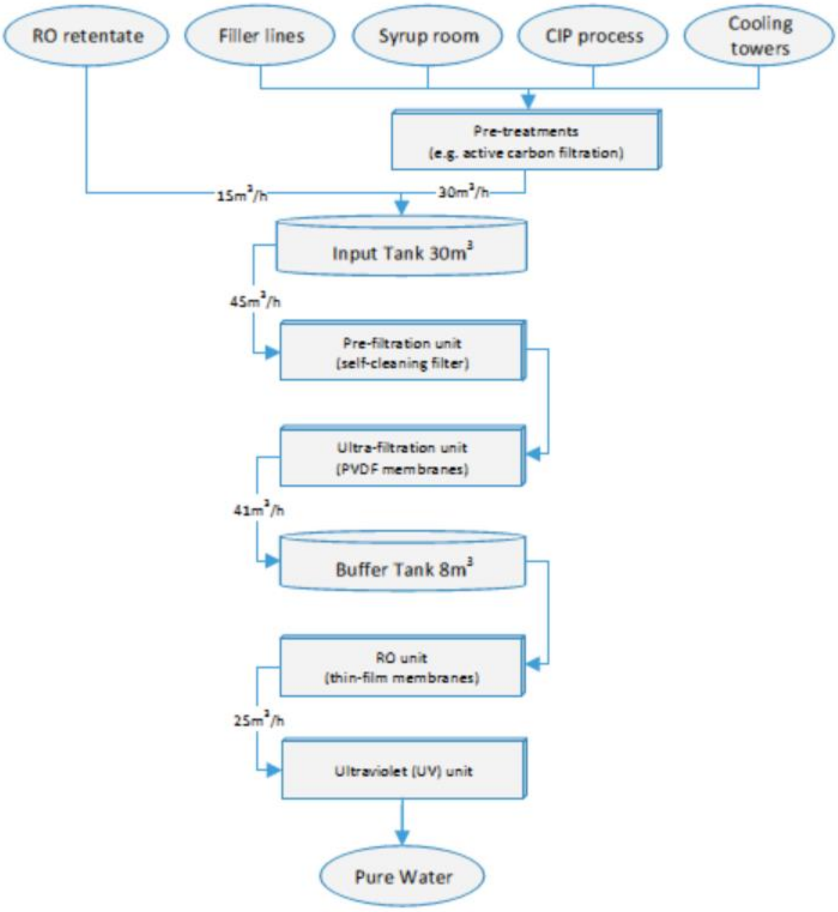

Figure 1. Recovery and purification system block diagram.

An input buffer tank of 30 m^3 allows collecting the water to treat. This tank is filled by the different streams of wastewater, RO retentate, and filler cleaning water, mainly. In addition, in the case some preliminary treatments are necessary, due to specific water pollutants that must be cut off immediately, the correspondent module is added. For example, water from the fillers has peracetic acid contamination to neutralize adopting an activated carbon filter before feeding the main purification treatment. The input buffer tank feeds the pre-filtration and, then, ultrafiltration units aimed at removing the suspended solid compounds from the water stream. Such units are sized for 45 m^3/h of entry water to treat. Particularly, the pre-filtration unit is to tackle the largest particulate matter, up to 50 μm, including suspended organics, protecting the ultrafiltration module from the excessive fouling and forthcoming stops for cleanings. Such a latter module is a parallel of multiple sub-units matching the target flow rate and able to guarantee a filtration capacity up to 75 nm. The core of the ultrafiltration module are the PVDF membranes able to work both in cross-flow and dead-end mode and reducing the suspended solids up to 0.1 mg/L (0.1 NTU) with an average efficiency of about 90% [14,15]. No action is on the dissolved solids. To this purpose, the output water flow entries the RO module targeted for the separation of the dissolved solids, e.g., dissolved salts [16]. The polyamide thin-film composite RO membranes are set in a parallel of multiple modules matching the required flow rate with a nominal filtration efficiency of about 60%. Finally, to guarantee the microbiological charge is under control a standard UV unit (wavelength 253 nm and irradiation 40 mJ/cm^2) is added as the last stage of the purification chain. The clean in process unit to wash the purification membranes when the pressure drop rises over the nominal limit set by the manufacturers completes the plant hardware together with an 8 m^3 buffer tank to decouple the ultrafiltration and the RO units. The plant P and ID is shown in Figure 2.

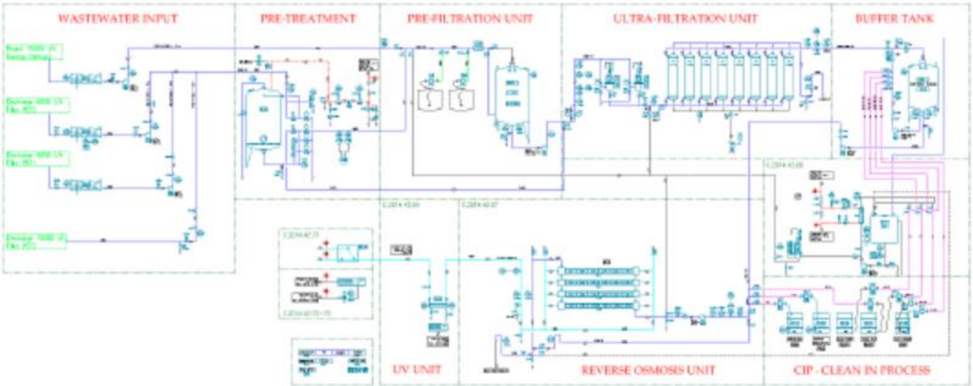

Figure 2. Recovery and purification system executive P and ID.

2.2. *System Supervising and Control*

The supervising system allows the autonomous run of the plant, managing both the up time and the periodic clean in process cycles. The local custom PLC acquires the signals from the field, manages the plant, and collects the run data to store and communicate via Ethernet. To this purpose, the key nodes of the plant are equipped with sensors getting real-time the flow rate, temperature, pH, redox, pressure drop, and turbidity (Figure 3). Further details on the system structure, i.e., process and control modules, are available in [17].

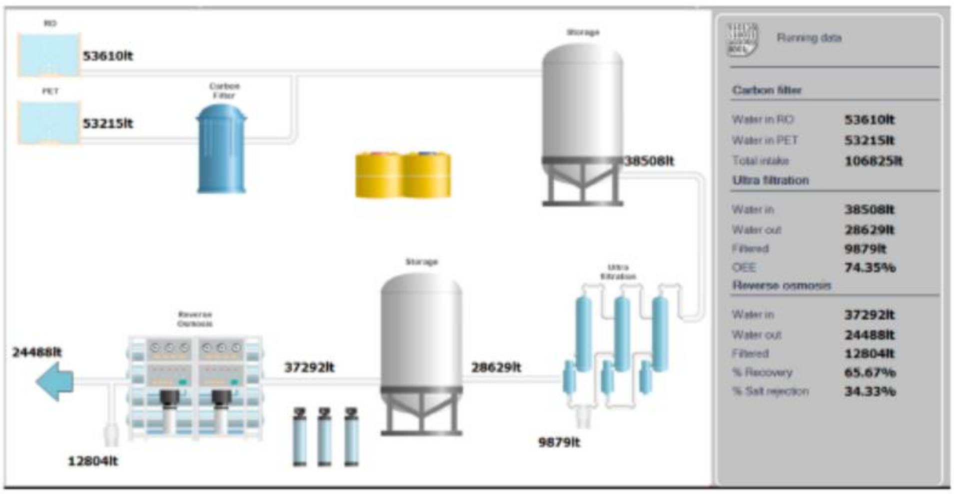

Figure 3. Sketch of the system supervising and control panel.

3. Field-Test and Technical Validation

A full-scale prototype of the proposed recovery and purification system is installed at an Italian mid-size F&B company processing soft drinks, sauces, juices, and colas. The company actually obtains the required process water from different on-site wells and drains the wastewater immediately after use with no recovery, i.e., an open-loop cycle. Such a condition is frequent within the F&B industry. The average water requirement to feed the production lines is of about 2.5 billion liters of pure water per year.

At the end of the mandatory setup and plant tuning, a field-campaign allows validating the system technical performances and collecting data for the forthcoming economic and environment assessments. Two sets of plant field-tests are done. The former is made of multiple short runs; each of them is by feeding the system with a specific polluted wastewater, covering a wide range of the spectrum of possible plant input. The latter is an extensive plant run, useful to measure the average working conditions and collecting the data to obtain the plant overall efficiency. Results from both sets of tests are in the following.

3.1. Field-Tests with Different Contaminants

The proposed system must be able to purify multiple wastewater streams, corresponding to the most common contaminated water flows generally drained by the F&B industry. To field-test the potential and flexibility of the proposed plant, a major set of short runs with wastewater contaminated with specific pollutants is done. The following Table 2 shows the investigated contaminants, presenting the eight developed short runs.

Table 2. Short-test description, wastewater origin, and main contaminants.

Run Id.	Wastewater Origin	Main Contaminants
#1	RO retentate	Dissolved salts
#2	Fillers	Peracetic acid
#3	Clean in process (a)	Caustic soda + dissolved salts
#4	Clean in process (b)	HCl + dissolved salts
#5	Syrup room—sugar	Sugar syrup (0.1% avg conc.)
#6	Syrup room—pear and peach	Organic matter: pear and peach puree (0.6% avg conc.)
#7	Syrup room—tomato	Organic matter: tomato puree (0.3% avg conc.)
#8	Syrup room—orange	Organic matter: orange puree (0.1% avg conc.)

Run #1 and #2 process wastewater representative of the most significant quantitative flows, while the other runs include a specific contaminant coming from the process. In runs #3 to #8, the contaminated wastewater is mixed with fillers and/or RO retentate to guarantee acceptable flow rates. The following Table 3 summarizes the field-test results comparing, for each run, the input and output water quality. It further shows the target to reach to make the output water potentially available for bottling reuse [5,6]. The input and output sample analyses are by an independent physical and chemical laboratory. The complete dataset about all the analyzed physical, chemical, and microbiological categories are available upon request to the authors.

Results confirm the possibility to reach good quality of the purified water starting from a wide range of input water contaminants. Improvements and further investigations are necessary in the future for the clean in process wastewater, i.e., Run #3 and #4, because of the borderline pH and alkalinity levels and for the sugar syrup contaminated wastewater, i.e., Run #5, because of the high turbidity of the output water. Nevertheless, such pollution categories are not far from being acceptable and the correspondent wastewater flow rate is limited.

Table 3. Field-tests with different contaminants and water quality results.

Category	Target Limits	Run #1		Run #2		Run #3		Run #4	
		Input	Output	Input	Output	Input	Output	Input	Output
Total hardness [mg/L]	<250	1240	66	78	34	728	2	837	3.8
Oxidability (Kubel) [mg/L]	<5	<0.5	<0.5	<0.5	<0.5	0.9	0.5	1.6	<0.5
Conductivity [μS/cm]	<2500	3080	30.7	158	<20	2810	274	3510	67
pH	>4.9	7.7	7.8	3.7	7.2	11.5	10.9	2.6	4.8
Redox potential [mV]	-	238	294	509	327	54	5	293	101
Suspended solids [mg/L]	<500	1.5	0.5	5.5	0.5	1120	7.6	5.4	2.4
Turbidity [NTU]	<0.5	<0.4	<0.4	<0.4	<0.4	745	0.4	1.8	<0.4
Total alkalinity [mg/L]	<85	978	29.1	32	17	865	84.9	<5	<5
Category	**Target Limits**	**Run #5**		**Run #6**		**Run #7**		**Run #8**	
		Input	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**
Total hardness [mg/L]	<250	767	<2	1130	26	452	28	222	10
Oxidability (Kubel) [mg/L]	<5	3530	2.1	31.1	1.9	111	<0.5	2900	<0.5
Conductivity [μS/cm]	<2500	1625	20	2450	29.2	1098	26.2	414	24
pH	>4.9	4.1	5.9	6.6	5.4	6.2	5.7	5.9	5.5
Redox potential [mV]	-	201	404	239	160	266	131	183	184
Suspended solids [mg/L]	<500	1280	20	570	<5	230	<5	83	<5
Turbidity [NTU]	<0.5	135	0.6	69.2	<0.4	32.6	<0.4	18	<0.4
Total alkalinity [mg/L]	<85	281	18.7	639	23	270	5.3	48	4.2

3.2. *Extensive System Field-Test*

With the aim of testing the system performances over a long working time and a mix of input wastewater flows, a 250 days extensive field-test is done. During the test period the system operated for 4064 working hours with and average flow rate of about 15.3 m^3/h. The input wastewater comes from RO retentate (41%), fillers (55%) and other minor discontinuous sources (4%). Such data are representative of the working plans of the F&B company hosting the system, while the lower flow rate with respect to the plant capacity is due to external production constraints not affecting the results, directly.

3.2.1. Plant Performances and Reference Index Calculation

Globally, during the field-test, 62,179.3 m^3 of wastewater are processed (input), generating 35,271.3 m^3 of pure water (output). The overall system efficiency, in mass, is of about 57% matching the nominal design value. The physical, chemical, and microbiological quality target limits are fully respected. The water independent analyses are available upon request to the authors and they are done on multiple water samples collected during the field-test, periodically.

In addition, thanks to the system supervising and control unit, the aggregate data about energy need and use of chemicals are collected allowing the calculation of reference indices useful to develop the economic and environmental system assessments. The following Table 4 presents such data.

Table 4. Use of chemicals and electric power, reference indices.

	Consumption	Reference Index
Chemicals		
Antiscalant	344 L	0.00537 L/m^3
$Na_2S_2O_5$ 25%	688 L	0.01074 L/m^3
HCl 30%	77,800 L	0.12544 L/m^3
HClO 15%	273 L	0.00439 L/m^3
Soda 30%	236 L	0.00380 L/m^3
Steam	15,240 kg	0.14510 kg/m^3
Electric Power	71,099 kWh	1.14345 kWh/m^3

3.2.2. Ultrafiltration and RO Unit Performances

Due to their crucial role within the developed recovery and purification system, the ultrafiltration and RO functional unit performances are investigated, separately, to outline their contribution to the global system efficiency. Particularly, the ultrafiltration unit reaches a global efficiency of 92.3%, while the key water losses are due to backwashes, chemical cleanings, and water cycle fluxes. In addition, the specific electric power need is of about 0.1890 kWh/m^3 of processed wastewater. Concerning the RO unit, operating in cross-flow mode, the overall efficiency is of about 61.5% with water drains due to process retentate and water cycle fluxes. Due to the pumps to guarantee the working pressure, the module energy intensity is relevant with an average requirement of about 0.8054 kWh/m^3 of processed wastewater.

4. Economic Assessment

The economic performance assessment aims at validating the proposed system against economic metrics expressing the overall long-term sustainability of investing in the proposed plant for the wastewater recovery and purification. According to the standard practice, the present economic analysis starts from the evidences and reference indices presented in Section 3 within the system technical validation and refers to the investments and rising costs, including the opportunity costs due to savings in raw water consumption, occurring during the plant lifetime. A standard reference year is considered and the analysis adopts the net-present-value (NPV) and payback-time economic assessment methods. To develop the economic assessment, a 15 years lifetime horizon is used with 6400 working hours per year. Furthermore, a realistic utilization factor of 90% is assumed according to the fluctuations of the production plans of F&B industry, presenting a seasonal component. In addition, the cost of raw water and of the electric energy are 2.12 €/m^3 and 0.2 €/kWh according to the Italian tariffs. Furthermore, the plant investment, i.e., turnkey—all included, is of about 355,000 € and the yearly O and M cost is estimated as the 4% of the initial investment. Finally, a fair share of the general costs are included. Starting from such data, coming from industry and the good practice, and other relevant drivers of cost, Table 5 shows the annual differential cash flow analysis with and without the adoption of the proposed system.

Table 5. Annual cash flow differential analysis.

Driver	Unitary Cost		Cash Flow	
Initial extra-investment (turnkey, all included)	355,000	€		
O&M (incidence on investment)	4	%	14,200.00	€/year
Grid electric power (industry)	0.2	€/kWh	59,279.04	€/year
Power factor (includes all needs & auxiliaries)	1.14345	kWh/m^3		
Chemicals				
NaClO 15%	0.2160	€/L	245.73	€/year
Soda 30%	0.2660	€/L	261.35	€/year
HCl 30%	0.9525	€/L	30,916.43	€/year
Antiscalant 100%	4.2000	€/L	6013.93	€/year
$Na_2S_2O_5$ 25%	0.3935	€/L	1126.90	€/year
General plant differential costs			5000.00	€/year
Raw water saving (opportunity cost)	0.00212	€/L	(311,149.50)	€/year
Operative contribution margin			**194,106.12**	**€/year**

A yearly positive contribution margin of 194,106.12 €/year rises due to the minor cost of raw water because of the closed-loop cycle introduced by the proposed system. Starting from this evidence and extending the analysis over the plant lifetime with a weighted average cost of capital of about 5%, representative of the investment risk, the NPV graph of Figure 4 follows. The NPV analysis includes extra investments, i.e., membrane replacement, of 26,000 € every five years.

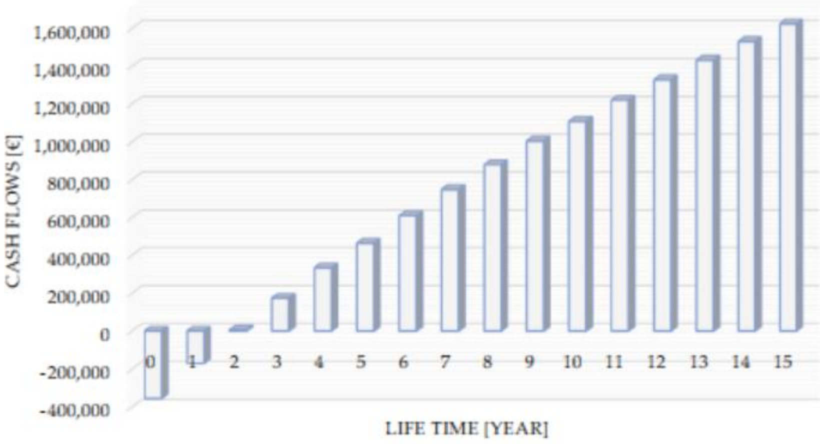

Figure 4. Cash flow trend over the system lifetime.

The investment in the proposed recovery and purification system generates a positive NPV of about 1.6 M€ over the 15 years lifetime, while the initial investment payback-time is of about two years (without any accelerated amortization policy). Differences in the obtained results may occur mainly because of the raw water cost fluctuations, the system effective utilization factor, the cost of grid energy and minor auxiliaries cost changes. Nevertheless, the highly-positive results allow concluding about the potential economic relevance of investing in the proposed closed-loop wastewater recovery and purification system.

5. Life-Cycle-Assessment (LCA)

LCA is a powerful methodology to evaluate the environmental impact of a system over its life cycle. According to ISO 14040:2006 (E), the LCA framework includes four steps, i.e., goal and scope definition, inventory analysis, impact assessment, and result interpretation [18–21]. A cradle-to-grave perspective and SimaPro 7.3.3 by PRé Consultants software (Amersfoort, The Netherlands) are used. Furthermore, the impact assessment step compares Eco-indicator 99 Hierarchical version (EI99H) and IPCC 2007 Global Warming Potential (GWP) methods.

5.1. Goal and Scope Definition

The focused functional unit is the assembly, use, and disposal of the introduced wastewater closed-loop recovery and purification system described in Section 2. The confines of the system are from cradle-to-grave. Deep attention is on the water and energy consumption.

5.2. Inventory Analysis (LCI)

The inventory analysis considers raw material extraction processes, module manufacturing and assembly, shipments, water and energy use and saving, maintenance activities, recycling, and final disposal. Process data, material, and energy consumption are from field measurements and reliable assumptions, while unitary emissions and waste generation are from the Ecoinvent databank. Within the analysis, an important positive contribution is the avoided output because of the closed-loop due to the water recovery and local reuse.

Concerning manufacturing and assembly, the LCI focuses on each functional module, starting from its bill of materials. Low influence elements such as gaskets, heat exchangers, aspiration spears, PVC reductions and minor electronic components are neglected. The key materials are steel (S), aluminum (AISI 304L), polypropylene (PP), polyamide (PA), polyester, polycarbonate, and polyvinyl fluoride film (PVDF). All the processes necessary to the extraction and transformation of such raw materials and to manufacture and assembly the system are computed. The main manufacturing processes include welding, folding, cold impact extrusion, drawing of pipes, thermoforming, sheet rolling, wire drawing, and injection molding. Finally, the shipment phase is considered for all the components and materials.

The system use phase is 15 years long and it includes, as input, the water, energy, and chemical consumption and draining, together with the membrane replacement every five years. Raw water savings are included as avoided output.

Finally, the "waste scenario/US" from the SimaPro database is the base disposal scenario. Changes are according to the EU recovery and recycling goals and policy constraints including, for example, 85% and 55% of steel and plastic materials to recycle, respectively.

5.3. Impact Assessment (LCIA)

Table 6 shows the impact assessment of the proposed system according to EI99H for the assembly, operating and disposal life-cycle phases. Results highlight the operating and disposal phases as less environmentally sustainable, while the RO module use is responsible for about 45% of the total environmental burden, mainly due to fossil fuel use. Such results are confirmed by developing the environmental analysis according to the GWP method. Table 7 shows a system GWP close to 9,000 tonnes of CO_2-eq. RO module use contributes for 50.47% and disposal contributes for 35.42% of the total equivalent carbon dioxide emissions.

Table 6. Damage assessment of the system life-cycle, according to EI99H, in single points.

Impact Category	Assembly	Operating			Disposal	Total
		Filtration	RO	Others		
Carcinogens	2922.3	678.0	26,127.1	295.2	12,087.8	42,110.4
Resp. organics	2.2	5.0	48.6	5.4	184.2	245.5
Resp. inorganics	5380.5	11,229.7	96,173.7	11,490.5	99,838.1	224,112.6
Climate change	925.4	5479.2	42,815.4	5590.0	30,181.9	84,991.9
Radiation	13.1	48.0	748.9	36.1	330.1	1176.2
Ozone layer	0.2	2.3	79.8	1.5	23.6	107.5
Ecotoxicity	809.1	278.7	5721.8	373.4	7950.2	15,133.2
Acidification	179.0	578.3	4440.2	565.9	6528.2	12,291.6
Land use	349.5	−2.8	772.2	0.0	4222.2	5341.1
Minerals	305.2	−128.1	2227.7	2.2	1152.4	3559.4
Fossil fuels	2570.5	21,604.4	160,339.8	22,206.6	165,289.2	372,010.5
Total	13,457.1	39,772.7	339,495.1	40,566.8	327,788.1	**761,079.8**
	1.77%	5.23%	44.61%	5.33%	43.07%	

Table 7. Damage assessment of the system life-cycle, according to GWP.

	Assembly	Operating			Disposal	Total
		Filtration	RO	Others		
GWP [kg CO_2-eq.]	95,596.3	575,874.0	4,500,555.6	587,338.8	3,158,389.9	**8,917,754.6**
	1.07%	6.46%	50.47%	6.59%	35.42%	

Finally, following the same differential approach adopted for the system economical assessment, the graph of Figure 5 compares the EI99H impact categories of the most frequently adopted open-loop water management, i.e., wastewater drain, toward the closed-loop water management, using the proposed system.

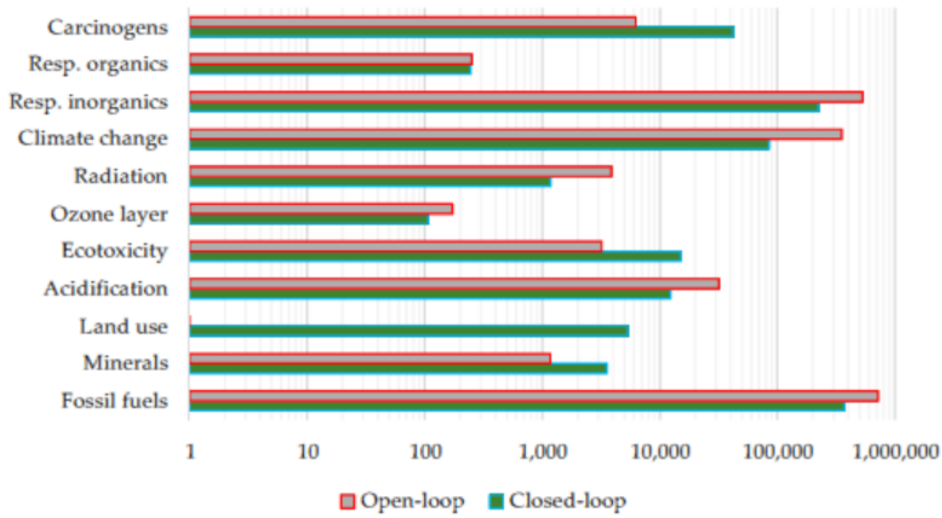

Figure 5. Comparison between open-loop and closed-loop water management, EI99H single point (logarithmic scale).

Despite the increase of some of the impact categories, the global environmental impact reduction is of 887,525.4 Pt (−53.8%) corresponding to a GWP saving of 28,122.4 tonnes of CO_2-eq. not emitted over the plant lifetime (−75.9%).

5.4. Result Interpretation

The LCA analysis demonstrates that the assembly, use and disposal of the proposed closed-loop recovery and purification system allows getting a lower environmental impact respect to the standard practice of draining the F&B line wastewater. Globally, the environmental assessment allows concluding about the system sustainability and environmental convenience.

The LCIA outlines that the functional module with a major impact is the RO. This is particularly true during the system use phase. The RO module allows removing the dissolved solutes, e.g., salts, and it is responsible of 50.47% of the emitted CO_2-eq. and of 44.61% of the damage points according to EI99H. The reasons for such an environmental burden are due to RO principle requiring high osmotic pressures, provided by pumps, to force the flow through the semipermeable membrane. Efforts to improve or replace RO are a research next step.

6. Conclusions and Next Steps

This paper presents a systematic description of the design, prototyping, and assessment activities developed within a European Union (EU) Eco-Innovation Project aiming at reducing the food and beverage (F&B) water footprint by introducing a wastewater local recovery and purification system. The system includes a wastewater collection unit and a combination of filtration technologies allowing getting pure water potentially usable within the F&B plant. The overall nominal system efficiency, field-tested through a full-scale prototype installed at an F&B Italian company, is of about 56% in quantity, while the water quality fits the target limits in force for advanced industrial uses in this sector. Furthermore, the economic and life-cycle assessments confirm the long term sustainability of the system, i.e., payback time of about two years, and a net CO_2-eq. reduction of about 28,122.4 tonnes (−75.9%).

Next research steps deal with refinements in the system to validate and enlarge the spectrum of the processable wastewater thanks to the screening of parallel suitable technologies, actually at a lower technology readiness level (TRL), to spread the closed-loop water chain concept to a broader company set. Finally, the performance assessment based on extensive data from years of plant operation are of strong interest to confirm the promising results coming from the full-scale prototype field-test.

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