

1 **Comparative life cycle environmental and economic assessment of anaerobic membrane**
2 **bioreactor and disinfection for reclaimed water reuse in agricultural irrigation: a case**
3 **study in Italy**

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16
17 **ABSTRACT**

18 Reuse of treated wastewater for irrigation purposes is a measure to reduce water stress and
19 overexploitation of freshwater resources. This study aims to investigate the environmental and
20 economic impacts of a current conventional wastewater treatment plant (WWTP) in Peschiera
21 Borromeo (Milan, Italy), and compare possible scenarios to enable reclaimed water reuse for
22 agriculture purposes. Accordingly, we propose alternative disinfection methods (i.e. enhanced
23 UV, peracetic acid) and replace conventional activated sludge (CAS) with upflow anaerobic
24 sludge blanket (UASB) for biological treatment and use anaerobic membrane bioreactor
25 (AnMBR) as the tertiary treatment. Life cycle assessment (LCA) and life cycle costing (LCC)
26 were implemented on the existing full-scale wastewater treatment line and the hypothetical
27 scenarios. In most cases, the impact categories are primarily influenced by fertilizer application

28 and direct emissions to water (i.e. nutrients and heavy metals). The baseline scenario appears
29 to have the largest environmental impact, except for freshwater eutrophication, human
30 ecotoxicity and terrestrial ecotoxicity. As expected, water depletion is the most apparent impact
31 category between the baseline and proposed scenarios. The UASB + AnMBR scenario gives
32 relatively higher environmental benefits than other proposed scenarios in climate change (-
33 28%), fossil fuel depletion (-31%), mineral resource depletion (-52%), and terrestrial
34 ecotoxicity compared to the baseline. On the other hand, the highest impact on freshwater
35 eutrophication is also obtained by this scenario since the effluent from the anaerobic processes
36 is rich in nutrients. Moreover, investment and operational costs varied remarkably between the
37 scenarios, and the highest overall costs are obtained for the UASB + AnMBR line mostly due
38 to the replacement of membrane modules (24% of the total cost). The results highlighted the
39 importance of the life cycle approach to support decision making when considering possible
40 upgrading scenarios in WWTPs for water reuse.

41 **Keywords:** Anaerobic membrane bioreactor (AnMBR); irrigation; life cycle assessment
42 (LCA); life cycle cost (LCC) analysis; tertiary wastewater treatment; reclaimed water reuse
43

44 **1. Introduction**

45 Mediterranean region has been facing increasing pressure from water scarcity and droughts
46 where freshwater availability is likely to decrease substantially by 2% to 15% for 2°C increase
47 of global temperature due to climate change alone (MedECC Network, 2019). Between 50%
48 and 90% of the total water demand in the Mediterranean basin is dedicated to irrigation, and
49 this demand is projected to rise by 18% until the end of the century (UNEP/MAP Plan Bleu,
50 2019). Meanwhile, seawater intrusion is another critical problem along the Mediterranean
51 coasts as a consequence of over-exploitation of groundwater (Giannoccaro et al., 2019). All of
52 these issues together with population and economic growth continuously stress freshwater

53 supplies, which consequently increase the demand for non-conventional water resources (Lee
54 et al., 2018).

55 Reclaimed wastewater reuse is seen as a solution to help to address above-mentioned
56 challenges, but its potential remains largely untapped from a technical and legislative point of
57 view (Rizzo et al., 2018). Treated wastewater can be used either for non-potable purposes, such
58 as aquifers recharge, irrigation/fertigation, and industrial use, or as a source for drinking water
59 supply after additional treatments. This can help to protect the environment and to enhance
60 water security by managing water resources of the hydrological cycle in a more circular way
61 (Diaz-Elsayed et al., 2019; Giannoccaro et al., 2019). The reuse for agricultural irrigation is by
62 far the most established end-use for reclaimed water (Rizzo et al., 2020). However, the use of
63 reclaimed water relies on many types of advances, not only related to technological approaches
64 but also health, socioeconomic and legal aspects (Salgot and Folch, 2018). In most cases, water
65 reuse strategies are often intended to address the problem of water scarcity without aggravating
66 other environmental problems, thus reflecting the need for their environmental assessment
67 (Meneses et al., 2010). Moreover, water reuse practices can be expensive since a high degree
68 of treatment is required and a separate piping system is needed for the reuse systems to
69 distribute the water.

70 Currently, approximately 1 billion cubic meters of treated urban wastewater is reused in the EU
71 annually, which accounts for about 2.4% of the treated urban wastewater effluents and less than
72 0.5% of annual EU freshwater withdrawals. Water-scarce EU countries such as Italy, Spain,
73 and Greece only reuse between 5% to 12% of their effluents (EC, 2020a). This is mainly due
74 to the existing constraints for reclaimed water reuse at the national level. For example, in Italy,
75 the agricultural use of reclaimed water is strongly restricted by law D.Lgs 185/2003 (Ventura
76 et al., 2019). Indeed, the treated wastewater must comply with a range of water directives at the
77 EU and national levels to protect the environment, but the reuse of reclaimed water has to

78 comply with additional directives/regulations depending on the purpose (Vojtěchovská
79 Šrámková et al., 2018). Recently, the European Commission has developed the Regulation
80 2020/741 on “*Minimum Requirements for Water Reuse*” (EC, 2020b), where specific
81 indications are provided for the assessment of reclaimed water reuse.

82 Tertiary treatment (including filtration and/or disinfection) is commonly required to meet the
83 quality standards of reused treated wastewater (Carré et al., 2017). Conventionally, chemical
84 or physical disinfection is applied during wastewater treatment, complying with the stringent
85 microbial safety required for water reuse (Angelakis and Snyder, 2015). Alternatively, well
86 designed and operated membrane bioreactors (MBRs) can also provide efficient removals of
87 solids and pathogens (Foglia et al., 2020). Hai et al. (2014) provided an in-depth overview of
88 the mechanisms and influencing factors of pathogens removal by MBRs and highlighted the
89 practical issues, such as reduced chemical disinfectant dosages and associated economic and
90 environmental benefits. Anaerobic MBR (AnMBR) is a very attractive technology in terms of
91 energy efficiency with energy recovered from sewage and without aeration requirements. In
92 fact, AnMBR has been reported to be net energy positive, leading in cost savings up to €0.023
93 per m³ of treated water (Pretel et al., 2016). At the same time, the combined use of
94 anaerobically treated effluent for fertigation can further reduce CO₂ emissions (Jiménez-
95 Benítez et al., 2020).

96 In most cases, decisions about wastewater treatment are primarily influenced by direct capital
97 and operating costs as long as the design is meeting the required standards, while life-cycle cost
98 (LCC) and life-cycle environmental impacts are rarely considered (Awad et al., 2019). The
99 consideration of a life cycle perspective can help to achieve sustainable wastewater treatment.

100 The Life Cycle Thinking approach is widely applied to assess the environmental sustainability
101 of treatment processes and reveal trade-offs across various environmental impact categories.
102 Besides, life cycle assessment (LCA) provides quantitative information that can support

103 decision making in water reuse practices when considering possible operational scenarios
104 during a strategic planning of reclaimed water reuse (Corominas et al., 2020). For instance,
105 Meneses et al. (2010) investigated tertiary treatment alternatives (i.e. chlorination plus UV
106 treatment; ozonation; and ozonation plus hydrogen peroxide) to enable urban wastewater reuse
107 for non-potable uses (both agricultural and urban uses). Although the assessed disinfection
108 methods had similar environmental impacts, most of the indicators were about 50% higher than
109 the UV disinfection except for the acidification (100% higher) and photochemical oxidation
110 (less than 5%), while chlorination plus UV treatment disinfection was found to have the lowest
111 impact. Up to date, there have been few studies that investigated the LCA of tertiary disinfection
112 methods for reclaimed water reuse (Carré et al., 2017; Muñoz et al., 2009; Pan et al., 2019;
113 Pasqualino et al., 2011) (see the **e-Supplementary file**). Although LCA and market prospects
114 for AnMBR technology are discussed in the review work of Krzeminski et al. (2017b), there
115 are still limited studies on the LCA of AnMBRs for urban wastewater treatment and water reuse
116 mainly due to the lack of full-scale data (Krzeminski et al., 2017a).

117 In this study, advanced tertiary treatment processes were assessed within the frameworks of life
118 cycle approach to analyze water reuse options in a municipal WWTP of Peschiera Borromeo
119 in Northern Italy. LCA and LCC were carried out to compare the impacts of treated wastewater
120 discharge and using conventional sources to supply the water and nutrient demand of the
121 surrounding agricultural area (Baseline scenario) with proposed alternative reuse strategies.
122 Fertigation coupled with different disinfection methods, such as peracetic acid (PAA) and UV-
123 disinfection, was evaluated as the alternative scenarios. Furthermore, a third scenario was
124 suggested to replace the conventional activated sludge process with an anaerobic biological
125 process (i.e. upflow anaerobic sludge blanket (UASB)) and to use AnMBR as tertiary treatment
126 and finally to reuse the effluent in fertigation practice. The main aim was to identify: i) potential
127 environmental and economic benefits and ii) undesired impacts of integrated wastewater

128 treatment and water reuse system. We believe that the outcomes of this work can help to guide
129 reclamation managers for possible upgrading opportunities in WWTPs considering the
130 sustainability aspects.

131 **2. Materials and methods**

132 **2.1. Description of the study area**

133 2.1.1. Peschiera Borromeo WWTP

134 The target WWTP is located in the municipality of Peschiera Borromeo (Lombardy, Italy) and
135 serves a large urban territory (Milan and neighboring municipalities) with a total catchment
136 area of 2,230 ha. Currently, the final effluent is discharged into the Lambro River. The plant
137 has a real treatment capacity of 322,376 population equivalent (PE) with a total average inflow
138 rate of 126,322 m³/d in 2019 treated in two different wastewater lines as shown in **Fig. 1**. Line
139 1 (**Fig. 1a**) collects and treats the wastewater from the municipalities of Brugherio (MB),
140 Carugate, Cassina de' Pecchi, Cernusco sul Naviglio, Cologno Monzese, Peschiera Borromeo,
141 Pioltello, Segrate, and Vimodrone. Line 2 treats the wastewater from the eastern district of
142 Milan. After pre- and primary treatments, Line 1 consists of a conventional activated-sludge
143 process followed by biological filtration to remove inorganic nitrogen and a final chemical
144 disinfection using peracetic acid (PAA). Line 2 (**Fig. 1b**) includes a two-stage upflow biological
145 filtration (Biofor ®) and two parallel lines of UV disinfection operating at a UV dose of 50
146 mWs/cm². Although Line 2 is designed for the purpose of reclaimed water reuse, the effluent
147 is discharged into the Lambro River in both cases. The sludge line consists of the following
148 processes: gravity and dynamic pre-thickening, two-stage anaerobic digestion, gravity post-
149 thickening, and dewatering via centrifuges. The dewatered sludge is transformed in defecation
150 lime and then applied as soil improver. The produced biogas is valorized in two combined heat
151 and power (CHP) units recovering electricity for internal purposes and thermal energy to heat

152 the digesters. The biogas is stored in two gasometers where the unused fraction is burned by
 153 two torches.

154 2.1.2. Surrounding irrigation area

155 Peri-urban areas in the south of Milan (near Parco Agricolo Sud Milano) suffer from water
 156 scarcity. Its water demand (12.03 hm³/y) is mainly required for irrigation purposes. This request
 157 can be widely covered by the outflow of Line 2. The surrounding agricultural land has an area
 158 of approximately 1500 ha and its main crop is tomato. The nutrient needs (N and P) of tomato
 159 in drip irrigation systems are 160 kg N/ha/y and 20 kg P/ha/y (Jiménez-Benítez et al., 2020).

160 **2.2. Treatment scenarios**

161 In order to enable the reuse of the final effluent for agricultural purposes, the following
 162 proposed scenarios focused only on the Line 2 of Peschiera Borromeo WWTP. The
 163 environmental impacts of the current no reuse configuration was compared to alternative
 164 reclamation solutions permitting water reuse. **Table 1** illustrates the effluent characteristics of
 165 the plant and the wastewater reuse limits set out by the current Italian legislation as well as
 166 those established by the new European Regulation 2020/741 on minimum requirements for
 167 water reuse (EC, 2020b).

168 **Table 1.** Effluent concentrations and wastewater reuse limits.

Parameters	Unit	Effluent Line 1	Effluent Line 2	DM183/2005 **	2020/741 Class A	2020/741 Class B	2020/741 Class C
<i>E. coli</i>	CFU/100ml	284	847	<10	<10	<100	<1000
COD	mg/l	19.3	17.9	<100	-	-	-
BOD ₅	mg/l	6.7	6	<20	<10	<25	<25
TN	mg/l	10.3	8.4	<15	*	*	*
NH ₄	mg/l	3.9	1.1	<2	*	*	*
TP	mg/l	0.5	0.7	<2	*	*	*
TSS	mg/l	7.2	6.5	<10	<10	<35	<35
Al	mg/l	0.19	0.12	<1	*	*	*
Fe	mg/l	0.19	0.31	<2	*	*	*

* Italian Ministerial Decree on Water Reuse

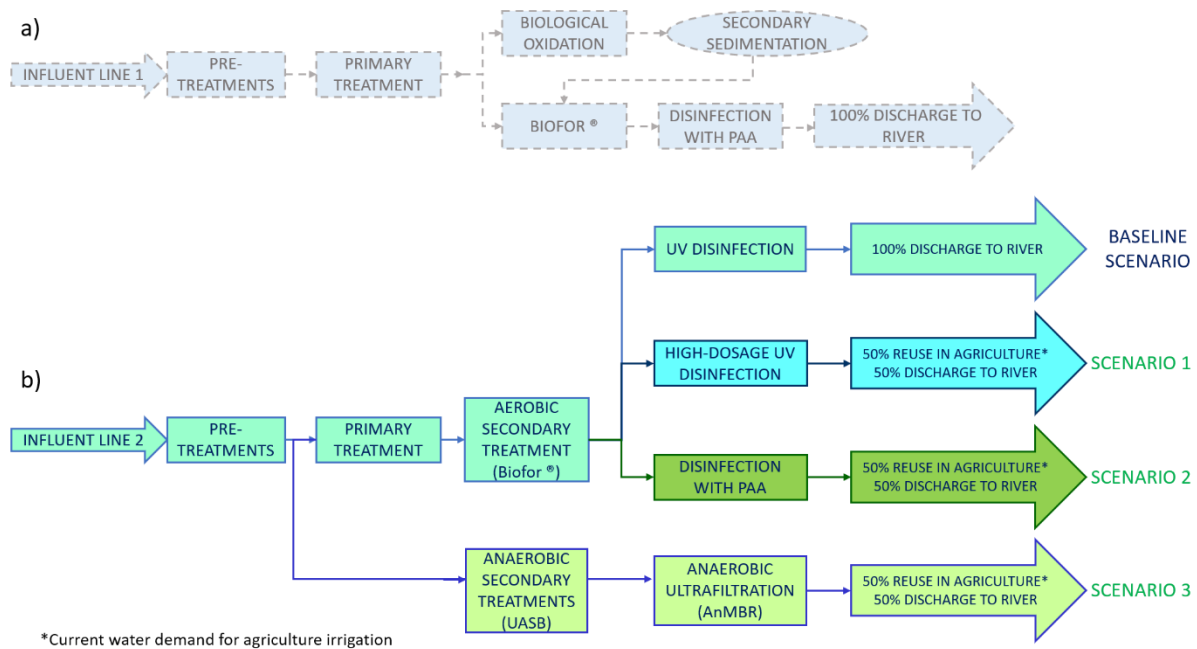
** defined by a site-specific risk assessment to be carried out

169

170 The initial (baseline) scenario refers to the current treatment chain of Line 2 where the final
171 effluent is discharged on surface water and the irrigation and nutrient demand are supplied by
172 freshwater and spreading of mineral fertilizers, respectively.

173 To comply with the water reuse regulation, the proposed reuse scenarios (Figure 1) involve
174 upgrading or process modifications of Line 2 as follows:

- 175 • UV disinfection at higher UV dose (Scenario 1),
- 176 • Chemical disinfection using peracetic acid PAA (Scenario 2)
- 177 • Biological treatment with UASB followed by AnMBR (Scenario 3).



178

179 **Fig. 1.** Flow scheme of the Peschiera Borromeo WWTP: a) Line 1 and b) baseline and proposed
180 scenarios applied to Line 2.

181 In Scenario 1, the existing UV disinfection operates at a dose of 80 mWs/cm² to ensure a 3.5
182 log reduction (DEMOWARE, 2016) required to achieve a quality effluent of Class A. In
183 Scenario 2, the UV disinfection is substituted by chemical disinfection unit of 2200 m³, with a
184 contact time of 49 min and a dosage of 5 mgPAA/L to guarantee the same log reduction
185 (Antonelli et al., 2013) of Scenario 1. Finally, in Scenario 3, an UASB reactor is installed

186 replacing the aerobic secondary treatment. The UASB reactor works at ambient temperature
187 and has a volume of 24,106 m³, with a hydraulic retention time (HRT) of 9 hours. Then, the
188 UASB is coupled with an anaerobic hollow-fiber ultrafiltration membrane (AnMBR) as the
189 tertiary treatment. The membrane (267,842 m²) has a nominal pore size of 0.03 μm and operates
190 at the specific flux of 10 L/m²/h. The ultrafiltration technology in Scenario 3 provides pathogen-
191 free effluent. Therefore, all the alternative scenarios are modeled to reach reclaimed water of
192 class A quality (*E. coli* < 10 CFU/100 ml).

193 The described configurations are assumed to treat the entire inflow rate of Line 2 (64,282 m³/d).
194 On the other hand, the effective request of water for irrigating the surrounding area is accounted
195 for the half of the WWTP flow. Therefore, 32,959 m³/d are reused in agriculture and 31,323
196 m³/d are discharged in the Lambro river. At the same time, the nutrient demand of crops is first
197 covered by the N- and P-content of the reclaimed water and then by a supplementary amount
198 of mineral fertilizer if needed.

199 **2.3.Life cycle assessment methodology**

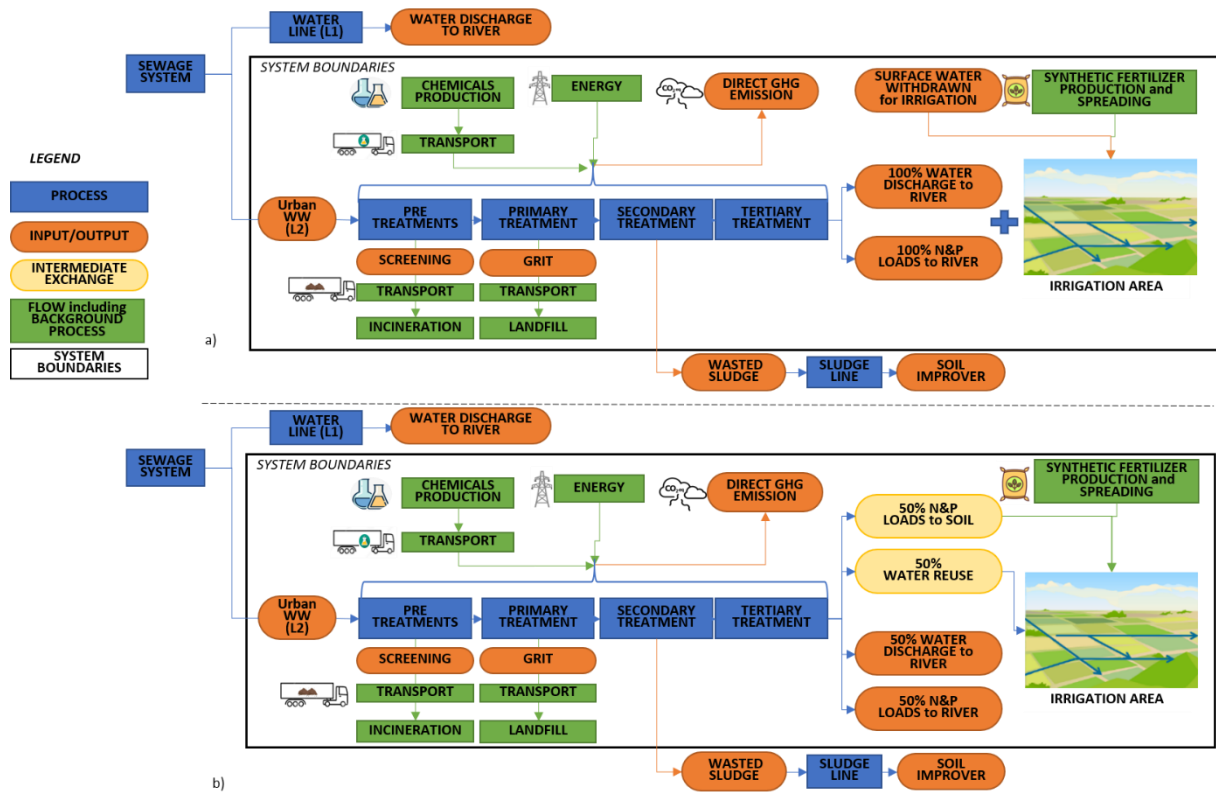
200 The above-described scenarios were compared to determine the sustainability of the different
201 water reclamation and reuse practices in terms of environmental and economic impacts. The
202 study was carried out following four phases: goal and scope definition, inventory analysis,
203 impact assessment and interpretation. This approach was followed within the framework and
204 principles universally valid to plan and conduct an LCA as established by ISO14044(ISO,
205 2006).

206 The analysis considered the environmental impact directly related to the treatment system
207 (foreground system), as well as the background impact from the supplementary supply chains
208 delivering energy, chemicals, or auxiliaries (background system) using the Ecoinvent v.3.6
209 databases published and maintained by the Ecoinvent Centre in Switzerland, since it is the most
210 renowned database for life cycle inventory (LCI) datasets. It contains approximately 4500-5000

211 harmonized, reviewed and validated datasets for use in LCA that are all fully documented. The
212 Life Cycle Impact Assessment (LCIA) phase was largely automated thanks to the use of LCA
213 software Umberto LCA+ v10.0 in this research. It uses graphic modelling of the product life
214 cycle and allows analyzing, assessing and visualizing the environmental impacts in different
215 impact categories.

216 2.3.1. System boundaries and functional unit

217 The physical system boundaries (**Fig. 2**) were defined according to the goal and scope of the
218 study, i.e. the comparison of different tertiary treatment schemes. It included not only the water
219 line processes (L2) but also the water and nutrient demand of the surrounding irrigation area
220 (1500 ha). To model foreground and background processes, the following data were considered:
221 the volume and the quality of all water streams, direct GHG emissions from processes, energy
222 consumption, production and transportation of chemicals, wastes disposal, surface water
223 withdrawal and production and spreading of fertilizer. To compare the environmental
224 performance of the different scenarios, 1 m³ of treated wastewater was selected as the functional
225 unit.



226

227 **Fig. 2.** System boundaries for the life cycle assessment: a) baseline configuration; b) alternative
 228 scenarios.

229 2.3.2. Life cycle inventory

230 A summary of the Life cycle inventory (LCI) of all the scenarios is given in **Table 2**. The data
 231 refer to the main units investigated in this study. The principal parameters of the foreground
 232 processes (primary data) were provided by the water utility of the Peschiera Borromeo WWTP.
 233 Water quality, consumption of energy and chemicals, amount of waste produced, and related
 234 distance to disposal sites refer to the information gathered in 2019. For alternative scenarios,
 235 relevant literature values were mainly considered. In Scenario 1, to apply a UV dose of 80
 236 mJ/cm^2 (DEMOWARE, 2016), the disinfection unit utilizes 5,472 kWh/d of electricity.
 237 Irrigating with the treated wastewater, 275 kgN/d and 34 kgP/d are provided to crops.
 238 Therefore, a supplementary consumption of mineral fertilizer (383 kgN/d and 48 kgP/d) were
 239 considered to ensure required plant growth (Jiménez-Benítez et al., 2020). In Scenario 2, the
 240 chemical disinfection consumes 2009 kg/d of 16% PAA and 43 kWh/d of electricity. The need

241 for supplementary mineral fertilizer (N and P) was assumed to be equal to Scenario 1. In
 242 Scenario 3, based on the data taken from the study of Pretel et al. (2013), the electricity
 243 consumption of the UASB was accepted to be 900 kWh/d, while the electricity and thermal
 244 energy productions were taken as 1350 kWh/d and 4236 MJ/d, respectively. Furthermore, the
 245 electricity consumption of the AnMBR was calculated as 12,381 kWh/d according to Pretel et
 246 al. (2013). Considering the membrane cleaning, the amount of NaOCl at 15% for the ordinary
 247 cleaning and citric acid at 100% for the recovery cleaning were estimated as 618 kg/d and 93
 248 kg/d, respectively. The N-content in the AnMBR effluent exceeds the N-demand for crops
 249 growth, thus only 18 kg/d of supplementary P-fertilizer was considered to be applied to cover
 250 the crop requirements.

251 **Table 2.** Life cycle inventory of the operation stage for the four scenarios.

		Baseline scenario	Scenario 1	Scenario 2	Scenario 3
		No reuse	Reuse of class A reclaimed water		
Parameters	Units	UV	High dosage UV	PAA	AnMBR
Q treated (L2)	m ³ /d	64,282	64,282	64,282	64,282
Q discharged to river	m ³ /d	64,282	31,323	31,323	31,323
Q required by crop	m ³ /d	32,959	32,959	32,959	32,959
Q surface water withdrawn	m ³ /d	32,959	0	0	0
Q water reused for irrigation	m ³ /d	0	32,959	32,959	32,959
TN effluent concentration	g/m ³	8	8	8	24
TN required by crop	kg/d	658	658	658	658
TN added by water	kg/d	0	275	275	791
TN added by mineral fertilizers	kg/d	658	383	383	-
Excess TN to soil	kg/d	-	-	-	133
TN discharged to surface water	kg/d	536.35	261.35	261.35	751.73
TP effluent concentration	g/m ³	1.04	1.04	1.04	1.94
TP required by crop	kg/d	82	82	82	82
TP added by water	kg/d	-	34	34	64
TP added by mineral fertilizers	kg/d	82	48	48	18
Excess TP to soil	kg/d	0	0	0	0
TP discharged to surface water	kg/d	67.12	32.71	32.71	60.88
Consumed electricity (secondary treatments)	kWh/d	9792	9792	9792	900

Consumed electricity (tertiary treatments)	kWh/d	2517	5472	43	12,381
Consumed electricity (whole plant)	kWh/d	20,318	23,273	17,844	21,290
Produced electricity	kWh/d	0	0	0	1350
Self-produced heat	MJ/d	0	0	0	4236
PAA at 16% w/w	kg/d	0	0	2009	0
Citric acid at 100% w/w (membrane cleaning)	kg/d	0	0	0	93
NaOCl at 15% w/w (membrane maintenance)	kg/d	0	0	0	618

252

253 Regarding the background processes, the following assumptions were considered: the PAA
254 production was modeled by the production processes of acetic acid (CH₃COOH) and hydrogen
255 peroxide (H₂O₂) assuming that the production of 1 kg of PAA requires 0.45 kg of CH₃COOH,
256 0.79 kg of H₂O₂ and 0.28 kg of water (Buonocore et al., 2018). The lifetime of a UV lamp is
257 equal to 10,000 hours as indicated by the WWTP manager. The residues from screening
258 (disposed of in municipal incineration) were assumed to be composed of 50% of “waste
259 packaging paper” and 50% of “plastic mixture” (Buonocore et al., 2018; Doka, 2003). The final
260 disposal in landfill of the residues from gritting was simulated with “disposal, inert waste, to
261 inert material landfill” (Buonocore et al., 2018; Lorenzo-Toja et al., 2016). The electricity was
262 modeled based on the “Market for electricity, low voltage [IT]”.

263 As conducted in other studies (Yoshida et al., 2018), “calcium ammonium nitrate production
264 [RER]” and “triple superphosphate production [RER]” were considered for the N and P
265 fertilizer production, respectively. The mineral fertilizer application was, instead, modeled by
266 the Ecoinvent process “fertilising, by broadcaster [CH]”.

267 The impact of transport derives from “Freight, lorry 3.5-7.5 metric ton, EURO 4” for chemicals
268 and “Freight, lorry 16-32 metric, EURO 4” for wastes and sludge disposal. Furthermore, direct
269 GHGs emissions like non-fossil carbon dioxide, fossil methane, and dinitrogen monoxide were
270 also considered in the model.

271 2.3.3. Impact assessment

272 The life cycle impact assessment was carried out by applying the “ReCiPe 2008 Midpoint (H)
273 V1.13 no LT” (results without long-term emissions) method for the following impact
274 categories: climate change (CC), fossil fuel depletion (FD), freshwater eutrophication (FE),
275 mineral resource depletion (MRD), water depletion (WD), freshwater ecotoxicity (T-FET),
276 human toxicity (T-HT) and terrestrial ecotoxicity (T-TET).

277 **2.4.Life cycle cost assessment methodology**

278 Direct capital costs include the cost of infrastructures, mechanical equipment and installation,
279 and electrical and automation systems (Harclerode et al., 2020). For the conventional treatment
280 facilities, the capital expenditures (CAPEX) was developed based on the scaling of costs from
281 comparable projects implemented by the authors, while costs for less common processes like
282 AnMBR were estimated using equipment market pricing and estimated quantities for materials,
283 such as concrete, tank covers, and pre-engineered buildings. The effects of price development
284 (e.g. rising energy prices) and inflation (i.e. the loss of value for money) were not considered
285 in the calculation. The investment cost for a conventional aerobic secondary treatment was
286 taken as 0.04 €/m³ considering a lifetime of 25 years (Harclerode et al., 2020). Similarly, the
287 CAPEX for the disinfection units were assumed to be 0.0008 and 0.0002 €/m³ for the UV
288 (scenario 1) and the PAA disinfection (scenario 2), respectively (Collivignarelli et al., 2000;
289 Luukkonen et al., 2015). For scenario 3, a specific total CAPEX of 0.096 €/m³ was assumed
290 for both secondary and tertiary treatments (Harclerode et al., 2020). For operating expenses
291 (OPEX), most of the information was provided by the water utility, otherwise the Ecoinvent
292 database was considered.

293 The economic lifetime was set to 25 years to be conservative since the investment cost includes
294 both constructions and buildings with a typical lifespan higher than 30 years and machinery to
295 be replaced every 20 years or less. This choice is stated in the ‘‘EVALUATION of the Council
296 Directive 91/271/EEC of 21 May 1991’’ concerning urban waste-water treatment that suggests

297 a lifetime of 25 years for WWTPs. **Table 3** provides a summary of the main CAPEX and
 298 specific OPEX values.

299 **Table 3.** CAPEX and OPEX cost considered in the proposed scenarios.

CAPEX costs (Peschiera WWTP)	U.M	Values	Reference
Preliminary and primary treatment	k€	8836	(Harclerode et al., 2020)
Conventional activated sludge secondary treatment	k€	22396	(Harclerode et al., 2020)
Disinfection UV	k€	470	(Collivignarelli et al., 2000)
Disinfection PAA	k€	147	(Luukkonen et al., 2015)
Anaerobic treatment (UASB+AnMBR)	k€	36450	(Harclerode et al., 2020)
Biogas conditioning and CHP	k€	11772	(Harclerode et al., 2020)
Specific OPEX costs (Peschiera WWTP)	U.M	Values	Reference
Electricity	€/kWh	0.14	Company information
PAA 16%	€/kg	0.74	Company information
NaOCl 100%	€/kg	0.34	Ecoinvent EURO2005
Citric acid 100%	€/kg	0.78	Ecoinvent EURO2005
MBR replacement frequency	years	10	(Harclerode et al., 2020)
MBR replacement cost for WW treated	€/m ³ /d	190	(Harclerode et al., 2020)
UV replacement frequency	hours	10000	Trojan UV technical factsheet
UV lamp cost	€/lamp	343	Trojan UV technical factsheet
N fertilizer	€/kg N	0.47	Ecoinvent EURO2005
P fertilizer	€/kg P ₂ O ₅	0.24	Ecoinvent EURO2005
Number of labors	N°	6	Company information
Labor salary	€/h	25	Company information
Irrigation water withdrawn from the channel	€/m ³	0.016	ISPRA, 2012
Reclaimed water market price	€/m ³	0.016	ISPRA, 2012

300
 301 The total cost in the results is reported as the annual costs, corresponding to the annual OPEX
 302 with the CAPEX per annum:

303 Annual costs = OPEX (€/y) + CAPEX (€/y)

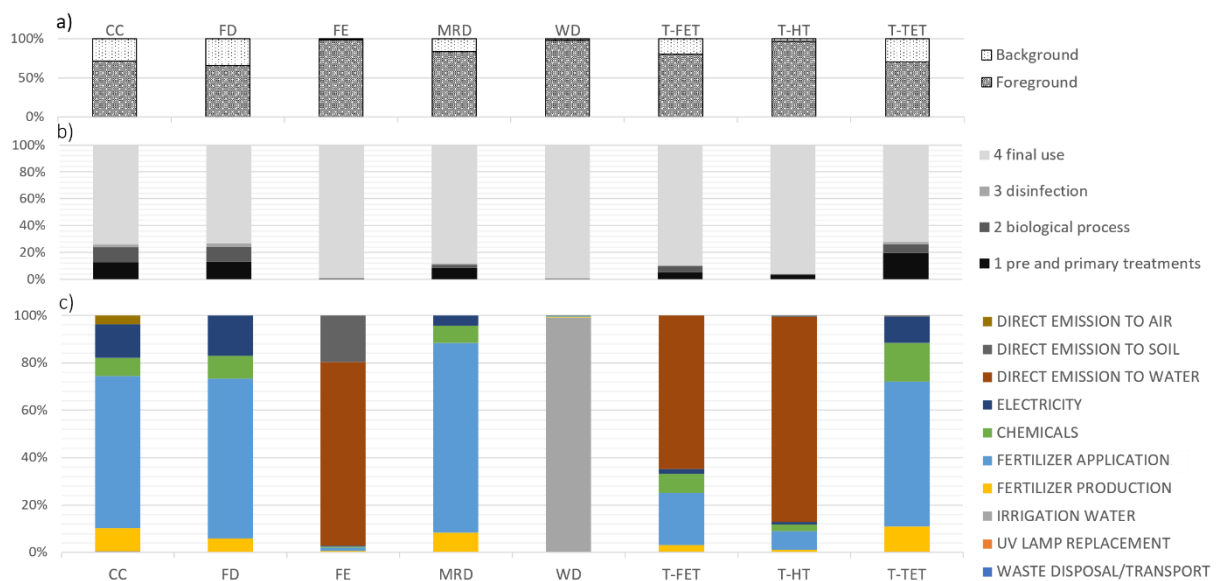
304 $CAPEX (€/y) = (\sum \text{investment costs } (€)) / (\text{economic lifetime } (y))$

305 3. Results

306 3.1. Baseline scenario assessment

307 **Fig. 3a** illustrates the allocation between foreground and background environmental impacts.
308 The foreground impact is dominating among all impact categories mainly as a result of the
309 agricultural activities (fertilizer spreading) and the direct emissions to air, water, and soil that
310 are related to the treatment process and to the final effluent discharge. More than 96% of the
311 impact on freshwater eutrophication (FE), water depletion (WD), and human toxicity (T-HT)
312 are caused by direct emissions. **Fig 3b** shows the breakdown of the environmental footprint
313 among the different stages of the water treatment supply chain, namely: pre- and primary
314 treatments, biological process, disinfection and final use. The latter includes water withdrawal
315 and fertilizer application in agriculture. As expected, the most significant environmental impact
316 is related to the final use, followed by primary treatment where phosphorous is chemically
317 removed by dosing poly-aluminium chloride (PAC). Specifically, the final use causes about
318 75% of the impact on climate change and fossil fuel depletion, and more than 98% on
319 freshwater eutrophication and water depletion. The relative impact of primary treatments
320 (>7%), as well as biological processes (>6%), are more evident on climate change, fossil fuel
321 depletion, mineral resource depletion and terrestrial ecotoxicity categories. As an energy-
322 intensive process, the disinfection affects mainly the fossil fuel depletion and climate change
323 categories, however, it is still significantly lower than the other stages (<2%). **Fig. 3c** shows
324 the contribution analysis of each impact category based on the origin of the impact and related
325 resources (i.e. energy, chemicals, direct emissions, etc.). Fertilizer spreading has a significant
326 contribution to climate change, fossil fuel depletion, mineral resource depletion and terrestrial
327 ecotoxicity since it is strongly related to fossil fuel combustion. The direct emissions to water
328 refer to the nutrients and heavy metals content of the discharged effluent to the surface water
329 body. They affect mainly the freshwater eutrophication, the freshwater ecotoxicity, and human
330 ecotoxicity with relative contributions of about 77%, 65%, and 86%, respectively.
331 Approximately 20% of the environmental burden in the freshwater eutrophication category is

332 due to the P-content in the irrigation water (direct emission to soil) and 80% is due to the P-
 333 content in the discharged water (direct emission to water). The water depletion is influenced
 334 almost entirely by the direct withdrawal of water from the environment while climate change,
 335 fossil fuel depletion, and terrestrial ecotoxicity are mainly affected by electricity consumption
 336 and transportation. The chemicals mostly have an impact on the categories of terrestrial
 337 ecotoxicity (20%), fossil fuel depletion (8%), freshwater ecotoxicity (7%), and climate change
 338 (7%).

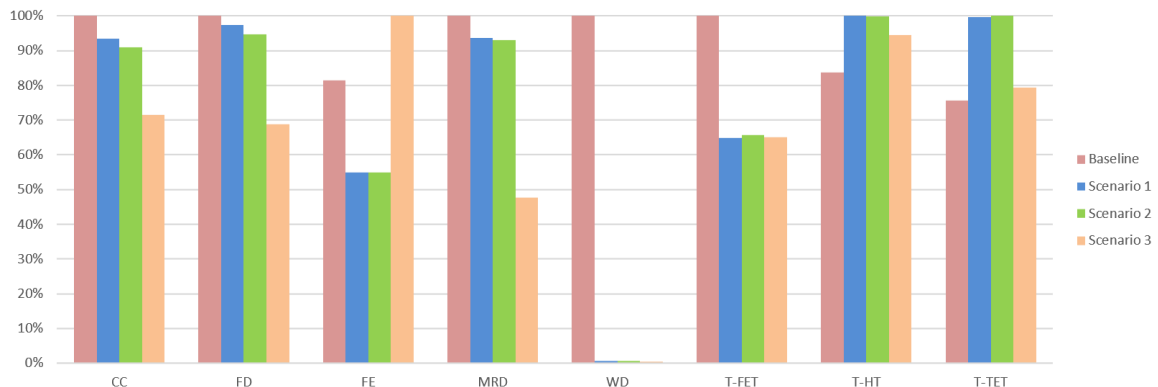


339
 340 **Fig. 3.** Environmental profile of the existing treatment configuration (baseline scenario) in the
 341 Peschiera Borromeo WWTP **a)** foreground and background environmental impacts **b)** impact
 342 of each treatment stage **c)** contributions on each impact category

343 3.2.Scenario analysis

344 An overall comparison of the relative impacts of each scenario is presented in **Fig. 4.** In most
 345 impact categories, the proposed water reuse scenarios show significant environmental benefits.
 346 The baseline scenario represents the largest environmental impact in all categories, except for
 347 freshwater eutrophication, human toxicity, and terrestrial ecotoxicity. As expected, the largest
 348 benefit is observed in water depletion category since the abstraction of freshwater is replaced
 349 with reclaimed water reuse. Scenario 1 and 2 show a significant reduction in freshwater

350 eutrophication due to the lower amount of P directly discharged to the river. On the other hand,
 351 Scenario 3 rises the impact on freshwater eutrophication since the UASB + AnMBR effluent is
 352 highly rich in nutrients that leads to higher rate of P-release even if the same low quantity of
 353 water is discharged into the river. However, due to the savings of producing and spreading
 354 mineral fertilizer, this scenario has a relatively lower impact on fossil fuel depletion (68%). A
 355 slight reduction of 3% and 6% in fossil fuel depletion impact is observed in Scenarios 1 and 2
 356 compared to baseline scenario, respectively, since they are strongly related to fossil fuel
 357 combustion required in energy production and in the transport of the disinfection agents.
 358 Looking at the toxicity-related categories, the toxicity in the water environment is higher in the
 359 Baseline since traces of heavy metals present in the effluent are fully discharged into the river.
 360 However, increased toxicity levels for terrestrial and human categories are observed in the
 361 alternative scenarios where the toxic compounds are partially sent to the soil.

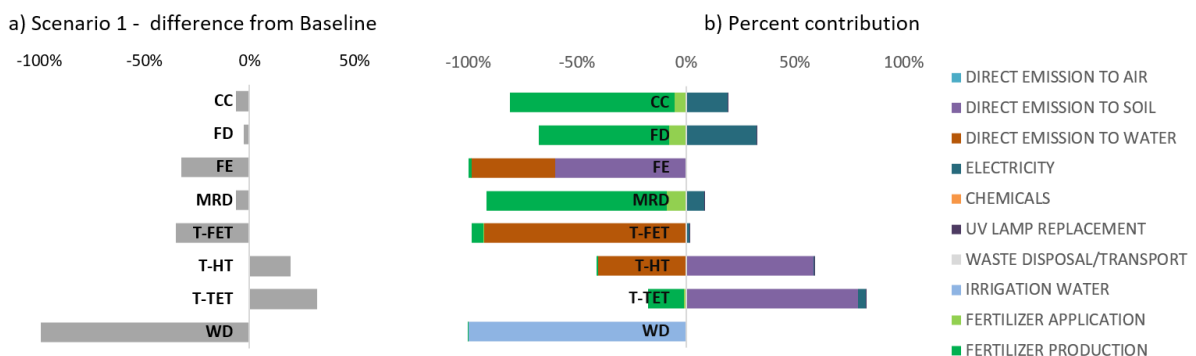


362
 363 **Fig. 4.** Comparison of the relative environmental impacts of each scenario.

364 3.2.1. Scenario 1 – Enhanced UV disinfection

365 Scenario 1 is the upgraded version of the baseline scenario with an enhanced UV application
 366 to reach an effluent quality of class A (*E. coli* <10) to be reused in agriculture. The current plant
 367 configuration performs poor nutrient removal resulting in a final effluent of N=8mg/l and P=1
 368 mg/l. **Fig. 5** shows the environmental performance of Scenario 1 relative to the baseline
 369 scenario. Although there is higher electricity consumption in Scenario 1, the climate change
 370 impact shows a 7% reduction. This is because the avoided emissions of the displaced fertilizer

371 production and application that are much higher than the ton of CO₂ equivalent related to the
 372 intensified energy demand. Since the irrigation water comes from the reuse of reclaimed water,
 373 the largest benefit is observed in the water depletion category. Freshwater eutrophication shows
 374 a significant reduction (32%) due to the avoided direct emissions to water produced by the
 375 effluent discharge. For the same reason, a large change (-35%) is seen in the freshwater
 376 ecotoxicity category compared to the baseline scenario. However, a significant negative impact
 377 is observed in human toxicity (+19%), and terrestrial ecotoxicity (+32%) due to the presence
 378 of traces of heavy metals in the reclaimed water. The shift of direct emissions from water to the
 379 soil results in a trade-off between freshwater ecotoxicity and human toxicity and terrestrial
 380 ecotoxicity. The reduction of the mineral resource depletion (6%) is also affected by the
 381 displaced N and P fertilizer.



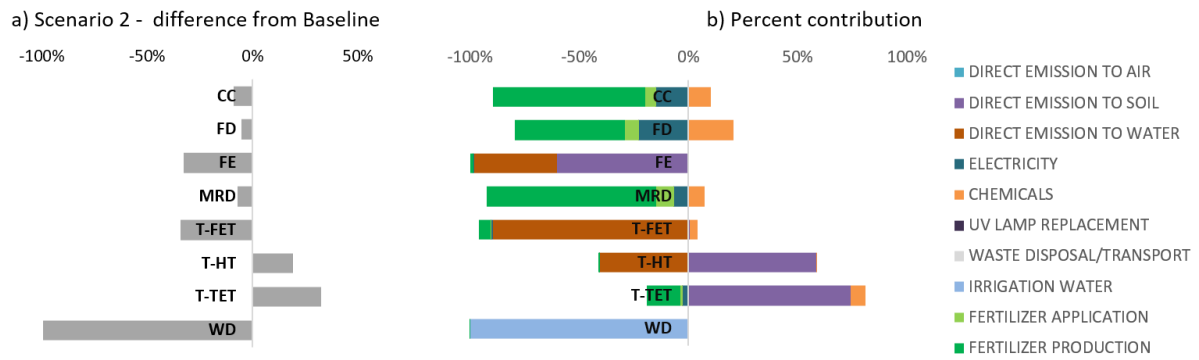
382
 383 **Fig. 5.** Environmental performance of enhanced UV disinfection relative to baseline scenario
 384 a) as overall relative differences in each category; b) percentage contribution analysis based on
 385 the individual processes and sources of impact.

386

387

388 3.2.2. Scenario 2 - Chemical disinfection using peracetic acid

389 Scenario 2 is the alternative version of the baseline scenario where the UV disinfection is
 390 replaced by PAA disinfection. **Fig. 6** shows the environmental performance of Scenario 2
 391 relative to the baseline scenario.



392

393 **Fig. 6.** Environmental performance of scenario with chemical disinfection using peracetic acid
 394 relative to baseline scenario: a) as overall relative differences in each category; b) percentage
 395 contribution analysis based on the individual processes and sources of impact.

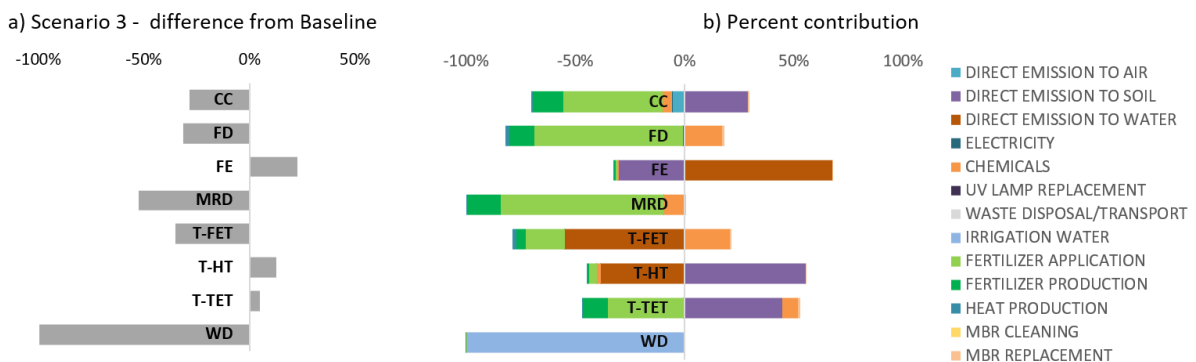
396

397 The overall environmental performance of the chemical disinfection scenario is similar to that
 398 of Scenario 1. The use of chemicals for disinfection leads to an additional impact in climate
 399 change (+9%), fossil fuel depletion (+18%) and mineral resource depletion (+6%) compared to
 400 baseline case. However, the avoided emissions from energy savings and displaced fertilizer
 401 outweigh them significantly and result in an overall reduction in most of the impact categories.
 402 The chemical disinfection of Scenario 2 shows a slightly higher reduction (2%) compared to
 403 the energy-intensive UV disinfection of Scenario 1, both in climate change and fossil fuel
 404 depletion. Similar to Scenario 1, there is a significant reduction in freshwater ecotoxicity while
 405 the end-use of water on land plays a large role in human toxicity and terrestrial ecotoxicity.
 406 Finally, the impact reduction on freshwater eutrophication is again determined by the avoided
 407 direct emissions to water.

408 3.2.3. Scenario 3 - Biological treatment with UASB followed by AnMBR as tertiary
 409 treatment

410 Scenario 3 includes the UASB as biological treatment followed by the AnMBR as the tertiary
 411 treatment and thus eliminates the need for a disinfection unit. The final effluent is richer in N
 412 and P contents compared to the other scenarios as 24 mg/l and 2 mg/l, respectively. **Fig. 7** shows

413 the environmental performance of Scenario 3 relative to the baseline scenario. Besides water
 414 depletion, Scenario 3 shows much higher relative benefits than Scenario 1 and 2 in climate
 415 change (-28%), fossil fuel depletion (-31%), mineral resource depletion (-52%) and freshwater
 416 ecotoxicity (-35%) compared to the baseline scenario (**Fig.7 a**). As can be seen from the
 417 contribution analysis in (**Fig.7 b**) the latter is attributed to the avoided fertilizer spreading,
 418 where relative reductions of 45% in climate change, 68% in fossil fuel depletion, 74% in
 419 mineral resource depletion and 18% in freshwater ecotoxicity are obtained. The direct
 420 emissions to soil (heavy metals and nutrients) are the main contributor to human toxicity
 421 (+55%) and terrestrial ecotoxicity (+45%). It is assumed that the dissolved methane in the
 422 permeate is not recovered through advanced treatment and thus raising the global warming
 423 potential by 28%. However, this is balanced by the avoided direct emissions from aerobic
 424 processes and the reduced amount of chemicals required for P-removal via chemical
 425 precipitation. Moreover, the greater nutrient content of the effluent provides the highest
 426 fertilizer substitution rate. It produces the most positive effect on impact reduction. However,
 427 Scenario 3 shows a significantly larger impact on eutrophication (68%) due to the increased
 428 amount of direct emissions to water (+23% compared to the baseline) mainly related to the
 429 fraction of nutrient-rich water which is not reused but directly discharged into a water body.
 430 The additional impact from membrane replacement, maintenance and cleaning results in a
 431 negligible additional impact (<1%) compared to other factors. Finally, differently to Scenarios
 432 1 and 2, the trade-off between the toxicity categories is relatively smaller.



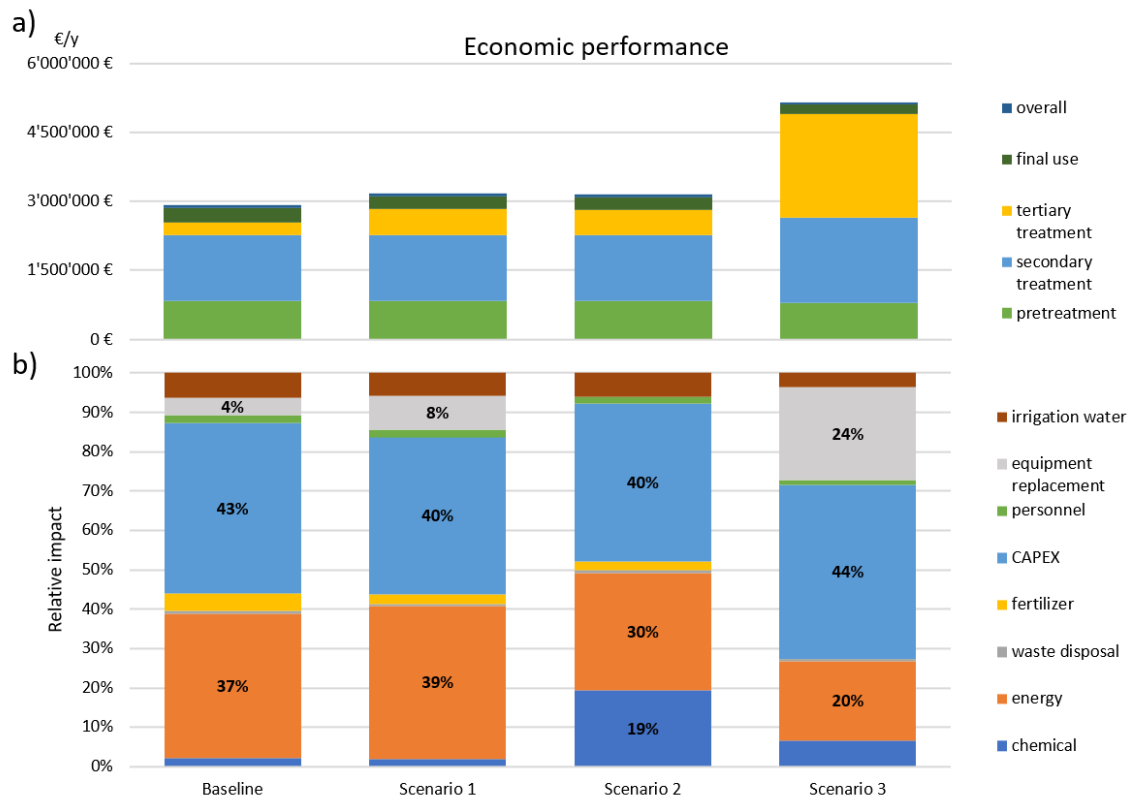
433

434 **Fig. 7.** Environmental performance of UASB followed by AnMBR relative to baseline
435 scenario: a) as overall relative differences in each category; b) percentage contribution analysis
436 based on the individual processes and sources of impact.

437

438 **3.3.Economic performance assessment**

439 The economic performance of the considered scenarios is shown in **Fig. 8.** In terms of biological
440 treatment, Scenario 3 does not have a significant rising in CAPEX compared to the other
441 scenarios. CAPEX comprises 40-44% of the total cost during the lifetime of the plant. In all
442 scenarios, the greatest OPEX belongs to energy consumption except for Scenario 3 where the
443 membrane replacement plays a major role followed by the energy demand. The differences
444 between the UV disinfection (scenario 1), PAA disinfection (scenario 2) and the baseline are
445 negligible in terms of total costs. On the other hand, the relative contributions are different.
446 Specifically, in Scenario 1, the UV replacement has a relative impact of 8%, while in Scenario
447 2, the chemical consumption has a relative impact of 19%. The larger cost for PAA supply is
448 balanced by lower energy consumption and the avoided periodic replacement of expensive
449 equipment like a UV lamp. Although the Scenario 3 has the best environmental performance
450 considering almost all the indicators, it has the highest overall costs due to the membrane
451 investment and replacement. The substitution every ten years of the membrane modules
452 contributes to 24% of the total cost. From a wastewater treatment point of view, the
453 environmental benefit of Scenario 3 should encompass the highest investment and operational
454 cost of the membrane reactor.



455

456 **Fig 8.** Economic evaluation in each scenario: a) phase contribution b) relative impact.

457 **4. Discussion**

458 This work demonstrated that the combination of anaerobic secondary treatments (i.e. UASB)
 459 with an ultrafiltration chamber (AnMBR) can strongly reduce the environmental impact of final
 460 discharges compared to the CAS line followed by disinfection processes (Baseline, Scenario 1
 461 and Scenario 2) when the reclaimed water is intended to be reused in agriculture. Furthermore,
 462 it showed the necessity to recognize WWTPs more like water resource recovery facilities
 463 (WWRFs) where not only water but also value-added materials, nutrients and energy are
 464 recovered (Akyol et al., 2020), while economic cost and carbon footprint are minimized. At the
 465 same time, this could provide an economic benefit for farmers since they can reduce mineral
 466 fertilizer acquisition, resulting in an economic and environmental win-win situation. In
 467 alternative scenarios, high environmental impacts are associated with eco- and human toxicity
 468 categories as a result of using reclaimed water in agriculture. The impacts on eco- and human
 469 toxicity are primarily related to heavy metals contamination of soil. Tangsubkul et al. (2005)

470 noted that the increased impacts on the terrestrial environments might be inevitable when
471 selecting a technology that optimizes the recycling of wastewater nutrients, due to the
472 potentially higher metals loading associated with the higher nutrient recovery and reuse (Fang
473 et al., 2016). Turan et al. (2018) evaluated the effects of chitosan (CH) and biochar (BC) on
474 growth and nutritional quality of brinjal plant together with in situ immobilization of heavy
475 metals in a soil polluted with heavy metals due to irrigation with wastewater. In fact, this is a
476 critical point that the reclamation managers and farmers should pay attention to the possible
477 ways to neglect heavy metal contamination via reclaimed wastewater reuse. Strong exposure
478 of plants to heavy metals in the soil modifies the majority of metabolic and cellular processes
479 in plant cells, which in return pose serious ecological risks and human health hazards (Turan,
480 2019).

481 In a recent study, environmental and human health impacts of water reclamation for crop
482 irrigation was comparatively evaluated by the combination of scenario modeling, life-cycle
483 impact analyses and Monte Carlo simulations (Pan et al., 2019). Similar to our findings, the
484 authors indicated that adverse environmental and human health impacts were dependent on
485 energy and chemical inputs (such as iron chloride for enhanced phosphorus removal). In fact,
486 the direct benefits of water reclamation could be offset by other adverse environmental and
487 human health impacts, (e.g. mineral depletion, global warming, ozone depletion, ecotoxicity)
488 which are associated with increased usage of energy and chemicals for rigorous removal of
489 contaminants, that can further affect decision-making. LCA may provide some surprising
490 results, too, such as the case of Carré et al., (2017). Five different tertiary treatments were
491 compared where the combination of a sand filter with UV disinfection or the use of UF alone
492 was found to be equivalent in terms of environmental impact for most of the midpoint indicators
493 chosen although the processes completely vary from each other.

494 Specifically, in our study, the system boundaries involved the water and nutrient demand of
495 crops, besides different technical solutions for water reclamation. Hence, our inventory includes
496 the off-set of mineral fertilizer production and freshwater withdrawn as conducted by previous
497 works (Cornejo et al., 2016; Pan et al., 2019). Further, the LCI also considers the spreading of
498 fertilizer via tractors, as well as nutrients excess due to reclaimed water if the case. The
499 spreading plays a major role in such impact categories related to fossil fuel combustion, while
500 nutrients in the eutrophication. When fertigation is implemented, N and P are directly supplied
501 through irrigation system avoiding the use of tractors and broadcasters. Therefore, it strongly
502 influences and reduces the environmental impact. This also stresses the higher benefits obtained
503 by the anaerobic processes (Scenario 3) in almost all the categories, except for the freshwater
504 eutrophication. To overcome the eutrophication issue that occurs when P-rich effluents are
505 discharged into water bodies, using both aerobic and anaerobic treatments is recommended.
506 This will make the modulation of the quality of the treated wastewater possible: the UASB-
507 AnMBR effluent will provide the crops with nutrients and water while the effluent from aerobic
508 CAS system will be used for nutrient dilution or irrigation. Temporal variability of the nutrients
509 and water demands from crops will determine the flow rate partition between the two treatment
510 lines.

511 **5. Conclusion**

512 All three proposed configurations aim to obtain an effluent quality of class A (*E. coli* < 10
513 CFU/100 ml) according to the new EU Regulation on minimum requirements for water reuse
514 in agriculture. The LCA clearly demonstrated that the reuse of reclaimed water provides more
515 environmental benefits than the discharge of treated water. No significant differences were
516 obtained between the disinfection by peracetic acid (PAA) or UV. The environmental
517 performance of the PAA disinfection scenario is mainly affected by chemical transportation,
518 while the UV disinfection is influenced by the energy production mix and amount of energy

519 used. The impact related to energy consumption is expected to be less significant in the future
520 with the increase amount of renewable energy. In almost every impact category, higher benefits
521 were obtained by applying the anaerobic configuration (UASB + AnMBR), except for the
522 freshwater eutrophication. Furthermore, the highest overall costs belong to the AnMBR line,
523 but its environmental benefits can encompass the high investment and operational cost. For
524 future research, actual removal of heavy metals, as well as contaminants of emerging concern,
525 can be considered in the proposed scenarios, especially stressing the differences between CAS
526 and AnMBR systems.

527 **AUTHOR CONTRIBUTIONS**

528 **Alessia Foglia:** Conceptualization, Investigation, Data Curation, Methodology, Software,
529 Formal Analysis. **Corinne Andreola:** Investigation, Data Curation, Methodology, Formal
530 Analysis, Software, Visualization, Writing - original draft. **Giulia Cipolletta:** Investigation,
531 Methodology, Software, Formal Analysis. **Serena Radini:** Investigation, Methodology,
532 Software, Visualization. **Çağrı Akyol:** Conceptualization, Writing - original draft. **Anna**
533 **Laura Eusebi:** Conceptualization, Supervision, Writing - review & editing. **Peyo Stanchev:**
534 Methodology, Software, Formal Analysis, Validation, Visualization, Writing - original draft.
535 **Evina Katsou:** Conceptualization, Supervision, Writing - review & editing. **Francesco**
536 **Fatone:** Conceptualization, Funding acquisition, Project administration, Resources,
537 Supervision, Writing - review & editing.

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