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

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ABSTRACT

Reuse of treated wastewater for irrigation purposes is a measure to reduce water stress and overexploitation of freshwater resources. This study aims to investigate the environmental and economic impacts of a current conventional wastewater treatment plant (WWTP) in Peschiera Borromeo (Milan, Italy), and compare possible scenarios to enable reclaimed water reuse for agriculture purposes. Accordingly, we propose alternative disinfection methods (i.e. enhanced UV, peracetic acid) and replace conventional activated sludge (CAS) with upflow anaerobic sludge blanket (UASB) for biological treatment and use anaerobic membrane bioreactor (AnMBR) as the tertiary treatment. Life cycle assessment (LCA) and life cycle costing (LCC) were implemented on the existing full-scale wastewater treatment line and the hypothetical scenarios. In most cases, the impact categories are primarily influenced by fertilizer application and direct emissions to water (i.e. nutrients and heavy metals). The baseline scenario appears to have the largest environmental impact, except for freshwater eutrophication, human ecotoxicity and terrestrial ecotoxicity. As expected, water depletion is the most apparent impact category between the baseline and proposed scenarios. The UASB + AnMBR scenario gives relatively higher environmental benefits than other proposed scenarios in climate change (-28%), fossil fuel depletion (-31%), mineral resource depletion (-52%), and terrestrial ecotoxicity compared to the baseline. On the other hand, the highest impact on freshwater eutrophication is also obtained by this scenario since the effluent from the anaerobic processes is rich in nutrients. Moreover, investment and operational costs varied remarkably between the scenarios, and the highest overall costs are obtained for the UASB + AnMBR line mostly due to the replacement of membrane modules (24% of the total cost). The results highlighted the importance of the life cycle approach to support decision making when considering possible upgrading scenarios in WWTPs for water reuse.

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

1. Introduction

Mediterranean region has been facing increasing pressure from water scarcity and droughts where freshwater availability is likely to decrease substantially by 2% to 15% for 2°C increase of global temperature due to climate change alone (MedECC Network, 2019). Between 50% and 90% of the total water demand in the Mediterranean basin is dedicated to irrigation, and this demand is projected to rise by 18% until the end of the century (UNEP/MAP Plan Bleu, 2019). Meanwhile, seawater intrusion is another critical problem along the Mediterranean coasts as a consequence of over-exploitation of groundwater (Giannoccaro et al., 2019). All of these issues together with population and economic growth continuously stress freshwater supplies, which consequently increase the demand for non-conventional water resources (Lee et al., 2018).

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

Currently, approximately 1 billion cubic meters of treated urban wastewater is reused in the EU annually, which accounts for about 2.4% of the treated urban wastewater effluents and less than 0.5% of annual EU freshwater withdrawals. Water-scarce EU countries such as Italy, Spain, and Greece only reuse between 5% to 12% of their effluents (EC, 2020a). This is mainly due to the existing constraints for reclaimed water reuse at the national level. For example, in Italy, the agricultural use of reclaimed water is strongly restricted by law D.Lgs 185/2003 (Ventura et al., 2019). Indeed, the treated wastewater must comply with a range of water directives at the EU and national levels to protect the environment, but the reuse of reclaimed water has to comply with additional directives/regulations depending on the purpose (Vojtěchovská Šrámková et al., 2018). Recently, the European Commission has developed the Regulation 2020/741 on "*Minimum Requirements for Water Reuse*" (EC, 2020b), where specific indications are provided for the assessment of reclaimed water reuse.

Tertiary treatment (including filtration and/or disinfection) is commonly required to meet the quality standards of reused treated wastewater (Carré et al., 2017). Conventionally, chemical or physical disinfection is applied during wastewater treatment, complying with the stringent microbial safety required for water reuse (Angelakis and Snyder, 2015). Alternatively, well designed and operated membrane bioreactors (MBRs) can also provide efficient removals of solids and pathogens (Foglia et al., 2020). Hai et al. (2014) provided an in-depth overview of the mechanisms and influencing factors of pathogens removal by MBRs and highlighted the practical issues, such as reduced chemical disinfectant dosages and associated economic and environmental benefits. Anaerobic MBR (AnMBR) is a very attractive technology in terms of energy efficiency with energy recovered from sewage and without aeration requirements. In fact, AnMBR has been reported to be net energy positive, leading in cost savings up to €0.023 per m^3 of treated water (Pretel et al., 2016). At the same time, the combined used of anaerobically treated effluent for fertigation can further reduce CO_2 emissions (Jiménez-Benítez et al., 2020).

In most cases, decisions about wastewater treatment are primarily influenced by direct capital and operating costs as long as the design is meeting the required standards, while life-cycle cost (LCC) and life-cycle environmental impacts are rarely considered (Awad et al., 2019). The consideration of a life cycle perspective can help to achieve sustainable wastewater treatment. The Life Cycle Thinking approach is widely applied to assess the environmental sustainability of treatment processes and reveal trade-offs across various environmental impact categories. Besides, life cycle assessment (LCA) provides quantitative information that can support decision making in water reuse practices when considering possible operational scenarios during a strategic planning of reclaimed water reuse (Corominas et al., 2020). For instance, Meneses et al. (2010) investigated tertiary treatment alternatives (i.e. chlorination plus UV treatment; ozonation; and ozonation plus hydrogen peroxide) to enable urban wastewater reuse for non-potable uses (both agricultural and urban uses). Although the assessed disinfection methods had similar environmental impacts, most of the indicators were about 50% higher than the UV disinfection except for the acidification (100% higher) and photochemical oxidation (less than 5%), while chlorination plus UV treatment disinfection was found to have the lowest impact. Up to date, there have been few studies that investigated the LCA of tertiary disinfection methods for reclaimed water reuse (Carré et al., 2017; Muñoz et al., 2009; Pan et al., 2019; Pasqualino et al., 2011) (see the **e-Supplementary file**). Although LCA and market prospects for AnMBR technology are discussed in the review work of Krzeminski et al. (2017b), there are still limited studies on the LCA of AnMBRs for urban wastewater treatment and water reuse mainly due to the lack of full-scale data (Krzeminski et al., 2017a).

In this study, advanced tertiary treatment processes were assessed within the frameworks of life cycle approach to analyze water reuse options in a municipal WWTP of Peschiera Borromeo in Northern Italy. LCA and LCC were carried out to compare the impacts of treated wastewater discharge and using conventional sources to supply the water and nutrient demand of the surrounding agricultural area (Baseline scenario) with proposed alternative reuse strategies. Fertigation coupled with different disinfection methods, such as peracetic acid (PAA) and UV-disinfection, was evaluated as the alternative scenarios. Furthermore, a third scenario was suggested to replace the conventional activated sludge process with an anaerobic biological process (i.e. upflow anaerobic sludge blanket (UASB)) and to use AnMBR as tertiary treatment and finally to reuse the effluent in fertigation practice. The main aim was to identify: i) potential environmental and economic benefits and ii) undesired impacts of integrated wastewater treatment and water reuse system. We believe that the outcomes of this work can help to guide reclamation managers for possible upgrading opportunities in WWTPs considering the sustainability aspects.

2. Materials and methods

2.1.Description of the study area

2.1.1. Peschiera Borromeo WWTP

The target WWTP is located in the municipality of Peschiera Borromeo (Lombardy, Italy) and serves a large urban territory (Milan and neighboring municipalities) with a total catchment area of 2,230 ha. Currently, the final effluent is discharged into the Lambro River. The plant has a real treatment capacity of 322,376 population equivalent (PE) with a total average inflow rate of 126,322 m^3/d in 2019 treated in two different wastewater lines as shown in **Fig. 1**. Line 1 (**Fig. 1a**) collects and treats the wastewater from the municipalities of Brugherio (MB), Carugate, Cassina de' Pecchi, Cernusco sul Naviglio, Cologno Monzese, Peschiera Borromeo, Pioltello, Segrate, and Vimodrone. Line 2 treats the wastewater from the eastern district of Milan. After pre- and primary treatments, Line 1 consists of a conventional activated-sludge process followed by biological filtration to remove inorganic nitrogen and a final chemical disinfection using peracetic acid (PAA). Line 2 (**Fig. 1b**) includes a two-stage upflow biological filtration (Biofor ®) and two parallel lines of UV disinfection operating at a UV dose of 50 mWs/cm^2. Although Line 2 is designed for the purpose of reclaimed water reuse, the effluent is discharged into the Lambro River in both cases. The sludge line consists of the following processes: gravity and dynamic pre-thickening, two-stage anaerobic digestion, gravity post-thickening, and dewatering via centrifuges. The dewatered sludge is transformed in defecation lime and then applied as soil improver. The produced biogas is valorized in two combined heat and power (CHP) units recovering electricity for internal purposes and thermal energy to heat the digesters. The biogas is stored in two gasometers where the unused fraction is burned by two torches.

2.1.2. Surrounding irrigation area

Peri-urban areas in the south of Milan (near Parco Agricolo Sud Milano) suffer from water scarcity. Its water demand (12.03 hm^3/y) is mainly required for irrigation purposes. This request can be widely covered by the outflow of Line 2. The surrounding agricultural land has an area of approximately 1500 ha and its main crop is tomato. The nutrient needs (N and P) of tomato in drip irrigation systems are 160 kg N/ha/y and 20 kg P/ha/y (Jiménez-Benítez et al., 2020).

2.2. Treatment scenarios

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

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
E. coli	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

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

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

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

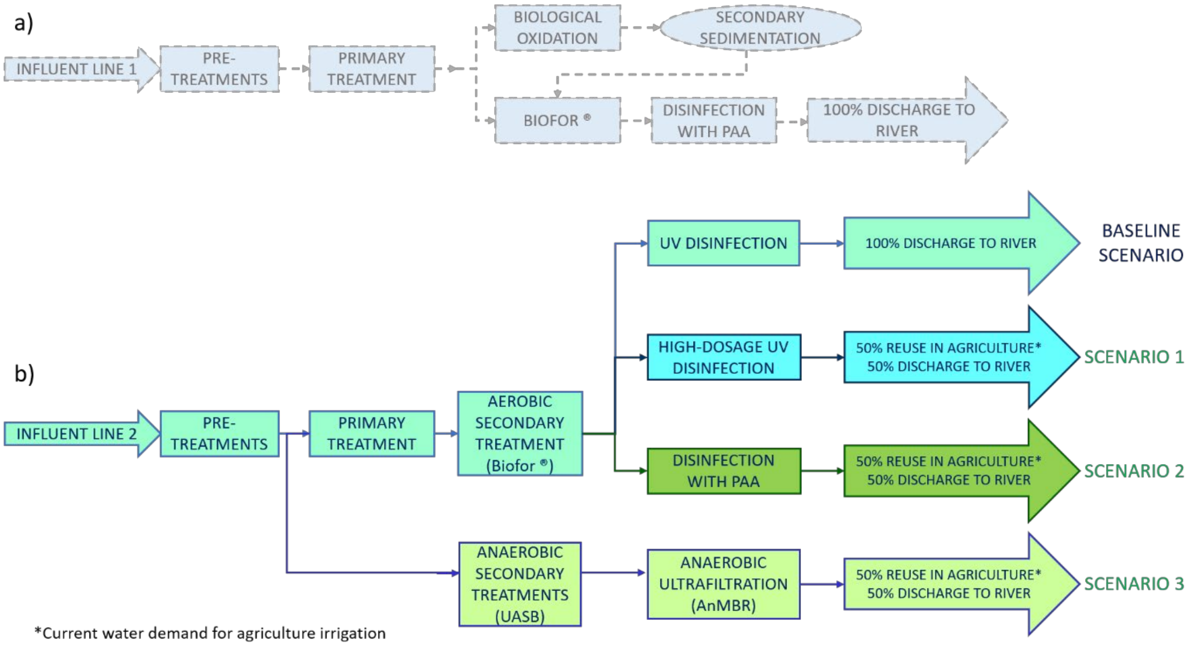

Fig. 1. Flow scheme of the Peschiera Borromeo WWTP: a) Line 1 and b) baseline and proposed scenarios applied to Line 2.

In Scenario 1, the existing UV disinfection operates at a dose of 80 mWs/cm^2 to ensure a 3.5 log reduction (DEMOWARE, 2016) required to achieve a quality effluent of Class A. In Scenario 2, the UV disinfection is substituted by chemical disinfection unit of 2200 m^3, with a contact time of 49 min and a dosage of 5 mgPAA/L to guarantee the same log reduction (Antonelli et al., 2013) of Scenario 1. Finally, in Scenario 3, an UASB reactor is installed replacing the aerobic secondary treatment. The UASB reactor works at ambient temperature and has a volume of 24,106 m^3, with a hydraulic retention time (HRT) of 9 hours. Then, the UASB is coupled with an anaerobic hollow-fiber ultrafiltration membrane (AnMBR) as the tertiary treatment. The membrane (267,842 m^2) has a nominal pore size of 0.03 µm and operates at the specific flux of 10 L/m^2/h. The ultrafiltration technology in Scenario 3 provides pathogen-free effluent. Therefore, all the alternative scenarios are modeled to reach reclaimed water of class A quality (*E. coli* < 10 CFU/100 ml).

The described configurations are assumed to treat the entire inflow rate of Line 2 (64,282 m^3/d). On the other hand, the effective request of water for irrigating the surrounding area is accounted for the half of the WWTP flow. Therefore, 32,959 m^3/d are reused in agriculture and 31,323 m^3/d are discharged in the Lambro river. At the same time, the nutrient demand of crops is first covered by the N- and P-content of the reclaimed water and then by a supplementary amount of mineral fertilizer if needed.

2.3. Life cycle assessment methodology

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

The analysis considered the environmental impact directly related to the treatment system (foreground system), as well as the background impact from the supplementary supply chains delivering energy, chemicals, or auxiliaries (background system) using the Ecoinvent v.3.6 databases published and maintained by the Ecoinvent Centre in Switzerland, since it is the most renowned database for life cycle inventory (LCI) datasets. It contains approximately 4500-5000 harmonized, reviewed and validated datasets for use in LCA that are all fully documented. The Life Cycle Impact Assessment (LCIA) phase was largely automated thanks to the use of LCA software Umberto LCA+ v10.0 in this research. It uses graphic modelling of the product life cycle and allows analyzing, assessing and visualizing the environmental impacts in different impact categories.

2.3.1. System boundaries and functional unit

The physical system boundaries (**Fig. 2**) were defined according to the goal and scope of the study, i.e. the comparison of different tertiary treatment schemes. It included not only the water line processes (L2) but also the water and nutrient demand of the surrounding irrigation area

(1500 ha). To model foreground and background processes, the following data were considered: the volume and the quality of all water streams, direct GHG emissions from processes, energy consumption, production and transportation of chemicals, wastes disposal, surface water withdrawal and production and spreading of fertilizer. To compare the environmental performance of the different scenarios, 1 m^3 of treated wastewater was selected as the functional unit.

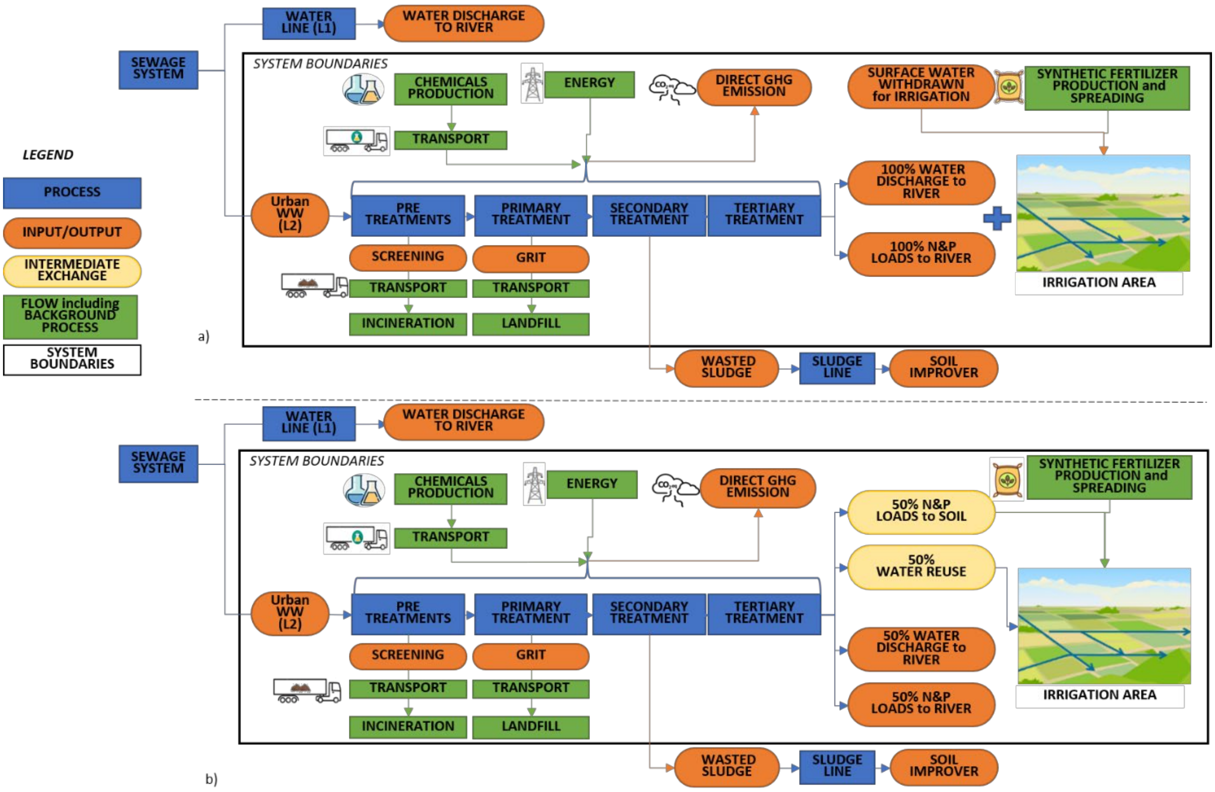

Fig. 2. System boundaries for the life cycle assessment: a) baseline configuration; b) alternative scenarios.

2.3.2. Life cycle inventory

A summary of the Life cycle inventory (LCI) of all the scenarios is given in **Table 2**. The data refer to the main units investigated in this study. The principal parameters of the foreground processes (primary data) were provided by the water utility of the Peschiera Borromeo WWTP. Water quality, consumption of energy and chemicals, amount of waste produced, and related distance to disposal sites refer to the information gathered in 2019. For alternative scenarios, relevant literature values were mainly considered. In Scenario 1, to apply a UV dose of 80 mJ/cm^2 (DEMOWARE, 2016), the disinfection unit utilizes 5,472 kWh/d of electricity. Irrigating with the treated wastewater, 275 kgN/d and 34 kgP/d are provided to crops. Therefore, a supplementary consumption of mineral fertilizer (383 kgN/d and 48 kgP/d) were considered to ensure required plant growth (Jiménez-Benítez et al., 2020). In Scenario 2, the chemical disinfection consumes 2009 kg/d of 16% PAA and 43 kWh/d of electricity. The need for supplementary mineral fertilizer (N and P) was assumed to be equal to Scenario 1. In Scenario 3, based on the data taken from the study of Pretel et al. (2013), the electricity consumption of the UASB was accepted to be 900 kWh/d, while the electricity and thermal energy productions were taken as 1350 kWh/d and 4236 MJ/d, respectively. Furthermore, the electricity consumption of the AnMBR was calculated as 12,381 kWh/d according to Pretel et al. (2013). Considering the membrane cleaning, the amount of NaOCl at 15% for the ordinary cleaning and citric acid at 100% for the recovery cleaning were estimated as 618 kg/d and 93 kg/d, respectively. The N-content in the AnMBR effluent exceeds the N-demand for crops growth, thus only 18 kg/d of supplementary P-fertilizer was considered to be applied to cover the crop requirements.

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

Regarding the background processes, the following assumptions were considered: the PAA production was modeled by the production processes of acetic acid (CH_3COOH) and hydrogen peroxide (H_2O_2) assuming that the production of 1 kg of PAA requires 0.45 kg of CH_3COOH, 0.79 kg of H_2O_2 and 0.28 kg of water (Buonocore et al., 2018). The lifetime of a UV lamp is equal to 10,000 hours as indicated by the WWTP manager. The residues from screening (disposed of in municipal incineration) were assumed to be composed of 50% of "waste packaging paper" and 50% of "plastic mixture" (Buonocore et al., 2018; Doka, 2003). The final disposal in landfill of the residues from gritting was simulated with "disposal, inert waste, to inert material landfill" (Buonocore et al., 2018; Lorenzo-Toja et al., 2016). The electricity was modeled based on the "Market for electricity, low voltage [IT]".

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

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

2.3.3. Impact assessment

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

2.4.Life cycle cost assessment methodology

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

(OPEX), most of the information was provided by the water utility, otherwise the Ecoinvent database was considered.

The economic lifetime was set to 25 years to be conservative since the investment cost includes both constructions and buildings with a typical lifespan higher than 30 years and machinery to be replaced every 20 years or less. This choice is stated in the ‘’EVALUATION of the Council Directive 91/271/EEC of 21 May 1991’’ concerning urban waste-water treatment that suggests a lifetime of 25 years for WWTPs. **Table 3** provides a summary of the main CAPEX and specific OPEX values.

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_2O_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

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

$$\text{Annual costs} = \text{OPEX (€/y)} + \text{CAPEX (€/y)}$$

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

3. Results

3.1. Baseline scenario assessment

Fig. 3a illustrates the allocation between foreground and background environmental impacts. The foreground impact is dominating among all impact categories mainly as a result of the agricultural activities (fertilizer spreading) and the direct emissions to air, water, and soil that are related to the treatment process and to the final effluent discharge. More than 96% of the impact on freshwater eutrophication (FE), water depletion (WD), and human toxicity (T-HT) are caused by direct emissions. **Fig 3b** shows the breakdown of the environmental footprint among the different stages of the water treatment supply chain, namely: pre- and primary treatments, biological process, disinfection and final use. The latter includes water withdrawal and fertilizer application in agriculture. As expected, the most significant environmental impact is related to the final use, followed by primary treatment where phosphorous is chemically removed by dosing poly-aluminium chloride (PAC). Specifically, the final use causes about 75% of the impact on climate change and fossil fuel depletion, and more than 98% on freshwater eutrophication and water depletion. The relative impact of primary treatments (>7%), as well as biological processes (>6%), are more evident on climate change, fossil fuel depletion, mineral resource depletion and terrestrial ecotoxicity categories. As an energy-intensive process, the disinfection affects mainly the fossil fuel depletion and climate change categories, however, it is still significantly lower than the other stages (<2%). **Fig. 3c** shows the contribution analysis of each impact category based on the origin of the impact and related resources (i.e. energy, chemicals, direct emissions, etc.). Fertilizer spreading has a significant contribution to climate change, fossil fuel depletion, mineral resource depletion and terrestrial ecotoxicity since it is strongly related to fossil fuel combustion. The direct emissions to water refer to the nutrients and heavy metals content of the discharged effluent to the surface water body. They affect mainly the freshwater eutrophication, the freshwater ecotoxicity, and human ecotoxicity with relative contributions of about 77%, 65%, and 86%, respectively. Approximately 20% of the environmental burden in the freshwater eutrophication category is due to the P-content in the irrigation water (direct emission to soil) and 80% is due to the P-content in the discharged water (direct emission to water). The water depletion is influenced almost entirely by the direct withdrawal of water from the environment while climate change, fossil fuel depletion, and terrestrial ecotoxicity are mainly affected by electricity consumption and transportation. The chemicals mostly have an impact on the categories of terrestrial ecotoxicity (20%), fossil fuel depletion (8%), freshwater ecotoxicity (7%), and climate change (7%).

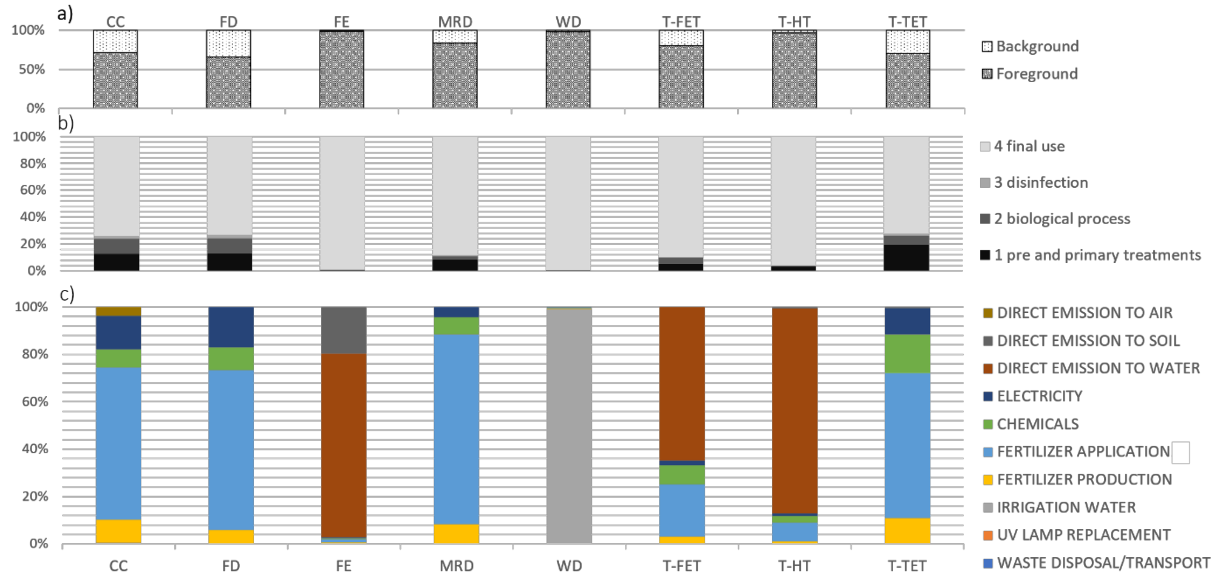

Fig. 3. Environmental profile of the existing treatment configuration (baseline scenario) in the Peschiera Borromeo WWTP **a)** foreground and background environmental impacts **b)** impact of each treatment stage **c)** contributions on each impact category

3.2.Scenario analysis

An overall comparison of the relative impacts of each scenario is presented in **Fig. 4**. In most impact categories, the proposed water reuse scenarios show significant environmental benefits.

The baseline scenario represents the largest environmental impact in all categories, except for freshwater eutrophication, human toxicity, and terrestrial ecotoxicity. As expected, the largest benefit is observed in water depletion category since the abstraction of freshwater is replaced with reclaimed water reuse. Scenario 1 and 2 show a significant reduction in freshwater eutrophication due to the lower amount of P directly discharged to the river. On the other hand, Scenario 3 rises the impact on freshwater eutrophication since the UASB + AnMBR effluent is highly rich in nutrients that leads to higher rate of P-release even if the same low quantity of water is discharged into the river. However, due to the savings of producing and spreading mineral fertilizer, this scenario has a relatively lower impact on fossil fuel depletion (68%). A slight reduction of 3% and 6% in fossil fuel depletion impact is observed in Scenarios 1 and 2 compared to baseline scenario, respectively, since they are strongly related to fossil fuel combustion required in energy production and in the transport of the disinfection agents. Looking at the toxicity-related categories, the toxicity in the water environment is higher in the Baseline since traces of heavy metals present in the effluent are fully discharged into the river. However, increased toxicity levels for terrestrial and human categories are observed in the alternative scenarios where the toxic compounds are partially sent to the soil.

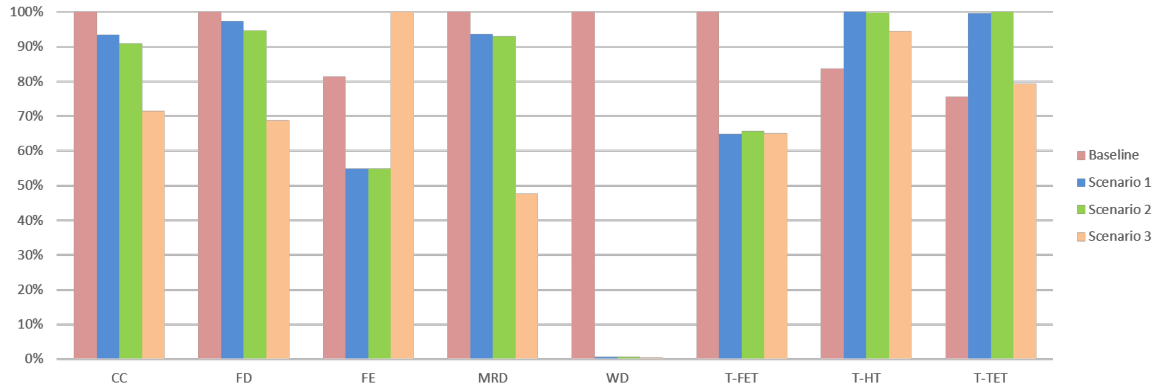

Fig. 4. Comparison of the relative environmental impacts of each scenario.

3.2.1. Scenario 1 – Enhanced UV disinfection

Scenario 1 is the upgraded version of the baseline scenario with an enhanced UV application to reach an effluent quality of class A (*E. coli* <10) to be reused in agriculture. The current plant configuration performs poor nutrient removal resulting in a final effluent of N=8mg/l and P=1 mg/l. **Fig. 5** shows the environmental performance of Scenario 1 relative to the baseline scenario. Although there is higher electricity consumption in Scenario 1, the climate change impact shows a 7% reduction. This is because the avoided emissions of the displaced fertilizer production and application that are much higher than the ton of CO_2 equivalent related to the intensified energy demand. Since the irrigation water comes from the reuse of reclaimed water, the largest benefit is observed in the water depletion category. Freshwater eutrophication shows a significant reduction (32%) due to the avoided direct emissions to water produced by the effluent discharge. For the same reason, a large change (-35%) is seen in the freshwater ecotoxicity category compared to the baseline scenario. However, a significant negative impact is observed in human toxicity (+19%), and terrestrial ecotoxicity (+32%) due to the presence of traces of heavy metals in the reclaimed water. The shift of direct emissions from water to the soil results in a trade-off between freshwater ecotoxicity and human toxicity and terrestrial ecotoxicity. The reduction of the mineral resource depletion (6%) is also affected by the displaced N and P fertilizer.

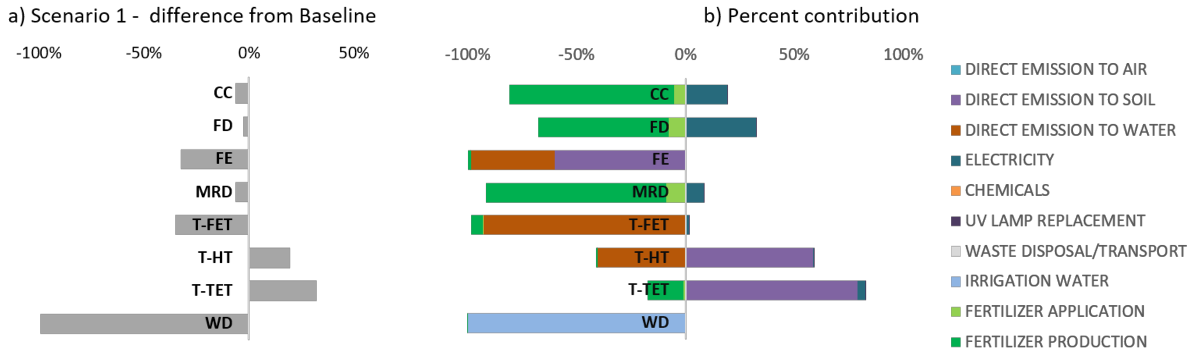

Fig. 5. Environmental performance of enhanced UV disinfection relative to baseline scenario a) as overall relative differences in each category; b) percentage contribution analysis based on the individual processes and sources of impact.

3.2.2. Scenario 2 - Chemical disinfection using peracetic acid

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

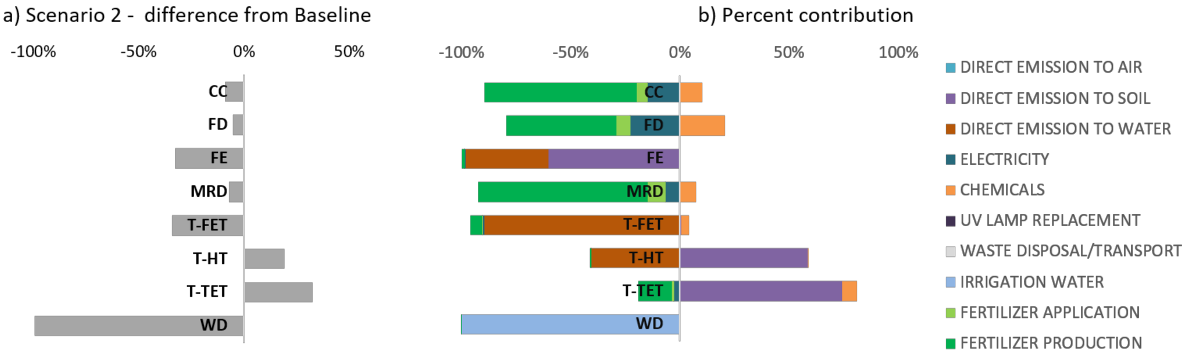

Fig. 6. Environmental performance of scenario with chemical disinfection using peracetic acid relative to baseline scenario: a) as overall relative differences in each category; b) percentage contribution analysis based on the individual processes and sources of impact.

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

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

Scenario 3 includes the UASB as biological treatment followed by the AnMBR as the tertiary treatment and thus eliminates the need for a disinfection unit. The final effluent is richer in N and P contents compared to the other scenarios as 24 mg/l and 2 mg/l, respectively. **Fig. 7** shows the environmental performance of Scenario 3 relative to the baseline scenario. Besides water depletion, Scenario 3 shows much higher relative benefits than Scenario 1 and 2 in climate change (-28%), fossil fuel depletion (-31%), mineral resource depletion (-52%) and freshwater ecotoxicity (-35%) compared to the baseline scenario (**Fig.7 a)**. As can be seen from the contribution analysis in (**Fig.7 b)** the latter is attributed to the avoided fertilizer spreading, where relative reductions of 45% in climate change, 68% in fossil fuel depletion, 74% in mineral resource depletion and 18% in freshwater ecotoxicity are obtained. The direct emissions to soil (heavy metals and nutrients) are the main contributor to human toxicity (+55%) and terrestrial ecotoxicity (+45%). It is assumed that the dissolved methane in the permeate is not recovered through advanced treatment and thus raising the global warming potential by 28%. However, this is balanced by the avoided direct emissions from aerobic processes and the reduced amount of chemicals required for P-removal via chemical precipitation. Moreover, the greater nutrient content of the effluent provides the highest fertilizer substitution rate. It produces the most positive effect on impact reduction. However, Scenario 3 shows a significantly larger impact on eutrophication (68%) due to the increased amount of direct emissions to water (+23% compared to the baseline) mainly related to the fraction of nutrient-rich water which is not reused but directly discharged into a water body. The additional impact from membrane replacement, maintenance and cleaning results in a negligible additional impact (<1%) compared to other factors. Finally, differently to Scenarios 1 and 2, the trade-off between the toxicity categories is relatively smaller.

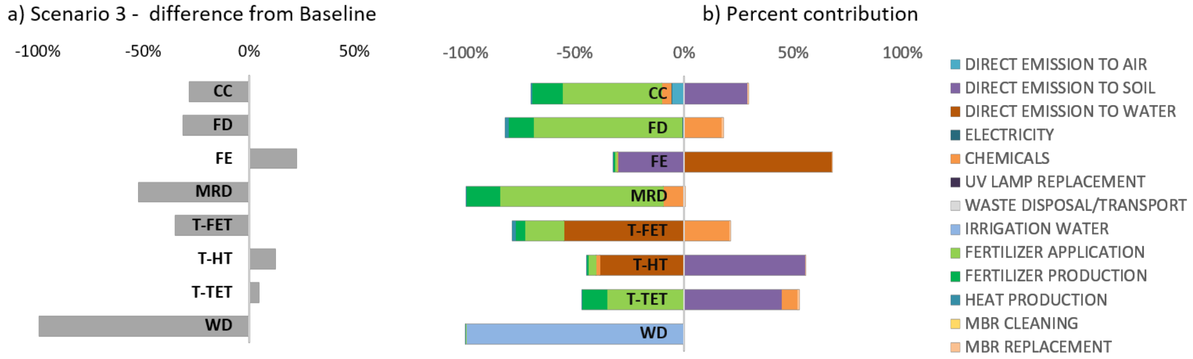

Fig. 7. Environmental performance of UASB followed by AnMBR relative to baseline scenario: a) as overall relative differences in each category; b) percentage contribution analysis based on the individual processes and sources of impact.

3.3.Economic performance assessment

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

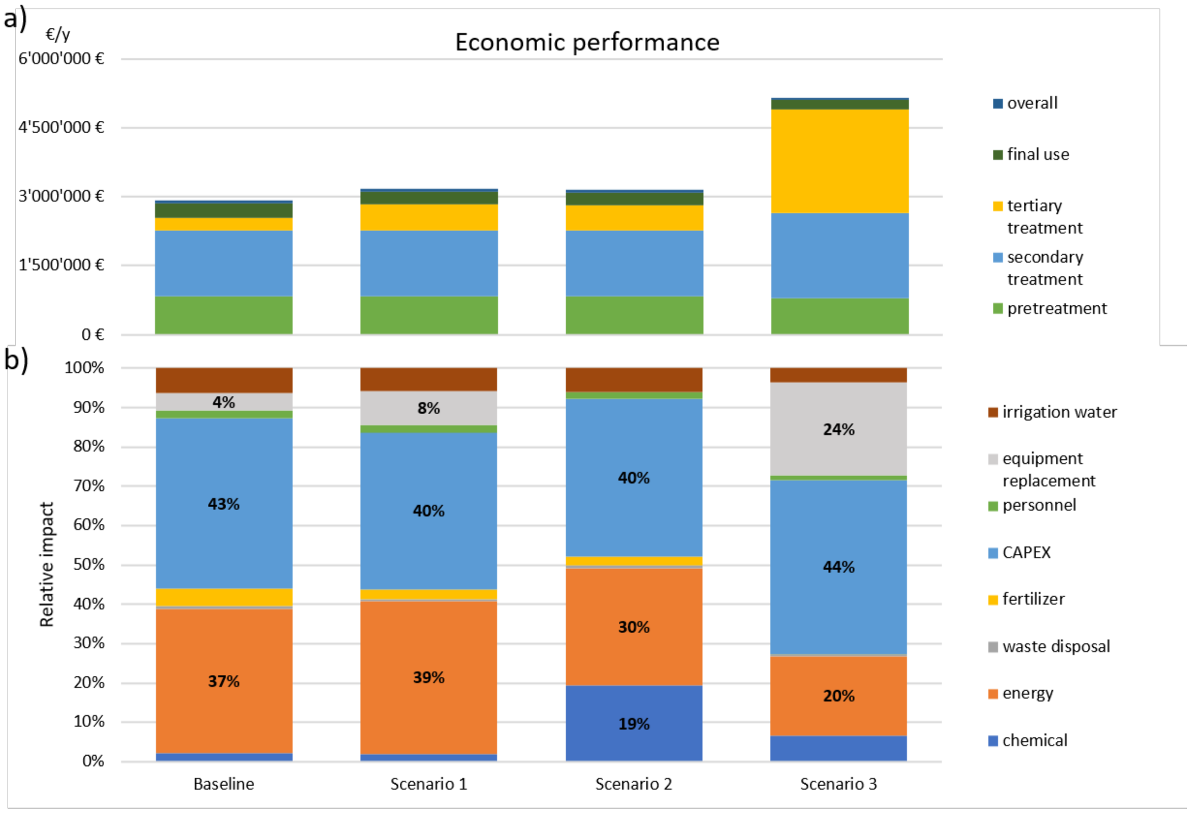

Fig 8. Economic evaluation in each scenario: a) phase contribution b) relative impact.

4. Discussion

This work demonstrated that the combination of anaerobic secondary treatments (i.e. UASB) with an ultrafiltration chamber (AnMBR) can strongly reduce the environmental impact of final discharges compared to the CAS line followed by disinfection processes (Baseline, Scenario 1 and Scenario 2) when the reclaimed water is intended to be reused in agriculture. Furthermore, it showed the necessity to recognize WWTPs more like water resource recovery facilities (WWRFs) where not only water but also value-added materials, nutrients and energy are recovered (Akyol et al., 2020), while economic cost and carbon footprint are minimized. At the same time, this could provide an economic benefit for farmers since they can reduce mineral fertilizer acquisition, resulting in an economic and environmental win-win situation. In alternative scenarios, high environmental impacts are associated with eco- and human toxicity categories as a result of using reclaimed water in agriculture. The impacts on eco- and human toxicity are primarily related to heavy metals contamination of soil. Tangsubkul et al. (2005) noted that the increased impacts on the terrestrial environments might be inevitable when selecting a technology that optimizes the recycling of wastewater nutrients, due to the potentially higher metals loading associated with the higher nutrient recovery and reuse (Fang et al., 2016). Turan et al. (2018) evaluated the effects of chitosan (CH) and biochar (BC) on growth and nutritional quality of brinjal plant together with in situ immobilization of heavy metals in a soil polluted with heavy metals due to irrigation with wastewater. In fact, this is a critical point that the reclamation managers and farmers should pay attention to the possible ways to neglect heavy metal contamination via reclaimed wastewater reuse. Strong exposure of plants to heavy metals in the soil modifies the majority of metabolic and cellular processes in plant cells, which in return pose serious ecological risks and human health hazards (Turan, 2019).

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

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

5. Conclusion

All three proposed configurations aim to obtain an effluent quality of class A (*E. coli* < 10 CFU/100 ml) according to the new EU Regulation on minimum requirements for water reuse in agriculture. The LCA clearly demonstrated that the reuse of reclaimed water provides more environmental benefits than the discharge of treated water. No significant differences were obtained between the disinfection by peracetic acid (PAA) or UV. The environmental performance of the PAA disinfection scenario is mainly affected by chemical transportation, while the UV disinfection is influenced by the energy production mix and amount of energy used. The impact related to energy consumption is expected to be less significant in the future with the increase amount of renewable energy. In almost every impact category, higher benefits were obtained by applying the anaerobic configuration (UASB + AnMBR), except for the freshwater eutrophication. Furthermore, the highest overall costs belong to the AnMBR line, but its environmental benefits can encompass the high investment and operational cost. For future research, actual removal of heavy metals, as well as contaminants of emerging concern, can be considered in the proposed scenarios, especially stressing the differences between CAS and AnMBR systems.

AUTHOR CONTRIBUTIONS

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

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