

Life cycle assessment of wastewater treatment systems: Challenges and approaches

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Article Info	Abstract
Article type:	Water crisis and pollution increase have encouraged researchers to
Research Article	rehabilitate wastewater as an alternative water source. Wastewater
Article history: Received:November 2021 Accepted: February 2022 Corresponding author: haiar abyar@yahoo.com	treatment plants (WWTPs) implementation with high environmental and economic compatibility can be achieved using life cycle assessment (LCA). In this regard, the current review compared three well-known WWTPs including anaerobic/anoxic/aerobic (A ₂ O), membrane bioreactor-reverse osmosis (MBR-RO), and integrated fixed-film activated sludge membrane bioreactor (IFAS-MBR) systems from an environmental perspective. The
najar.ao ya @yanoo.com	largest environmental impacts of the IFAS-MBR and MBR-RO were
Keywords:	associated with climate change (27.5-95.13%) and human health (67.57-
Life cycle assessment Wastewater treatment Climate change Greenhouse gases	92%), while the midpoint and endpoint impacts of A ₂ O were attributed to freshwater eutrophication (31.62%), marine ecotoxicity (29.94%), and resources (60.18%). The maximum and minimum energy consumption were observed in the A ₂ O and MBR-RO configurations, respectively. The obtained results revealed that fossil fuels utilization remarkably influenced greenhouse gas (GHG) emission, specifically CO ₂ . The sensitivity analysis also elucidated that electricity is the main indicator, which affected climate change (3.09-8%) and ozone depletion (18.97%) categories. Therefore, the results of the present study can be utilized as a guideline for further investigations in the LCA of various WWTPs.

Cite this article: Hajar Abyar. 2022. Life cycle assessment of wastewater treatment systems: Challenges and approaches. Environmental Resources Research, 10 (1), 41-50. DOI: 10.22069/IJERR.2022.6030

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Introduction

Population explosion and the change in human lifestyle have led to enormous environmental challenges on a global scale. The increasing demand for clean water along with a 40% reduction in global water supply by 2030 has reinforced the necessity of wastewater reuse (Sun et al., 2020). It is noteworthy to mention that treated municipal wastewater provides a high-quality water source in comparison to desalinated seawater, harvested rainwater, or water from melted icebergs (Diaz-Elsayed et al., 2019). Although wastewater treatment plants (WWTPs) are principally established to remove organic matter, nutrients, and suspended solids, however, they can emit greenhouse gas (GHG) and intensify global warming due to their significant energy utilization (Sabeen et al., 2018; Awad et al., 2019). In addition, the residuals from WWTPs such as waste sludge may contain large amounts of pathogens and heavy metals, which have detrimental effects on human health (Hong et al., 2009). Therefore, the type, structure, and function of WWTPs

should be continuously monitored and managed to decrease negative impacts on the environment (Abyar et al., 2018b; Sabeen et al., 2018). Hence, wastewater treatment can be considered to achieve a sustainable development approach (Ahmadpour et al., However, 2021). despite extensive endeavors to upgrade wastewater treatment processes and the related regulations, the modifications have not been satisfactory due to incompatibility of designed systems with economic and environmental concepts. Consequently, to achieve an overview of the designed WWTP, the environmental and economic assessment in the preliminary stages should not be ignored (Nowrouzi et al., 2021).

Life cycle assessment (LCA) has nowadays been recognized as a suitable and powerful technique for comprehensive environmental evaluation of a product or a system (Bai et al., 2019). LCA has been applied to WWTPs since the 1990s, which is essential for assessing the negative environmental impacts, originated from their establishment and maintenance. LCA prpvides a sophisticated tool that analyzes and interprets all impacts concerning a process or a cycle from cradle to grave. (Parra-Saldivar et al., 2020). The capability of LCA to determine the efficiency of wastewater treatment and predict its drawbacks has been proved (Corominas et al., 2020; Mathuriya et al., 2020). Since different variables such as resource and energy consumption, pollutants emission into the air, water, soil, and waste sludge production are taken into account in the LCA process, prestigious and detailed results could be attained (Lopes et al., 2020). To distinguish the most environmentally friendly wastewater treatment system, three widespread applied configurations i.e. anaerobic/anoxic/aerobic (A2O), membrane bioreactor-reverse osmosis (MBR-RO), and integrated fixed-film activated sludge membrane bioreactor (IFAS-MBR) have been investigated from an environmental point of view. The results present a map for environmentalists and industry owners by providing useful information.

The A₂O bioreactors have received attention for their simplicity, ease of

operation, and high functional longevity. Low space requirement and low energy usage to remove COD and nutrients are other advantages of the A₂O systems. However, the high nutrient capacity of this system might result in destructive competition between beneficial organisms and pathogens during the treatment process, which significantly diminishes the removal of pollutants (Abyar et al., 2018a; Ye et al., 2018). The hybrid MBR-RO systems have more popularity than the conventional WWTPs due to their potential in highquality wastewater treatment and low energy of demand. The application two conventional treatment systems, MBR and RO, into a hybrid one not only decreases the extra costs but also considerably enhances the removal of impurities. Moreover, the facilitates MBR-RO system the biodegradability of contaminants through micro-pollutants trapping in the membrane resulting in a decrement of total environmental burdens and ecological footprint (Tomasini et al., 2019; Abyar and Nowrouzi, 2020; Racar et al., 2020). The main advantage of a hybrid IFAS-MBR system is that it creates a synergistic effect on nutrient biodegradation by providing a suitable site for nitrifiers and denitrifiers on biofilm. The IFAS-MBR system assembles ammonia-oxidizing bacteria (AOB) and boosts the capacity of aerobic units. Hence, it ameliorates biological nutrient removal (Malovanyy et al., 2015).

Life cycle assessment framework

LCA, as a decision-making technique, requires the input and output data comprising chemicals, fuels, electricity, and GHG emission for monitoring a product's environmental impacts over its lifetime. In this study, the IFAS-MBR, MBR-RO, and A₂O systems were simulated using GPS-X 8.0, Hydromantis 2019. The systems involved boundaries and inventories pollutants emissions, chemicals, and energy consumption in the operational stage illustrated in Figure 1 and Table 1. Treatment of 1 m³ wastewater was considered as the functional unit (Abyar and Nowrouzi, 2020; Nowrouzi and Abyar, 2021). The impact assessment was

performed based on the International Organization for Standardization (ISO) 14040 (ISO, 2006b) and 14044 (ISO, 2006a) guidelines, using Simapro v. 8 software. The ReCiPe (H) midpoint and endpoint methods from the *Ecoinvent v3.4* database were chosen to compare the function of WWTPs. The midpoint method includes categories that are expressed in the midpathway of impact, between the primary data and endpoints. However, endpoint indicators encompassing human health, ecosystem, and

resources categories were utilized to facilitate the interpretation of the results Nowrouzi, 2020). (Abyar and GHG emissions were determined using the greenhouse gas protocol (GGP), which is categorized in CO₂ emission from fossil fuels, biogenic, land transformation, and CO₂ uptake. The cumulative energy demand (CED) method was applied to quantify the energy consumption of pumps, mixers, boilers, combined heat and power (CHP), and sludge digester (Cashman et al., 2018).



Figure 1. System boundaries of IFAS-MBR, MBR-RO, and A2O

Midpoint environmental impacts

The environmental impacts of A₂O, MBR-IFAS-MBR RO, and systems are demonstrated in Table 2. The climate change category stood at the first rank for the IFAS-MBR (27.5%) and MBR-RO freshwater (95.13%). Marine and ecotoxicity for the **IFAS-MBR** and photochemical oxidant formation and freshwater ecotoxicity for the MBR-RO were located in the next ranks with the contribution percentage of 23.2%, 21.76%, 4.66%, and 0.06%, respectively. Regarding the A₂O system, freshwater eutrophication (31.62%), marine ecotoxicity (29.94%), and human toxicity (6.59%) were the most significant environmental burdens. The analysis per substance associated with the climate change category depicted that CH₄, CO₂, and other components such as propane, ethane, dinitrogen monoxide, and sulfur hexafluoride were the key parameters in the intensification of climate change. This result was in agreement with Lopes et al. (2020) who mentioned the effective role of CH₄ and nitrous oxide in global warming the photochemical oxidation and phenomenon.

LCA inventory	Unit	Value	IFAS-MBR	MBR-RO	A ₂ O
Parameters					
COD	mg/L	2250			
BOD ₅	mg/L	1190			
TSS	mg/L	3080			
NH4 ⁺ -N	mg/L	50.37			
TN	mg/L	171			
TKN	mg/L	90.2			
TP	mg/L	9.60			
Power					
Electricity	kWh		7089.93	244.86	8032.66
Heat	kWh		0.0359	21.99	10.23
Fuel	m ³		80.8	2.06	5.6
Emission to air					
Carbon dioxide	kgCO ₂ e		3501.6	3021.54	3416.4
Methane	kgCO ₂ e		928.2	129725	1300
Nitrous oxide	kgCO ₂ e		605.02	141.97	459.31
Emission to water					
COD	mg/L		43.71	56.9	53
BOD ₅	mg/L		0.56	0.47	1.2
TSS	mg/L		0.02	-	0.16
NH4 ⁺ -N	mg/L		0.155	4.02	5.6
TN	mg/L		1.2	6.79	13.2
TP	mg/L		6.74	5.24	2.72
Emission to soil					
Waste sludge	kg		1490	111	860

Table 1. Life cycle inventory of the IFAS-MBR, MBR-RO, and A_2O systems (Functional unit: 1 m³ wastewater treatment)

Furthermore, Resende et al. (2019) declared that climate change and photochemical oxidants originated from the GHG emission of septic tanks. In fact, microorganisms in an anaerobic condition produce biogas, which is full of CH₄. However, the majority of produced biogas is wasted because of the lack of efficient technology for biogas recovery (Resende et al., 2019; Lopes et al., 2020).

Table 2. Normalization results of ReCiPe midpoint (H) for the IFAS-MBR, MBR-RO, and A2O

Impact category	IFAS-MBR	MBR-RO	A ₂ O
Climate change	4.59×10^{-4}	4.13×10^{-2}	7.63×10^{-4}
Ozone depletion	1.52×10^{-6}	$4.83 imes 10^{-8}$	1.56×10^{-5}
Terrestrial acidification	4.70×10^{-5}	4.32×10^{-6}	7.43×10^{-4}
Freshwater eutrophication	3.43×10^{-5}	5.39×10^{-6}	1.70×10^{-2}
Marine eutrophication	6.89×10^{-6}	8.51×10^{-6}	2.15×10^{-3}
Human toxicity	1.18×10^{-4}	7.00×10^{-6}	3.55×10^{-3}
Photochemical oxidant formation	3.74×10^{-5}	2.02×10^{-3}	2.57×10^{-4}
Particulate matter formation	3.70×10^{-5}	2.35×10^{-6}	6.58×10^{-4}
Terrestrial ecotoxicity	7.96×10^{-6}	$5.08 imes 10^{-6}$	1.07×10^{-4}
Freshwater ecotoxicity	3.66×10^{-4}	2.69×10^{-5}	1.02×10^{-2}
Marine ecotoxicity	3.90×10^{-4}	2.09×10^{-5}	1.61×10^{-2}
Ionising radiation	1.68×10^{-5}	5.50×10^{-7}	2.04×10^{-4}
Agricultural land occupation	1.87×10^{-7}	2.41×10^{-7}	1.33×10^{-5}
Urban land occupation	7.94×10^{-7}	3.20×10^{-8}	1.08×10^{-4}
Natural land transformation	9.14×10^{-6}	1.01×10^{-6}	1.04×10^{-4}
Water depletion	9.06×10^{-6}	-	-
Metal depletion	6.50×10^{-6}	$2.78 imes 10^{-7}$	4.18×10^{-4}
Fossil depletion	1.43×10^{-4}	7.60×10^{-6}	1.40×10^{-3}

The analysis per process specified that wastewater type and flow, anaerobic digestion process, and biogas recovery in the IFAS-MBR system had 84.31% contribution to the GHG emission. Electricity (13.5%) was also responsible for CO_2 release due to the high electricity demand of wastewater pumping and mixing, aeration, and waste sludge recycling (Kamble et al., 2019; Singh et al., 2020). The analysis per substance for the and freshwater ecotoxicity marine categories highlighted the impact of metals for the IFAS-MBR system. Vn (17%), Br (14.7 to 64.4%), Ba (6.47 to 11%), Ni (6.54 to 10.49%), and Cu (7.1 to 10%) were the most significant metals leading to the marine and freshwater ecotoxicity. The previous investigations also referred to the impact of Ni, Cu, and Zn on freshwater ecotoxicity (0.001)kg 1,4-DB eq). Moreover, the marine ecotoxicity category (0.00096 kg 1,4-DB eq) for the IFAS-MBR system in the present study revealed a remarkable difference with the results of Kamble et al. (2019), who reported 650.7 kg 1,4-DB eq for the MBR system which can be relevant to the high energy consumption of MBR. Natural gas (32.12 to 69.24%), electricity (26.91%) production, and sulfide tailing (6.56%) were identified as responsible for freshwater and marine ecotoxicity. It should be noticed that the release of heavy metals such as Cu and Zn. which emanated from electricity production, is impressive in the occurrence of the aforementioned categories (Nowrouzi and Abyar, 2021).

The climate change and photochemical oxidation associated with the MBR-RO system were extremely dependent on wastewater influent flow (99.95%), electricity production, and TSS. The increase of influent flow requires a high capacity basin, land occupation, and extensive aeration which increase the energy demand. On the other hand, the overconsumption of fossil fuels for heat and energy provision causes climate change and GHG emissions (Abyar and Nowrouzi, 2020). Hence, the optimization of influent wastewater flow should be considered parallel with the other operational units. Electricity showed <1% contribution in the GHG release, which was mostly consumed for the wastewater pumping and mixing and the recovery of heat and electricity by CHP. Therefore, to compensate for a system's high energy requirement, the utilization of renewable energy sources including waves, microbial fuel cells (MFC), wind, and tidal energy has been recommended (Resende et al., 2019). CH₄ and nitrogen oxides showed a key role in the photochemical oxidant formation concerning the MBR-RO system. Nitrogen oxides are usually originated from urea, nitrate, and protein decomposition in the wastewater. However, they can be during nitrification released and processes denitrification (Gupta and Bhattacharyya, 2011). Approximately 95% of emitted nitrogen oxides is in the form of NO, which is oxidized in the photochemical phenomenon (Notario et al., 2012).

Although the A₂O performance in the (93.7%) nitrogen removal of and phosphorus (71.68%) was considerable, a high initial nutrient concentration in the led wastewater to freshwater eutrophication, which was mostly attributed to phosphate with a 99.8% contribution. It should be noticed that despite nitrogen and its derivatives contribute to the algal bloom and dissolved oxygen reduction, phosphate is known as a limiting factor in freshwater ecosystems (Abyar et al., 2020). The A_2O potential in the occurrence of the eutrophication process was estimated as 0.02 kg PO₄ $^{3-}$ eq, which was lower than previous literature (Sabeen et al., 2018). The analysis per substance for the marine ecotoxicity indicated the contribution of Cu, Vn, Ni, and Mn, which was consistent with Pradel and Aissani (2019). The appraisal of the human toxicity category demonstrated that the release of Mn, As, Ba, and Vn from fossil fuels consumption to produce electricity was the main related parameter (Hernández-Padilla et al., 2017). Yay (2015) also reported a significant contribution of Cr, Ni, and Ba in the human toxicity category.



Figure 2. ReCiPe endpoint (H) analysis(a), characterization per process for CED(b), and GGP analysis(c)

Endpoint environmental impacts

of endpoint The descending order environmental impacts was as follows: resources human health (67.57%)> ecosystem (7.38%) (25.05%)> for the IFAS-MBR, human health (>92%)> ecosystem (7.76%)> resources (0.02%) for the MBR-RO, and resources (60.18%)> human health (36.6%) ecosystem (3.22%)for the A_2O system (Fig. 2a). The wastewater treatment process (81.32%) and electricity (15%) were the crucial elements

affecting human health in the IFAS-MBR configuration through the emission of 70.67% CH₄ and 25.05% CO₂. This result was comparable with Singh et al. (2020) expressed the high who electricity consumption of the IFAS systems. According to the results, the resources category was impacted by natural gas (60.3%) and petroleum (33.39%) which were utilized for energy provision. On the other hand, the wastewater treatment process and electricity production in the ecosystem category emitted 72.57% and 25.76% of CH₄ and CO₂, respectively.

Regarding the MBR-RO system, climate change and particulate matter formation caused the highest impact on human health which was compatible with the results of Ioannou-Ttofa et al. (2016). The ecosystem damage was also emanated from agricultural land occupation and climate change. However, the significant parameter in the human health and ecosystem categories for the A₂O system was the release of CO₂ from fossil fuels, while sulfur dioxide, nitrogen oxides, and CH₄ showed a low contribution. It is noteworthy that nitrogen oxides are produced when reduced to N₂ NO₃⁻ was in the denitrification process. The emission of sulfur dioxide might be ascribed to H₂SO₄ Moreover, production. electricity and ammonia production generation affected the human health and ecosystem categories, in agreement with Alyaseri and Zhou (2017).

Cumulative energy demand (CED)

The CED analysis revealed that the maximum energy consumption (70 MJ/m³) was related to the A₂O configuration while the IFAS-MBR and the MBR-RO exhibited 8.75 MJ/m³ and 0.46 MJ/m³, respectively. More than 81% of the total energy consumption in all three systems was supplied by non-renewable fossil fuels (NR-fossil fuels). Natural gas, crude oil, and hard coal production processes were involved in energy production equal to 62-20.51-32.43%, and 74.68%, 1-1.4%, respectively (Fig. 2b). The aeration process used the majority of electricity consumption in the A₂O system (Abyar et al., 2020). In addition, ammonium chloride production, which was considered as an energy and nitrogen source for the microorganisms, required 9.7 MJ/m³ electricity. The water and nuclear energy sources provided 1.83 MJ/m³ and 2.08 MJ/m³ energy for electricity production, respectively. The total energy consumption of the MBR-RO was less than the reported values for MBR (207 MJ) and RO (97.3 MJ) (Ribera-Pi et al., 2020), which illustrated the outstanding compatibility of the hybrid MBR-RO system with the environmental regulations. The analysis per process clearly depicted that 72.32% of the MBR-RO energy demand was supplied through natural gas followed by petroleum and diesel production (0.8-18.7%). It is worth noting that CHP provided the required energy and heat of anaerobic digestion using natural gas (Kelly et al., 2014). It is useful to highlight that there is rarely available information concerning the IFAS-MBR's LCA. aeration strategy, and energy consumption. To the best of our knowledge, the high energy usage has only been assessed for mixing and supporting attached microorganisms in the IFAS configurations and preventing membrane fouling in the MBRs (Singh et al., 2020). Hence, the hybrid IFAS-MBR system alongside the optimization process and energy control can considerably minimize the environmental impacts.

GGP analysis

GGP analysis explained 99.95% of CO_2 emissions, derived from fossil fuels consumption (Fig. 2c). Moreover, CH₄ (77.55%) and CO₂ (23.34%), released from the wastewater treatment process and electricity generation, were responsible for the increase of environmental impacts. Indeed, the GGP analysis confirmed that climate change was the most environmental burden arising from the WWTPs operation. Based on this, the utilization of clean energy sources would be a promising approach to decrease the negative impacts of the climate change category.

Sensitivity analysis

Sensitivity analysis was employed to assess the data accuracy and precision. According to the LCA results, electricity was identified as the most effective contributor to the environmental burdens. A 20% alteration of initial electricity in the IFAS-MBR system led to a 3.09% and 19.88% reduction in the climate change and ozone depletion categories, respectively. In terms of the MBR-RO system, the sensitive categories were ozone depletion, ionising radiation, urban land occupation, and metal depletion, which fluctuated in the range of 13.7-18.97%. The alterations of marine eutrophication, photochemical oxidant formation. climate change, terrestrial ecotoxicity, and agricultural land occupation categories were <1% in the MBR-RO system. An almost 8% change was detected in climate change, ozone depletion, terrestrial ecotoxicity and relevant to the A₂O system. Therefore, the energy provision of WWTPs should be evaluated not only from an economic but also from an environmental point of view.

Conclusion

The wastewater reclamation has attracted the researchers' attention in the last decades regarding the water crisis. The LCA analysis can illustrate a straightforward route towards the design of a WWTP with highest compatibility the with the environmental regulations. Hence, in the present study, the IFAS-MBR, MBR-RO, and A₂O configurations were appraised and compared from an environmental perspective. The climate change (27.5%) and CH₄ and CO₂ emission were the environmental impacts of the IFAS-MBR originating system from influent quality wastewater and electricity production. In addition, 67.6% of GHG

emissions and remarkable negative impacts on human health were observed in the IFAS-MBR system. The MBR-RO performance was almost similar to the IFAS-MBR system and revealed a 95.13% contribution in the climate change category, while the A₂O bioreactor significantly affected the freshwater eutrophication, resources marine ecotoxicity, and categories. The consumed fossil fuels for energy provision was the main crucial environmental parameter considering the CED and GGP analyses. According to the results, it should be pointed out that the least environmental impacts and energy consumption were achieved in the IFAS-MBR and MBR-RO configurations, respectively. Summing up, the control of waste sludge, reduction of energy demand, and prevention of chemicals release will undoubtedly minimize the environmental and fulfill burdens the sustainable development goals.

Acknowledgment

The author wishes to thank the Gorgan University of Agricultural Sciences and Natural Resources, Iran, the Ministry of Science for their support, and Dr. Mohsen Nowrouzi for his invaluable assistance with the current study.

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