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Life cycle assessment of wastewater treatment systems: Challenges and approaches

Hajar Abyar[1*]

[1] Assistant Professor, Department of Environmental Sciences, Faculty of Fisheries and Environmental Sciences, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan,Iran. Email: hajar.abyar@yahoo.com

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Corresponding author:
hajar.abyar@yahoo.com

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Abstract

Water crisis and pollution increase have encouraged researchers to rehabilitate wastewater as an alternative water source. Wastewater 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_2O), membrane bioreactor-reverse osmosis (MBR-RO), and integrated fixed-film activated sludge membrane bioreactor (IFAS-MBR) systems from an environmental perspective. The largest environmental impacts of the IFAS-MBR and MBR-RO were associated with climate change (27.5-95.13%) and human health (67.57-92%), while the midpoint and endpoint impacts of A_2O 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_2O 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.

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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., 2021). However, 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 (A_2O), 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 A_2O 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 A_2O 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 high-quality wastewater treatment and low energy demand. The application of 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 MBR-RO system facilitates 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 A_2O systems were simulated using GPS-X 8.0, Hydromantis 2019. The systems boundaries and inventories involved pollutants emissions, chemicals, and energy consumption in the operational stage illustrated in Figure 1 and Table 1. Treatment of 1 m^3 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 (Abyar and Nowrouzi, 2020). GHG emissions were determined using the greenhouse gas protocol (GGP), which is categorized in CO_2 emission from fossil fuels, biogenic, land transformation, and CO_2 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).

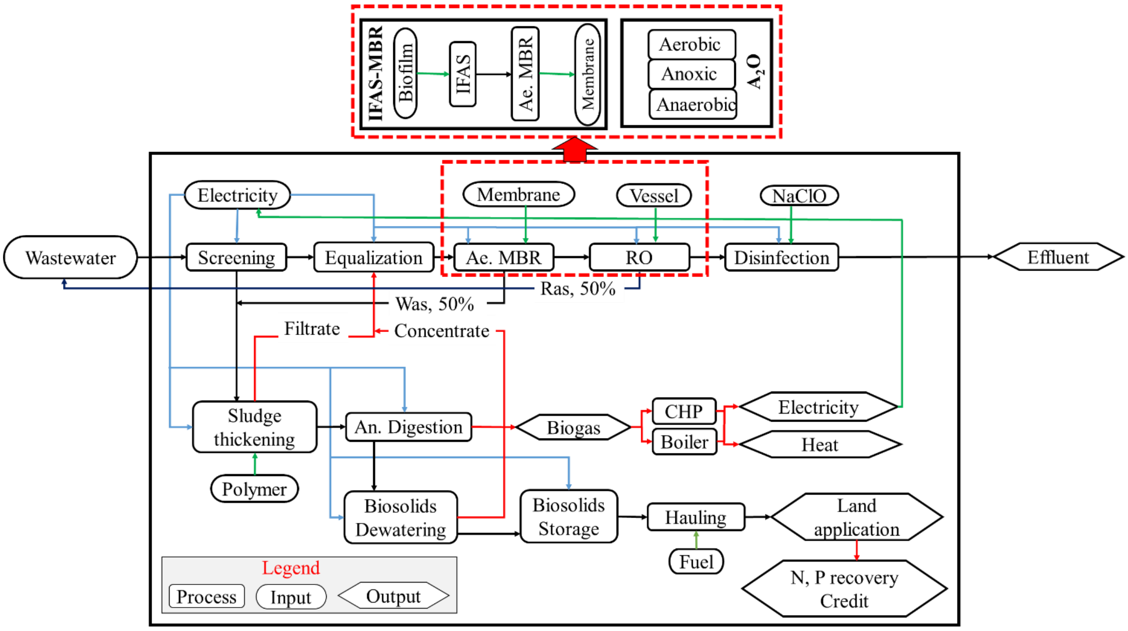

Figure 1. System boundaries of IFAS-MBR, MBR-RO, and A_2O

Midpoint environmental impacts

The environmental impacts of A_2O, MBR-RO, and IFAS-MBR systems are demonstrated in Table 2. The climate change category stood at the first rank for the IFAS-MBR (27.5%) and MBR-RO (95.13%). Marine and freshwater 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 A_2O 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 CH_4, CO_2, 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 CH_4 and nitrous oxide in global warming and the photochemical oxidation phenomenon.

Table 1. Life cycle inventory of the IFAS-MBR, MBR-RO, and A_2O systems (Functional unit: 1 m^3 wastewater treatment)

LCA inventory	Unit	Value	IFAS-MBR	MBR-RO	A_2O
Parameters					
COD	mg/L	2250			
BOD_5	mg/L	1190			
TSS	mg/L	3080			
NH_4^+-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	$kgCO_2e$		3501.6	3021.54	3416.4
Methane	$kgCO_2e$		928.2	129725	1300
Nitrous oxide	$kgCO_2e$		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
NH_4^+-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

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 CH_4. 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 A_2O

Impact category	IFAS-MBR	MBR-RO	A_2O
Climate change	4.59×10^{-4}	4.13×10^{-2}	7.63×10^{-4}
Ozone depletion	1.52×10^{-6}	4.83×10^{-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}	5.08×10^{-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}	2.78×10^{-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 marine and freshwater ecotoxicity 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). CH_4 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 released during nitrification and denitrification processes (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 A_2O performance in the removal of nitrogen (93.7%) and phosphorus (71.68%) was considerable, a high initial nutrient concentration in the wastewater led 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 $PO_4{}^{3-}$ 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.

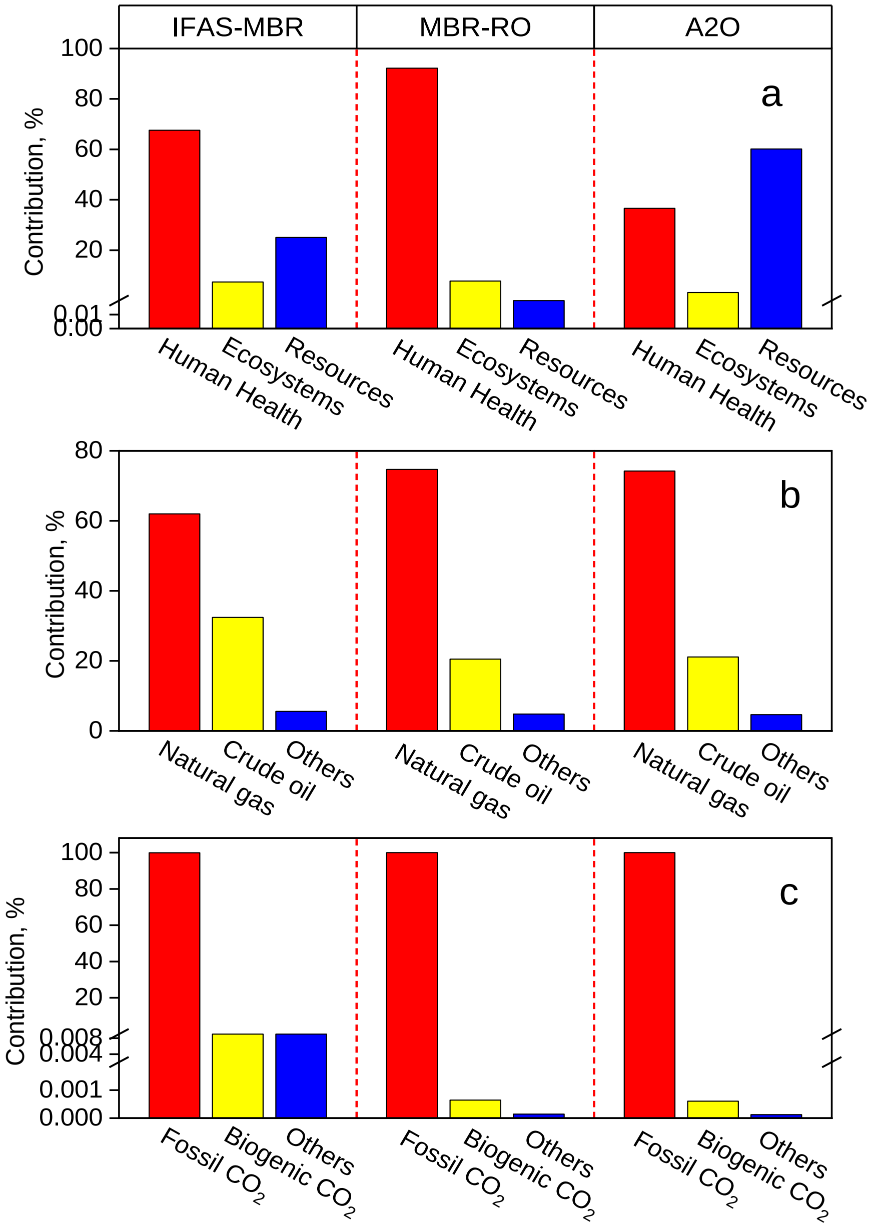

Figure 2. ReCiPe endpoint (H) analysis(a), characterization per process for CED(b), and GGP analysis(c)

Endpoint environmental impacts

The descending order of endpoint environmental impacts was as follows: human health (67.57%)> resources (25.05%)> ecosystem (7.38%) 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% CH_4 and 25.05% CO_2. This result was comparable with Singh et al. (2020) who expressed the high 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 CH_4 and CO_2, 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 A_2O system was the release of CO_2 from fossil fuels, while sulfur dioxide, nitrogen oxides, and CH_4 showed a low contribution. It is noteworthy that nitrogen oxides are produced when NO_3^- was reduced to N_2 in the denitrification process. The emission of sulfur dioxide might be ascribed to H_2SO_4 production. Moreover, electricity generation and ammonia production 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/m^3) was related to the A_2O configuration while the IFAS-MBR and the MBR-RO exhibited 8.75 MJ/m^3 and 0.46 MJ/m^3, 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 62-74.68%, 20.51-32.43%, and 1-1.4%, respectively (Fig. 2b). The aeration process used the majority of electricity consumption in the A_2O 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/m^3 electricity. The water and nuclear energy sources provided 1.83 MJ/m^3 and 2.08 MJ/m^3 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, CH_4 (77.55%) and CO_2 (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, and terrestrial ecotoxicity relevant to the A_2O 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 the highest compatibility with the environmental regulations. Hence, in the present study, the IFAS-MBR, MBR-RO, and A_2O configurations were appraised and compared from an environmental perspective. The climate change (27.5%) and CH_4 and CO_2 emission were the environmental impacts of the IFAS-MBR system originating from influent wastewater quality 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 A_2O bioreactor significantly affected the freshwater eutrophication, marine ecotoxicity, and resources 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 burdens and fulfill the sustainable development goals.

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