Iranian Reasearch Organization for Science and Technology (IROST)

Advances in Environmental Technology 9(2) 2023, 115-123

Advances in Environmental Technology

Journal home page: https://aet.irost.ir/

# Evaluation of life cycle, exergy, and carbon footprint of wastewater treatment system by activated sludge method in petrochemical industries

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## ARTICLE INFO

*Document Type:*
Research Paper

*Article history:*
Received 3 March 2023
Received in revised form
24 June 2023
Accepted 26 June 2023

**Keywords:**
Life cycle assessment
System exergy
Carbon footprint
Activated sludge treatment system

## ABSTRACT

Wastewater management in petrochemical industries plays an effective role in reducing their environmental consequences. This study utilized life cycle assessment and carbon footprint methodologies to assess these environmental impacts. The objectives of the investigation were pursued using the ReciPe 2016, Cumulative Energy Demand, Cumulative Exergy Demand approaches, and sensitivity analysis. The outcomes of the endpoint analysis revealed that damage to resources, human health, and ecosystems received more than 98% of the total impact due to electricity consumption. Furthermore, electricity consumption and COD were responsible for the most significant midpoint-level consequences. The sensitivity analysis showed that a change of approximately 20% in electricity and chemical oxygen demand had the most significant impact on the ozone depletion category. The primary gas emitted as a result of the wastewater treatment process was carbon dioxide, which accounted for 99.78% of the carbon footprint associated with the process. Based on these findings, it can be inferred that replacing the current energy source with renewable alternatives would reduce over 90% of the environmental impacts of the wastewater treatment process in these industrial units.

## 1. Introduction

Mitigating the environmental consequences stemming from industrial operations has consistently proven to be a crucial driver of sustainable development. Therefore, it is imperative for industrial entities to amend their wastewater before entering the ecosystem to curtail detrimental impacts and safeguard the environment. Biological treatment methods have received more attention than other methods due to their ease of use, high efficiency, and compatibility with the environment for wastewater treatment (WWT) in different practical conditions. However, despite the numerous positive effects of wastewater treatment, they have a direct and

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DOI:10.22104/AET.2023.6163.1696

indirect role in environmental pollution due to their processes. Significant energy consumption, which influences greenhouse gas emissions and global warming, is one of these effects [1]. In addition, sludge waste and biosolids resulting from these methods may also contain large amounts of pathogens and heavy metals, which lead to harmful effects on human health [2]. Therefore, increasing system efficiency and reducing environmental effects, energy flow, and especially greenhouse gas emissions should be considered in the design and use of these biological treatment methods [3]. The basis of an activated sludge system is the conversion of organic matter into carbon dioxide, water, and bacterial cells, which play a major role in the emission of carbon dioxide, methane, and other greenhouse gases. Hence, the most important environmental challenges associated with activated sludge systems are affected by excess sludge disposal and greenhouse gas emissions. Therefore, the comprehensive environmental assessment of these systems is considered a major step in identifying and providing preventive solutions against the occurrence of these harmful environmental effects [4]. Today, life cycle assessment (LCA) is known as the most comprehensive method of evaluating the environmental consequences of a process [5]. LCA quantifies the environmental effects of a project by analyzing and interpreting all input and output data related to the system's raw materials, transportation, storage, emission to the atmosphere, and waste in water in an integrated manner. Choosing a comprehensive method related to the desired goal is considered to be one of the other effective criteria for the successful completion of an LCA project. It covers the total environmental effects related to the project and presents effective solutions to reduce the possible environmental burdens [6]. Among the various existing methods, the ReCiPe Midpoint (H) method is considered one of the most popular and practical methods for describing the role of effective parameters and analyzing the obtained results [1]. The ReCiPe method describes the collection of environmental burdens in two categories comprising midpoint and endpoint levels. It facilitates the interpretation of the results for the user, making it easier to draw conclusions and provide management solutions in this field. Along with the evaluation of the environmental effects, the energy flow in the system and its energy efficiency are also considered as other influential parameters in the successful economic and environmental evaluation of a wastewater treatment system. Optimizing energy consumption in treatment systems reduces the harmful effects on the environment and is very important from an economic aspect. It can be considered as a major incentive for investing in this field, due to the more favorable profitability of a wastewater treatment project [7]. In addition, reducing greenhouse gas emissions is one of the most important aspects emphasized by designers and environmentalists in the design of a wastewater treatment system [8]. Therefore, the objectives of this study are as follows: 1) to comprehensively evaluate the environmental effects of the wastewater treatment system on petrochemical industries, 2) to investigate the energy flow and estimate the useful energy of the system, 3) to accurately evaluate greenhouse gas emissions and estimate the carbon footprint of the wastewater treatment system, 4) to apportion the effects of the wastewater treatment system on human health, ecosystems, and resources, and 5) to provide management solutions to reduce adverse environmental effects and achieve sustainable development.

## 2. *Materials and methods*

### *2.1. Activated sludge system*

This study assessed the LCA, energy and exergy analyses, and carbon footprint of an activated sludge system used by a petrochemical company to treat its wastewater. The plant is located in the coastal region of the Persian Gulf, south of Iran, and its system daily treats 2,400 $m^3$ of industrial wastewater. The main components of the wastewater treatment system are depicted in Figure 1. After the primary and secondary treatment steps, the treated wastewater is discharged to the receiving environment, and only a part of the settled sludge is returned to the biological system into the clarifier. The excess sludge is removed from the system

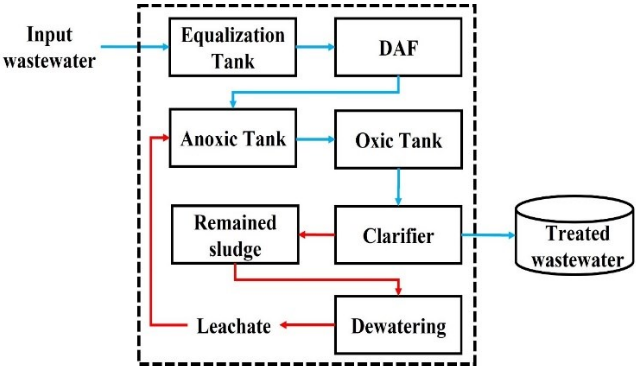

**Fig. 1.** System boundary of the wastewater treatment system (WWTS) in the present study. (The functional unit is 1 $m^3$ of wastewater treatment).

### *2.2. Applied software and database*

The LCA analysis and assessment of environmental burdens that emerged from the wastewater treatment system (WWTS) were conducted using SimaPro software (v. 9.3) and the Ecoinvent database (v.3.4) [9].

### *2.2.1. Goal and scope*

The functional unit in this study was the treatment of 1 $m^3$ of petrochemical industry wastewater on a "gate-to-gate" scale. The system boundary for the WWTS is depicted in Figure 1.

### *2.2.2. The WWTS Inventory*

The inventory for the activated sludge system was derived from mean annual field data and is presented in Table 1. Aggregating these data followed ISO 14040 and 14044 standards [9-11].

**Table 1.** The inventory of activated sludge WWTS (1 $m^3$).

| *Variables* | *Units* | *Values* |
|---|---|---|
| ***Inputs*** | | |
| COD | g/d | 13.37 |
| BOD | g/d | 1.33 |
| TP | g/d | 0.05 |
| $NH_4^+ - N$ | g/d | 0.875 |
| Electricity | kWh | 3.255 |
| ***Emission to water*** | | |
| COD | g/d | 0.725 |
| TSS | g/d | 0.3 |
| $NH_4^+ - N$ | g/d | 0.025 |
| TP | g/d | 0.025 |
| $NO_3^-$ | g/d | 0.775 |
| Organic nitrogen | g/d | 0.075 |

### *2.2.3. Environmental impact assessment*

The environmental impact assessment was carried out using the ReCiPe 2016 method. The energy flow and exergy of the system were estimated by the Cumulative Energy Demand (CED) and Cumulative Exergy Demand (CExD) methods, respectively. Greenhouse gas emissions (carbon footprint) were evaluated using the Greenhouse Gas Protocol (GGP) method [8,9].

### *2.2.4. Sensitivity analysis*

Electricity and COD were the most influential parameters in this study. The effects of the change on other parameters were identified by applying a +20% change in the values of these two parameters [12].

## *3. Results and discussion*

The total environmental burdens at the midpoint and endpoint, the sensitivity analysis results, the system's energy and exergy, and the global warming potential of the WWTS are presented in the following text.

### *3.1. The midpoint impacts*

The midpoint impacts derived from the petrochemical industry WWTP are depicted in Fig. 2. Regarding this matter, electricity (>88%) and COD (<10%) showed the most important role in emerging the environmental burdens. The role of the three remaining factors comprising $NH_4^+$-N, BOD, and TP was negligible (<1%). The maximum effect of electricity appeared in the OD category (99.47%). Also, although the effect of COD compared to electricity on all categories was estimated to be much less and <11% in total, unlike electricity, the greatest effect of COD was observed on the water consumption (WC) category (10.14%). Given this, the appraisal of the midpoint impacts demonstrated the significant role of electricity consumption with an 88% contribution. In this regard, Abyar et al. [13] assessed the LCA of an anaerobic/anoxic/oxic ($A_2O$) system and reported a 93% contribution of electricity in $CO_2$ emission and global warming due to the utilization of natural gas and fossil fuels in electricity production. Moreover, Morelli et al. [14] pointed out a share of 38% and 26% of electricity in the global warming category in legacy and upgraded WWTPs, respectively. The released $CH_4$ from the anaerobic digestion of sludge and $N_2O$ from the nitrification and denitrification processes could be the other effective parameters [15]. Meanwhile, the ecotoxicity impacts mainly originate from biological and physicochemical reactions that ultimately lead to the release of heavy metals. Kamble et al. [16] announced the freshwater ecotoxicity (FET) value of 0.001 kg 1,4-DB eq, which resulted from the release of Ni, Cu, and Zn from the MBR system due to the high electricity consumption.But a higher value of FET in the present study (0.019 1,4-DB eq) could be attributed to a different source of electricity production or higher energy consumption. Nowrouzi and Abyar [17] also referred to the dominant role of natural gas (32-69%) and electricity (26.91%) in freshwater and marine ecotoxicity (MET). Generally, energy production is considered a key parameter in the emergence of environmental impacts due to the multiplicity of complex processes involved. On the other hand, the share of 83% of electricity in the MET category was also reported by Ibn-Mohammed et al. [18]. The emitted heavy metals during electricity production, such as Cu and Zn, indicated the largest contribution in the MET and FET categories [19]. The eutrophication potential of the activated sludge system in the present study was equivalent to $20.6 \times 10^{-5}$ (kg P eq) and $1.1 \times 10^{-4}$ (kg N eq) in marine and freshwater ecosystems, respectively, which was lower than the reported values for activated sludge process and UASB system in a previous investigation [20]. The low value of eutrophication potential depicts a substantial capability of the activated sludge bioreactor for nutrient removal. It is notable that some processes, such as dewatering and waste sludge, reuse can reduce the overall environmental burdens [21]. In addition, the development and control of the aeration function in the bioreactor can decrease the eutrophication process [22]. Bai et al. [23] presented the effect of COD in the effluent on the eutrophication process, which was in agreement with the obtained results in this study. Furthermore, the adverse impact of photochemical oxidation on the ozone depletion (OD) category can be associated with the complexity and various operational stages of the wastewater treatment system, which induces the release of $CH_4$ and sulfur dioxide [24]. It should be noted that hydropower dedicates the most contribution to electricity generation in Iran, which not only has resulted in adverse effects on the land use (LD) category but also enhances the evaporation of available water resources and affects the WC category [8]. Moreover, the combustion of fossil fuels for electricity generation leads to the release of suspended particles in the atmosphere, which can lead to respiratory diseases and incurable cancers when inhaled [9].

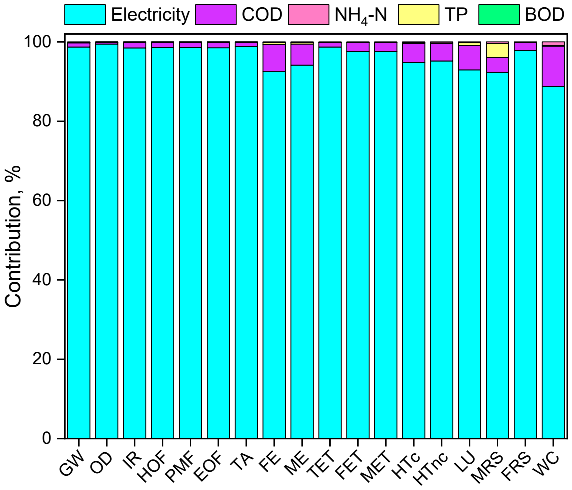

**Fig. 2.** The environmental impacts at the midpoint level.

### *3.2. The endpoint impacts*

Figure 3a shows the environmental effects of WWT in three categories: damage to resources, human health, and ecosystems. As it is clearly evident in the figure, in accordance with the results shown in Figure 2, most of the damages are related to electricity consumption (<98%) and then COD (<1.2%). The analysis per process also confirmed the highlighted role of electricity consumption and COD, while the roles of other parameters were very insignificant. The result of analysis per substance is demonstrated in Figure 3c, indicating that the human health (52%) and ecosystem (47.68%) categories received more impact from $CO_2$ emission. Also, after $CO_2$ emission, water consumption (WC) with ~27% endured the most burden in the ecosystem category. The reflected burdens in the resources category were somewhat different from the others, significantly emanating from natural gas consumption (58.47%). The evaluation of the endpoint impacts showed the prominent role of electricity generation and utilization on human health, ecosystems, and resource categories. The environmental impacts mainly emanated from natural gas and oil consumption to provide energy for the WWTP.

These results were in accordance with, who reported that using crude oil as a source of electricity supply induced irreparable effects on the existing resources. Benetto et al. [26] also declared that electricity production could contribute up to 60% to the depletion of natural resources, which confirmed the obtained results. According to the literature [27,28], the release of minerals from WWTPs intensifies respiratory problems and endangers human health, which has been proven by previous investigations [1,25]. The $CO_2$ emission from fossil fuel combustion was determined as the main factor in the human health and ecosystem categories. In other words, the release of sulfur dioxide and its combination with atmospheric water vapor produces sulfuric acid, negatively affecting human health and ecosystems. The role of electricity and the emitted chemicals and natural gas from the sludge burning process on human health was also reported by [29].

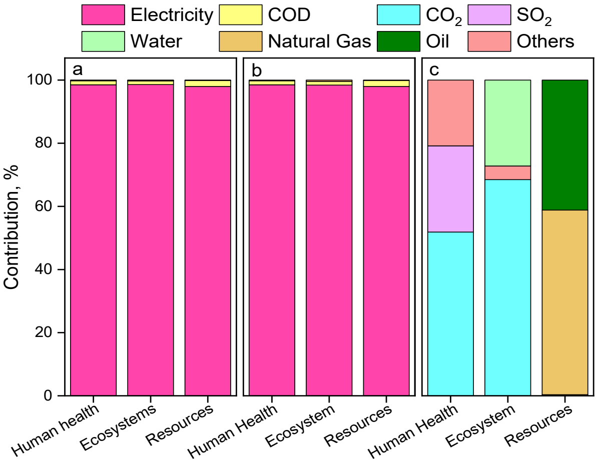

**Fig. 3.** (a) The environmental impacts at the endpoint level (b) analysis per process and (c) analysis per substance.

### *3.3. Energy and exergy of WWTS*

The energy flow in the system and the total energy required in the activated sludge WWTS were evaluated using CED analysis. In this research, the main energy sources of the system were as follows: non-renewable fossil fuels (97.75%)> non-renewable nuclear fuel (2.17%)> and other sources (2.08%). Per the analysis results of the midpoint and endpoint levels, it is evident in Figure 4a that electricity production (96%) was the most important source of energy consumption in the WWTS process. After electricity, the COD component occupied second place (<4%). The role of other factors in this field was very small and negligible. The analysis per process in the category of non-renewable fossil fuels was carried out as the most important source of energy supply in this study (Figure 4b). This analysis showed that electricity production and COD played a role of 97.88% and 1.99% in the consumption of non-renewable fossil fuels, respectively. On the other hand, analysis per substance was performed to determine the type of energy sources in the category of non-renewable fossil fuels (Figure 4c). The results illustrated that natural gas and oil had a role of respectively 63.16% and 35% in providing energy from fossil fuel consumption. However, to better evaluate the energy efficiency and the amount of useful energy of the activated sludge WWTS, $CE_xD$ analysis was performed; the results are drawn in Figures 4d-f. As shown in the figure, the energy and exergy of the WWTS followed a completely similar trend. Based on the analysis, 96.77% of the total consumed energy in the system (40.19 MJ) supplied from the source of non-renewable fossil fuels was optimally consumed, and the rest was wasted in unobtainable forms of energy. The main effects of CED were attributed to fossil fuel utilization in the electricity supply. In this regard, Mehboudi et al. [12] pointed out the contribution of 95.75% of non-renewable fossil fuels in CED, which natural gas and crude oil mostly contributed with a share of 63.78% and 34.66%, respectively, confirming the results of the current study. The contribution of natural gas and crude oil in energy production was detected as 61.35% and 36.74%, respectively, which was in line with Abyar et al. [7]. They referred to the key role of fossil fuels (94.43%) in the CED analysis of the Step Bio-P system concerning crude oil and natural gas utilization. Although WWTPs are different in terms of structure and function, they have a certain and similar technology. Therefore, the role of fossil fuels as the main supplier of energy in WWTPs cannot be ignored, especially regarding aeration, which accounts for 40% to 55% of the total energy consumption. The $CE_xD$ analysis also determined the significant role of electricity in the environmental burdens, mainly attributed to natural gas (61.34%) and crude oil (36.74%), which were consistent with the findings of Benetto E. et al. [26]. The difference in $CE_xD$ values with the literature [30] was due to the difference in the influent wastewater characteristics, especially the COD value.

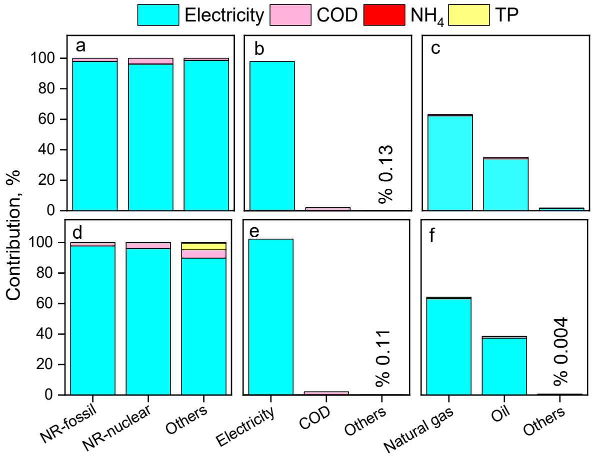

**Fig. 4.** (a) Energy flow of the activated sludge WWTS, (b) Analysis per process, (c) Analysis per substance, (d) Exergy analysis, (e) Analysis per process, and (f) Analysis per substance.

### *3.4. Carbon footprint and GHG emission*

The GGP analysis was conducted to evaluate the carbon footprint and GHG emissions. The highest $CO_2$ release was as follows: emission from fossil fuels (99.78%)> biogenic (0.13%)> other sources (0.09%). According to Figure 5a, electricity production contributed the most to the emission of $CO_2$ in all impact categories. The per-process analysis also depicted the significant role of electricity (98.75%) and COD (1.05%) in the $CO_2$ emission originating from fossil fuel consumption (Figure 5b). On the other hand, the per-substance analysis (Figure 5c) indicated the substantial role of electricity in $CO_2$ (93.72%) and $CH_4$ (22.4%) emissions. Regarding the global warming potential analysis, fossil fuels (99.78%) were the main source of emitted $CO_2$ from the wastewater treatment system, which was used in electricity production. The main GHGs were $CO_2$ and $CH_4$, contributing 92.77% and 4.03%, respectively. Nowrouzi and Abyar [17] reported the contribution of fossil fuel consumption (95.99%) in $CO_2$ emissions, which $CH_4$ (77.55%) and $CO_2$ (23.34%) release and electricity consumption (11.61%) were mainly responsible for global warming. Another study [8] also presented the contribution of GHG in $CO_2$ emissions as $CO_2$ >> $CH_4$ > $N_2O$, which was consistent with the results of the present study. Notably, the aerobic wastewater treatment and anaerobic digestion of organic materials, as well as the combustion of fossil fuels to provide electricity and thermal energy are critical factors in the emission of GHGs [7]. Given this, the replacement of fossil fuels with clean energy sources and the application of advanced wastewater treatment technologies with an energy-saving approach is vital.

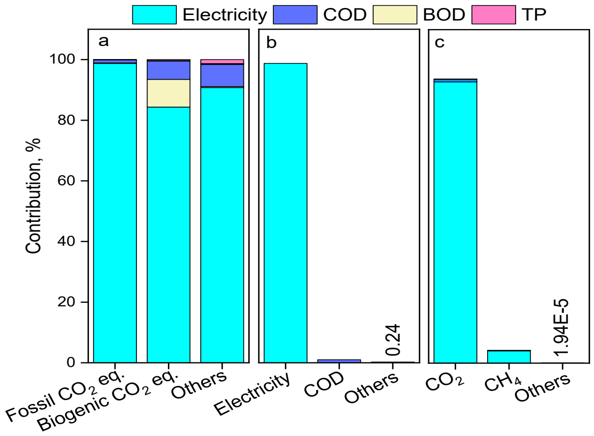

**Fig. 5.** GGP analysis of the wastewater treatment system (a), per-process (b), per-substance and (c) analyses.

### *3.5. Sensitivity analysis*

The sensitivity analysis provides a management approach to identify the priority of operational parameters to control. The characterization analysis showed the highest contribution of electricity and COD parameters to environmental impacts. Hence, a change of +20% in the two aforementioned factors was conducted. As can be seen in Table 2, the OD category (19.89%) was the most sensitive impact category, followed by TA (19.77%) > PMF (19.71%) > EOF (19.70%) categories. The sensitivity of the parameters to COD changes was much lower than that for electricity, including the WC (2.028%) > LC (1.239%) > EF (1.06%) categories. The sensitivity analysis showed the main role of electricity in the environmental burdens of the wastewater treatment system. Nowrouzi and Abyar [17] also declared the influence of 88.19%-3.09% of electricity on global warming and ozone depletion, respectively. In addition, Abyar et al. [13] mentioned the contribution of electricity in the environmental impact of the $A_2O$ system from -11.97% to +8.55%; also, the reduction of energy and fossil fuel consumption subsequently decreased the adverse impact of global warming, ozone depletion, and ecotoxicity, which confirmed the results of the present study. Therefore, controlling energy usage is essential to optimize the environmental impacts of the activated sludge system in petrochemical industries.

## 4. Conclusions

Given the essential role of electricity in the emergence of environmental impacts, it can be concluded that replacing fossil fuel-based energy with renewable energies can significantly reduce environmental burdens. Moreover, the activated sludge system can be applied on an industrial scale to reduce environmental pollutants. It is worth mentioning that performing LCA projects before the application of WWTPs on a large scale can considerably highlight the environmental effects. This information can be valuable to decision-makers in improving the efficiency of industrial projects and ensuring their compatibility with environmental principles to achieve sustainable development.

## References

[1] Abyar, H., Nowrouzi, M. (2020). Highly efficient reclamation of meat-processing wastewater by aerobic hybrid membrane bioreactor-reverse osmosis simulated system: A comprehensive economic and environmental study. *ACS sustainable chemistry and engineering*, *8*(37), 14207-14216. https://doi.org/10.1021/acssuschemeng.0c05298

[2] Hong, J., Hong, J., Otaki, M., Jolliet, O. (2009). Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. *Waste management*, *29*(2), 696-703. https://doi.org/10.1016/j.wasman.2008.03.026

[3] Nowrouzi, M., Abyar, H., Rostami, A. (2021). Cost coupled removal efficiency analyses of activated sludge technologies to achieve the cost-effective wastewater treatment system in the meat processing units. *Journal of environmental management*, *283*, 111991. https://doi.org/10.1016/j.jenvman.2021.111991

[4] Ye, C., Zhou, Z., Li, M., Liu, Q., Xu, T., Li, J. (2018). Evaluation of simultaneous organic matters and nutrients removal from municipal wastewater using a novel bioreactor (D-$A_2O$) system. *Journal of environmental management*, *218*, 509-515. https://doi.org/10.1016/j.jenvman.2018.04.075

[5] Abyar, H., Younesi, H., Nowrouzi, M. (2020). Life cycle assessment of $A_2O$ bioreactor for meat processing wastewater treatment: An endeavor toward the achievement of environmentally sustainable development. *Journal of cleaner production*, *257*, 120575. https://doi.org/10.1016/j.jclepro.2020.120575

[6] Khaki, E., Abyar, H., Nowrouzi, M., Younesi, H., Abdollahi, M., Enderati, M. G. (2021). Comparative life cycle assessment of polymeric membranes: Polyacrylonitrile, polyvinylimidazole and poly (acrylonitrile-co-vinylimidazole) applied for $CO_2$ sequestration. *Environmental technology and innovation*, *22*, 101507. https://doi.org/10.1016/j.eti.2021.101507

[7] Abyar, H., Nowrouzi, M., Rostami, A. (2022). A comprehensive study of biological phosphorus removal systems from economic and environmental perspectives based on the optimization approach. *Environmental technology and innovation*, *28*, 102811. https://doi.org/10.1016/j.eti.2022.102811

[8] Nowrouzi, M., Abyar, H., Younesi, H., Khaki, E. (2021). Life cycle environmental and economic assessment of highly efficient carbon-based $CO_2$ adsorbents: A comparative study. *Journal of $CO_2$ utilization*, *47*, 101491. https://doi.org/10.1016/j.jcou.2021.101491

[9] Naranjo, G. P. S., Bolonio, D., Ortega, M. F., García-Martínez, M. J. (2021). Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain. *Journal of cleaner production*, *291*, 125883. https://doi.org/10.1016/j.jclepro.2021.125883

[10] International standards organization (ISO). (2006). Environmental management—life-cycle assessment—principles and framework (ISO 14040).

[11] International Organization for Standardization. (2006). *Environmental management: life cycle assessment; requirements and guidelines* (Vol. 14044). Geneva, Switzerland: ISO.

[12] Mehboudi, N., Nowrouzi, M., Abyar, H. (2022). Life cycle assessment of graphite carbon

nitride synthesis with application approach in industries located in the Persian Gulf basin. *Journal of natural environment*, *74*(4), 855-868.
https://doi.org/10.22059/JNE.2022.326730.2245

[13] Abyar, H., Younesi, H., Nowrouzi, M. (2020). Life cycle assessment of A2O bioreactor for meat processing wastewater treatment: An endeavor toward the achievement of environmentally sustainable development. *Journal of cleaner production*, *257*, 120575.
https://doi.org/10.1016/j.jclepro.2020.120575

[14] Morelli, B., Cashman, S. (2017). Environmental life cycle assessment and cost analysis of bath. *NY wastewater treatment plant: Potential upgrade implications*, 3-9.

[15] Tabesh, M., Feizee Masooleh, M., Roghani, B., Motevallian, S. S. (2019). Life-cycle assessment (LCA) of wastewater treatment plants: a case study of Tehran, Iran. *International journal of civil engineering*, *17*, 1155-1169.
https://doi.org/10.1007/s40999-018-0375-z

[16] Kamble, S., Singh, A., Kazmi, A., Starkl, M. (2019). Environmental and economic performance evaluation of municipal wastewater treatment plants in India: a life cycle approach. *Water science and technology*, *79*(6), 1102-1112.
https://doi.org/10.2166/wst.2019.110

[17] Nowrouzi, M., Abyar, H. (2021). A framework for the design and optimization of integrated fixed-film activated sludge-membrane bioreactor configuration by focusing on cost-coupled life cycle assessment. *Journal of cleaner production*, *296*, 126557.
https://doi.org/10.1016/j.jclepro.2021.126557

[18] Ibn-Mohammed, T., et al., Ibn-Mohammed, T., Koh, S. C. L., Reaney, I. M., Acquaye, A., Wang, D., Taylor, S., Genovese, A. (2016). Integrated hybrid life cycle assessment and supply chain environmental profile evaluations of lead-based (lead zirconate titanate) versus lead-free (potassium sodium niobate) piezoelectric ceramics. *Energy and environmental science*, 9(11), 3495-3520.
https://doi.org/10.1039/C6EE02429G

[19] Tarpani, R. R. Z., Alfonsin, C., Hospido, A., Azapagic, A. (2020). Life cycle environmental impacts of sewage sludge treatment methods for resource recovery considering ecotoxicity of heavy metals and pharmaceutical and personal care products. *Journal of environmental management*, *260*, 109643.
https://doi.org/10.1016/j.jenvman.2019.109643

[20] Kalbar, P. P., Karmakar, S., Asolekar, S. R. (2013). Assessment of wastewater treatment technologies: life cycle approach. *Water and environment journal*, *27*(2), 261-268.
https://doi.org/10.1111/wej.12006

[21] Flores, L., García, J., Pena, R., Garfí, M. (2019). Constructed wetlands for winery wastewater treatment: A comparative Life Cycle Assessment. *Science of the total environment*, *659*, 1567-1576.
https://doi.org/10.1016/j.scitotenv.2018.12.348

[22] Renou, S., Thomas, J. S., Aoustin, E., Pons, M. N. (2008). Influence of impact assessment methods in wastewater treatment LCA. *Journal of cleaner production*, *16*(10), 1098-1105.
https://doi.org/10.1016/j.jclepro.2007.06.003

[23] Bai, S., Wang, X., Huppes, G., Zhao, X., Ren, N. (2017). Using site-specific life cycle assessment methodology to evaluate Chinese wastewater treatment scenarios: A comparative study of site-generic and site-specific methods. *Journal of cleaner production*, *144*, 1-7.
https://doi.org/10.1016/j.jclepro.2016.12.172

[24] Yay, A. S. E. (2015). Application of life cycle assessment (LCA) for municipal solid waste management: a case study of Sakarya. *Journal of cleaner production*, *94*, 284-293.
https://doi.org/10.1016/j.jclepro.2015.01.089

[25] Ioannou-Ttofa, L., Foteinis, S., Chatzisymeon, E., Fatta-Kassinos, D. (2016). The environmental footprint of a membrane bioreactor treatment process through Life Cycle Analysis. *Science of the total environment*, *568*, 306-318.
https://doi.org/10.1016/j.scitotenv.2016.06.032

[26] Benetto, E., Nguyen, D., Lohmann, T., Schmitt, B., Schosseler, P. (2009). Life cycle assessment of ecological sanitation system for small-scale wastewater treatment. *Science of the total environment*, *407*(5), 1506-1516.
https://doi.org/10.1016/j.scitotenv.2008.11.016

[27] Foteinis, S., Borthwick, A. G., Frontistis, Z., Mantzavinos, D., Chatzisymeon, E. (2018). Environmental sustainability of light-driven processes for wastewater treatment applications. *Journal of cleaner production*, *182*, 8-15. https://doi.org/10.1016/j.jclepro.2018.02.038

[28] Mathuriya, A. S., Hiloidhari, M., Gware, P., Singh, A., Pant, D. (2020). Development and life cycle assessment of an auto circulating bio-electrochemical reactor for energy positive continuous wastewater treatment. *Bioresource technology*, *304*, 122959. https://doi.org/10.1016/j.biortech.2020.122959

[29] Alyaseri, I., Zhou, J. (2017). Towards better environmental performance of wastewater sludge treatment using endpoint approach in LCA methodology. *Heliyon*, *3*(3). https://doi.org/10.1016/j.heliyon.2017.e00268

[30] Ledon, Y. C., Rivas, A., Lopez, D., Vidal, G. (2017). Life-cycle greenhouse gas emissions assessment and extended exergy accounting of a horizontal-flow constructed wetland for municipal wastewater treatment: a case study in Chile. *Ecological indicators*, *74*, 130-139. https://doi.org/10.1016/j.ecolind.2016.11.014