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Environmental Sustainability Assessment of Wastewater Treatment Processes: Case Study

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Abstract
An environmental sustainability assessment of a wastewater treatment plant (WWTP) operation in the United Arab Emirates (UAE) is presented in this study. Various emissions from the wastewater treatment facility, as well as their environmental parameters, are assessed using OpenLCA, a Life Cycle Assessment (LCA) software. The functional unit is 1 m3 of wastewater. The treatment process showed substantial negative effects on the analyzed categories: global warming, human toxicity, ecotoxicity, and eutrophication. The biggest contributors to global warming are two processes: wastewater transportation, which accounts for about 43% of the entire effect, and bioreactor air blowers, which account for 38% of the total impact. The transportation process, in addition to the filtration anthracite production, are the key contributors to the generation of fine particulate matter. Whereas, in terms of fossil resource scarcity, the operation and maintenance of activated carbon uses up to 0.5 kg of oil per functional unit, accounting for 93 percent of total fossil resource use. Briefly, The main contributors to the environmental impact were found to be the transportation of the wastewater in addition to the production of the materials used in the treatment processes.

Keywords
Environmental Sustainability, Wastewater Treatment Plant, Operational Assessment, OpenLCA Software.

1. Introduction

Wastewater treatment plant is to purify untreated water from a variety of sources such as households, workplaces, labs, and sewerage systems, so that it may be safely disposed or reused. One of the core roles of wastewater treatment systems is to reduce environmental consequences. However, the treatment plant may have environmental consequences. They should be built in such a way that their overall environmental impact is minimized (Bakhit & Eltayeb, 2021). Wastewater treatment plants if not managed efficiently can impose substantial effect on the environment and the human health. Untreated wastewater includes a high concentration of toxins that are hazardous to the environment and humans. Wastewater may contain large amount of Biological Oxygen Demand (BOD), nutrients, organic matter, and bacteria, all of which can cause harm if dumped into the environment without being treated.

The wastewater is usually treated through primary and secondary processes through the wastewater treatment plant. These treatment techniques saved enormous populations from illness; however, society was unaware of the additional environmental expenses involved with water treatment (Corominas et al., 2013). Even though wastewater treatment plants lessen the negative impact of untreated wastewater on the environment, they still have a negative environmental impact of their own due to the use of raw natural resources in their installation and operation (Lopsik, 2013). As a result, while choosing the best technology, not only technical and economic factors must be considered, but also environmental factors (Molinos-Senante et al., 2014). On a local and global scale, poor design, and operation of wastewater treatment plants (WWTPs) can result in serious environmental issues (Sabeen et al., 2018; Xiong et al., 2018). For this reason, sustainability in a wastewater treatment plant is a cause of concern for the researcher (Bakhit & Eltayeb, 2021).

Environmental sustainability assessment is a strategy for quantifying the impacts associated with the product, service, or activity. It is one of the tools that may be used to perform analysis which is based on a thorough knowledge of the process and the collection of reliable data, the collection and assessment of the outputs and possible environmental consequences of a product system. Environmental studies assist in determining the most environmentally friendly process. In this paper, the focus is on the operation mainly and the transportation, to analyze the environmental impacts associated with those processes. The environmental dimension shown to be the most important factor in the sustainability aspect (Omran et al., 2021). Even in developing countries, sustainable wastewater treatment is one of the most difficult issues to solve (Bakhit & Eltayeb, 2021). Wastewater treatment is neither an environmentally friendly nor cost-effective procedure. It uses a lot of energy as well as some chemicals. As a result, an environmental sustainability assessment of the environmental advantages of water conservation and the environmental harm caused by water treatment is necessary. Since the urban areas in UAE keep expanding, the need for new wastewater treatment plants is increasing all around the country, especially with the Environment Vision 2030 (Abu Dhabi) of following more sustainable and environmentally friendly to preserve fresh water, there is a need for basic studies that show the environmental impact of the commonly used wastewater treatment methods in UAE. The study will represent a case study of one of the new wastewater treatment plants to be built in the UAE and could be used as a benchmark for future work to be compared with other case studies of wastewater treatment plants using different treatment methods, this way a clearer vision of the most environmentally friendly treatment method could be provided for further development.

The goal of this study is to evaluate the environmental impacts of a wastewater treatment plant in the United Arab Emirates. The research is being carried out in order to evaluate the impact of the processes used in the proposed wastewater treatment plant for future comparison with other processes and a basis for future decision making for the most sustainable wastewater treatment processes with the least environmental impact. It is important to note that due to the data limitation, the scope of the environmental sustainability assessment in this project is limited to the processes and operational aspect of the wastewater treatment plant. The impact assessment will be limited to the transportation of the wastewater, the energy used by the equipment to operate the WWTP, and the main materials that will be used/changed frequently. There are substantial environmental impacts remains from the waste residuals management within a wastewater treatment plant. This led to several studies focused on the reuse of waste sludge to minimize the environmental consequences (Kaakani et al., 2017; Mortula, 2006). However, this remains outside the scope of this paper.

2. Methodology

The environmental impact of the wastewater treatment plant is shown and analyzed using an environmental sustainability assessment. To do that, data were collected from a wastewater treatment plant provider located in UAE, meetings were taken to get the data and understand it from the engineer working there. Followed by analysis as explained in detail in the next sections.

The assessment modeling is done through OpenLCA software and Agribalyse database by using the well-known ReCiPe impact assessment midpoint approach. The environmental sustainability assessment is done through several steps as shown in Figure 18 1) goal and scope definition, 2) inventory analysis, and 3) impact assessment.

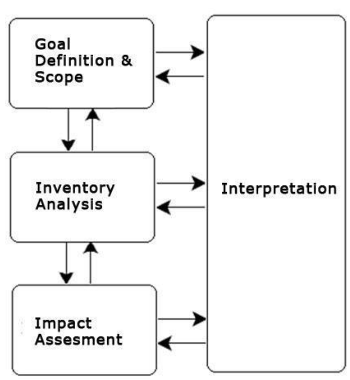

Figure 18: Assessment methodology (International Organization for Standardization [ISO], 2006)

2.1 Wastewater treatment processes

Several processes are proposed for the wastewater treatment which are aeration, settling, and tertiary treatment. The raw sewage is transferred to treatment facility using the sewage trucks commonly used in the UAE. Once in the treatment plant and in the equalization tank for primary storage, they go through the lifting station to the rest of the processes.

The treatment process of the wastewater goes as follow:

- Screening: remove large particle
- Bioreactor: biological treatment through active bacteria
- Settling: transfer through gravity to form flocs and settle
- Filtration: filtration through PVC trickling filters followed by multimedia sand filtration
- Disinfection: sodium hypochlorite dosage and contact tank

2.1.1 Functional unit

Data collected and used in the assessment all have different units and are measured compared to different parameters. A functional unit of $1m^3$ of wastewater was chosen to unify all parameters and to be able to compile and compare their impact. For example, the wastewater treatment plant has a capacity $100m^3$/day equivalent to $4.2m^3$/h. electrical energy used is given in kWh, which will be divided by 4.2 to get how many kW were used to treat $1m^3$ of wastewater. In addition to that, results were analyzed annually as shown in table 2 to provide a broader picture of the environmental impacts.

2.1.2 Assumptions

The data available in the literature and provided by the company were not enough to get all the inputs needed for the environmental sustainability assessment, thus some assumptions had to be made based on commonly used information and from literature review:

- Trucks:
  - Capacity: $20m^3$
  - Number of trucks needed: 5
  - Fleet distance: 40km
  - Diesel consumption: 25liters/100km
- Lifespan:
  - PVC: 25 years
  - Anthracite: 1.5 years
  - Activated carbon regeneration: 6 months
  - Activated carbon replacement: 5 years

2.2 Life cycle inventory

Interviews with working employees at the company that designed and installed the plant were conducted to gather process-specific data. The data input gathered from the company regarding the energy consumption of the machinery in the treatment plant, the dosage of chemicals used, and the effluent characteristics are listed in Table 18. The energy input was then converted into CO_2 emissions based on data released by the UAE's ministry of environment and water which is 600g CO_2/kWh. For the lifting's station activated carbon filter, the data was collected from the literature review for both production and regeneration and are presented in Figure 19. The inventory for the anthracite production was extracted from the literature review as well and is divided into emissions to water Figure 20 and emissions to air Figure 21. For the rest of the inventory, the direct impact for the production of sodium hypochlorite and the production and maintenance of PVC pipes were found in the literature and added to the impact assessment section, the data is presented in Figure 22 and Figure 23 respectively.

Specific details of the wastewater treatment plant such as area, location, etc. can't be shown, as agreed when the data was taken from the responsible company since the project is governmental and confidential. So, information will not be publicly released; readers may contact the authors for more details.

Table 18: Data collected from the contractor's company

Input	Values
Lifting station pump	1.06 kW/h
Automatic screen	0.25 kW/h
Bioreactor air blower	7.5 kW/h
Chlorination dosing pump	0.075 kW/h
Sodium hypochlorite dose	10 mg/l
Multimedia filter pump	1.2 kW/h
BOD	< 10 mg/l
COD	< 10 mg/l
TSS	< 10 mg/l
NH_4	< 10 mg/l

Process	Amount	Units
Continuous dye treatment (10 kg dry weight GAC)		
Pumping	2.79	kWh
GAC production (1 kg GAC)		
Hard coal	1.00	kg
Hard coal combustion	60.8	MJ
Electricity, medium voltage, production UCTE	1.60	kWh
Deionised water	12.0	kg
Natural gas combustion	13.2	MJ
GAC regeneration (10 kg to regenerate, 9 kg produced)		
Electricity, medium voltage, production UCTE	0.30	kWh
Hard coal combustion	30.4	MJ
Steam	6.00	kg
Natural gas combustion	105	MJ

Figure 19: Activated carbon production and regeneration input (Gabarrell et al., 2012)

Waterborne emissions from coal production

No.	Parameter	Coal mine[a]	Coal cleaning[b]	Uncontaminated river[a]
1	pH	3.5	6.2	6.5
2	BOD_5 (g/m^3)	52.4	13.6	42.6
3	Total suspended solid (g/m^3)	103	68	4
4	Total solid (g/m^3)	278.47	NA	6.30
5	Arsenic (As) (g/m^3)	0.0056	0.0046	0.0021
6	Total Nitrogen (N) (g/m^3)	1.75	NA	1.12
7	Total Phosphorus (P) (g/m^3)	1.40	NA	0.26
8	Cadmium (Cd) (g/m^3)	0.11	0.012	0.03
9	Total Chromium (Cr) (g/m^3)	0.0046	0.0002	0.0029
10	Copper (Cu) (g/m^3)	0.34	0.012	0.05
11	Iron (Fe) (g/m^3)	234	2	0.6
12	Manganese (Mn) (g/m^3)	12.02	0.86	0.46
13	Mercury (Hg) (g/m^3)	0.0008	0.0005	0.0001
14	Lead (Pb) (g/m^3)	0.056	0.006	0.003
15	Nitrates (NO_3^-) (g/m^3)	6.85	1.64	0.67
16	Sulfates (SO_4^{2-}) (g/m^3)	745	351	32
17	Oils (g/m^3)	1.4	0.2	0.0

Figure 20: Anthracite production, emissions to water (Chinh et al., 2007)

Air emissions from anthracite production in Vietnam

Pollutant	Coal extraction	Coal preparation	Transport
PM10 (g/tonne)	88,194	532	189
SO_2 (g/tonne)	56	25	3
NO_x (g/tonne)	92	68	10
CO_2 (g/tonne)	48,995	21,854	999
CO (g/tonne)	978	96	2
N_2O (g/tonne)	0.73	0.48	0.04
CH_4 (g/tonne)	1760	28	0.60
NMVOC (g/tonne)	47	17	2
Metals (g/tonne)	0.48	0.28	0.01

Figure 21: Anthracite production, emissions to air (Chinh et al., 2007)

Chemical	Impact category	Process LCA	Input–output LCA			Hybrid LCA
			Zero order	Higher order	Total	
Sodium hypochlorite (13 % w/w)	GWP, kg CO_2-eq	3.58E+02	1.45E+02	1.96E+02	3.41E+02	4.09E+02
	PE, GJ	4.05E+00	1.60E+00	1.32E+00	2.92E+00	4.12E+00
	WU, ML	4.70E−02	5.15E−04	4.55E−04	9.71E−04	4.71E−02
	FETP, kg DCB-eq	1.46E−01	3.90E−03	3.44E−03	7.34E−03	1.47E−01
	METP, kg DCB-eq	1.10E+04	2.77E+02	2.14E+02	4.92E+02	1.10E+04
	TEP, kg DCB-eq	4.31E+00	4.40E−01	2.12E−01	6.52E−01	4.34E+00
	HTP kg DCB-eq	2.84E+00	5.51E−01	1.92E−01	7.43E−01	2.88E+00

Figure 22: Life cycle impact assessment of sodium hypochlorite production (Alvarez-Gaitan et al., 2013)

Categories	Unit	Primary PVC
		Value
Climate change	kg CO_2 eq	2.82×10^3
Ozone depletion	kg CFC-11 eq	9.30×10^{-5}
Terrestrial acidification	kg SO_2 eq	9.59
Freshwater eutrophication	kg P eq	0.03
Marine eutrophication	kg N eq	0.48
Human toxicity	kg 1,4-DB eq	428.42
Photochemical oxidant formation	kg NMVOC	12.29
Particulate matter formation	kg PM_{10} eq	3.58
Terrestrial ecotoxicity	kg 1,4-DB eq	14.99
Freshwater ecotoxicity	kg 1,4-DB eq	0.76
Marine ecotoxicity	kg 1,4-DB eq	6.29
Ionising radiation	kBq U235 eq	110.41
Agricultural land occupation	m^2a	10.34
Urban land occupation	m^2a	7.20
Natural land transformation	m^2	0.17
Water depletion	m^3	57.52
Metal depletion	kg Fe eq	48.48
Fossil depletion	kg oil eq	1.12×10^3

Figure 23: Life cycle impact assessment of PVC production (Ye et al., 2017)

2.3 Impact assessment

For every inventory input, a relation to an impact had to be defined. The database used for the impact assessment was ReCiPe Midpoint (H). If any of the parameters had no impact in this specific database then it was added, data was collected from different databases with common factors to similar impacts, this way a larger database was created for the project to consider all the inputs added.

The ReCiPe Midpoint (H) assess the following impacts: Fine particulate matter formation, Fossil resource scarcity, Freshwater ecotoxicity, Freshwater eutrophication, Global warming, Human carcinogenic toxicity, Human non-carcinogenic toxicity, Ionizing radiation, Land use, Marine ecotoxicity, Marine eutrophication, Mineral resource scarcity, Ozone formation, Human health, Terrestrial ecosystems, Stratospheric ozone depletion, Terrestrial acidification, Terrestrial ecotoxicity, Water consumption.

3. Results and discussions

After adding the inventory and linking them to the corresponding impacts, a software run was conducted, and the results for the functional unit of $1m^3$ of wastewater were analyzed. To get a more realistic view of the wastewater processes impact, the impact for 1 year of operation was calculated as well and added to the results shown in Table 2. Results show that the most significant impact is global warming, human non-carcinogenic toxicity, fine particulate matter formation, marine toxicity, marine eutrophication, and fossil resource scarcity.

The main contributors to the global warming are two processes: the wastewater transportation generating up to 1.3 kg CO_2 eq contributing to almost 43% of the total impact, the bioreactor air blowers generating up to 1.1 kg CO2 eq contributing to around 38% of the total global warming impact. On the other hand, for the fine particulate matter formation the main contributors are the transportation process (~1.8E-4 kg PM_{25} equivalent to 65% of total PM_{25} emitted) in addition to the filtration anthracite production (~8.7E-5 kg PM_{25} equivalent to 32% of total PM_{25} produced). Whereas for the fossil resource scarcity the operation and maintenance of the activated carbon holds the higher contribution by using up to 0.5 kg of oil per functional unit consisting of 93% of the total fossil resources usage. The results show that the main contributor to the environmental impact is the transportation of the wastewater, which suggest that different alternatives need to be considered to transport the wastewater, perhaps a renovation and building a connecting sewer system may be a good alternative on the long run. An environmental sustainability assessment of the alternatives needs to be done and compared to the current one to be able to choose the most sustainable option to move forward and start applying it.

Table 19: Life cycle impact assessment results

Impact category	Reference unit	Result (per m3)	Results (per year)
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.000268113	9.79
Fossil resource scarcity	kg oil eq	0.53408355	19,494.05
Freshwater ecotoxicity	kg 1,4-DCB	2.9595E-06	0.11
Freshwater eutrophication	kg P eq	5.50036E-08	0.00
Global warming	kg CO_2 eq	2.81618897	102,790.90
Human carcinogenic toxicity	kg 1,4-DCB	2.86713E-05	1.05
Human non-carcinogenic toxicity	kg 1,4-DCB	0.100690559	3,675.21
Land use	m^2 crop eq	0.00153	55.85
Marine ecotoxicity	kg 1,4-DCB	0.110010305	4,015.38
Marine eutrophication	kg N eq	0.003440772	125.59
Metal depletion	kg Fe eq	7.41744E-05	2.71
Ozone formation, Human health	kg NOx eq	0.001600733	58.43
Stratospheric ozone depletion	kg CFC11 eq	1.4229E-10	0.00
Terrestrial acidification	kg SO_2 eq	0.000591263	21.58
Terrestrial ecotoxicity	kg 1,4-DCB	6.63347E-05	2.42
Water consumption	m^3	0.000282646	10.32

4. Conclusions

Water is a valuable resource, and with the scarcity that the world is facing, wastewater treatment is a necessity. Different wastewater processes are available and implemented worldwide, but although the processes will help reduce the environmental impact of the wastewater, they themselves contribute to the impact on the environment as well. This paper analyzes the environmental impact of the processes used in the operation of a wastewater treatment plant newly built in the UAE. An impact assessment was conducted to set a baseline for future project to be able to compare and chose the option that has the least impact on the environment. Results showed that the main contributor to the environmental impact is the transportation of the wastewater to the treatment plant using trucks, thus different alternatives need to be studied to compare their impact. In addition, the production of the materials used in the processes were found to have a significant impact on the environment as well, which opens the research for different alternatives and different processes to be studied for comparisons and improvements.

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