

ENVIRONMENTAL SUSTAINABILITY OF RURAL WASTEWATER-TREATMENT PLANTS VIA LIFE-CYCLE ASSESSMENT WITH EMPHASIS ON CONSTRUCTED WETLANDS

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Abstract. Sustainability plays a pivotal role in environmental engineering and management. Life Cycle Assessment (LCA) serves as a valuable methodology for evaluating the environmental footprint of products, services, or processes throughout their life cycles. LCA offers a quantitative approach and aids in identifying strategies that address environmental challenges rather than merely transferring them. It proves particularly relevant for assessing the sustainability and design of wastewater treatment systems. This study employs the LCA framework to compare various wastewater treatment options suitable for small, decentralized areas. Specifically, the focus lies on evaluating the constructed wetland (CW) within the wastewater treatment (WWT) system across its three main phases: construction, operation, and decommissioning. The investigation examines the impact on diverse environmental categories such as abiotic depletion, global warming, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication, adhering to LCA standards. Findings reveal that natural wastewater treatment methods exhibit lower environmental footprints due to their reduced resource requirements. However, the construction phase of the CW emerges as the primary contributor to most impact categories, accounting for 89% of the overall impact. Notably, marine aquatic ecotoxicity ranks as the most significant impact category, while ozone layer depletion and photochemical oxidation potentials exhibit minimal values.

Keywords: *wastewater, sustainability, constructed wetland, decommissioning, green initiatives*

Introduction

Human activities inevitably result in significant environmental impacts that must be mitigated to uphold environmental sustainability and safeguard environmental quality (Von Sperling, 2007). Therefore, preserving ecosystems, optimizing natural resource utilization, and minimizing environmental footprints are paramount objectives. Life Cycle Assessment (LCA) serves as a crucial tool in this endeavor, offering a comprehensive analysis of the environmental impacts associated with various systems, including products, processes, and activities, from production to disposal (Zampori et al., 2016). The scope of LCA encompasses the entire life cycle of materials, spanning from manufacturing, transportation, product use, to disposal or recycling (Chordia et al., 2021; Szulc et al., 2021; Tabesh et al., 2019). The ISO 14040 standards provide the foundational principles for conducting LCA studies, outlining general and methodological guidelines of ISO, 1997 (Dewalkar and Shastri, 2021). While wastewater treatment plants (WWTPs) are designed to mitigate organic contaminants and minimize adverse effects on aquatic environments, understanding their environmental impacts throughout their life cycles is crucial in aligning with green initiatives. In rural areas, decentralized wastewater treatment systems like constructed wetlands (CW) are often preferred, offering a range of options and technologies

(Gallego-Schmid and Tarpani, 2019; Machado et al., 2007). The existing literature has examined the life cycle inventory and environmental impact assessment of CW and obtained mixed results on environmental factors (Alam et al., 2023; Lourenço and Nunes, 2021; Flores et al., 2019; Corominas et al., 2013; Machado et al., 2007). his study aims to address two fundamental objectives: firstly, to compile average inventory data derived from previous research, particularly focusing on the construction, operation, and maintenance phases of CW; and secondly, to conduct an environmental impact assessment of CW utilizing this compiled data.

Materials and Methods

The study assessed the environmental impacts associated with a constructed wetland treatment plant across its key stages of construction, operation, and dismantling using Life Cycle Assessment (LCA). Inventory data pertaining to the constructed wetland (CW), encompassing its construction, operation, and maintenance phases, were gathered from relevant literature sources, and average values were used in this study as input data for LCA (*Table 1*). To ensure data uniformity, measurements provided in different units within the literature were standardized to appropriate units, such as kg, m³, and MJ. Where necessary, conversion was facilitated using flow rates and hydraulic retention times. The Mobius web-based software served as the primary tool for characterizing emissions and assessing their associated environmental impacts. Data analysis and normalization were conducted using Mobius-openlca, lcia v2.04, 2019, along with the CML-IA baseline method. Mobius software aligns with ISO 14000 guidelines and covers various impact categories, including global warming (GW), abiotic depletion (AD), human toxicity (HT), ozone layer depletion (OLD), marine aquatic ecotoxicity (MAE), freshwater aquatic ecotoxicity (FWA), photochemical oxidation (PO), terrestrial ecotoxicity (TE), eutrophication (E), and acidification (A). Notably, the software incorporates a range of emission databases and methods for emission characterization (Gmünder et al., 2020).

Table 1. The inventory results of wastewater treatment in various constructed wetlands.

Inventory Data	Unit	Min	Max	Average	SD
Flowrate	m ³ /day	1	30	15	10.3
Area	m ²	1	594	253	227.7
Construction phase					
Concrete	m ³	0.1	0.3	0.2	0.1
Gravel	ton	0.0	10.8	6.2	4.0
Sand	kg	0.0	913	259.6	379.1
Steel	kg	3.6	31	17.6	11.2
Iron/cast iron	kg	0.0	331	94.9	137.0
PVC	kg	0.0	8.9	2.5	3.7
PE/HDPE	kg	0.012	0.014	0.013	0.001
Fossil fuel	kg	0.1	0.7	0.4	0.3
Aluminum	kg	0.1	0.1	0.1	0.0
Polypropylene(PP)	kg	0.0	0.7	0.3	0.3
Operation					
COD emissions to water	kg	0.2	283	178.1	110.1
TN emissions to water	kg	0.0	76.9	43.6	33.9
TP emissions to water	kg	0.0	60.7	28.1	27.0
Electricity	kWh	1.5	1428	579.8	612.7
Dismantling					
Construction waste	kg	0.2	156	78.1	77.9
General waste	kg	1.3	655	328	327
Total fossil fuel	kg	1.3	1.3	1.3	0.0

Note: SD=Standard Deviation.

Source: Alam et al. (2023) (average values of the 5 CWs); Lourenço and Nunes (2021) (average values of the CW and VF); Flores et al. (2019); Machado et al. (2007).

Results and Discussion

The inventory data, obtained with a comprehensive "cradle to grave" approach, were sourced from various literatures pertaining to the constructed wetland (CW) process in small, decentralized communities. These data, spanning different stages, underwent meticulous analysis and were meticulously presented in *Table 1*, providing detailed insights into construction, operation, and dismantling. This information formed the basis for evaluating the performance of four small and decentralized wastewater treatment plants through an extensive life cycle assessment (LCA) study. Additionally, the emission factors utilized to translate inventory data into environmental impacts were scrutinized across various impact categories, as delineated in *Table 2*. Materials selected for construction were carefully chosen to ensure suitability throughout the entire life cycle of the system, with no alternative options explored. Notably, residual organics such as COD, as well as phosphorus and nitrogen quantities in the effluent from the treatment process, were identified as emissions to water. It's worth noting that the construction phase emerged as the most crucial stage within the LCA inventory, underscoring its pivotal role in the overall environmental impact assessment. The most important inventories affecting environmental impact categories were found to be emissions to water (19-100%), aluminum usage (35-59%), and iron usage (27-40%) (Figure 1 to Figure 10). The effect levels of the categories have been arranged in the following order during the life cycle of the constructed wetlands (CWs): MAE>CW>TE>PO>A>TE>FWAE>OLD>E>AD. Similar to our results, Fang et al. (2023) and Lakho et al. (2022) pointed out that MAE was considerably higher than other impact categories for CWs. The high potential of marine ecotoxicity in CWs may result from several reasons, including: (i) chemical pollutants in the wastewater, such as heavy metals, pesticides, pharmaceuticals, and industrial chemicals, which may not be effectively removed by the treatment processes in CWs and can accumulate in the water, sediments, and biota, (ii) high levels of organic matter and nutrients in the wastewater may still be present in the effluent discharged from CWs, leading to eutrophication and subsequent oxygen depletion in receiving marine ecosystems, (iii) alterations to local hydrology, sediment transport, and habitat structure caused by artificial wetlands can affect the abundance and distribution of marine organisms and their exposure to pollutants.

Table 2. The emission factors of each inventory to calculate impact categories.

ID	U	S	A	B	C	D	E	F	G	H	I	J	DB
Concrete	kg/m ³	Mobius	0.77	0.36	3.83x10 ⁻⁶	3.83x10 ⁻⁶	0.12	1.49x10 ⁻⁵	3.14x10 ⁴	0.03	1.18	2.82x10 ²	Ecoinvent v3.8, Cut-Off, 239
		Reference	0.79 ^(b)	0.438 ^a	1.05x10 ^{-4(b)}	1.21x10 ^{-3(a)}	0.20 ^(b)	3.5x10 ^{-5(b)}	3.83x10 ^{4(a)}	3.14x10 ^{-2(b)}	5.07 ^a	2.4x10 ^{2(b)}	Ecoinvent (v 3.5) ^a , Ecoinvent (v 3.5) ^b
Gravel	kg/ton	Mobius	2.03x 10 ⁻³	1.9x 10 ⁻⁴	6 x10 ⁻³	0.98	2.31x10 ⁻⁴	3.9x10 ⁻⁸	19.08	2x10 ⁻³	1.3x10 ⁻³	3.97	Nationale Milieudatabase v3.3 (Dutch)
		Reference ^(c)	1.41x10 ⁻³ 2.25x10 ⁻²	6.99x10 ⁻⁴ 4.28x10 ⁻³	-	1.82x10 ⁻¹ 1.12	1.84x10 ⁻⁴ 1.19x10 ⁻³	2.65x10 ⁻⁹ 6.35x10 ⁻⁷	24.7-204.7	1.62x10 ⁻⁴ 1.47x10 ⁻²	1.58x10 ⁻³ 9.24x10 ⁻³	0.29-4.02	LICYMIN
Sand	kg/kg	Mobius	7.5x 10 ⁻⁵	1.95x10 ⁻⁵	2.36x10 ⁻¹¹	2.36x10 ⁻¹	1.25x10 ⁻⁵	1.49x10 ⁻⁹	2.87	3.1x10 ⁻⁶	9.6x10 ⁻⁵	0.63	ELCD 3.2 GreenDelta V2.18 Europe Licymim
		Reference ^(c)	1.28x10 ⁻³ 1.93x10 ⁻²	6.99x10 ⁻⁴ 3.87x10 ⁻³	-	7.57x10 ⁻² 1.03	1.50x10 ⁻⁴ 1.03x10 ⁻³	2.65x10 ⁻⁹ 4.26x10 ⁻⁷	24.68- 176.48	1.60x10 ⁻⁴ 1.81x10 ⁻³	1.58x10 ⁻³ 8.38x10 ⁻³	0.25-3.45	Licymim
Steel	kg/kg	Mobius	8.6x10 ⁻³	0.02	9.05x10 ⁻⁶	2.71	1.44x10 ⁻³	1.3x10 ⁻⁷	7.61x10 ²	1.27x10 ⁻³	0.02	2.05	Ecoinvent v3.5, Cut-Off, Europe (Sensitivity analysis) ^w
		Reference ^(w)	8.06x10 ⁻³	8.14x10 ²	-	3.59x10 ⁻²	4.79x10 ⁻⁵	4.87x 10 ⁻¹	-	1.52x10 ⁻³	-	2.81	Ecoinvent v3.8, Cut-Off, market for cast iron (Per functional unit) ^d
Iron/cast iron	kg/kg	Mobius	6.15x 10 ⁻³	0.07	1.22x10 ⁻⁸	0.91	8.52x10 ⁻⁴	9.03x10 ⁻⁸	8.69x10 ²	8.73x10 ⁻⁴	0.03	1.74	Ecoinvent v3.8, Cut-Off, market for cast iron (Per functional unit) ^d
		Reference ^(d)	4.53x10 ⁻³	-	8.28x10 ⁻⁶	-	8.3x10 ⁻⁴	5.4x10 ⁻⁷	-	3.23x10 ⁻⁴	-	1.67	Ecoinvent v3.8, Cut-Off, market for cast iron (Per functional unit) ^d
PVC	kg/kg	Mobius	7.08x10 ⁻⁵	2.42x10 ⁻⁵	2.37x10 ⁻¹¹	4.55x10 ⁻³	2.29x10 ⁻⁵	2.62x10 ⁻⁹	6.82	1.31x10 ⁻⁵	1.83x10 ⁻³	0.07	Nationale Milieudatabase v3.5 (Dutch), Netherlands (Ecoinvent V3.4) ^f
		Reference	8.28x10 ^{-3(e)}	7.90x10 ^{-2(f)}	1.48x10 ^{-6(e)}	4.6x10 ^{-2(f)}	1.93x10 ^{-3(e)}	9.97x10 ^{-7(e)}	-	5.7x10 ^{-4(e)}	4.3x10 ^{-2(f)}	2.68 ^(e)	Ecoinvent V3.4) ^f

PE/HDPE	kg/kg	Mobius	2.33×10^{-3}	3.05×10^{-3}	1.48×10^{-6}	0.25	3.96×10^{-4}	5.04×10^{-8}	2.17×10^2	1.1×10^{-4}	$7.16 \cdot 10^{-3}$	0.68	v3.5) ^e Ecoinvent v3.5, Cut-Off, Europe CML, USETox, ReCiPe and IPCC
		Reference ^(g)	1.31×10^{-2}	-	-	3.35×10^{-7}	1.27×10^{-2}	4.07×10^{-5}	-	1.95×10^{-3}	-	-3.09	
Fossil fuel	kg/kg	Mobius	1.81×10^{-3}	1.1×10^{-3}	1.02×10^{-6}	0.13	5.2×10^{-4}	3.43×10^{-8}	43.89	9.78×10^{-5}	4.77×10^{-3}	0.24	Ecoinvent v3.5, Cut-Off, Canada, Québec
Aluminum	kg/kg	Reference	$1.0 \times 10^{-3(h)}$	-	-	-	$2.0 \times 10^{-4(h)}$	-	-	-	-	$0.523^{(h)}$	CML2 Ecoinvent v3.5, Switzerland GaBi database
		Mobius	1.78	6.27	4.52×10^{-3}	6.25×10^{-2}	0.36	3.51×10^{-5}	1.89×10^5	0.17	4.87	3.64×10^2	
Polypropylene (PP)	kg/kg	Reference ⁽ⁱ⁾	0.13	-	-	-	0.011	2.9×10^{-10}	-	0.0085	-	16.5	ELCD 3.2 GreenDelta V2.18
		Mobius	9.07×10^{-3}	6.91×10^{-4}	3.56×10^{-7}	0.08	6.43×10^{-4}	1.7×10^{-7}	3.24×10^2	6.7×10^{-4}	7.7×10^{-3}	2.36	
Emissions to water (COD)	kg/kg	Reference	$4.9 \times 10^{-3(j)}$	-	-	$0.077^{(j)}$	$1.4 \times 10^{-3(k)}$	$5.1 \times 10^{-8(k)}$	----	$4.2 \times 10^{-3(l)}$	-	$1.59^{(j)}$	Ecoinvent v3.5, Cut-Off, Europe Eco-Indicator 99, CML and Impact 2002
		Mobius	3.61×10^{-3}	1.63×10^{-3}	3.48×10^{-7}	0.09	5.29×10^{-4}	6.57×10^{-8}	3.97×10^2	1.19×10^{-4}	3.06×10^{-3}	0.61	
Emissions to water (TN)	kg/kg	Reference	-	-	-	-	$2.2 \times 10^{-2(o)}$	-	-	-	-	$0.58^{(o)}$	Ecoinvent v3.8, Cut-Off, China, 201
		Mobius	3.45×10^{-3}	7.52×10^{-4}	2.8×10^{-7}	0.43	3.34×10^{-4}	1.94×10^{-7}	3.17×10^2	2.11×10^{-4}	0.06	2.77	
Emissions to water (TP)	kg/kg	Reference ^(l)	-	-	-	-	0.42 ^(l)	-	-	-	-	-	EcoInvent v1.0 database Ecoinvent v3.8, Cut-Off, China, 201
		Mobius	3.45×10^{-3}	7.52×10^{-4}	2.8×10^{-7}	0.43	3.34×10^{-4}	1.94×10^{-7}	3.17×10^2	2.11×10^{-4}	0.06	2.77	
		Reference	-	-	-	-	0.42 ^(l)	-	-	-	-	-	EcoInvent v1.0 database

Emissions to water (TP)	kg/kg	Mobius	0.19	0.01	4×10^{-7}	0.2	1.9×10^{-4}	2.3×10^{-3}	3.03	0.21	2.8×10^{-3}	2.90×10^{-1}	Ecoinvent v3.5, Cut-Off, 201 Global Ecoinvent ⁷ database Version 3.4. Ecoinvent v3.5, Cut-Off, Brazil GaBi 2016 datasets Ecoinvent v3.8, Cut-Off, 429 Global: Generic, trade association supplier Ecoinvent v3.8, Cut-Off 201, Europe GaBi SP40 (2020)
		Reference ^(m)	1.37×10^{-1}	1.84×10^{-3}	-	2.5×10^{-1}	1.5×10^{-4}	3×10^{-4}	2.9	$2.43 \times 10^{-1(m)}$	1.5×10^{-4}	3.75×10^{-1}	
Electricity	kg/MJ	Mobius	2.24×10^{-5}	2.61×10^{-5}	2.12×10^{-8}	8.3×10^{-3}	3.74×10^{-6}	3.9×10^{-10}	1.62	1.3×10^{-6}	3.3×10^{-5}	6.7×10^{-3}	Ecoinvent v3.8, Cut-Off, 429 Global: Generic, trade association supplier Ecoinvent v3.8, Cut-Off 201, Europe GaBi SP40 (2020)
		Reference ⁽ⁿ⁾	2.2×10^{-5}	3.6×10^{-5}	6×10^{-8}	5.12×10^{-3}	2.7×10^{-6}	2.2×10^{-8}	7.44×10^{-4}	1.6×10^{-6}	4×10^{-5}	5.6×10^{-3}	
Construction waste	kg/kg	Mobius	4.01×10^{-4}	5.5×10^{-5}	6.5×10^{-6}	0.59	3.3×10^{-4}	3.9×10^{-9}	1.13×10^{-3}	3.4×10^{-4}	3.1×10^{-5}	0.045	Nationale Milieudatabase v3.5 (Dutch), Netherlands
		Reference	32×10^{-6}	-	-	0.683	469×10^{-6}	1.95×10^{-9}	-	-	-	0.059	
General waste	kg/kg	Mobius	0.01	75×10^{-4}	3.65×10^{-8}	0.19	7.29×10^{-4}	2.87×10^{-9}	1.06×10^2	7.5×10^{-4}	0.01	3.66	Nationale Milieudatabase v3.5 (Dutch), Netherlands
		Reference	$3.68 \times 10^{-4(q)}$	-	$1.9 \times 10^{-10(p)}$	-	$8.97 \times 10^{-7(p)}$	$2.12 \times 10^{-16(q)}$	-	$1.4 \times 10^{-6(p)}$	$7.3 \times 10^{-8(q)}$	$6.6 \times 10^{-1(q)}$	
Total fossil fuel	kg/kg	Mobius	3.52×10^{-3}	3.65×10^{-3}	1.53×10^{-8}	0.16	1.26×10^{-3}	5.43×10^{-8}	1.63×10^2	2.2×10^{-4}	0.02	0.58	
		Reference	-	-	-	-	-	-	-	-	-	-	

Note: ID=Inventory Data; U=Unit; S=Source; A=A kg SO₂ eq; B=TE kg 1,4-DB eq; C=AD kg Sb eq; D=HT kg 1,4-DB eq; E=E kg PO₄-eq; F=OLD kg CFC-11 eq; G=MAE kg 1,4-DB eq; H=PO kg C₂H₄ eq; I=FWA kg 1,4-DB eq; J=GW kg CO₂ eq; DB=DataBase
 Source: Onninen (2024)^p; Alam et al. (2023)^j; Adhikari et al. (2022)^k; Gülçimen and Uzal (2022)^b; Issaoui (2022)^m; Mali and Garrett (2022)ⁿ; Alsabri et al. (2021)^j; Marson et al. (2021)^e; Olagunju and Olanrewaju (2021)^a; Liu et al. (2020); Montesó Tarrida (2020)^h; Hydro Aluminium (2019)^q; TEPPFA (2019)^d; Braskem Company (2016)^g; Nunez and Jones (2016); Ramsey et al. (2014)^l; Korre and Durucan (2009)^c; Halleux et al. (2006)^o.

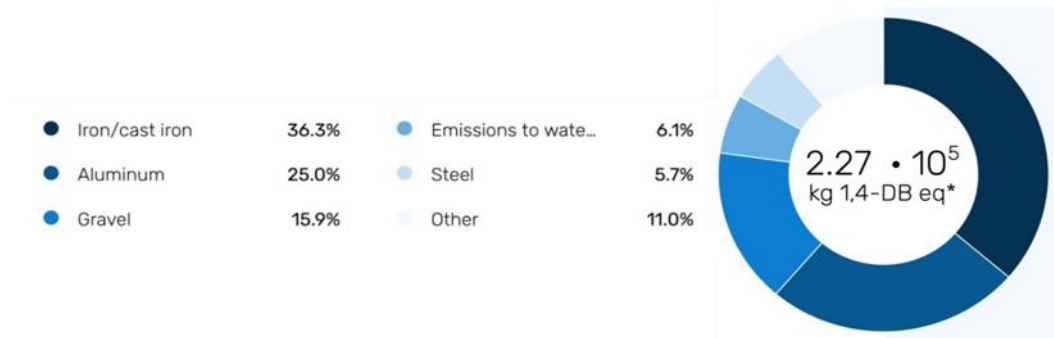


Figure 1. Comprehensive breakdown of the contributors for CWs on the impact of MAE.

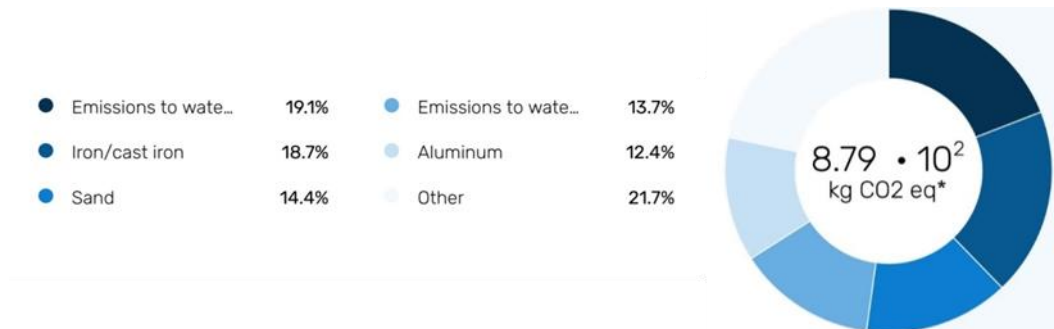


Figure 2. Breakdown of the leading contributors for CWs on the impact of global warming potential (GWp100a).

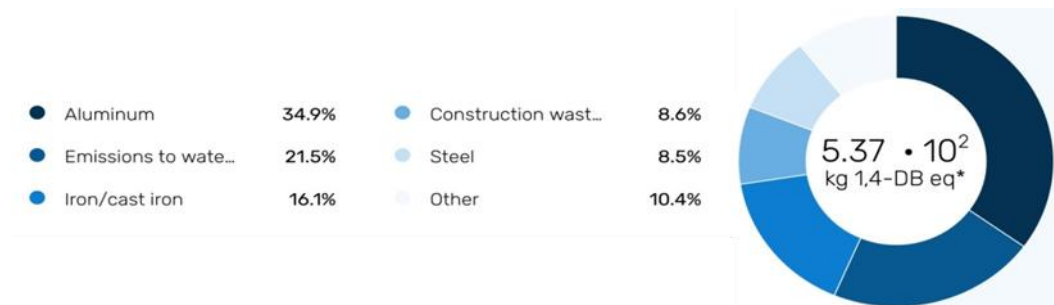


Figure 3. Breakdown of the contributors for CWs on the impact of HT.



Figure 4. Breakdown of the contributors for CWs on the impact of PO.

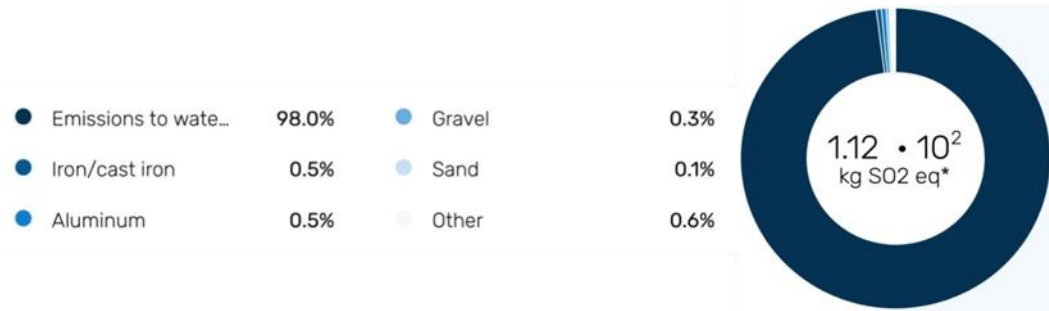


Figure 5. Breakdown of the leading contributors for CWs on the impact of A.

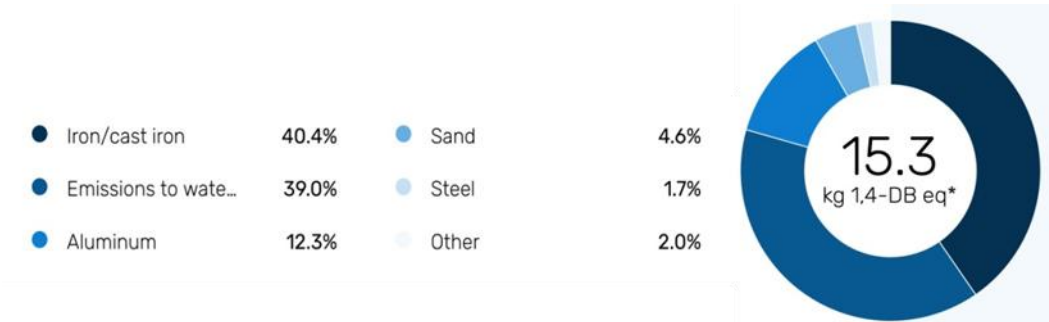


Figure 6. Breakdown of the leading contributors for CWs on the impact of TE.

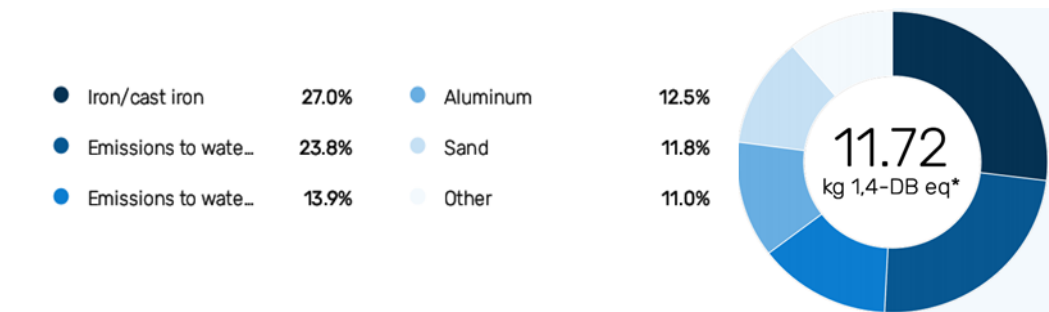


Figure 7. Comprehensive breakdown of the contributors for CWs on the impact of FWAE.



Figure 8. An analysis of the leading contributors for CWs on the impact of OLD.

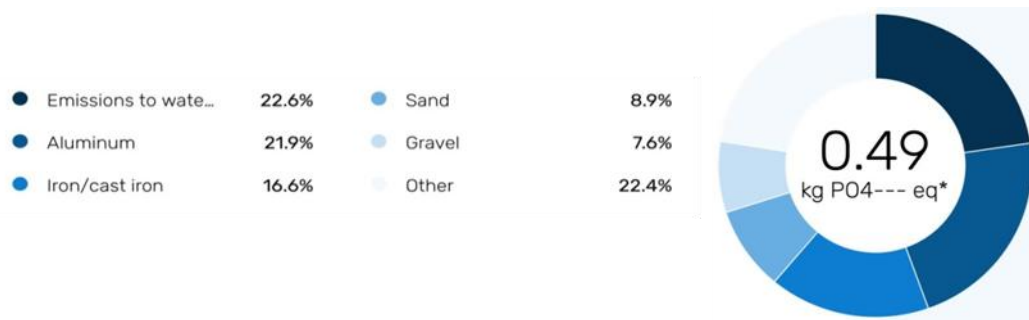


Figure 9. Breakdown of the contributors for CWs on the impact of E.

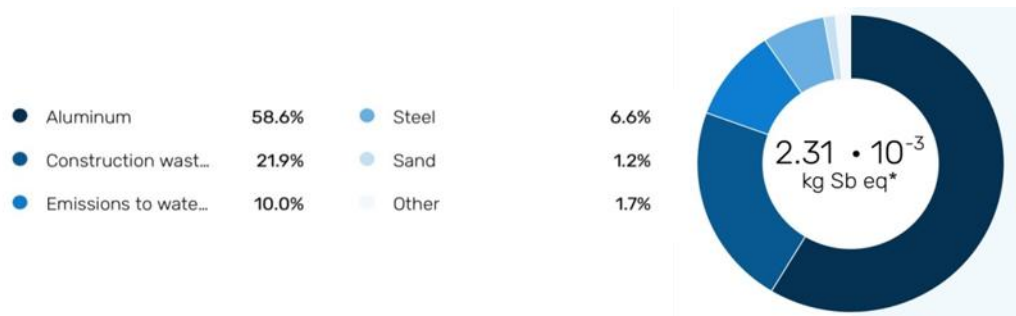


Figure 10. Breakdown of the significant contributors for CWs on the impact of AD.

CW activities have been determined to have a considerable impact on the greenhouse gas (GHG) category, indicating significant emissions of greenhouse gases. Wastewaters have been treated in CWs through aerobic, anoxic, and anaerobic biological processes, releasing greenhouse gases such as carbon dioxide, methane, and nitrous oxide into the atmosphere. These emissions contribute significantly to the phenomenon of global warming and subsequent climate change. HT demonstrates another notable impact, highlighting potential risks to human health arising from exposure to toxic substances released during CW operations. These substances may encompass heavy metals, pesticides, or other hazardous chemicals. The acidification potential (A) was determined to be 112 kg SO₂ eq over the life cycle of the constructed wetland (CW). This category suggests a significant contribution to acidity levels in ecosystems due to emissions of acidic compounds like sulfur dioxide and nitrogen oxides. Such emissions can lead to acid rain and subsequent acidification of soil and water bodies, impacting plant and animal life. Additionally, it is estimated that the acidification potential (A) may result from the formation of organic acids and carbonic acid as by-products/end products during wastewater treatment, as well as acid rain generated by the oxidation of nitrous oxide in the atmosphere. Moreover, PO and FWAE categories with 123 kg C₂H₄ eq and 11.7 kg 1,4-DB eq respectively, indicate potential adverse effects on air and freshwater ecosystems resulting from CW activities. Photochemical oxidation refers to the formation of ozone and other harmful pollutants in the atmosphere, while freshwater aquatic ecotoxicity pertains to the toxicity of substances to aquatic organisms in freshwater environments. These variations in impact values underscore the diverse environmental significance across different categories, influenced by factors such as pollutant types, quantities, and their potential ecological and human health implications. Low impact value in the AD category suggests that CW operations have negligible effects on the depletion of non-living natural resources. In a study similar to our result

that conducted by Corbella et al. (2017), researchers have discovered that AD has a lower impact compared to other environmental factors.

According to *Figure 11*, which depicts the life cycle phases considered in the study—construction, operation, and dismantling—the construction phase of CWs exhibited the highest contribution to most environmental impact categories. Notably, the construction phase accounted for 89% of the MAE impact category. This high contribution can be attributed to activities such as excavation, chemical usage, waste disposal, and habitat alteration, which can release pollutants into water bodies, posing risks to aquatic ecosystems. Efforts should thus focus on minimizing the environmental impact of this phase. The operation phase made significant contributions to impact categories such as ozone layer depletion (100%), photochemical oxidation (99.8%), and acidification (95%). During CW operation, the use of equipment like pumps and machinery may involve lubricants or hydraulic fluids containing ozone-depleting substances like chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs). Any leakage or mishandling of these fluids during maintenance can release these substances, contributing to ozone layer depletion. In contrast, the dismantling phase had negligible contributions to impact categories such as AD, HT, and E (22%, 10%, and 5%, respectively). During CW dismantling, environmental impacts are minimized due to reduced activity levels, decreased material and chemical usage, proper waste management, site remediation efforts, and careful design and planning. This results in a reduced environmental footprint during the dismantling phase. The minimal impact of factors like GW, OLD, and others during CW dismantling may be attributed to the design's focus on harnessing natural processes for wastewater treatment and environmental restoration.

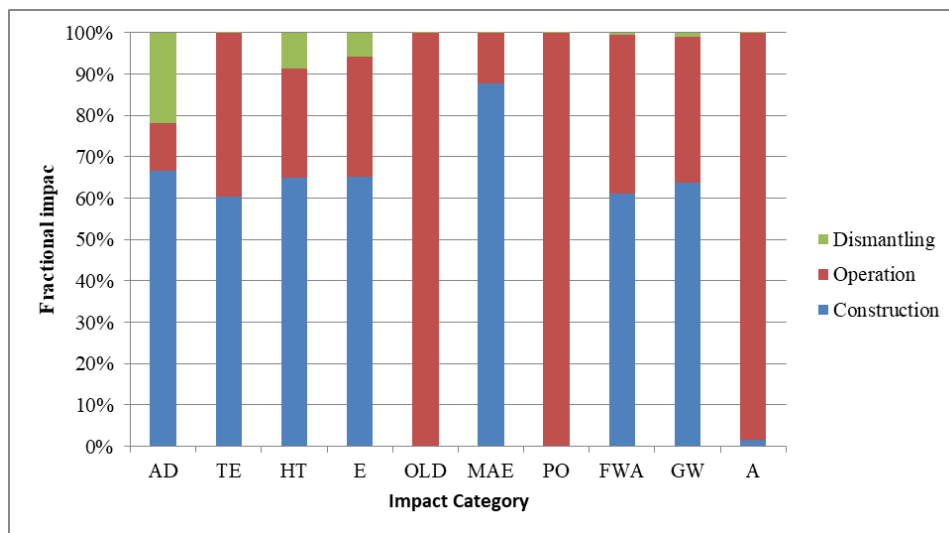


Figure 11. Contribution of life cycle phases of constructed wetland to environmental impact categories.

According to *Table 3* in this study, investigated how using constructed wetlands, a specific type of pond, affects the environment in rural wastewater treatment areas. We examined various wastewater treatment methods to understand their environmental impacts. Our findings revealed that some methods have a greater environmental impact than others. The reason behind this discrepancy in environmental impact lies in the operational mechanisms of these methods and their effectiveness in removing

pollutants. For instance, high-tech methods often require large amounts of energy or the use of chemicals, resulting in increased pollution compared to simpler methods like constructed wetlands. Additionally, these advanced methods typically rely on complex equipment and consume significant energy, further contributing to their environmental footprint. Another crucial factor is the location of the treatment plant and the available resources. Constructed wetlands can be a cost-effective and environmentally friendly option in rural areas with ample space and lower population densities. However, in densely populated urban areas or places with limited space, alternative methods may be preferred despite their higher environmental impact. Moreover, regulations and community preferences play a significant role in method selection. Legal requirements and community preferences may dictate the use of specific methods to meet water quality standards. In such cases, the environmental impact of a method becomes a critical consideration alongside factors like ease of use and cost. This study highlighted the importance of considering all aspects when choosing wastewater treatment methods. While constructed wetlands are beneficial for the environment and cost-effective in certain contexts, selecting the best method requires evaluating its performance, location suitability, and adherence to regulations. For example, in this study, the value for "Global Warming" was 8.8×10^2 kg CO₂ eq, while the constructed wetland's value for "GW" was 135 kg CO₂ eq. This indicates that the study's impact on global warming is greater than that of the constructed wetland. Similarly, in advanced biological treatment, the "GW" value was 2.4 kg CO₂ eq, demonstrating that the study's impact is greater than that of this treatment method. Lastly, in activity sludge treatment, the "GW" value was 183 kg CO₂ eq, further

Table 3. Comparison of This Study with Other Academic Findings on Wastewater Treatment Systems.

TM	A	B	C	D	E	F	G	H	I	J
(Constructed Wetland) ^a	0.5	0.16	2.9	27.1	8.97	5.02×10^{-6}	612	0.04	1.92	135
(Advanced Biological Treatment) ^d	3×10^{-3}	5.8×10^{-2}	3.9×10^{-6}	9×10^{-2}	1.2×10^{-2}	6×10^{-8}	4×10^2	3×10^{-4}	8×10^{-3}	2.4
(Slow rate infiltration) ^c	38	-	39.3	-	3.4×10^3	1.2×10^{-3}	-	2.61	-	1.87×10^5
(Advanced Treatment) ^b	0.5-2.9	0.2-0.8	4.5-32	47-230	24-202	8-36	1-8.5	0.3-1.3	0.8-9.3	140-482
(Activity Sludge) ^a	1.07	0.32	2.07	28.3	7.5	1.7×10^{-6}	6.4×10^3	0.061	1.43	183
This study	1.12×10^2	15.3	2.3×10^{-3}	5.4×10^2	0.49	1.33	2.3×10^5	1.2×10^2	11.72	8.8×10^2

Note: TM=Treatment Method; A=A kg SO₂ eq; B=TE kg 1,4-DB eq; C=AD kg Sb eq; D=HT kg 1,4-DB eq; E=E kg PO₄-eq; F=OLD kg CFC-11 eq; G=MAE kg 1,4-DB eq; H=PO kg C₂H₄ eq; I=FWA kg 1,4-DB eq; J=GW kg CO₂ eq.

Source: ^aÇankaya and Pekey (2024); ^bTarpani and Azapagic (2023); ^aLourenço and Nunes (2021); ^cMachado et al. (2007).

Conclusion

In the investigation of LCA for rural wastewater treatment plants, we have gained valuable insights into the environmental impact across different phases of CWs the construction, operation, and dismantling phases. The study underscores the critical role of the construction phase in contributing to the environmental footprint of CWs, with

MAE emerging as the most impacted category, at a notable 89%. This high impact is a direct result of activities like excavation, chemical usage, waste disposal, and habitat alteration, which have the potential to release pollutants into water bodies, thereby posing a threat to aquatic ecosystems. These findings emphasize the importance of focusing efforts on minimizing the environmental impact during the construction phase, particularly in rural settings where ecological sensitivity can be heightened. Moreover, the operation phase of CWs significantly influences impact categories such as OLD, PO, and HT. This impact stems from the usage of equipment containing substances like CFCs or HCFCs, which, if not properly handled, can lead to the depletion of the ozone layer or human toxicity concerns. Conversely, the dismantling phase of CWs exhibits a negligible impact on most of the environmental categories. This low impact is a reflection of reduced activity levels, minimized material and chemical usage, proper waste management, site remediation, and thoughtful design and planning. It is a testament to the commitment to maintaining an environmentally friendly footprint throughout the dismantling phase, aligning with the rural areas' needs for sustainable and sensitive practices.

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

REFERENCES

- [1] Adhikari, B., Lister, T.E., Reddy, R.G. (2022): Techno-economic and life cycle assessment of aluminum electrorefining from mixed scraps using ionic liquid. – *Sustainable Production and Consumption* 33: 932-941.
- [2] Alam, M.K., Islam, M.A.S., Saeed, T., Rahman, S.M., Majed, N. (2023): Life cycle analysis of lab-scale constructed wetlands for the treatment of industrial wastewater and landfill leachate from municipal solid waste: a comparative assessment. – *Water* 15(5): 20p.
- [3] Alsabri, A., Tahir, F., Al-Ghamdi, S.G. (2021): Life-cycle assessment of polypropylene production in the gulf cooperation council (GCC) region. – *Polymers* 13(21): 14p.
- [4] Braskem Company (2016): I'm green: PE life cycle assessment. – Braskem Company 6p.
- [5] Çankaya, S., Pekey, B. (2024): Evaluating the environmental and economic performance of biological and advanced biological wastewater treatment plants by life cycle assessment and life cycle costing. – *Environmental Monitoring and Assessment* 196(4): 22p.
- [6] Chordia, M., Nordelöf, A., Ellingsen, L.A.W. (2021): Environmental life cycle implications of upscaling lithium-ion battery production. – *The International Journal of Life Cycle Assessment* 26(10): 2024-2039.
- [7] Corbella, C., Puigagut, J., Garfí, M. (2017): Life cycle assessment of constructed wetland systems for wastewater treatment coupled with microbial fuel cells. – *Science of the Total Environment* 584: 355-362.

- [8] Corominas, L., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., Morera, S., Shaw, A. (2013): Life cycle assessment applied to wastewater treatment: state of the art. – *Water Research* 47(15): 5480-5492.
- [9] Dewalkar, S.V., Shastri, S.S. (2021): Environmental impact assessment of wastewater treatment systems: State of the art. – *Advance and Innovative Research* 8(1): 8p.
- [10] Fang, Y.K., Wang, H.C., Fang, P.H., Liang, B., Zheng, K., Sun, Q., Li, X.Q., Zeng, R., Wang, A.J. (2023): Life cycle assessment of integrated bioelectrochemical-constructed wetland system: environmental sustainability and economic feasibility evaluation. – *Resources, Conservation and Recycling* 189: 10p.
- [11] 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.
- [12] Gallego-Schmid, A., Tarpani, R.R.Z. (2019): Life cycle assessment of wastewater treatment in developing countries: a review. – *Water Research* 153: 63-79.
- [13] Gmünder, S., Zollinger, M., Dettling, J. (2020): Biogenic Carbon Footprint Calculator for Harvested Wood Products. – *World Wide Fund for Nature (WWF)* 29p.
- [14] Gülçimen, S., Uzal, N. (2022): Comparative Life Cycle Assessment of the Environmental Impacts of Precast Concrete and Brick Walls. – *Erciyes Üniversitesi Fen Bilimleri Enstitüsü Fen Bilimleri Dergisi* 38(3): 426-433.
- [15] Halleux, H., Lassaux, S., Germain, A. (2006): Comparison of life cycle assessment methods, application to a wastewater treatment plant. – In 13th CIRP International Conference on Life Cycle Engineering, Leuven, Bélgica 4p.
- [16] Hydro Aluminium, A.S. (2019): Environmental Product Declaration in accordance with ISO 14025. – *The International EPD System* 18p.
- [17] Issaoui, R. (2023): Sustainable phosphate management: Environmental and Social life cycle assessment of phosphate mining in Tunisia. – *KIT Scientific Publishing* 254p.
- [18] Korre, A., Durucan, S. (2009): Life cycle assessment of aggregates, EVA025–Final report: Aggregates industry life cycle assessment model: Modelling tools and case studies. – *Waste and Resources Action Programme, Oxon* 10p.
- [19] Lakho, F.H., Qureshi, A., Igodt, W., Le, H.Q., Depuydt, V., Rousseau, D.P., Van Hulle, S.W. (2022): Life cycle assessment of two decentralized water treatment systems combining a constructed wetland and a membrane based drinking water production system. – *Resources, Conservation and Recycling* 178: 15p.
- [20] Liu, H., Li, Q., Li, G., Ding, R. (2020): Life cycle assessment of environmental impact of steelmaking process. – *Complexity* 9p.
- [21] Lourenço, N., Nunes, L.M. (2021): Life-cycle assessment of decentralized solutions for wastewater treatment in small communities. – *Water Science and Technology* 84(8): 1954-1968.
- [22] Machado, A.P., Urbano, L., Brito, A.G., Janknecht, P., Salas, J.J., Nogueira, R. (2007): Life cycle assessment of wastewater treatment options for small and decentralized communities. – *Water Science and Technology* 56(3): 15-22.
- [23] Mali, S., Garrett, P. (2022): Life cycle assessment of electricity production from an onshore V150-4.2 MW wind plant. – *Vestas* 134p.
- [24] Marson, A., Manzardo, A., Piron, M., Fedele, A., Scipioni, A. (2021): Life cycle assessment of PVC-A polymer alloy pipes for the impacts reduction in the construction sector. – *Chemical Engineering Transactions* 86: 721-726.
- [25] Montesó Tarrida, A. (2020): Environmental impact assessment of synthetic natural gas of renewable origin from pilot plant. – *Universitat Autònoma de Barcelona* 28p.
- [26] Nunez, P., Jones, S. (2016): Cradle to gate: life cycle impact of primary aluminium production. – *The International Journal of Life Cycle Assessment* 21(11): 1594-1604.
- [27] Olagunju, B.D., Olanrewaju, O.A. (2021): Life cycle assessment of ordinary Portland cement (OPC) using damage oriented (endpoint) approach. – In *Proceedings of the*

- International Conference on Industrial Engineering and Operations Management, Singapore 51p.
- [28] Onninen, A.S. (2024): Environmental product declaration. – The International EPD System 13p.
- [29] Ramsey, D., Ghosh, A., Abbaszadegan, A., Choi, J. (2014): Life cycle assessment of Pre-cast concrete vs. Cast-in-place concrete. – Phoenix, AZ: University of Arizona State, School of Sustainable Engineering and the Build Environment 16p.
- [30] Szulc, P., Kasprzak, J., Dymaczewski, Z., Kurczewski, P. (2021): Life cycle assessment of municipal wastewater treatment processes regarding energy production from the sludge line. – *Energies* 14(2): 29p.
- [31] 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(7): 1155-1169.
- [32] Tarpani, R.R.Z., Azapagic, A. (2023): Life cycle sustainability assessment of advanced treatment techniques for urban wastewater reuse and sewage sludge resource recovery. – *Science of The Total Environment* 869: 16p.
- [33] The European Plastic Pipes and Fittings Association (TEPPFA) (2019): PVC plastic pipe systems vs ductile iron environmental impact comparison. – TEPPFA 4p.
- [34] Von Sperling, M. (2007): Wastewater characteristics, treatment and disposal. – IWA publishing 304p.
- [35] Zampori, L., Saouter, E., Schau, E., CRISTOBAL, G.J., Castellani, V., Sala, S. (2016): Guide for interpreting life cycle assessment result. – Publications Office of the European Union 60p.