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Life cycle assessment of industry wastewater treatment plant: a case study in Vietnam

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This study employs Life Cycle Assessment (LCA) to evaluate the environmental impacts of wastewater treatment systems in industrial zones of Vietnam. Focusing on two treatment technologies—Anoxic–Oxic (OA) and Sequencing Batch Reactor (SBR)—as well as different electricity production methods and sludge management strategies, the research aims to identify opportunities for enhancing sustainability and reducing environmental footprints. Utilizing the ReCiPe v1.13 method and SimaPro 9.6.0.1 software, the study assesses key impact categories: climate change, freshwater eutrophication, human toxicity and freshwater ecotoxicity. The results showed that the OA system resulted in 30% lower climate change impacts than the SBR system (0.61 *vs.* 0.87 $\mathrm{kg_{CO_2\ eq}}$) but 24% higher freshwater eutrophication (6.17×10^{-4} *vs.* 4.69×10^{-4} $\mathrm{kg_{P\ eq}}$). Utilizing electricity produced from natural gas resulted in an 8.4% reduction in climate change impacts compared to using electricity from the local grid (0.6 *vs.* 0.66 $\mathrm{kg_{CO_2\ eq}}$) and an 81% reduction in freshwater ecotoxicity (1.29×10^{-3} *vs.* 2.18×10^{-5} $\mathrm{kg_{1,4\text{-}DB\ eq}}$). Additionally, endpoint analysis of Scenario 0 highlights that the AAO biological and coagulation tanks are the main contributors to Human Health and Resource impacts, with respective scores of 13.8 mPt and 11.5 mPt, demonstrating areas for targeted improvement. The utilization of sewage sludge as fertilizer reduces the impact on climate change by 80% (0.036 *vs.* 0.3 $\mathrm{kg_{CO_2\ eq}}$) and nearly eliminates freshwater eutrophication (5.01×10^{-6} *vs.* 1.77×10^{-4} $\mathrm{kg_{P\ eq}}$) compared to landfill. These findings provide detailed insights into different treatment processes and resource utilization strategies, offering a robust framework for enhancing sustainability in developing countries.

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Sustainability spotlight

Industrial wastewater treatment in Vietnam is crucial due to its significant environmental impact and the need for effective management practices. Our study advances sustainability by employing Life Cycle Assessment (LCA) to compare the environmental performance of Anoxic–Oxic (OA) and Sequencing Batch Reactor (SBR) technologies. This approach provides insights into energy use, emissions and sludge management, promoting more sustainable practices in wastewater treatment. By identifying more efficient technologies and practices, our work contributes to reducing environmental burdens and supports the UN Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production), by improving the sustainability of industrial wastewater management.

Introduction

Climate change and environmental degradation are urgent global challenges that demand cooperation between nations and industries to protect our planet. The 28th United Nations Climate Change Conference (COP 28) in Dubai, UAE, reinforced the global commitment to limiting temperature rise and pursuing a net-zero economy. Achieving net-zero emissions involves not only reducing greenhouse gases but also adopting comprehensive strategies to manage and minimize environmental impacts from all economic activities, including industrial wastewater treatment systems.[1]

Industrial zones, with their concentration of manufacturing activities, are essential to the economy but are also significant sources of environmental pollution. If wastewater treatment systems in these zones are not effectively designed and managed, they can contribute to water, air and soil pollution, as well as increase greenhouse gas emissions.[2,3] Therefore, enhancing the efficiency and sustainability of these systems is crucial.

Life Cycle Assessment (LCA) is a critical tool for evaluating the environmental impacts of products and processes. It has gained traction in recent years as a method for assessing wastewater treatment systems. LCA examines emissions and resource use throughout a system's life cycle, identifying

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opportunities to enhance efficiency and reduce environmental impact.[4] In developing countries, where wastewater infrastructure often lags behind, LCA can provide a structured approach to improve wastewater treatment processes, optimize resource allocation and reduce energy consumption.[5] For instance, studies have shown that improvements in biogas recovery and sludge management through LCA can significantly reduce greenhouse gas emissions and overall environmental footprint.[6]

As demonstrated in multiple studies, the global application of LCA in industrial wastewater treatment has been expanding. A significant number of studies have applied LCA to industrial wastewater, particularly in countries like China, India and Brazil, where industrial activities are booming.[5] However, even though many developing countries have shown interest in LCA, the application of LCA in Vietnam's wastewater treatment sector, particularly in industrial wastewater systems, remains limited.[7] This limitation represents a gap in the broader effort to mitigate environmental damage and improve sustainability in this region.

Applying LCA to industrial wastewater treatment systems could provide several significant benefits. First, LCA can identify the stages or processes with the most considerable environmental impacts, enabling targeted improvements.[8] Second, it offers a scientific basis for comparing and selecting treatment technologies that optimize both performance and environmental impact.[9] Lastly, by supporting the net-zero emissions goal, LCA can help businesses and policymakers better understand the primary sources of emissions and develop appropriate mitigation strategies.[10,11]

This study investigates the potential benefits of applying LCA to industrial wastewater treatment systems in Vietnam, where its use has been limited. By focusing on specific case studies within actual wastewater treatment systems, the research aims to demonstrate how LCA can help minimize harmful environmental impacts. The study also highlights the use of clean energy and sludge recovery for fertilizer, offering a comprehensive perspective on waste reuse and natural gas utilization in the context of a developing country where environmental concerns are still emerging.

Methodology

The LCA study followed the guidelines of the ISO 14040 standard series.[12] The ReCiPe v1.13 2016 (H, hierarchist) method was selected for environmental impact assessment, converting life cycle inventory data into environmental impact scores using characterization factors. The impact categories were then calculated using SimaPro 9.6.0.1 software.

Goal and scope

This study assessed the potential environmental impacts of two wastewater treatment systems—Anoxic–Oxic (OA) and Sequencing Batch Reactor (SBR)—at the centralized wastewater treatment plant located in a southern province of Vietnam. Each system has an average treatment capacity of approximately 1500 m^3 per day. The facility comprises equalization tanks, coagulation–flocculation tanks, either OA or SBR as the main treatment method (the key difference between the two construction phases of the plant), disinfection tanks, sludge tanks and dewatering units. Treated water is discharged into a nearby river, while chemicals for the treatment process are transported from Sai Gon Port JSC – Hiep Phuoc Terminal. Dewatered sludge is treated and buried at the Cu Chi – TSN waste treatment plant.

A cradle-to-gate approach was adopted for this study, focusing on the operational phase due to limited data on the construction and demolition stages. This approach encompasses all chemical, energy and transport consumption related to wastewater treatment processes. The system boundary, illustrated in Fig. 1, includes wastewater inflow, treatment processes, energy inputs, sludge handling and treated water outputs but excludes upstream impacts such as infrastructure development and transportation of end products like fertilizer to users.

Industrial wastewater from factories within the park is channeled into the centralized treatment plant. In the regulation tank, the flow and concentration of the wastewater are balanced for optimal processing. Next, in the coagulation–flocculation stage, pollutants are removed. Biological treatment then follows, utilizing OA technology during the first construction phase and SBR technology during the second. Once biologically treated, the wastewater undergoes disinfection to eliminate harmful bacteria before being discharged into the nearby river. Sludge produced during treatment is dewatered and either buried in a landfill or reused as fertilizer, depending on the operational scenario.

To evaluate and compare the environmental impacts, four operational scenarios were analyzed based on experimental data:

✓ Scenario 0 (baseline – green): the plant operates with OA as the primary treatment technology and dewatered sludge is buried in a landfill.

✓ Scenario 1 (red): a comparison of the two treatment technologies—OA and SBR—to assess environmental performance differences.

✓ Scenario 2 (blue): the plant operates entirely on energy sourced from natural gas instead of the local power grid.

✓ Scenario 3 (orange): biological sludge is either reused as DAP (diammonium phosphate) fertilizer or buried in a sanitary landfill.

Functional unit (FU)

In this study, the FU is defined as 1 m^3 of input wastewater. This standardization allows for consistent LCA analysis and makes it easier to compare the environmental impacts of different treatment scenarios.[7,13]

Life cycle inventory (LCI)

Wastewater properties data were collected and analyzed directly from a typical wastewater treatment system in Long An,

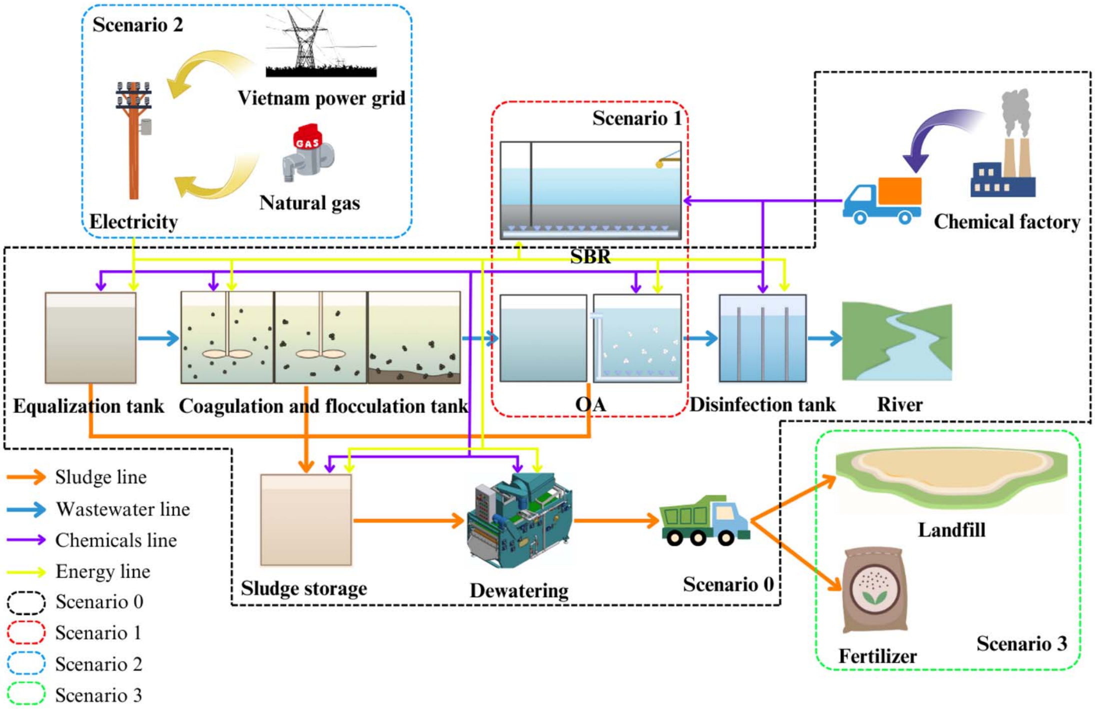

Fig. 1 System diagram and boundaries for LCI inventory of WWTP in different scenarios.

Vietnam using OA and SBR activated sludge methods and are presented in Table 1.

Direct N_2O emissions from wastewater treatment were calculated according to Bao *et al.*, 2016 (ref. 14) and Liu *et al.*, 2014.[15] Operational data provided by plant managers and data collected in January 2024 were used as baseline inventory data. The life cycle inventory (LCI) is presented in Table 2.

The DAP fertilizer recovered from the sludge in the bioreactor is based on the assumption that the fertilizer production efficiency is 80% of the total phosphorus content in the sludge (assuming all treated phosphorus is converted into sludge). The baseline data is derived from the ecoinvent v3.10 database, as detailed below:

- Electricity production in Vietnam (Hydro electricity 36.6%, thermal power 44.1%, electricity from oil 2.2%, electricity from gas 13.1%, electricity from renewable energy 4.1%).[16]
- Chemical production: data on chemical production (PAC, PAM, molasses, NaOH, DAP, *etc.*).
- Lorry with a capacity of 3.5–7.5 tons (Euro 5) are selected as means of transporting chemicals.
- Lorry with a capacity of 7.5–16 tons (Euro 5) are selected as means of transporting sludge.
- Electricity production using natural gas.

Table 1 Input and output parameters of wastewater at WWTP

Parameters	Unit	Influent	Effluent
pH		6–6.5	7.5–8
BOD	mg L^{-1}	410–453	25–27
COD	mg L^{-1}	800–885	52–58
Total suspended solids	mg L^{-1}	384–424	43–47
Residual chlorine	mg L^{-1}	2–2.1	0.4–0.42
Total nitrogen	mg L^{-1}	55–61	2.5–3
Total phosphorous	mg L^{-1}	5.3–6	0.45–0.52

Life cycle impact assessment (LCIA)

Life Cycle Impact Assessment (LCIA) was conducted with specific environmental impact points from the ReCiPe Midpoint 2016 methodology using SimaPro software to compare environmental indicators in different documents. Environmental managers often mainly assess impacts related to climate change and environmental quality issues. Therefore, we propose 11 impacts to be used for price assessment in this study including: climate change (CC – kg CO_2 eq), ozone depletion (OD – kg CFC-11 eq), terrestrial acidification (TA – kg SO_2 eq), freshwater eutrophication (FE – kg P eq), human toxicity (HT – kg 1,4-DB eq), photochemical oxidant formation (PCOF – kg NMVOC), particulate matter (PMF – kg PM10 eq), terrestrial ecotoxicity (TET – kg 1,4-DB eq), freshwater ecotoxicity (FET – kg 1,4-DB eq), ionizing radiation (IR – kBq U235 eq).[17] Additionally, the ReCiPe Endpoint 2016 methodology was employed to aggregate impacts into three endpoint categories—Human Health, Ecosystems and Resources—expressed in a common unit (mPt). These results provide a comprehensive perspective for Scenario 0, offering insights into the overall environmental performance of the system.

As mentioned, the utilization of sludge for DAP fertilizer production is considered a recovered product. Therefore, it is considered as an avoided product of equivalent production processes.[18] Since they represent an environmental benefit in the total impact of the system, they are subtracted from the

Table 2 WWTP inventory

Processes	Influent	Value	Unit	Effluent	Value	Unit
Equalization	Wastewater	1500	m^3	Wastewater	1499.93	m^3
	Electricity	21	kW h	Waste (solids, grease, sand)	70	kg
Coagulation and flocculation tank	Wastewater	1499.93	m^3	Wastewater	1497.93	m^3
	Electricity	32.016	kW h	Sludge	514.2	kg
	PAC	75	kg			
	NaOH	5	kg			
	PAM	8.2	kg			
	Transports, chemicals	3.969	tkm			
OA	Wastewater	1497.93	m^3	Wastewater	1496.93	m^3
	Electricity	95.874	kW h	Sludge	360	kg
	NaOH	5.625	kg	N_2O (emission)	1.392	kg
	Molasses	5	kg			
	Transports, chemicals	0.47813	tkm			
Disinfection tank	Wastewater	1496.93	m^3	Wastewater	1496.93	m^3
	Electricity	12.7	kW h			
	NaOCl	49.89	kg			
	Transports, chemicals	2.24505	tkm			
Sludge storage and dewatering tank	Electricity	12.41	kW h	Sludge	874.2	kg
	PAM	16.3	kg			
	Transports, sludge	17.484	tkm			
	Transports, chemicals	0.7335	tkm			
SBR	Wastewater	1497.93	m^3	Wastewater	1496.93	m^3
	Electricity	60.69	kW h	Sludge	403	kg
	Molasses	13.76	kg	N_2O (emission)	2.82495	kg
	Transports, chemicals	0.6192	tkm			

system and shown as a negative value in the interpretation of the results.

Results and discussion

LCA for wastewater treatment systems

The impact assessment results for LCA of WTTP for case 0 are presented in Table 3. It can be seen that the environmental indicators of this WTTP are lower than those of other industrial wastewater treatment plants. The CC, FET, FE indicators of a paper wastewater treatment plant were 1.54 $\mathrm{kg_{CO_2\ eq}}$, 0.12 $\mathrm{kg_{1,4\text{-}DB\ eq}}$, 0.0026 $\mathrm{kg_{P\ eq}}$, respectively.[2] In another report by Çapa *et al.*, 2022 [4] on an industrial wastewater treatment plant, the CC index was 0.85 $\mathrm{kg_{CO_2\ eq}}$ or 3.18 $\mathrm{kg_{CO_2\ eq}}$ according to Boldrin *et al.*, 2022 [9] on a municipal wastewater treatment plant. This may be due to the regulation that factories must conduct preliminary treatment before connecting to the centralized wastewater treatment system of the industrial park. Therefore, this treatment system does not consume too much chemicals, electricity, *etc.*

To gain a deeper understanding of the scale of the impact indicators, the indicator results were normalized using the ReCiPe/World H v1.13 reference method (Fig. 2). The scale of the indicators is highlighted here. Scenario 0 has the highest environmental impact on FE (0.0021) followed by FET and HT at 0.0018 and 0.0004, respectively. The results show that although climate change has the largest impact on WWTP, its total impact on global climate change is negligible. Therefore, the impact categories associated with Scenario 0 are FE, FET and HT.

The results presented in Fig. 3 show that the FE indicator was assessed over the entire life cycle, including direct nutrient emissions from the wastewater treatment system to the receiving environment, as well as indirect emissions from

Table 3 Total impact of Scenario 0

Impact category	Unit	Total	Equalization tank	Coagulation and flocculation tank	OA	Disinfection tank	Sludge storage and dewatering tank
CC	kg CO_2 eq	6.06×10^{-1}	9.20×10^{-3}	1.31×10^{-1}	3.24×10^{-1}	9.02×10^{-2}	5.11×10^{-2}
OD	kg CFC-11 eq	6.46×10^{-9}	3.94×10^{-11}	4.10×10^{-9}	7.38×10^{-10}	8.32×10^{-10}	7.47×10^{-10}
TA	kg SO_2 eq	1.72×10^{-3}	6.63×10^{-5}	7.12×10^{-4}	3.31×10^{-4}	3.87×10^{-4}	2.24×10^{-4}
FE	kg P eq	6.17×10^{-4}	3.50×10^{-6}	4.77×10^{-5}	1.83×10^{-5}	5.37×10^{-4}	1.13×10^{-5}
HT	kg 1,4-DB eq	1.34×10^{-1}	2.90×10^{-3}	6.57×10^{-2}	1.57×10^{-2}	3.70×10^{-2}	1.27×10^{-2}
PCOF	kg NMVOC	1.19×10^{-3}	3.55×10^{-5}	4.99×10^{-4}	1.83×10^{-4}	2.95×10^{-4}	1.75×10^{-4}
PMF	kg PM10 eq	7.09×10^{-4}	2.04×10^{-5}	2.91×10^{-4}	1.07×10^{-4}	2.13×10^{-4}	7.66×10^{-5}
TET	kg 1,4-DB eq	4.61×10^{-5}	3.05×10^{-7}	2.52×10^{-5}	2.31×10^{-6}	1.04×10^{-5}	7.82×10^{-6}
FET	kg 1,4-DB eq	7.79×10^{-3}	9.68×10^{-5}	3.55×10^{-3}	6.09×10^{-4}	2.58×10^{-3}	9.57×10^{-4}
IR	kBq U235 eq	1.62×10^{-2}	3.39×10^{-5}	6.58×10^{-3}	6.77×10^{-4}	7.42×10^{-3}	1.48×10^{-3}

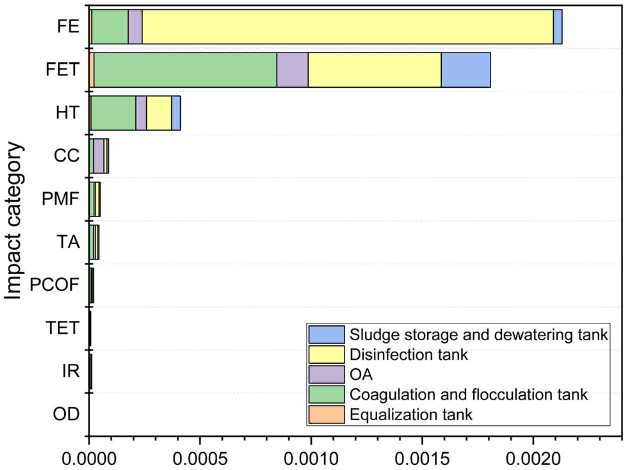

Fig. 2 Normalized impact assessment results for Scenario 0.

energy production, supply and chemical inputs used in various treatment processes. For the OA treatment technology, the influent water quality is detailed in Table 1. Fig. 4 highlights that nutrient emissions from the treatment system constitute the majority of the FE indicator, accounting for up to 81%, while indirect impacts from the system contribute approximately 19%. This finding aligns with other studies, which indicate that WWTPs often retain nutrients, particularly nitrogen and phosphorus in the water.[8,19,20] These results suggest that FE can be reduced by implementing more effective treatment methods to thoroughly remove nitrogen and phosphorus from the water.[21] This would not only enhance the quality of fertilizer production but also help reduce eutrophication at the receiving water bodies.

The FET indicator, which reflects the potential release of harmful chemicals into the environment during the life cycle of a product or process,[22] highlights the significant impact of chemical-intensive stages such as coagulation, flocculation, disinfection and sludge dewatering. Specifically, these stages contribute 45.4%, 33.1% and 12.3% to the FET index, respectively. Of these, polyaluminum chloride (PAC), used for coagulation, contributes about 36% to the total FET index, while sodium hypochlorite (NaOCl), a disinfectant, accounts for approximately 32.2%. Additionally, polyacrylamide (PAM), used in dewatering and sludge flocculation, contributes around 17%. These figures underscore the importance of managing chemical use in water treatment processes to minimize environmental impacts.

Each process within a treatment plant has the potential to cause toxicity and affect human health. The HT indicator must be carefully considered, especially in relation to the benefits of reducing other indicators such as CC, FE and FET. Notably, toxic impacts often do not arise directly from emissions into the air or wastewater but rather from indirect activities such as mining, chemical production and energy generation. Fig. 4 clearly demonstrates that chemical processes involving PAC, NaOCl, PAM and electricity contribute significantly to toxicity.[17]

In the LCA analysis, the OA treatment process contributes the largest share to the CC indicator, accounting for 53.5%. Other treatment processes, such as coagulation and flocculation, disinfection, sludge storage and dewatering and equalization, contribute 21.7%, 14.9%, 8.42% and 1.52%, respectively. Nitrous oxide (N_2O), a potent greenhouse gas with a global warming potential 300 times greater than that of carbon dioxide (CO_2),[23] is produced during nitrogen conversion in WWTPs and accounts for 45.6% of emissions from biological treatment systems.[24] Additionally, the use of electricity and various chemicals in wastewater treatment also significantly impacts the CC indicator, contributing between 10% and 15%. The total impact on the CC indicator in this study is 0.6 $kg_{CO_2\ eq}\ m^{-3}$. Similar results were also shown in the study of Pasqualino *et al.* (2011) with the traditional 3 step treatment system with CC index of about 0.8 $kg_{CO_2\ eq}\ m^{-3}$ (ref. 25) and fluctuating around 0.4–0.86 $kg_{CO_2\ eq}\ m^{-3}$ with the study of Bao *et al.* (2016).[14] In contrast, factors such as transportation, nutrients and sodium hydroxide (NaOH) during the treatment stages have a negligible impact on the CC indicator. This finding contrasts with studies by previous studies,[6,20,26] which identified energy consumption as the largest contributor to the CC indicator. This difference may be due to the relatively low energy consumption of the WWTP in this study, which is approximately 0.116 kW h m^{-3}, a small figure compared to the range reported by Li *et al.* (2021)[19] of 0.036 to 2.17 kW h m^{-3}, corresponding to 0.055 to 5.3 $kg_{CO_2\ eq}\ m^{-3}$.

Fig. 4 illustrates the endpoint analysis for the treatment system, showing a trend consistent with the midpoint assessment, with impacts expressed in a common unit, mPt. The total impact score is 37.9 mPt, distributed across Human Health (24.8 mPt), Resources (10.9 mPt) and Ecosystems (2.22 mPt). The AAO biological tank and coagulation tank are the most impactful stages, contributing 13.8 mPt and 11.5 mPt, respectively. Notably, the AAO tank accounts for 10.8 mPt in the Human Health category, the largest contributor to this impact, while the coagulation tank significantly affects Resource consumption, contributing 4.26 mPt. Table 4 compares the endpoint results with other wastewater treatment technologies, including UASB, activated sludge and MBBR. In the Human Health category, this system (24.8 mPt) performs better than activated sludge (35.22 mPt) and MBBR (28.6 mPt) but exhibits higher impacts than UASB (15.67 mPt). For Ecosystems, the impact of this system (2.22 mPt) is comparable to MBBR (2.6 mPt) and lower than activated sludge (4.82 mPt), showcasing its reduced ecological footprint. In Resource consumption, the system (10.9 mPt) demonstrates a balanced performance, with impacts lower than MBBR (15.9 mPt)[27] but higher than UASB (8.03 mPt) and activated sludge (8.08 mPt).[28] These findings underline the competitive advantages of the treatment system in this WWTP, particularly its lower ecological and resource-related impacts compared to activated sludge and MBBR systems. The integration of the AAO biological and coagulation tanks effectively addresses key environmental categories, making this system a promising alternative for achieving balanced sustainability in wastewater treatment.

LCA for scenarios

Midpoint analysis was selected for evaluating the scenarios due to its ability to provide detailed, specific insights into

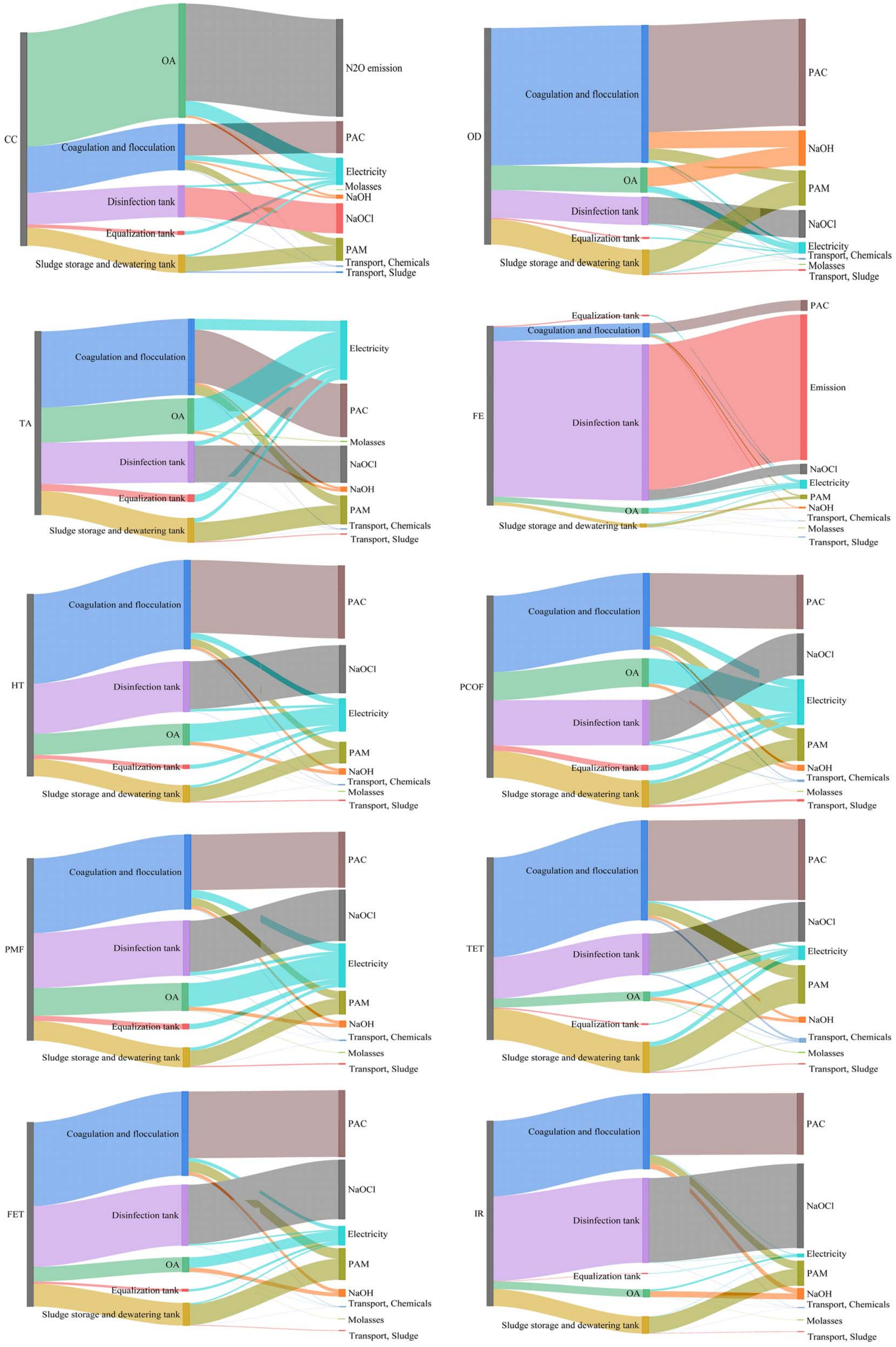

Fig. 3 Midpoint analysis in Scenario 0.

environmental impacts, which is particularly beneficial at this stage. It allows for the identification of weaknesses and improvement opportunities across different treatment systems or process stages.[29] This approach facilitates direct comparisons between options, offering a clearer understanding of environmental trade-offs. Additionally, midpoint analysis minimizes

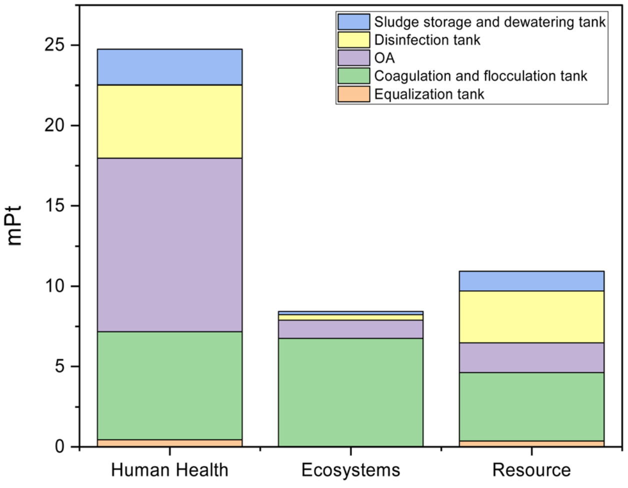

Fig. 4 Endpoint analysis in Scenario 0.

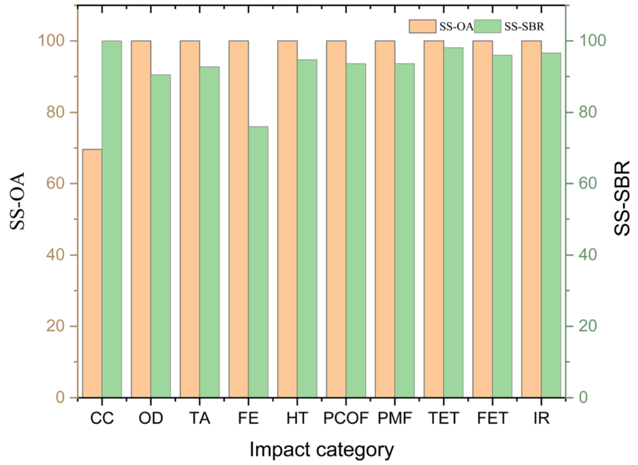

Fig. 5 Comparison of LCA results of two treatment systems OA and SBR.

complexity and uncertainty by reducing reliance on assumptions or conversion factors, which could otherwise influence the results.[30] As a result, the following scenarios could be assessed using midpoint analysis, ensuring a clear, consistent comparison of their environmental impacts and enabling the precise identification of strengths and weaknesses.

Scenario 1. The comparison between the two techniques (OA and SBR) was based on four key indicators: CC, FE, HT and FET (Fig. 5). The OA system exhibited 30% lower emissions for the CC indicator compared to the SBR system. However, despite the SBR system's higher N_2O emissions, it proved to be more efficient in both treatment and operation. For the other major impact indicators—FE, HT and FET—the SBR system outperformed the OA system, with reductions of 24%, 5.3% and 4%, respectively. These improvements are likely due to the SBR system's more effective management, reduced chemical usage and lower energy consumption. Additionally, optimizing aeration time in the SBR system can further decrease greenhouse gas emissions and reduce operating costs through energy savings.[31]

Scenario 2. The primary sources of electricity in Vietnam are hydropower and thermal power, which together account for 80.7% of the national electricity output, with hydropower contributing 36.6% and coal-fired power 44.1%. Gas, oil and renewable energy provide smaller shares, at 13.1%, 2.2% and 4.1%, respectively. Both coal-fired power and hydropower are associated with relatively high emissions per kW h of electricity produced, particularly nitrogen oxides NO_x, which contribute to eutrophication. Fig. 6 shows that utilizing entirely to electricity can significantly reduce key indicators such as CC, FE, FET and HT compared to using the local grid. Although the OD indicator is more than twice as high when using electricity compared to the grid, this increase is minor relative to the reductions in other important indicators.

Each LCA methodology reveals different impact points. For example, electricity generation in Vietnam emits approximately $0.66\ \text{kg}_{\text{CO}_2\ \text{eq}}\ \text{kW}^{-1}\ \text{h}^{-1}$ from the grid and $1.06\ \text{kg}_{\text{CO}_2\ \text{eq}}\ \text{kW}^{-1}\ \text{h}^{-1}$ from gas. In comparison, electricity generation from coal power in Indonesia also emits about $1.06\ \text{kg}_{\text{CO}_2\ \text{eq}}\ \text{kW}^{-1}\ \text{h}^{-1}$, while

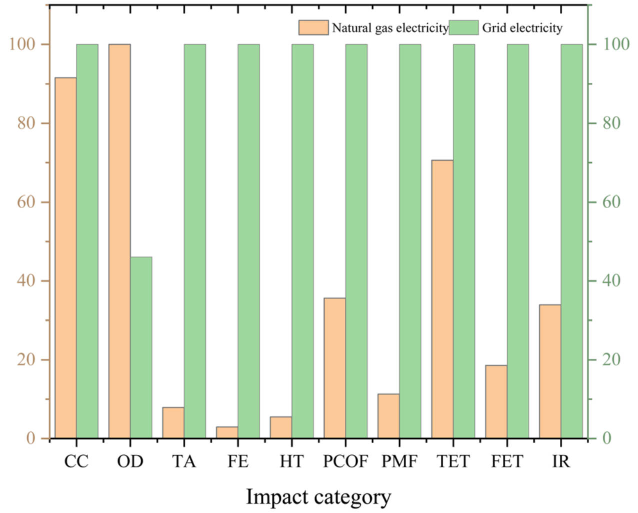

Fig. 6 Comparison of LCA results of 2 different electricity production processes.

Table 4 Endpoint impact comparison of wastewater treatment technologies

Category	Unit	This study	UASB[28]	Activated sludge[28]	MBBR[27]
Human health	mPt	24.8	15.67	35.22	28.6
Ecosystems	mPt	2.22	1.64	4.82	2.6
Resource	mPt	10.9	8.03	8.08	15.9

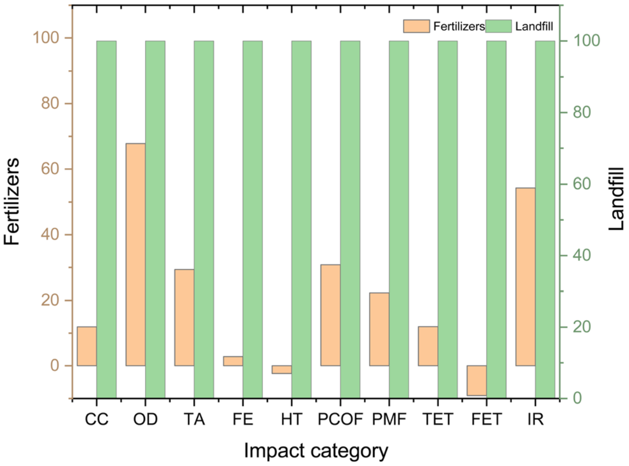

Fig. 7 Comparison of LCA results of 2 different sludge treatment processes.

Singapore emits approximately 0.45 $\mathrm{kg_{CO_2\ eq}}$ $\mathrm{kW^{-1}\ h^{-1}}$, Japan 0.4 $\mathrm{kg_{CO_2\ eq}}$ $\mathrm{kW^{-1}\ h^{-1}}$, Korea 0.49 $\mathrm{kg_{CO_2\ eq}}$ $\mathrm{kW^{-1}\ h^{-1}}$, Malaysia 0.69 $\mathrm{kg_{CO_2\ eq}}$ $\mathrm{kW^{-1}\ h^{-1}}$ and Thailand 0.63 $\mathrm{kg_{CO_2\ eq}}$ $\mathrm{kW^{-1}\ h^{-1}}$.[32,33]

Scenario 3. Sludge in wastewater treatment plants (WWTPs) is often neglected and inadequately managed, resulting in waste of resources and environmental pollution. This sludge contains valuable nutrients such as nitrogen, phosphorus and trace metals that are essential for plant growth. Therefore, the use of sludge to produce materials such as fertilizers is becoming increasingly popular. This study compares two sludge management methods: sludge composting and sanitary landfilling as shown in Fig. 7. LCA analysis shows that fertilizer production has significantly lower impacts on four key indicators—CC, FE, HT and FET—than landfilling. Specifically, the FET indicator shows a 9.1% reduction in the impact of fertilizer production. This reduction is due to effective sludge management and reduced hazardous waste emissions.[25]

However, the indicators in this study do not show negative emissions as reported by Pintilie *et al.* (2016),[8] possibly due to the limited amount of sludge recovered for fertilizer production and technical constraints. Nevertheless, the use of sludge as fertilizer is still an important step towards the goal of resource utilization. In addition, other sludge management methods, such as incineration, wet oxidation, pyrolysis and recycling with cementitious materials, have been explored in the literature.[34,35]

Conclusion

This study underscores the powerful potential of LCA in identifying key environmental indicators across various wastewater treatment scenarios. A comparative analysis between OA and SBR technologies reveals that while SBR systems offer superior treatment efficiency, they also demand higher resource consumption. Endpoint analysis in Scenario 0 further emphasizes that the AAO biological and coagulation tanks significantly contribute to Human Health (24.8 mPt) and Resource (10.9 mPt) impacts, highlighting critical areas for process optimization. Moreover, utilizing natural gas as an energy source significantly lowers environmental impacts and converting treated waste into compost proves to be more environmentally sustainable than traditional landfilling. These findings emphasize the critical role of integrating LCA into wastewater management strategies, offering essential insights for promoting long-term environmental sustainability and guiding decision-making in treatment technology selection and resource recovery.

Data availability

All data used or analyzed during this study are included in this article.

Author contributions

Writing—original draft preparation: Hao Anh Phan; conceptualization: Hung Van Tran; writing—review and editing: Ha Manh Bui. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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