Sustainability assessment of Hybrid constructed Wetlands vis-à-vis conventional activated Sludge processes for Municipal wastewater treatment

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Abstract
One of the life essential tool for estimation of environmental performance of any system is Life Cycle Assessment (LCA), which is equally, if not more, valid in assessing the environmental systems themselves, such as sewage treatment plants. The present study attempts a comparative LCA-based environmental assessment of a Constructed Wetland (CW) and an Activated Sludge Processing (ASP) based Sewage Treatment Plant (STP), using the SIMAPRO software, encompassing the evaluation of various impact categories, in addition to energy demand and water footprint as well.

The studies revealed the STP's to be higher energy-intensive and emission-generating processes where as CW's demonstrated a much lower carbon footprint and resource-consuming process. In fact, as per normalized impact assessment, CW also proves to be a low global warming, resource depletion and eco-toxicity and even significantly low energy and water footprint option.

Keywords: Constructed Wetland, Activated Sludge Process, Energy Footprint, Water Footprint, Life Cycle Assessment.

Introduction

Municipal wastewater, by virtue of high organic matter, nutrients, pathogens and even emerging contaminants, possesses serious environmental threats including eutrophication and range of public health hazards (such as contaminating surface and groundwater resources, upsetting ecosystems and decreasing biodiversity), a wide range of communicable diseases like cholera, dysentery etc. and associated economic implications such as higher medical expenses and lost productivity from illness, as well as possible losses in tourism and recreation[3,18].

Ironically more than half of the municipal wastewater generated are not duly treated worldwide and more so in India, constituting about 72% of the of the total accounted municipal wastewater generated i.e. 9,84,657 and 72,368 million litres per day respectively[14].

Most conventional sewage treatment processes (STP's) including, activated sludge process (ASP) normally comprises of primary (physical), secondary (biological) and tertiary (advanced) processes involving entailment of aeration of wastewater fostering growth of microorganisms[2].

Despite requiring a large amount of energy and infrastructure investment, it is frequently more effective than other traditional techniques like trickling filters because it permits higher concentrations of microorganisms and better nutrient removal[12].

However, despite its great effectiveness, often alternative approaches like constructed wetlands (CWs) seem to provide a more sustainable, affordable and environmentally beneficial alternative, although they do require a significant amount of land compared to STP's[5].

In fact, constructed wetlands (CW) use natural processes involving soil, vegetation and microorganisms to provide a more sustainable wastewater treatment option with reduced operating costs due to the fact that they do not require chemicals or electrical energy to operate related environmental benefits such as the enrichment of biodiversity, ease of maintenance due to lower operational and infrastructure costs compared to mechanical systems and even improved aesthetic values through integration with urban landscapes as green spaces[10,11,13].

It is becoming more widely acknowledged that evaluating the environmental sustainability of different wastewater treatment techniques is crucial for efficient resource management and environmental preservation. For assessing treatment techniques using frameworks, life cycle assessment (LCA) forms one of the primary unbiased tool for sustainability assessment[6]. In the present work, a comparative assessment of a conventional ASP-based STP and a hybrid-mode constructed wetland, which refers to a sequence of vertical and horizontal wetland, was carried out for various sustainable categories using Life Cycle Analysis (LCA) using SimaPro (version: 9.6.0.1)

Material and Methods

System Configuration: The system boundaries of the two wastewater treatment processes are conventional STP process and constructed wetland (CW) system (Figures 1A and 1B). In case of both the systems, the preliminary and primary treatment are common and hence excluded from the system boundaries, so also the sludge and effluent management, so as to address the comparative environmental assessment of activated sludge process *vis- à -vis* constructed wetland process.

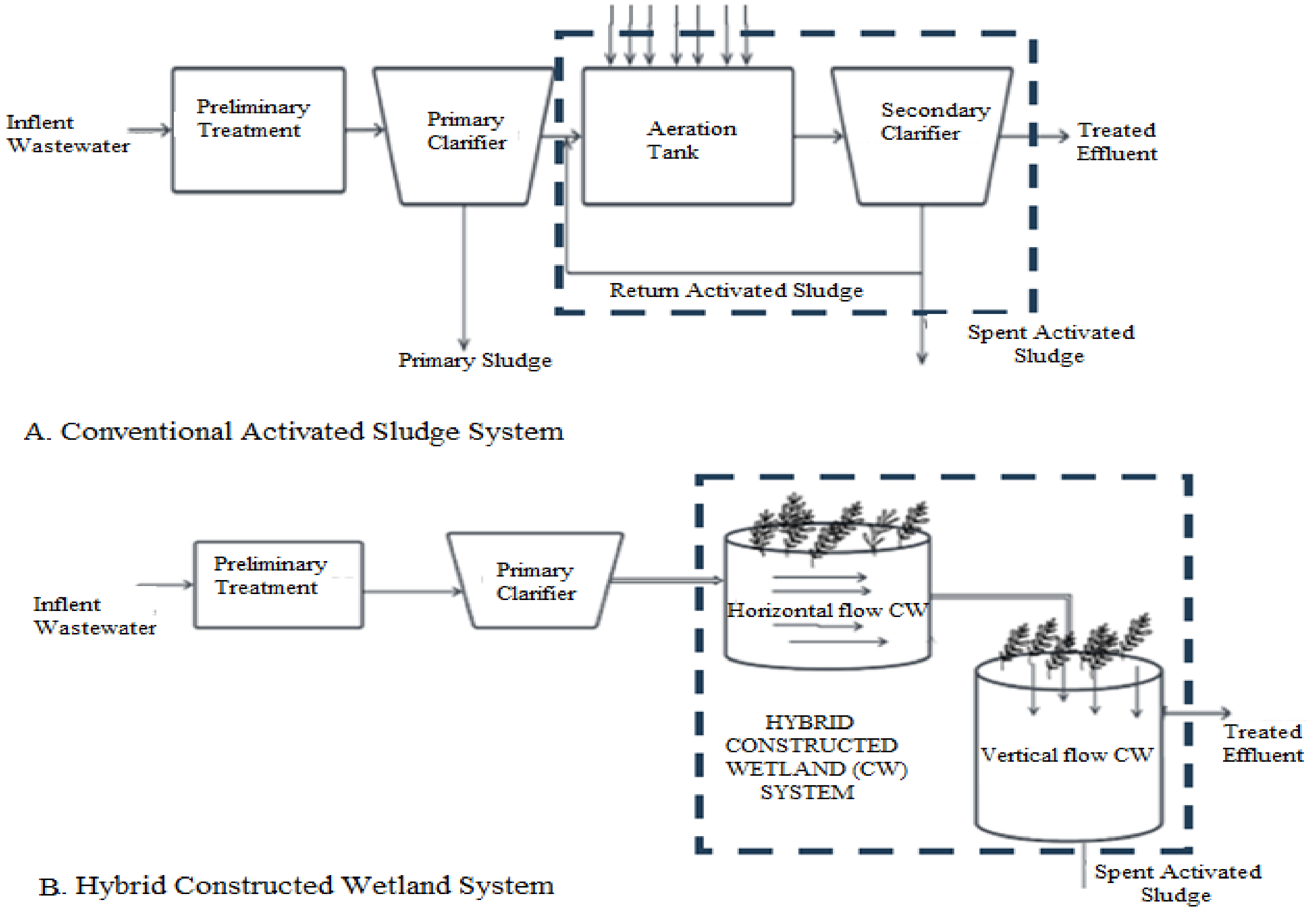

Figure 1: System Boundaries of two Wastewater Treatment Systems used in the present study

Process Description: In the conventional STP process (Figure 1A), the effluent is subjected to preliminary and primary treatment to remove coarse solids and settle able materials before entering the aeration tank[13]. The aeration tank is expected to facilitate biological treatment through the activated sludge process, where microorganisms would aerobically degrade organic pollutants. The secondary clarifier is likely to remove treated water from sludge, a part of which is being returned to aeration unit as return activated sludge (RAS) and rest as waste activated sludge(WAS) and nutrients, which undergo optional disinfection before being discharged or reused. Sludge from both primary and secondary clarifiers is further processed for disposal (or reuse). The treated effluent, likely to be low in total suspended solids (TSS), as well as biological oxygen demand (BOD), is allowed for discharge or suitable usage (gardening, toilet flushing, etc.).

Specific studies on the pollutant loading associated with disposal and usage of sludge and treated effluents are not included in the present study. In the case of the hybrid constructed wetland (HCW) system (Figure 1B), on the other hand, the effluent from the primary treatment enters the wetland system through a sequence of horizontal flow constructed wetland (HFCW) (consisting of a vegetated gravel bed where microbial activity, sedimentation and plant uptake are expected to remove organic matter and nutrients), followed by the vertical flow constructed wetland (VFCW) (so as to allow the outflow from HFCW to percolate through a sand or gravel substrate, further reducing organic matter, nitrogen and phosphorus)[16].

The proposed wetlands system is likely to remove pollutants through natural processes such as microbial activity, plant uptake, sedimentation and adsorption. In horizontal flow wetlands, BOD and TSS are likely to be reduced as water flows through vegetated (*Phragmites Australia*, *Typha spp.*, *Scirpus*, *Juncusspp.*, *Cyprusspp*.) substrates whereas limited nutrient removal occurs. The vertical flow wetlands would enhance TN and TP removal through improved oxygenation, nitrification, de-nitrification and phosphorus adsorption. Together, the wetland systems are expected to achieve comparable or better removal efficiencies for BOD and TSS and superior nutrient removal (TN and TP), enhanced oxygen transfer and overall reduction in pollutant-loadings, while being energy-efficient and environmentally friendly.

Life Cycle Assessment (LCA) Framework

The sustainable assessment of the system has been carried out through life cycle assessment, according to the ISO standard, to assess the environmental impact of conventional activated sludge processes and hybrid constructed wetland systems for treating municipal wastewater through LCA application, progressing through four sequences, namely, goal and scope definition, inventory analysis, impact assessment and interpretation of the results. Therefore, the LCA was applied following the phases outlined as follows.

Goal and Scope Definition: This research focuses on establishing the purpose, objectives and boundaries of the assessment. The primary goal is to compare the environmental impacts of the Conventional Activated Sludge (CAS) system and the Constructed Wetland System (CWS) for municipal wastewater treatment to identify the most sustainable option. This comparison is based on key environmental indicators such as energy consumption, greenhouse gas emissions, pollutant removal efficiency (BOD, TSS, TN, TP) and resource use across the entire life cycle of both systems. The functional unit of the assessment is the treatment of 1 cubic meter of municipal wastewater to meet discharge standards. The system boundaries were defined to include all stages from construction and operation to decommissioning, for both systems. The STP system uses energy for aeration, chemical inputs and sludge handling, whereas the CWS incorporates materials for construction, minimal energy for pumping and natural treatment processes. The scope also considers local contexts such as land availability and environmental conditions to ensure comprehensive and context-specific analysis.

Life Cycle Inventory (LCI)-Specifications, Bases and Characterization: Inventory analysis involves the procurement and evaluation of data for each stage of operation in relation to inputs and outputs corresponding to given functional unit i.e. rate of treatment as 180 KLD (kilolitres per day), focussing on resource usage (both materials and energy) as well as emission with associated impacts on air, water and soil over the entire operational life (assumed to be 20 years, here). The raw and treated wastewater characteristics (both physic-chemical and hydraulic) are provided in table 1.

Comparative Life Cycle Impact Assessment of Constructed Wetlands (CW) and Sewage Treatment Plants (STP): The analysis of life cycle impact assessment (LCIA) data for constructed wetlands (CW) and sewage treatment plants (STP) was carried out to assess the distinct trends and insights into their environmental performance. SimaPro (version: 9.6.0.1) was used for LCA modelling, eco-invent database (v3.1) for inventory data.

The global ReCiPe 2016 (v1.09) Midpoint method was used for interpretation of three primary categories of impact, viz. resource depletion, human health and ecosystem quality. For the reference year 2010, AWARE (v1.02) was used to explore water footprint. The life cycle impact assessment (LCIA) in this study evaluates the environmental consequences of natural resource procurement and chemical emissions across specific environmental impact categories (including climate change, acidification, eco toxicity and resource depletion) and their subcategories, following the standardized LCIA procedures outlined in ISO 14043:1997 guidelines.

Results and Discussion

Impact and Damage Assessment of the STP and CW-based Treatment methods on Human Health: With regard to environmental and health impacts (Table 2), the life cycle impact and damage assessment results for treated sewage from constructed wetlands (CWS) and sewage treatment plants (STP) highlight significant differences.

In terms of global warming-related human health impacts, STPs exhibit a higher total impact (3.66E-08 DALY) compared to CWS (2.90E-08 DALY). This aligns with findings that conventional wastewater treatment plants (WWTPs), like STPs, emit substantially more greenhouse gases, nearly 100 times more methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) than CWS annually.

Table 1
Raw and Treated wastewater characteristics (CASP and HCWS systems)

S.N.	Parameters	Unit	Design consideration for LCA		
Characteristics of influent wastewater			**Before Treatment**	**After Treatment**	
				STP	**HCWS**
1	Colour	---	Clear	Clear	Clear
2	pH	---	6.5-8.5	6.5-8.5	6.5-8.5
3	Biological Oxygen Demand (BOD)	mg/l	200	50	30
4	Total Suspended Solids (TSS)	mg/l	240	60	20
5	Total Nitrogen (TN)	mg/l	35	26	30
6	Total Phosphorus (TP)	mg/l	27	15	5
Influent flow properities					
7	Average Design Flow Rate	m^3/day	230		
8	Average flow rate	m^3/hour	29		
9	Temperature	Deg C	22-35		
10	Design Reactor Temperature	Deg C	22-35		

Table 2
Life Cycle Impact & Damage Assessment of Human Health Categories for CW and STP

Impact category (Unit)	**Type**	**Impact Assessment (Emission) of Treated Sewage**					
		CWS			**STP**		
		Total	**Short-term**	**Long-term**	**Total**	**Short-term**	**Long-term**
Global warming, Human health (DALY)	Impact	2.90E-08	2.03E-08	8.7E-09	3.66E-08	3.64E-08	2.2E-10
	Damage	6.95E-10	4.87E-10	2.08E-10	8.77E-10	8.72E-10	5.35E-12
Stratospheric ozone depletion (DALY)	Impact	3.00E-12	3.00E-12	4E-19	5.37E-12	5.37E-12	8E-19
	Damage	7.20E-14	7.20E-14	1.00E-20	1.29E-13	1.29E-13	2.00E-20
Ionizing radiation (DALY)	Impact	9.64E-12	1.01E-12	8.6E-12	1.72E-11	1.80E-12	1.5E-11
	Damage	2.31E-13	2.42E-14	2.07E-13	4.14E-13	4.33E-14	3.70E-13
Ozone formation, Human health (DALY)	Impact	4.35E-11	4.35E-11	2.2E-16	4.77E-09	7.79E-11	4.7E-09
	Damage	1.04E-12	1.04E-12	5.30E-18	1.14E-10	1.87E-12	1.12E-10
Fine particulate matter formation (DALY)	Impact	3.39E-08	3.39E-08	1.1E-11	3.49E-07	6.07E-08	2.9E-07
	Damage	8.14E-10	8.14E-10	2.58E-13	8.37E-09	1.46E-09	6.91E-09
Human carcinogenic toxicity (DALY)	Impact	8.78E-09	2.79E-10	8.5E-09	1.57E-08	4.99E-10	1.5E-08
	Damage	2.11E-10	6.69E-12	2.03E-10	3.77E-10	1.20E-11	3.64E-10
Human non-carcinogenic toxicity (DALY)	Impact	7.25E-09	9.80E-10	6.3E-09	1.30E-08	1.75E-09	1.1E-08
	Damage	1.74E-10	2.35E-11	1.50E-10	3.11E-10	4.21E-11	2.69E-10
Water consumption, Human health (DALY)	Impact	2.15E-11	2.15E-11	0	3.85E-11	3.85E-11	0
	Damage	5.15E-13	5.15E-13	0	9.23E-13	9.23E-13	0

These emissions are driven by energy-intensive processes in STPs which dominate short-term impacts while CWS demonstrates a more distributed effect over time due to its reliance on natural processes and lower energy demands[8,9].

The damage assessment corroborates this trend, indicating that greenhouse gas emissions from STPs contribute significantly to climate-related health risks such as respiratory illnesses and heat stress. The Intergovernmental Panel on Climate Change (IPCC) recognizes that the short-cycle CO_2 produced during organic matter breakdown in CWS does not contribute to the greenhouse effect, further supporting the lower climate impact of CWS[8]. Additionally, studies show that optimizing CWS systems by integrating plant resource recovery can reduce their environmental impact by up to 85%, making them even more sustainable[19].

Stratospheric ozone depletion is also more pronounced in STPs (5.37E-12 DALY) compared to CWS (3.00E-12 DALY), with nearly all effects occurring in the short term due to direct chemical emissions during treatment operations. Similarly, ionizing radiation impacts are higher for STPs (1.72E-11 DALY) than for CWS (9.64E-12 DALY), with long-term effects linked to radioactive emissions from industrial effluents treated in these systems[7]. Ozone formation related to human health shows a stark contrast, with STPs exhibiting an order of magnitude of higher impact (4.77E-09 DALY) than CWS (4.35E-11 DALY). This is attributed to the significant release of NO_x and volatile organic compounds (VOCs) in STPs, which contribute heavily to ground-level ozone formation and exacerbate respiratory conditions[9].

Fine particulate matter formation presents one of the most pronounced disparities, with STP emissions reaching 3.49E-07 DALY, nearly tenfold higher than CWS at 3.39E-08 DALY, reinforcing their substantial contribution to air pollution and associated health risks [9]. The human toxicity analysis reveals that STPs pose a higher risk for both carcinogenic and non-carcinogenic toxicity, with carcinogenic toxicity at 1.57E-08 DALY for STP versus 8.78E-09 DALY for CWS and non-carcinogenic toxicity at 1.30E-08 DALY for STP versus 7.25E-09 DALY for CWS. This reflects the greater presence of harmful substances such as heavy metals and organic pollutants in STP effluents[4,7]. Water consumption-related human health impacts are also more significant for STPs (3.85E-11 DALY) compared to CWS (2.15E-11 DALY), reflecting the higher resource demands of conventional treatment facilities[9] .

Impact and Damage Assessment of the STP and CW-based Treatment methods on Ecosystem: Beyond human health impacts, environmental consequences extend to ecosystems (Table 3).

For terrestrial species loss due to global warming, STPs have a higher impact (1.79E-09 species·yr) than CWS (1.42E-09 species·yr). This is consistent with findings that land use and habitat alteration are more significant in STPs due to their infrastructure requirements[9,14]. Ozone formation in terrestrial ecosystems is also significantly more pronounced in STPs (1.12E-09 species·yr) than in CWS (1.01E-10 species·yr), reflecting the ecological degradation caused by NO_x and VOC emissions from conventional treatment processes[9].

Table 3
Life Cycle Impact & Damage Assessment of Ecosystem Categories for CW and STP

Impact category (Unit)	**Type**	**Impact Assessment (Emission) of Treated Sewage**					
		CWS			**STP**		
		Total	**Short-term**	**Long-term**	**Total**	**Short-term**	**Long-term**
Global warming, Terrestrial ecosystems (species.yr)	Impact	1.42E-09	9.94E-10	4.2E-10	1.79E-09	1.78E-09	1.1E-11
	Damage	2.10E-12	1.47E-12	6.27E-13	2.65E-12	2.63E-12	1.61E-14
Global warming, Freshwater ecosystems (species.yr)	Impact	3.87E-14	2.71E-14	1.2E-14	4.89E-14	4.86E-14	3E-16
	Damage	5.73E-17	4.02E-17	1.71E-17	7.23E-17	7.19E-17	4.40E-19
Ozone formation, Terrestrial ecosystems (species.yr)	Impact	1.01E-10	1.01E-10	5E-16	1.12E-09	1.81E-10	9.4E-10
	Damage	1.49E-13	1.49E-13	7.40E-19	1.66E-12	2.67E-13	1.39E-12
Terrestrial acidification (species.yr)	Impact	2.33E-10	2.33E-10	3E-16	1.56E-09	4.17E-10	1.1E-09
	Damage	3.44E-13	3.44E-13	4.40E-19	2.31E-12	6.16E-13	1.69E-12
Freshwater eutrophication (species.yr)	Impact	1.43E-09	1.19E-09	2.4E-10	6.04E-10	1.73E-10	4.3E-10
	Damage	2.12E-12	1.76E-12	3.56E-13	8.94E-13	2.56E-13	6.37E-13
Marine eutrophication (species.yr)	Impact	7.41E-12	7.38E-12	3.6E-14	4.52E-12	4.45E-12	6.4E-14
	Damage	1.10E-14	1.09E-14	5.29E-17	6.68E-15	6.59E-15	9.47E-17
Terrestrial ecotoxicity (species.yr)	Impact	7.63E-12	7.58E-12	5.1E-14	1.37E-11	1.36E-11	9E-14
	Damage	1.13E-14	1.12E-14	7.47E-17	2.02E-14	2.01E-14	1.33E-16
Freshwater ecotoxicity (species.yr)	Impact	8.30E-12	1.04E-13	8.2E-12	1.49E-11	1.86E-13	1.5E-11
	Damage	1.23E-14	1.54E-16	1.21E-14	2.20E-14	2.75E-16	2.17E-14
Marine ecotoxicity (species.yr)	Impact	1.77E-12	7.81E-14	1.7E-12	3.16E-12	1.40E-13	3E-12
	Damage	2.61E-15	1.16E-16	2.49E-15	4.68E-15	2.07E-16	4.47E-15
Water consumption, Terrestrial ecosystem (species.yr)	Impact	1.26E-11	1.26E-11	0	2.25E-11	2.25E-11	0
	Damage	1.86E-14	1.86E-14	0	3.32E-14	3.32E-14	0
Water consumption, Aquatic ecosystems (species.yr)	Impact	3.48E-15	3.48E-15	0	6.24E-15	6.24E-15	0
	Damage	5.15E-18	5.15E-18	0	9.22E-18	9.22E-18	0

Terrestrial acidification follows a similar pattern, where STPs exhibit a much greater impact (1.56E-09 species·yr) than CWS (2.33E-10 species·yr), driven by sulphur and nitrogen emissions from energy-intensive operations[9]. Freshwater eutrophication presents an exception, with CWS showing a slightly higher impact (1.43E-09 species·yr) than STP (6.04E-10 species·yr), likely due to nutrient runoff associated with natural treatment methods[7,14]. However, marine eutrophication remains marginally higher for CWS (7.41E-12 species·yr) compared to STP (4.52E-12 species·yr), reinforcing concerns about nitrogen and phosphorus discharge from wetland systems[17].

Eco toxicity impacts are consistently greater in STPs across terrestrial, freshwater and marine environments due to the release of toxic substances during energy-intensive treatment processes[7,9]. For example, freshwater eco toxicity shows nearly double the impact for STPs compared to CWS, a trend that extends to marine ecosystems as well[4]. Water consumption also imposes a heavier burden on terrestrial ecosystems for STPs (2.25E-11 species·yr) compared to CWS (1.26E-11 species·yr)[9].

Impact and Damage Assessment of the STP and CW-based Treatment methods on Resource Depletion: Resource depletion analysis (Table 4) brings out certain characteristic variations with regard to the two treatment systems considered herewith i.e. STP and CW. The observations obtained herewith highlight similar disparities: land use impact is greater in STPs (1.14E-10 species·yr) than in CWS (6.35E-11 species·yr), indicating more habitat conversion and ecological disruption[14]. Mineral resource scarcity is also higher for STPs (3.43×10^{-12} USD2013) compared to CWS (1.92×10^{-12} USD2013). Fossil resource scarcity presents the most striking difference, with STPs exhibiting significantly greater impacts (6.97×10^$^{-10}$ USD2013 versus 3.89×10^{-10} USD2013 for CWS), reflecting their high energy dependency[9].

Overall, these findings indicate that while both systems have environmental impacts, constructed wetlands offer a more sustainable alternative with lower greenhouse gas emissions, reduced toxicity and minimal resource demands when compared to sewage treatment plants[7,8,17].

However, slight increases in eutrophication impacts for CWS suggest a need for improved nutrient removal strategies[14]. Promoting decentralized natural treatment systems like CWS could help reduce the environmental footprint of wastewater management while ensuring public health benefits[1,4].

Table 4
Life Cycle Impact and Damage Assessment of Resource Depletion Categories for CW and STP

Impact category (Unit)	Type	Impact Assessment (Emission) of Treated Sewage					
		CWS			STP		
		Total	Short-term	Long-term	Total	Short-term	Long-term
Land use (species.yr)	Impact	6.35E-11	6.35E-11	0	1.14E-10	1.14E-10	0
	Damage	9.39E-14	9.39E-14	0	1.68E-13	1.68E-13	0
Mineral resource scarcity (USD2013)	Impact	1.92E-12	1.92E-12	0	3.43E-12	3.43E-12	0
	Damage	5.37E-08	5.37E-08	0	9.62E-08	9.62E-08	0
Fossil resource scarcity (USD2013)	Impact	3.89E-10	3.89E-10	0	6.97E-10	6.97E-10	0
	Damage	1.09E-05	1.09E-05	0	1.95E-05	1.95E-05	0

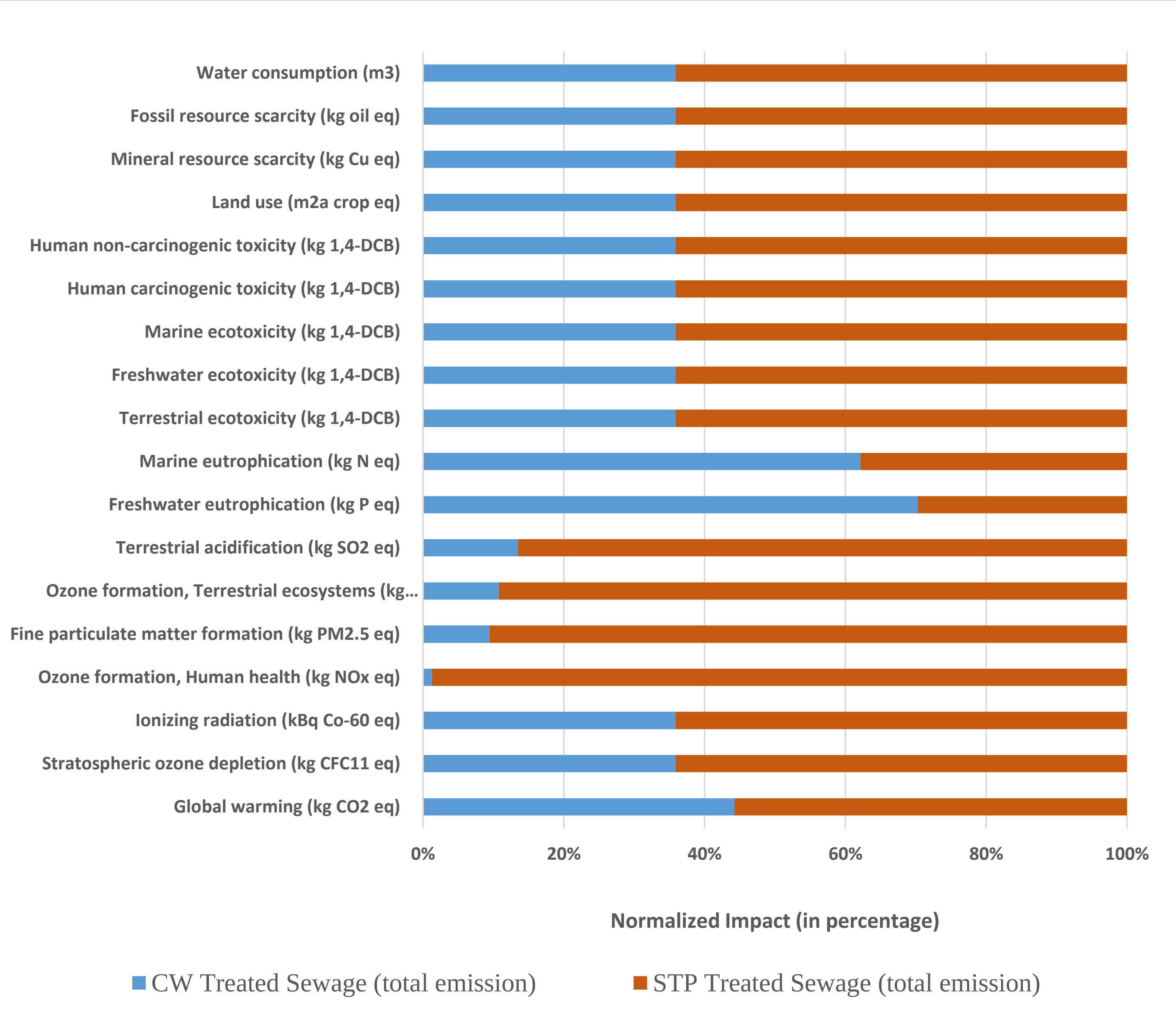

Figure 2: Comparative Assessment of Emission by the Treatment Systems

Moreover, integrating renewable energy into conventional treatment plants like STPs could mitigate their negative impacts by reducing fossil fuel dependency and improving pollutant removal efficiency[7,9].

Comparative Assessment of Emission by the Treatment Systems: Figure 2 highlights the comparative environmental impact of STP and CW across multiple categories. STP exhibits significantly higher emissions in most categories, particularly in resource consumption (water, fossil fuels, minerals, land use), toxicity (human and ecological), air pollution (fine particulates, ozone depletion) and climate change contributions (GHG emissions, ionizing radiation). These impacts stem from STP's energy-intensive processes, chemical usage and fossil fuel dependence.

Conversely, CW demonstrates lower overall emissions but higher freshwater and marine eutrophication potential due to nutrient retention in treated effluents. This suggests the need for enhanced nutrient management in CW systems. In fact, these findings align with the findings in table 2 which indicated a substantially greater global warming impact for STP compared to CW.

It may be noted that fine particulate matter formation follows a particularly stark contrast, with STP (3.49E-07 DALY) showing an order of magnitude higher impact than CWS (3.39E-08 DALY) (Table 2). These emissions arise primarily from fossil fuel combustion in STP operations, resulting in a significant burden on urban air quality. The high level of particulate matter can exacerbate respiratory conditions such as asthma and chronic obstructive pulmonary disease (COPD), particularly among vulnerable populations. Figure 3 further supports this finding (Table 2), illustrating that STP-treated sewage contributes disproportionately to PM2.5 emissions.

Category Specific Normalized Assessment of Impact Assessment of STP and CW-based Treatment Systems: On normalization of all the impact parameters (and subsequent grouping into the respective categories), the relative contribution of the two treatment systems unto the three impact categories (namely, human health, ecosystem and resource depletion) could be estimated (Figure 3). The normalized impact distribution across human health, ecosystems and resource depletion categories (Figure 3) highlights a consistently higher environmental burden associated with STP-treated sewage. The stark contrast in category-wise impact suggests that STP, due to its reliance on energy-intensive mechanisms, contributes significantly to climate change, toxicity and resource consumption.

It may be observed that the results from table 2 indicate that STP has a consistently higher impact across multiple categories, particularly in global warming, particulate matter formation and toxicity-related effects. These findings align with the graphical representation in figures 2 and 3 which show a greater normalized impact of STP on human health, ecosystems and resource depletion.

Besides, terrestrial acidification is also a major concern, with STP (1.56E-09 species.yr) having a significantly higher impact than CWS (2.33E-10 species.yr) (Table 3). This finding is reinforced by figure 3 which indicates that STP emits considerably more SO_2 equivalent pollutants, leading to acid rain and soil degradation. The damage assessment follows a similar pattern, emphasizing the potential for long-term loss of soil fertility and disruption of forest ecosystems.

Energy Footprint of STP and CW Systems: Figure 4 illustrates the energy demand of STP and CW across different energy sources. STP exhibits a substantially higher energy demand and resource depletion compared to CW, particularly from fossil fuels and nuclear energy, which are non-renewable and contribute to greenhouse gas emissions and environmental degradation. The reliance on these sources is primarily due to the high operational energy requirements of STP processes such as aeration, pumping and sludge treatment.

CW having lower energy footprint, drawing minimal energy from all sources. Its reliance on passive treatment mechanisms including microbial degradation and plant-based filtration, reduces the need for external energy inputs. The minimal demand for renewable energy sources such as biomass, wind and hydro, further highlights CW's efficiency in utilizing natural treatment processes with negligible energy dependency.

The fossil resource scarcity impact is particularly notable, with STP (6.97E-10 USD2013) consuming nearly double that of CWS (3.89E-10 USD2013) (Table 4). Figure 4 further highlights this trend, demonstrating that STP has a substantially higher energy demand, primarily due to aeration and chemical treatment processes.

The excessive energy consumption of STP not only increases greenhouse gas emissions but also raises operational costs, making it less sustainable in the long run. The stark contrast in energy consumption reinforces CW's sustainability advantage over STP**.** While STP ensures faster treatment and better pollutant removal, its high energy reliance increases its carbon footprint.

Water Footprint of STP and CW Systems: Figure 5 illustrates the water footprint of STP and CW, with STP accounting for 64% and CW for 36% of total water consumption. The higher water footprint of STP is primarily due to its energy-intensive processes, chemical treatments and sludge handling which require significant volumes of water for dilution, cleaning and system maintenance. Additionally, water losses occur through evaporation and residual moisture in sludge.

Conversely, CW has a lower water footprint (36%) indicating its efficiency in utilizing natural treatment processes with minimal additional water requirements. The passive nature of CW, relying on plant uptake and microbial degradation, reduces water loss and enhances overall sustainability.

As described in table 3, water consumption is another critical parameter, with STP placing a significantly higher demand on freshwater resources (3.85E-11 DALY) compared to CWS (2.15E-11 DALY). Figure 5 provides additional clarity, showing that STP-treated sewage accounts for 64% of the total water footprint whereas CWS contributes only 36%. This underscores the advantage of CWS in minimizing freshwater withdrawals, making it a more sustainable solution in water-scarce regions. This comparison highlights that while STP may provide faster and more controlled treatment, it does so at the cost of higher water consumption. In contrast, CW offers a more water-efficient alternative**,** making it a preferable choice in regions facing water scarcity.

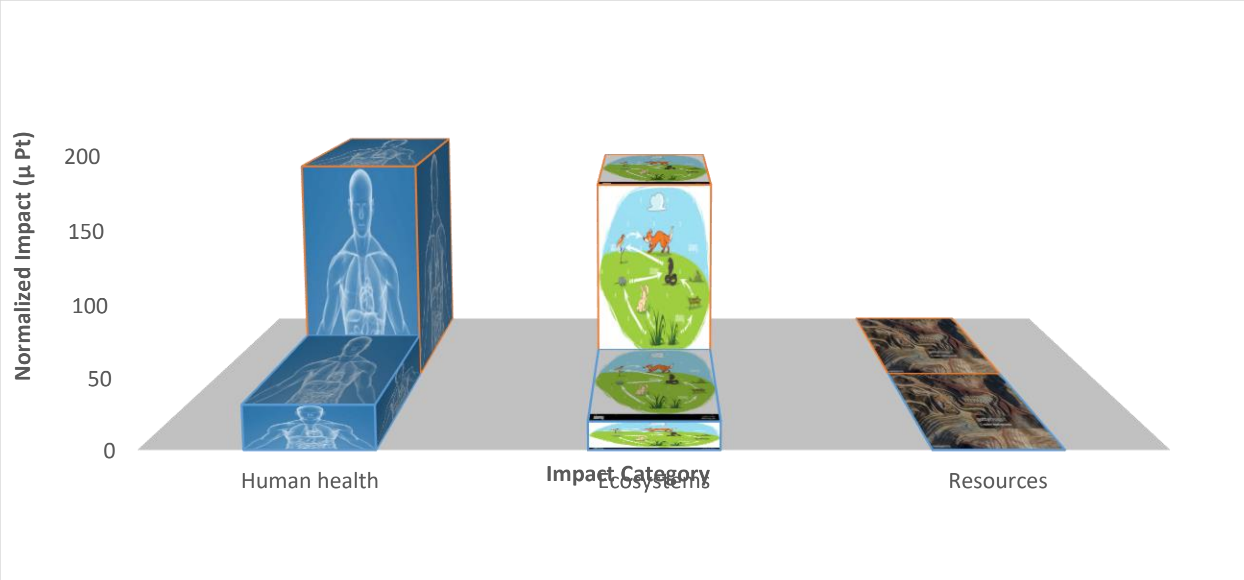

Figure 3: Category-wise Normalized Impacts by Different Treatment System

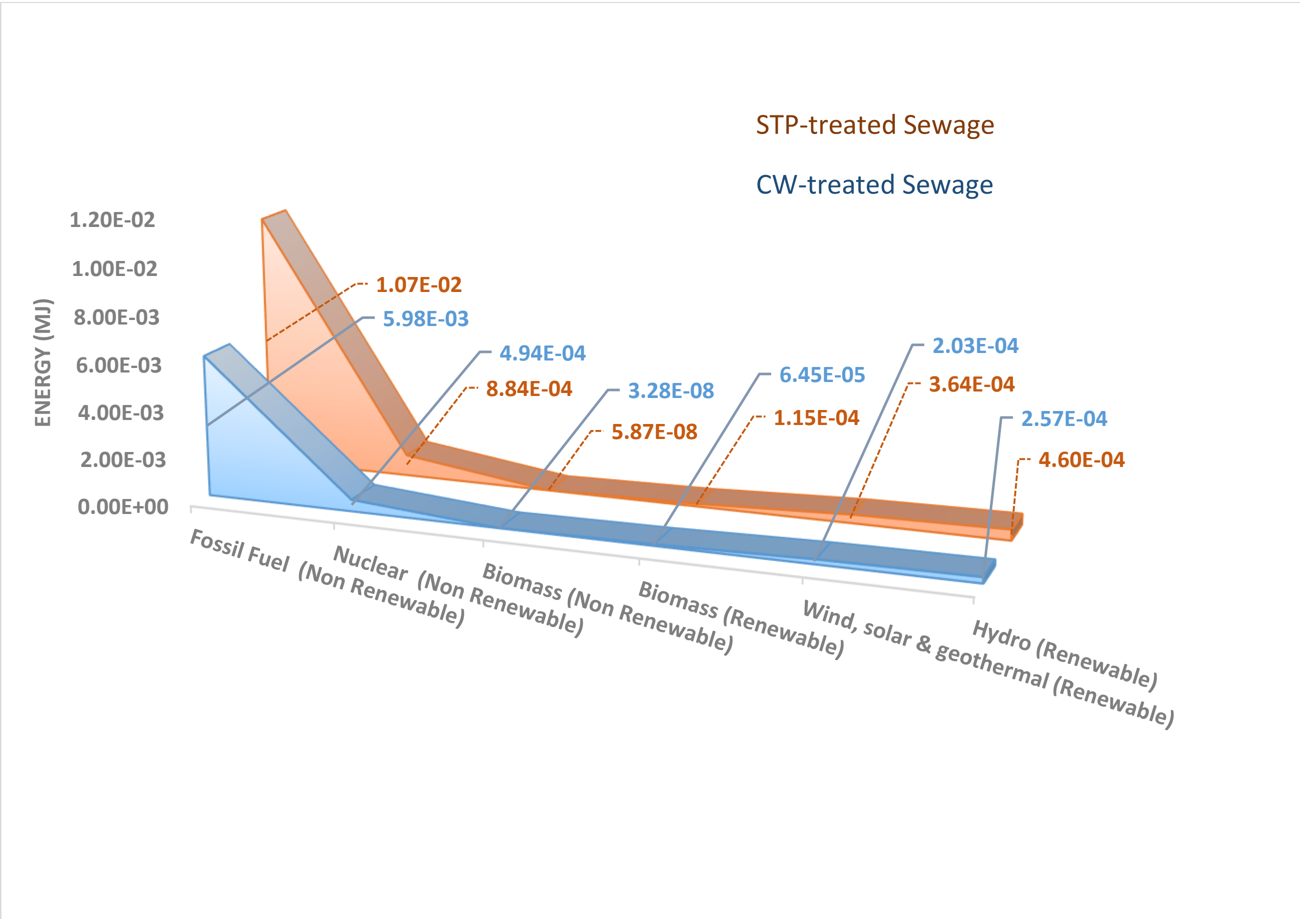

Figure 4: Energy Demand by the Treatment Systems

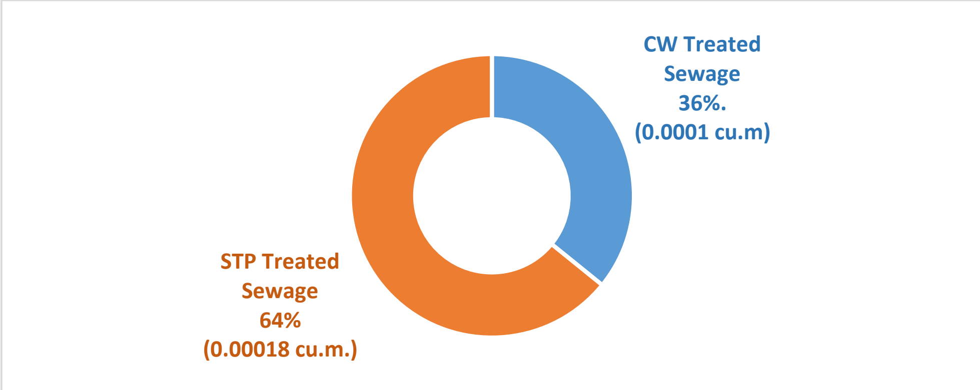

Figure 5: Water-Footprint of the Treatment Systems

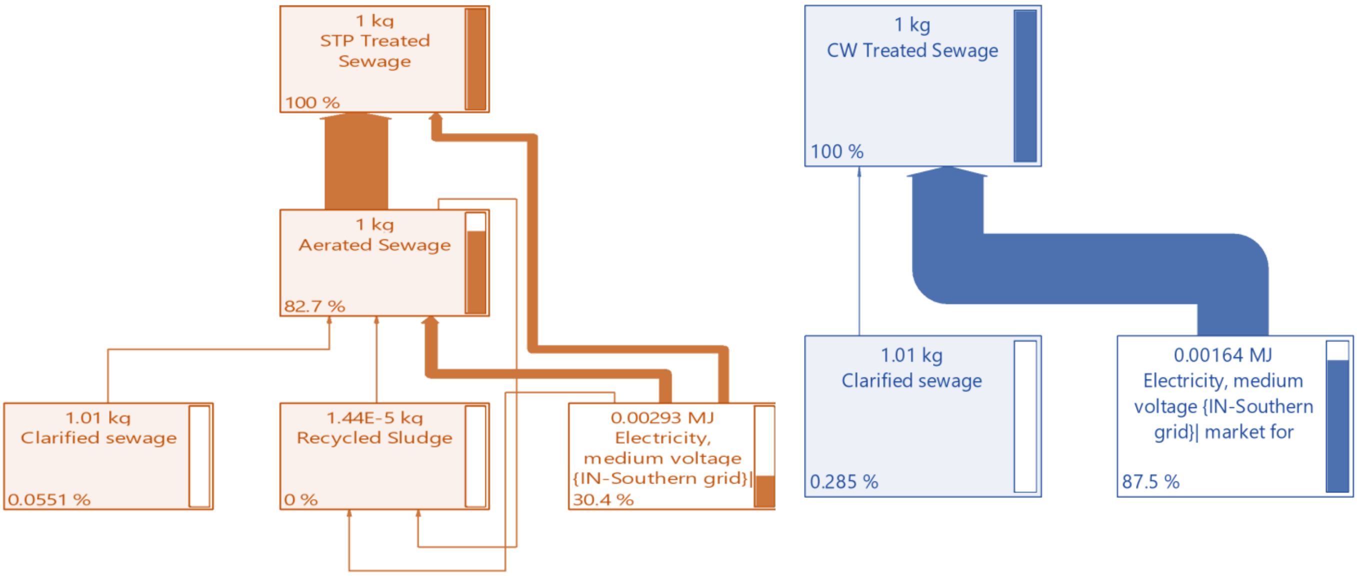

Figure 6: Component Assessment of Sewage Treatment Frameworks by two Treatment Systems

Process and Energy Flow in the Treatment Systems: Figure 6 presents a comparative process flow for 1 kg of treated sewage in STP and CW, further reinforcing the findings from previous figures on energy demand, emissions and water footprint. As presented in the figure, STP exhibits a complex, energy-intensive process, where 82.7% of the sewage undergoes aeration, consuming 0.00293 MJ of electricity, with 30.4% of this energy linked to medium-voltage electricity from the grid. Additionally, STP produces recycled sludge and clarified sewage (1.01 kg), but with a minimal efficiency of 0.0551% in water clarification. These inefficiencies explain the higher water footprint and energy demand seen in earlier assessments.

CW, in contrast, operates with significantly lower energy consumption and a more streamlined process. It requires only 0.00164 MJ of electricity, with 87.5% sourced from the grid, showcasing its minimal reliance on external energy. CW produces 1.01 kg of clarified sewage, with a higher efficiency (0.285%) compared to STP, demonstrating better resource use while maintaining treatment efficacy. STP's mechanical processes, though effective, come at a high environmental cost whereas CW provides a low-energy, sustainable alternative. In fact, from a sustainability perspective, CW offers clear advantages over STP in terms of resource consumption, toxicity reduction and air pollution control. However, the higher eutrophication potential of CW-treated sewage suggests that further optimizations are required to prevent nutrient accumulation. STP, while effective in pollutant removal, presents significant environmental drawbacks due to its high energy consumption, chemical dependency and GHG emissions.

Policy and Sustainability Implications

The findings underscore the need for sustainable wastewater treatment strategies. While STP remains the dominant technology due to its efficiency in pollutant removal, its environmental costs necessitate urgent mitigation measures. Process optimizations, renewable energy integration and advanced pollutant removal technologies could help lower STP's footprint.

Conversely, CWS presents a viable alternative, particularly for decentralized applications. However, its potential for nutrient accumulation calls for design improvements such as enhanced vegetation selection and optimized retention times. A hybrid approach that integrates the strengths of both systems could offer a balanced solution.

Conclusion

Based on the results obtained by the present work, it can be concluded that STP has a higher environmental impact across multiple impact categories compared to CW, including resource depletion, toxicity and greenhouse gas emissions, due to its energy-intensive operations and reliance on fossil fuels. On the other hand, CW demonstrates a more sustainable profile with lower contributions to global warming potential, marine and freshwater eco-toxicity and overall emissions. The impact normalization assessment reveals that CW significantly mitigates environmental burdens across short-term and long-term perspectives whereas STP continues to contribute to major environmental stressors. Energy demand assessment highlights that STP relies more on fossil fuels and non-renewable energy sources (particularly, for aeration, sludge treatment and chemical usage).

CW exhibits lower energy consumption and a reduced carbon footprint by dint of utilizing natural processes such as microbial degradation and plant filtration, thereby reducing dependency on electricity and fossil fuels. Similar results were obtained by water footprint analysis, confirming significantly less water in its operation in CW (36%) compared to STP (64%), making it a more resource-efficient alternative, esp. for water-scarce regions. With regard to specific sustainability parameters, STP seems to contribute significantly to global warming, ozone depletion and eco-toxicity whereas CW has a higher potential for eutrophication due to nutrient retention in treated effluent.

Process flow comparison shows STP's complex, energy-intensive treatment mechanisms**,** while CW maintains efficiency with simpler operations and lower resource utilization. A hybrid treatment approach integrating CW with STP could optimize treatment efficiency, reducing environmental burdens while ensuring effective pollutant removal. Hence, sustainable wastewater treatment strategies should prioritize CW or hybrid systems to enhance energy efficiency, to reduce emissions and to improve overall environmental performance. Future studies should explore optimization strategies for CW to further enhance its efficiency and expand its applicability in various geographical and climatic conditions.

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