Assessing the environmental impacts and greenhouse gas emissions from the common municipal wastewater treatment systems

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Abstract

This study measured the environmental impacts from three same-size wastewater treatment systems, specifically activated sludge, a constructed wetland, and a high rate algal pond. Detailed data inventories were employed using SimaPro 9 software to calculate the entire consequences by ReCiPe 2016 and Greenhouse Gas Protocol method. The environmental outcomes caused by substance emissions and resource extraction are presented in several impact categories at the endpoint level. For a better comparison, the single score tool was applied to aggregate all factors into three areas of protection: human health, ecosystem, and resource shortage. Results showed that concrete and steel are the main contributors to the construction phase, while electricity is responsible for the operation stage. The single score calculation indicates that the proportion of construction activities could be equal to or even higher than the operation stage for a small capacity plant. The total environmental impact of the conventional system was 2.3-fold and 3-fold higher than that of constructed wetland and high rate algal pond, respectively. High rate algal pond has the best environmental performance when generating the least burdens and greenhouse gas emissions of 0.72 kg CO_2 equivalent per m^3. Constructed wetland produces 5.69 kg CO_2, higher than an algal pond but much lower than activated sludge plant, emitting 11.42 kg CO_2 per m^3.

Keywords: Activated sludge, constructed wetland, high rate algal pond, conventional wastewater treatment plant, nature-based wastewater system, environmental impact, life cycle assessment.

LIST OF ABBREVIATIONS

AS	Activated sludge
BOD	Biochemical Oxygen Demand
BNR	Biological Nutrient Removal
CH_4	Methane
CO_2	Carbon dioxide
CO_2 eq	Carbon dioxide equivalent
CW	Constructed wetland
D	Day
DALYs	Disability adjusted life years
E	Egalitarian
GHG	Greenhouse Gas
GWP	Global Warming Potentials
H	Hierarchist
HH	Human health
HFCW	Horizontal flow constructed wetland
HRAP	High rate algal pond
I	Individualist
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Impact
LCIA	Life Cycle Impact Assessment
N_2O	Nitrous oxide
m^3	Cubic meter
mg	Milligram

PE	Population equivalent
PM	Particular matter
Pt	Eco point
t	Ton
VFCW	Vertical flow constructed wetland
WWTP	Wastewater treatment plant
WWTS	Wastewater treatment system
yr	Year

1. Introduction

Discharging unsatisfactorily treated sewage is one common source of pollution, which affects human health and ecosystems. The wastewater treatment system (WWTS) plays a vital role in ensuring aquatic environment quality. However, due to its energy and chemical requirements for construction, operation, and demolition activities, a WWTS also has a negative impact on the environment (Nguyen et al., 2020a). The WWTS consumption of resources depends on the size and treatment method (Kohlheb et al., 2020). Consequently, the effects of WWTSs on the environment are varied due to differences in technology, capability, and sewage types.

The activated sludge (AS) process is one of the most widely used secondary wastewater treatment methods, which can be applied in small to large regions. AS is the conventional bacteria-based technology where the system consists of a sewer and centralized wastewater treatment plant (WWTP) (Garfí et al., 2017). Due to multiple process components and additional resources for treatment activities, AS-based WWTPs require relatively high construction, operation, and maintenance costs. Meanwhile, natural wastewater treatment is a suitable and economical method, preferred for small to medium-sized WWTPs (Garfí et al., 2017; Tunçsiper, 2019). A natural treatment system is defined as reasonable investment, simple operation, and less external energy consumption due to natural self-treatment procedures and basic technology (Garfí et al., 2017).

Numerous studies have been conducted to determine the best type of WWTP. However, the results are not very convinced due to differences in size and treatment technique, and actual target investigations. The other influences are the data availability, local effluent quality standards, and evaluation methods. Life cycle assessment (LCA) is a useful tool that can identify which system is best for the environment, and overcoming their limitations for improvement (Nguyen et al., 2020b). LCA can explore the problems of a single product or a system by analyzing the influences from all relevant processes, which helps to avoid shifting problems from place to place (Nguyen et al., 2020b).

LCA assessed both activated sludge and nature-based WWTPs in scenarios of conventional or advanced types (Brockmann et al., 2021; Resende et al., 2019). However, only few studies have compared the environmental impacts between LCAs' activated sludge and natural treatment methods (Flores et al., 2020; Garfí et al., 2017; Kohlheb et al., 2020; Pan et al., 2011). Multiple impact indicators were measured in these studies, including greenhouse gas (GHG) emissions, electricity consumption, global warming potential (GWP), resource depletion, and eutrophication.

Analysing two small-scale of 15 population equivalent (PE) systems, the findings presented that nature-based solutions have more benefits than AS-based systems in 93% of cases (De Feo et al., 2017). It emerged that, depending on the impact category, a conventional AS WWTP is responsible for 2-5 times more problems than a hybrid constructed wetland (CW) or a high rate algal pond (HRAP) (Garfí et al., 2017). Meanwhile an AS contributes 1.2 to 3 times more than a HRAP in terms of eutrophication potential (EP) and global warming potential (GWP) (Kohlheb et al., 2020). Considering about land use, the results show that CW produces less GHG emissions and is more land-use efficient than AS (Fan et al., 2021; Pan et al., 2011). The CW and HRPA account for a similar level of impact (Garfí et al., 2017).

The limitation of most previous research is the comparison on midpoint environmental burdens categories. Results based on solely one impact index could not be representative of total ecological issues, and the uncertainty at the midpoint is adequately low (PRe', 2020). A wide range of assessment indicators leads to difficulties in finalising the outcome. Due to the differences in measurement units the results could not be summarized accurately, especially when the total effects are only approximate.

In this study, a number of same-size WWTS in term of daily influent rate and population served, including natural and AS-based technologies, will be evaluated. The environmental impacts are quantified at the endpoint indices in the same context. All the results refer to damage levels which are better for making a final comparison. Moreover, the problems originating from construction and operation phases are investigated in detail to better comprehend and develop effective GHG emissions management strategies. LCA is conducted to calculate the influence of different WWTSs to confirm the most environment-friendly structure and what construction and operation activities contribute to the final outcomes.

2. Materials and methods

2.1. Case study description

The selected case study is a hybrid CW consisting of a three-chamber septic tank, two vertical flow CW (VFCWs), and a horizontal flow CW (HFCW). The two VFCWs are working alternately (Garfí et al., 2017). The VFCW is used for high organic matter removal while *Phragmites australis* is put into the HFCW for disinfection purposes (Ávila et al., 2013). The other characteristics are described in Table 1.

Table 1. Case study systems description

System characteristics	Unit	Constructed wetland	High rate algal pond	Activated sludge
TSS	mg/l	280	280	280
BOD_5 removal efficiency	%	90	90	98
TSS removal efficiency	%	95	88	98
Surface area	m^2	5,350	9,000	900
Population serve	PE	1500	1500	1500
Flow rate	m^3/d	292.5	292.5	292.5
Wastewater type		domestic	domestic	domestic

The HRAP system in this case study consists of a three-chamber septic tank, two parallel HRAP, a settler, and a disinfection unit (Garfí et al., 2017). Other relevant information concerning the HRAP is documented in Table 1. The chosen WWTP to compare with natural systems is a conventional AS plant which uses an activated sludge reactor with extended aeration to treat wastewater. The case studies have an influent rate of approximate 300 m^3/day and a population of 1500 PE.

2.2. Life cycle assessment

The assessment follows four phases that are stipulated in ISO 14040: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006).

2.2.1. Goal and scope

The study's goal is to employ LCA to compare the environmental impacts of three WWTSs and finalize the contribution of a single phase in these systems. The chosen WWTPs comprise a CW, a HRAP, and an AS, which are described above. The lifespan of the assessment systems is 20 years. These designs are used to treat the same influent flow rate. The functional unit is 1 m^3 of treated water.

The boundaries include the construction and operation processes of these WWTPs. All the resources to produce materials for construction and chemical for the operation were considered as the input for assessment. GHG emissions and possible waste were included as the systems' output. Materials and wastes transportation are excluded from the study due to the local availability conditions. Neither demolition activity nor recovery process is considered in the research regarding the complexity or character of different scenarios. This research focuses on the waterline, with the exception of the sludge line.

2.2.2. Life cycle inventory (LCI) analysis

The data inventories include all the primary materials, chemicals, and energy for construction and operation phases. Obtaining input data based on each plant's project designs is the most accurate method, while the secondary data can be obtained from published literature (Morera et al., 2017). Of the most trusted database, the life cycle inventories of municipal WWTPs were created by Doka (2003), which generated information for 967 plants.

Primary input data for this research were taken from the engineering design (Garfí et al., 2017), while unavailable information was sourced from Doka (2003), as shown in Table 2. All the sources of information for inventories have their equivalent values which can be obtained from the Ecoinvent 3.5 (Weidema et al., 2013).

Table 2. Data for life cycle inventory analysis of each case study in SimaPro

Materials	per m^3	Activated sludge WWTP	Constructed wetland system	High rate algal pond
Input				
Construction				
Excavation	m^3	2.08E-03	2.08E-03	2.08E-03
Electricity	kWh	2.27E-05	2.27E-05	2.27E-05
Concrete	m^3	3.11E-02	1.13E-04	3.49E-04
Reinforcing steel	kg	9.72E-03	2.43E-02	3.57E-02
Tap water	kg	7.30E-02	7.30E-02	7.30E-02
Aluminium	kg	5.20E-04	5.20E-04	5.20E-04
Chromium steel	kg	3.73E-03	3.73E-03	3.73E-03
Glass fibre	kg	0.00E+00	0.00E+00	1.37E-04
Copper	kg	5.52E-04	5.52E-04	5.52E-04
Synthetic rubber	kg	5.29E-04	5.29E-04	5.29E-04
Bitument	kg	9.12E-02	4.73E-03	3.00E-04
Polyethylen	kg	8.30E-04	2.80E-03	8.12E-05
Limestone	kg	1.28E-02	1.28E-02	1.28E-02
Rock wool mat	kg	5.23E-04	5.23E-04	5.23E-04
Chemicals organic	kg	2.43E-03	2.43E-03	2.43E-03

Chemicals inorganic	kg	2.98E-04	2.98E-04	2.98E-04
Gravel	kg	7.19E-02	7.82E-01	0.00E+00
Brick	kg	0.00E+00	1.66E-02	0.00E+00
Operation				
Iron chloride	kg	1.30E-02	1.30E-02	1.30E-02
Sodium aluminate	kg	4.20E-02	1.53E-06	1.53E-06
Electricity	kWh	1.26E+00	2.20E-01	2.50E-01
Output				
Sludge	kg	1.35E-01	3.45E-01	3.45E-01
CO_2	kg		9.92E-01	
CH_4	kg	3.00E-03	1.10E-02	
N_2O	kg	1.36E-04	1.70E-02	1.70E-04

The output includes the waste and direct emissions from each system. The amount of waste was assumed based on Table 2, while the emissions were measured as follows. Emissions from AS plant were estimated based on the IPCC guidelines (IPCC, 2019). According to IPCC 2019, equations were employed to calculate methane (CH_4) and nitrous oxide (N_2O) emissions from WWTP. GHG emissions depend on the organic compound in wastewater (kg BOD/year or kg N/year) and the country-specific emissions factors (IPCC, 2019). The emissions from AS plants are 0.003 kg CH_4/m^3 and 0.00136 kg N_2O/m^3 of treated wastewater.

GHG emissions from CW and HRAP were obtained from systems with similar configurations. Emissions rates for CW are 0.992 kg CO_2/m^3, 0.011kg CH_4/m^3, and 0.017 g N_2O/m^3 (Garfí et al., 2017). Meanwhile, the level of N_2O emitted from HRAP was 0.00017 kg N_2O/m^3 (Kohlheb et al., 2020).

2.2.3. Life cycle impact assessment (LCIA)

All of the environmental impacts generated by the systems were analyzed by various subset indicators in ReCiPe 2016 and GHG Protocol V1.02. ReCePi is the global assessment method that can combine the ‘problem-oriented approach’ and ‘damage-oriented approach’ (PRe', 2020). ReCiPe 2016 has the widest time horizon and sufficient GHG emissions information. Global elements in ReCePi 2016 replaced the local factors in ReCiPe 2008. The endpoint impact categories were conducted in the egalitarian (E) perspective, which is considered the longest time frame (Nguyen et al., 2021). Using the endpoint factors could solve the limitation of the midpoint method where the impacts are presented in multiple characterization categories. All the effects are normalized, weighted, and aggregated into endpoint values, which is convenient for summary and comparation.

Figure 1 shows the procedure to convert midpoint to endpoint values (PRe', 2020) and how multiple impacts categories are integrated into single value. The requirements of raw materials and land use, and GHG emissions led to problems in several aspects. The problems are analysed and presented through 14 environmental midpoint indicators. Those indicators will be multiplied with matching damage factors to define the impacts on three endpoint areas, including damage to human health, destroy to ecosystems, and ruin to resource availability. These endpoint values are further integrated into the form of one indicator, known as the single score, where overall environmental performance is counted in eco-point (Pt).

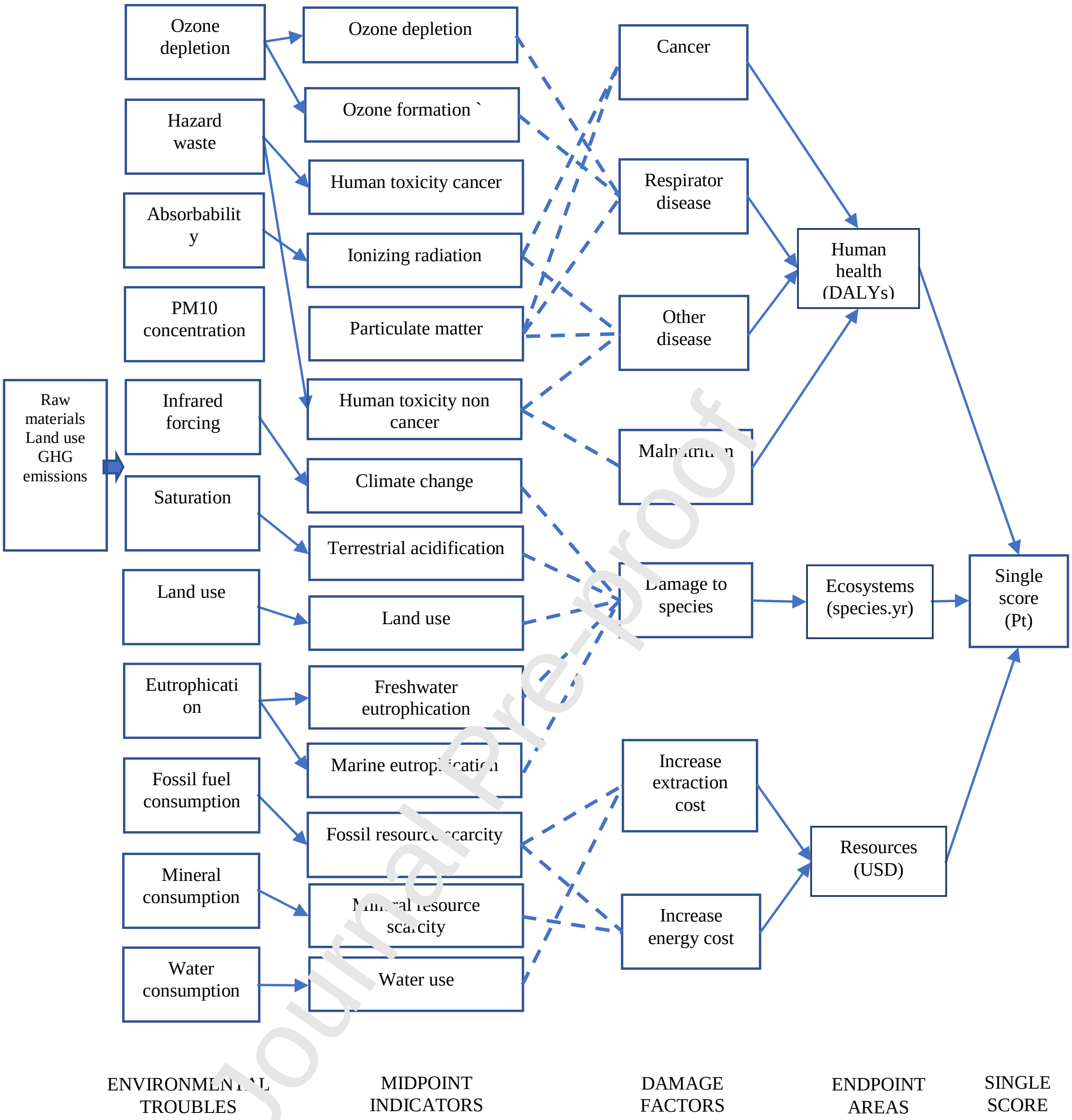


Figure 1. The connection between data inventories, midpoint, and endpoint indicators.

GHG Protocol is a method that can measure entire GHG emissions for a product inventory and convert non-CO_2 gases to CO_2 equivalent (Nguyen et al., 2021). According to this method, fossil and biogenic flows are described separately (PRe', 2020). The research employed SimaPro 9.1 software for assessment. All the data inventories were presented in their equivalent in Ecoivent 3.5.

2.2.4. Life cycle interpretation

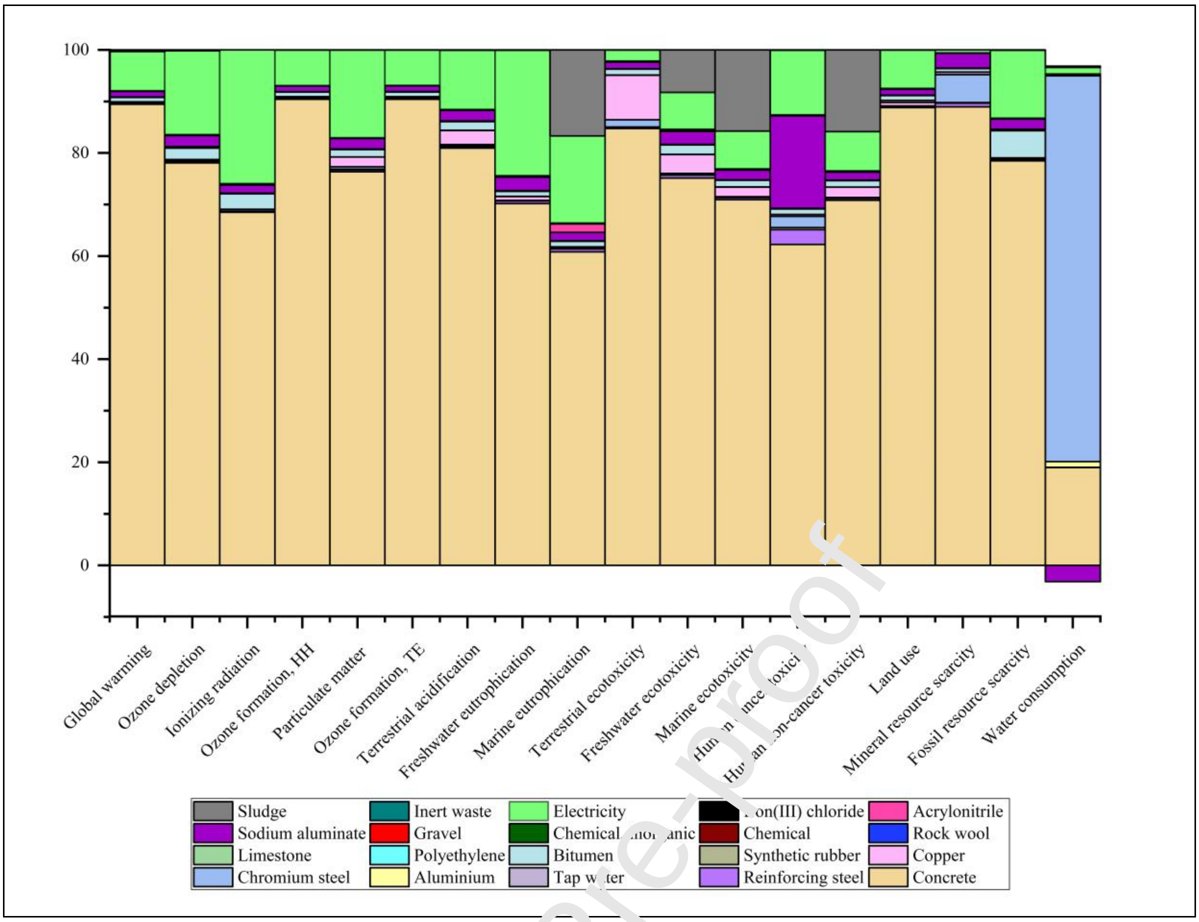
Inventory analysis and impact assessment results were considered and combined to interpret in the discussion and conclusion sections. The interpretation reflects the potential environmental impacts from relevant activities and explains the limitation of the study. This phase is affected by the availability and quality of the input data. Findings of the life cycle interpretation stage describe the results of the assessment indicators (ISO, 2006). In general, this phase is used for making decisions about the impacts on the environment.

3. Results and discussions

3.1. Contribution of construction and operation phases to environmental problems

Figure 2 presents the results of LCA for the AS, CW, and HRAP, respectively, based on ReCiPe 2016 midpoint impact categories. The influences of various elements on the construction phase are shown in these depictions. The list of material components for the three systems is quite similar. However, their impacts on the environment are significantly different. The primary contributors to environmental problems are concrete, steel, and electricity. It can be seen from Figure 2(A), with reference to the AS plant, that concrete and electricity play notable roles in most of the indicators. Electricity accounts for the highest impact on ionizing radiation and freshwater eutrophication. The greatest percentage of water consumption is caused by chromium steel. In addition, concrete dominates the remainder of the impact elements, which range from 20% to 88%. The other components that contribute to environmental challenges are sodium aluminate, sludge and copper.

2(A)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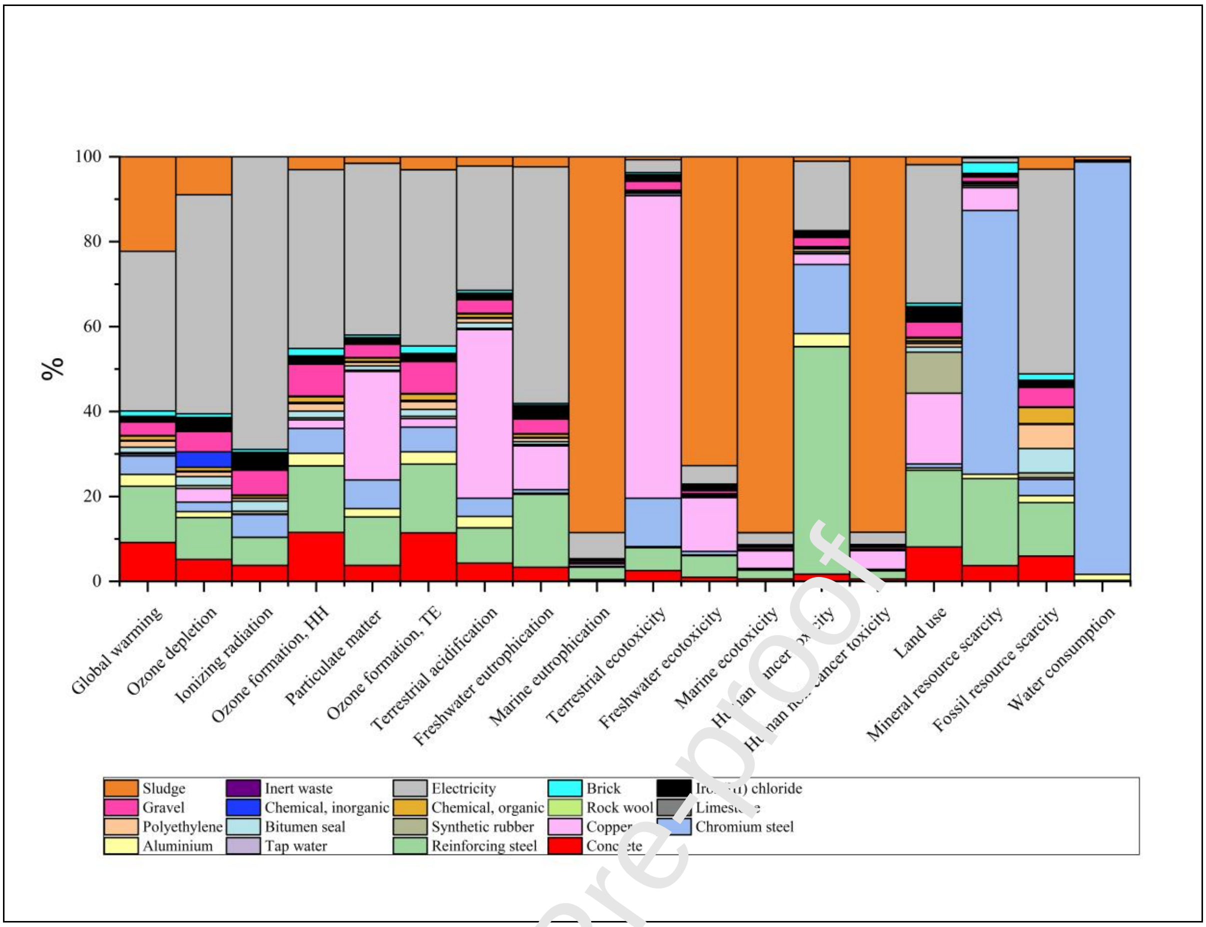
Ionizing radiation
Ozone formation, HH
Particulate matter
Ozone formation, TE
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human cancer toxicity
Human non-cancer toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption
Sludge
Inert waste
Electricity
Iron(III) chloride
Acrylonitrile
Sodium aluminate
Gravel
Chemical, inorganic
Chemical
Rock wool
Limestone
Polyethylene
Bitumen
Synthetic rubber
Copper
Chromium steel
Aluminium
Tap water
Reinforcing steel
Concrete

2(B)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Inert waste
Electricity
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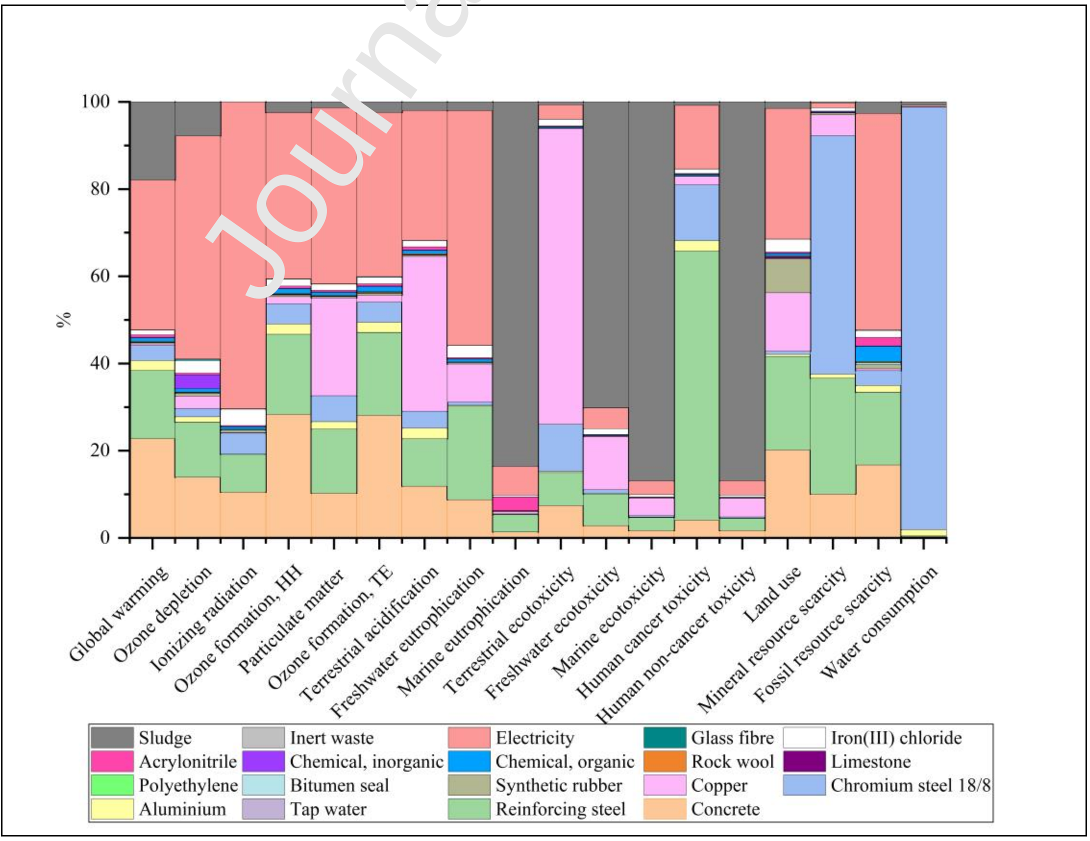
Gravel
Chemical, inorganic
Chemical, organic
Rock wool
Limestone
Polyethylene
Bitumen seal
Synthetic rubber
Copper
Chromium steel
Aluminium
Tap water
Reinforcing steel
Concrete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Marine ecotoxicity
Human cancer toxicity
Human non-cancer toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption
Sludge
Inert waste
Electricity
Glass fibre
Iron(III) chloride
Acrylonitrile
Chemical, inorganic
Chemical, organic
Rock wool
Limestone
Polyethylene
Bitumen seal
Synthetic rubber
Copper
Chromium steel 18/8
Aluminium
Tap water
Reinforcing steel
Concrete

2(C)

Figure 2(A) Life cycle impact analysis for activated sludge wastewater treatment plant; 2(B) Life cycle impact analysis for constructed wetland system; 2(C) Life cycle impact analysis for high rate algal pond.

In the HRAP system (Figure 2 (C)), after electricity, sludge and reinforcing steel, chromium steel, copper and sludge play similar roles when assessing what the consequences are. Concrete, in this case, is the least critical substance compared with AS, but it has a greater effect than that in CW (Figure 2(B)). It is worth mentioning that the quantity of concrete for HRAP is three times higher than CW. Steel is dominant in CW and HRAP, while its performance in AS is negligible. The reason is due to the variations in the volume of steel consumed in these systems.

In comparison to other cases, AS consumes the least amount of steel but the highest volume of concrete. Results demonstrate the relationship between the quantity of material and its environmental impacts, and concrete production brings a significant burden to steel manufacture. These findings have also been indicated in a recent study where the production of concrete results in higher GWP than steel due to greater energy requirements (Nguyen et al., 2020a).

Figures 2 (A), (B) and (C) depict the characterization calculations at endpoint grade in the egalitarian scenario which is known as the safest perspective (Nguyen et al., 2021). The environmental impact scores are presented at midpoint or endpoint characterization factors that contain uncertainties. The results show a strong relationship with the environmental flow at the midpoint level, while the endpoint characterizations deliver sufficient information regarding environmental relevance (Huijbregts et al., 2016). However, the consequences are defined under multiple categories. To better understand the contribution of each phase to the entire footprint, a single score calculation method was conducted and presented in Figure 3.

Figure 3 shows that the construction and operation phase influences on the total impacts are different among AS, CW, and HRAP. The construction stage was believed to make a minor contribution to the environment compared with the operation stage. However, this research shows that construction accounts for approximately 78% of the effect in AS WWTP. In the CW and HRAP systems, the consequences of the construction phase are quite small. Significant impacts are recorded on human health for both operation and construction phases. In contrast, their influences on resources are negligible.

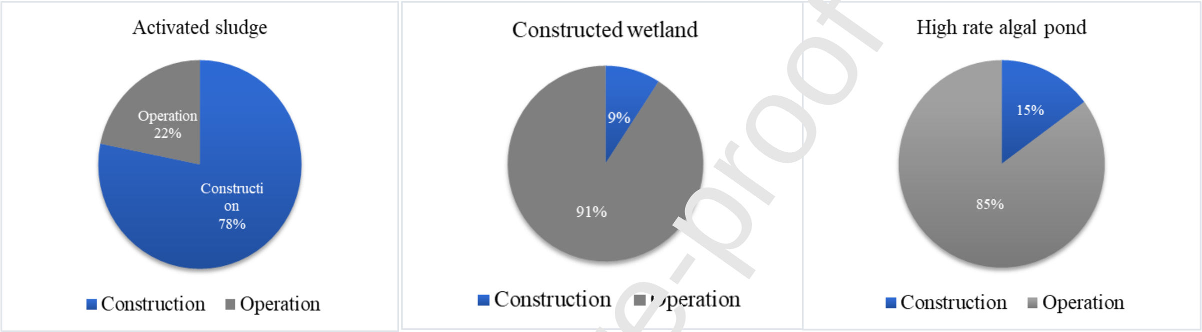

Figure 3. Proportion of problems caused by construction and operation

In comparison to the literature review, the contribution of the construction phase to the total impact in the natural based system is 15-50% (Flores et al., 2019; Fuchs et al., 2011). Results documented in this study are consistent with what other research reported for HRAP. Although lower impact is found for CW, it has the similar trend in general. However, according to their findings, construction dominates a few assessment indicators such as metal depletion, GWP, and photochemical oxidation (Arashiro et al., 2018; Garfí et al., 2017). The endpoint calculation in this study shows that construction could be the major contributor to various factors due to infrastructure materials (concrete, steel) on the environment.

A remarkable difference of this study to others is the share of the operation and construction to the entire burdens of the AS WWTP. Many papers conclude that the proportion of the building is under 5% and negligible (Corominas et al., 2020), while others report its influences is considerable, especially in terms of metal depletion (Morera et al., 2017; Nguyen et al., 2020a). In this study, construction has a 3.5-fold higher impact than the operation stage. The reason for this is the massive volume of building materials compared to lifetime energy and chemicals requirement (Table 3). Concrete, the primary substance with the greatest quantity, also contributes the most to the final outcomes (Figure 2A). It should be noted that the AS WWTP has a capability of 1500 PE, which is typical of the smallest size WWTP (Doka, 2003). Hence, in equivalent per functional unit (m^3), the energy and chemicals consumption are relatively lower than concrete usage. Subsequently, the operation stage wields less impact than construction activities. Although the specific site information does differ in some respects between this paper and others, the results can be used as a reference when measuring a WWTP footprint.

3.2. Environmental impacts and GHG assessment for conventional and nature-based WWTPs

Table 3 reveals the potential environmental effects related to each WWTS. The AS plant has much more of an environmental impact than CW and HRAP systems in all evaluation characterizations. Similar findings have been noted in other studies when comparing activated sludge and nature-based systems (Garfí et al., 2017; Kohlheb et al., 2020). The reason for this due to AS requiring a huge amount of resources compared to the two nature-based configurations. CW and HRAP, which are known as low-energy networks, consume five times less electricity than AS. Moreover, the quantity of concrete used for the AS framework is exceptionally larger than the other two plants. It should be recalled that concrete could produce more environmental damage than other construction materials (Nguyen et al., 2020a).

The assessment results are measured and exhibited in three units, namely disability adjusted life years (DALYs), species.yr, and USD2013. The endpoint characterization factors which appear with DALY unit have consequences for human health damage such as years of life lost or years spent being disabled in some way. For the environment, it means the vanishing of species in a specific location during a period of time. The potential for not having enough resources is expressed in terms of future resource manufacturers' excess cost (PRe', 2020). CW has less effect on climate change than HRAP, which in turn is more pronounced than CW.

Table 3. Damage assessment at endpoint level of the case studies

Impact category	Unit	Activated sludge	Constructed wetland	High rate algal pond
Global warming, Human health	DALY	1.37E-04	7.42E-05	6.58E-06
Global warming, Terrestrial ecosystems	species. yr	2.74E-07	1.48E-07	1.32E-08
Global warming, Freshwater ecosystems	species. yr	7.49E-12	4.05E-12	3.59E-13
Stratospheric ozone depletion	DALY	4.80E-09	2.64E-10	3.02E-10
Ionizing radiation	DALY	9.31E-09	6.11E-10	6.81E-10
Ozone formation, Human health	DALY	2.63E-08	7.49E-10	9.40E-10
Fine particulate matter formation	DALY	7.40E-06	5.43E-07	6.18E-07
Ozone formation, Terrestrial ecosystems	species. yr	3.77E-09	1.09E-10	1.36E-10
Terrestrial acidification	species. yr	5.69E-09	3.90E-10	4.36E-10
Freshwater eutrophication	species. yr	1.25E-09	9.55E-11	1.12E-10
Marine eutrophication	species. yr	3.29E-13	1.59E-13	1.68E-13
Terrestrial ecotoxicity	species. yr	4.61E-10	5.62E-11	5.91E-11
Freshwater ecotoxicity	species. yr	2.25E-10	6.52E-11	6.76E-11
Marine ecotoxicity	species. yr	2.32E-07	1.05E-07	1.07E-07
Human carcinogenic toxicity	DALY	6.52E-05	8.73E-06	1.11E-05
Human non-carcinogenic toxicity	DALY	4.24E-04	1.94E-04	1.98E-04
Land use	species.	1.32E-08	5.26E-10	6.52E-10

	yr			
Mineral resource scarcity	USD2013	2.67E-02	2.32E-03	2.64E-03
Fossil resource scarcity	USD2013	5.61E-01	2.18E-02	2.26E-02
Water consumption, Human health	DALY	1.10E-06	9.38E-07	9.39E-07
Water consumption, Terrestrial ecosystem	species.yr	6.74E-09	5.71E-09	5.71E-09
Water consumption, Aquatic ecosystems	species.yr	3.22E-13	2.57E-13	2.58E-13

As shown in Figure 4, all characterization factors are combined and weighted to explain how impact pathways destroy the environment and three variables of protection: human health, ecosystems, and resources. The total effect of CW and HRAP are approximate and similar to results in the literature review (Garfí et al., 2017). The important thing is that CW is responsible for a slightly higher burden than HRAP and consumes fewer materials (Table 2). The explanation for this is that CW emits more direct GHGs than HRAP. The results from Figure 5 support this assumption.

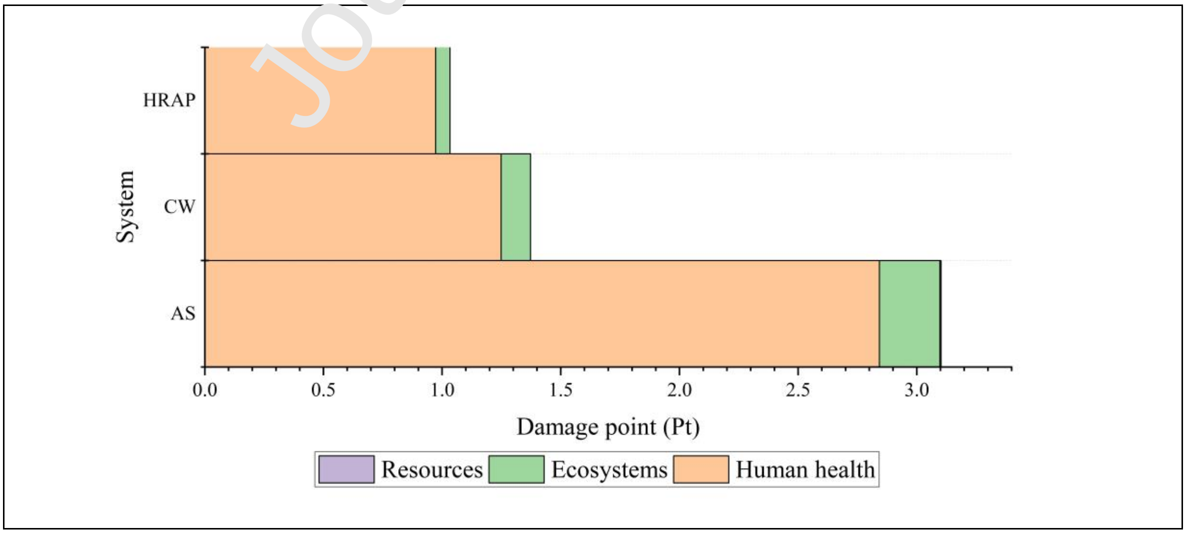

Figure 4. Indicators corresponding to the three areas of protection

Total GHG emissions from fossil sources, land transformation, biogenic component, and CO_2 uptake potential are presented in Figure 5. Carbon dioxide and non-CO_2 gases are measured and converted to CO_2 equivalent. The AS WWTP accounts for the largest emissions. Although AS has the highest quantity of CO_2 uptake, the CO_2 beneficial amount is negligible compared to fossil release weight. CW emits more fossil gas and has poorer CO_2 compensation ability than HRAP. Of the three systems, HRAP generates the least GHG emissions.

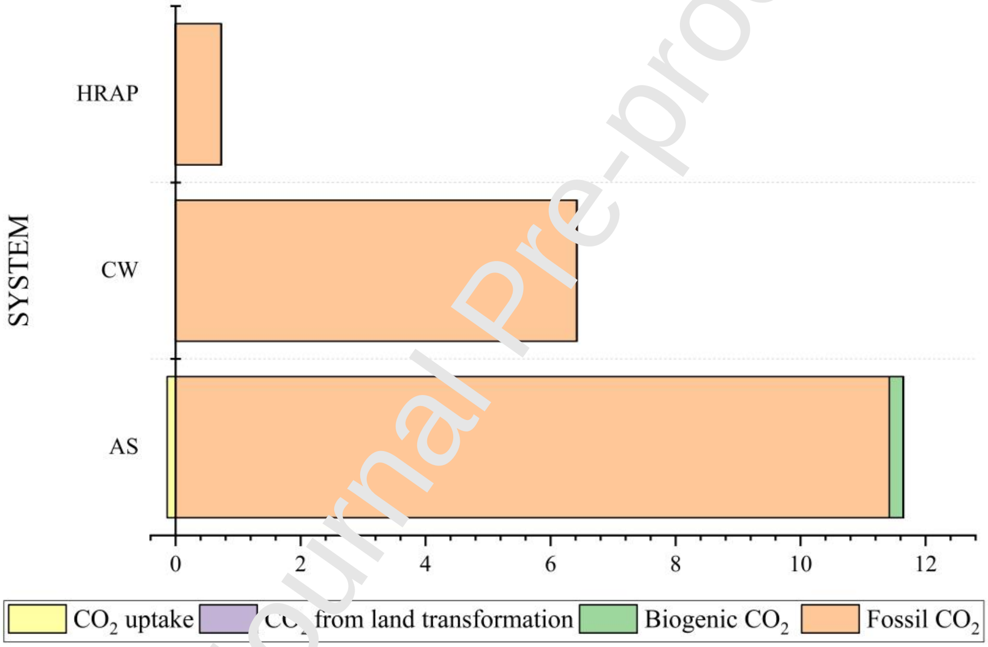

Figure 5. GHG emissions evaluation using the GHG Protocol method.

An uncertainty analysis has been conducted to explore the benefit to environment between CW and HRAP systems. Table 4 shows that CW is responsible for higher impact to global warming and water consumption. This calculation supports for the findings from Figure 4.

Table 4. Uncertainty analysis for constructed wetland and high rate algal pond systems

Impact category	CW ≥ HRAP	Mean	Median	SD	CV	2.5%	97.5%	SEM
Particulate matter	0	-1.19E-04	-1.18E-04	1.35E-05	-1.14E+01	-1.48E-04	-9.41E-05	4.28E-07
Fossil resource scarcity	0	-8.50E-03	-8.41E-03	1.81E-03	-2.13E+01	-1.23E-02	-5.33E-03	5.72E-05
Freshwater ecotoxicity	0	-3.48E-03	-3.32E-03	9.28E-04	-2.67E+01	-5.59E-03	-2.23E-03	2.94E-05
Freshwater eutrophication	0	-2.54E-05	-2.27E-05	1.18E-05	-4.65E+01	-5.68E-05	-1.17E-05	3.74E-07
Global warming	100	5.41E+00	5.41E+00	1.35E-02	2.49E-01	5.38E+00	5.43E+00	4.26E-04
Human cancer toxicity	0	-7.24E-01	-6.56E-01	5.93E-01	-8.19E+01	-1.42E+00	-3.42E-01	1.88E-02
Human non-cancer toxicity	0	-1.54E+01	-1.38E+01	6.55E+00	-4.26E+01	-3.29E+01	-8.39E+00	2.07E-01
Ionizing radiation	0	-4.92E-03	-3.74E-03	4.47E-03	-9.10E+01	-1.47E-02	-1.92E-03	1.41E-04
Land use	0	-1.41E-02	-1.35E-02	3.59E-03	-2.55E+01	-2.24E-02	-8.66E-03	1.14E-04
Marine ecotoxicity	0	-1.87E+01	-1.68E+01	7.87E+00	-4.21E+01	-3.91E+01	-1.03E+01	2.49E-01
Marine eutrophication	0	-5.49E-06	-5.48E-06	3.72E-07	-6.77E+00	-6.28E-06	-4.81E-06	1.18E-08
Mineral resource scarcity	0	-1.35E-03	-1.30E-03	3.05E-04	-2.27E+01	-2.06E-03	-8.42E-04	9.65E-06
Ozone formation, HH	0	-2.09E-04	-2.05E-04	3.55E-05	-1.70E+01	-2.90E-04	-1.50E-04	1.12E-06
Ozone formation, TE	0	-2.13E-04	-2.09E-04	3.61E-05	-1.70E+01	-2.95E-04	-1.53E-04	1.14E-06
Ozone depletion	0	-2.87E-08	-2.84E-08	3.90E-09	-1.36E+01	-3.73E-08	-2.18E-08	1.23E-10
Terrestrial acidification	0	-2.16E-04	-2.13E-04	2.86E-05	-1.33E+01	-2.75E-04	-1.64E-04	9.05E-07
Terrestrial ecotoxicity	0	-2.52E-01	-2.45E-01	7.68E-02	-3.05E+01	-4.25E-01	-1.24E-01	2.43E-03
Water consumption	44.6	-1.29E-03	-3.71E-03	3.00E-02	-2.33E+03	-5.40E-02	6.77E-02	9.49E-04

Regarding total environmental consequences and GHG emissions at the endpoint level, HRAP is the most environmentally friendly system, while AS WWTP performs the worst.

The single score estimation method is increasingly popular for making a comparative assessment (Kalbar et al., 2017). Although after aggregation, when the single scores supply less detailed information about the environmental mechanism, this problem could be solved by providing characterized and/or normalized calculations (ISO, 2006). The endpoint results in this study were concluded after analyzing both characterized and single scores factors. However, the findings are restricted by the specific information concerning the case studies. The results could be applied for the same size WWTS having identical configurations.

4. Conclusions

This study calculated and compared the potential contribution to environmental problems generated from three WWTSs. The assessment covers the construction and operation phases by obtaining the particular input data from the plant and Ecoinvent database. The chosen functional unit is 1 m^3 of treated wastewater. SimaPro 9.1 was conducted for the analysis. The key findings are as follows:

- The contribution of the construction phase varies and depends on the quantity of materials consumed. The proportion could be equal or even higher than the operation phase in some particular cases;
- All the environmental impacts of the WWTP are governed by the configuration, and treatment method;
- In comparison to nature-based systems, conventional WWTP generates 2 to 3 times more consequences and 2 to 15 times higher GHG emissions;
- HRAP emits 8.8 times less GHG emissions whilst leading to 1.3 times less problems than CW;
- The single score LCA method is more convenient for comparison when sufficient normalization calculations are provided.

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Highlights

- The construction phase’s contribution to small-sized WWTP is significant.
- High rate algal pond is more environmentally friendly than a constructed wetland.
- Conventional WWTP consumes more resources than nature-based plants.
- Nature-based plants produce fewer emissions than conventional WWTP.
- Factors at the endpoint level present more relevant environmental information.